Driver Cooling System
Final Design Review Report

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Senior Project
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Abstract

This document provides our Final Design Review for the Driver Cooling System Project. It contains our background research, which includes current product research, technical research, and information on our sponsor's needs as a customer as well our manufacturing process, test results, and final design. We created a problem statement to define the scope of the project, discuss sponsor and consumer needs and wants, and technical specifications. After brainstorming, we ultimately selected a thermoelectric cooling system (TEC) after presenting our Preliminary Design Report and Critical Design Report. We built the final prototype, as can be seen in the manufacturing plan, and tested it according to our Design Verification Plan & Review (DVP&R). The project management and future suggestions to improve on our design are in the last two sections (8 and 9) of the report.

TABLE OF CONTENTS

List of Figures

List of Tables

1 Introduction

Race car drivers take part in a variety of different kinds of races, with some spanning hundreds of miles. They wear a racing suit, with a couple of layers, while locked in a cockpit that can reach temperatures of around 140 °F. It is not hard to see that drivers can get hot quickly. To increase comfort and avoid the possibility of overheating, most drivers wear a shirt with cooled fluid running through sewn-in piping. Currently, there is a hole in the market for an affordable system that can sufficiently cool a driver for the full length of a race. Through California Polytechnic State University's Mechanical Engineering Senior Project Program, Justin Jang is funding an effort to create a system that can fill this gap in the market. In the following sections of this CDR, we will describe our problem and its background, and then systematically go through the objectives and our projected process of how we tackle each segment of the project. Finally, we will describe our final design and how well it meets our project specifications as well as the results of our tests on the system.

2 Background

For a better understanding of our competition, we have created a patent table to understand the current refrigeration cycle solutions and discuss why the lack of patents for thermoelectric cooling (TEC) solutions allow us more opportunity going forward with TECs.

When we were pitched this problem, we were given a thorough baseline of the problem and the goals of the new product. In addition, we cleared up questions about product life, vibrations, and size in our first meeting with our sponsor, Justin. Notes from this meeting are in Appendix A. With our preliminary questions answered, we continued with our background research of the project to create a concise problem statement and better understand our customers' wants and needs. These will be gone over in greater detail in the Objectives (Section 3).

2.1 Competitor Information

We considered the current products on the market and found two main competitors: Rini Technologies [1] and CoolShirt Systems [2].

Rini Technologies: The system is a compact cooling system that retails for $7800 and has a handful of professional racers who endorse the product. The Rini is a refrigeration-based system, powered by a 12 V, 6 A power source found in a majority of race cars. The product, as shown in Figure 1, uses a shirt with sewn-in tubing and runs cooled fluid through the tubes. Rini states its product can hold a 55°F fluid temperature and has four modes of adjustment. When the system is working, it seems to do very well. However, reliability is the Rini's main downfall, as it struggles to last a full racing season. At its price point, it is very hard for club racers to justify purchasing. The Rini system states that it uses patented technology. Rini cites four patents for their mini refrigeration systems [1]. All the patents seem to be regarding the compressor and condenser units. Refer to Appendix C to see the Rini System, as well as their patent information.

Figure 1. Rini Technologies' Cooling System

CoolShirt Systems: The system, shown in Figure 2, is based off an ice chest design, where water cooled by ice is pumped into the driver's shirt. CoolShirt makes two types of motorsport systems, one that just cools the body and one that cools the driver's head and body. On their website, the system can constantly displace 300 W [2]. Their system requires 2.5 to 4.9 A and 12 V. The only way to adjust the system is to increase the pump or fan speed, effectively meaning there is no user adjustability. The pumped water starts ice cold and gradually heats up as the ice melts. The system is ineffective once there is no more ice and will only pump warm water. CoolShirt Systems states that their system works up to three hours. This system is cheap and for this reason is appealing to the lower levels of motorsport. According to the company's LinkedIn page, they hold 24 different patents [3]. Refer to Appendix C to see CoolShirt Systems' product sheet.

Figure 2. CoolShirt Systems' Cooling System

2.2 Problem Research

When we first met with our sponsor, we speculated that the human body would roughly produce 100 W of heat in a stressed environment. In our research, we found an article from Cornell declaring that an average human can give off 227 to 402 W [5]. However, this calculation is for the worst-case scenario and is for the entire body. We are only dealing with the torso and arm region of the body, which at most contributes to 54% of the total surface area of the body, according to The Rule of Nines (Appendix E). Our cooling scenarios will range from 80 W to 220 W, depending on driver size and whether they have a suit that covers their entire upper body, excluding the head or just the torso. While this gives us a target range, we plan on testing this early in the ideation period of our work to help with the success of the project.

Since we were debating whether to go with a refrigeration or a thermoelectric cooling design, we decided to include a patent table (Table 1) with both solutions. We found four patents from Rini Technologies for their efficient, compact vapor-compression technology. For TEC solutions, we did not find patents specifically for cooling down fluid and pumping it through a shirt. There were two patents, one discussing TECs for food and beverage cooling and another describing a suit with TECs attached directly to it, worn by a motorcyclist. Since there are no patents with TECs being used for our purpose, there is less of an issue going for a TEC solution.

Table 1. Patent Summary

Patent Number	Brief Description
US 7,010,936	Rini Technologies - Method and apparatus for highly efficient compact vapor compression cooling
US 7,318,325	Rini Technologies - Method and apparatus for highly efficient compact vapor compression cooling
US 7,942,642	Rini Technologies - Method and apparatus for highly efficient compact vapor compression cooling
US 8,024,942	Rini Technologies - Method and apparatus for highly efficient compact vapor compression cooling
US 8,839,631	Thermoelectric cooling system for a food and beverage compartment
US 6,510,696	Thermoelectric air-condition apparatus

2.3 Possible Solutions

When this project was proposed to us, it was named "Refrigeration Based Driver Cooling System," and while in the beginning of our project we agreed that a refrigeration cycle may be our best option, we did not want to lock ourselves into a certain design without considering other methods. With that said, we examined alternative technologies.

One of the more promising technologies we considered were heat pipes. Heat pipes are a two-phase passive capillary heat transfer system [4]. They come in a wide range of sizes and materials, from copper and aluminum shells to water and nitrogen working fluids. They can be manufactured to be flexible or rigid and the flexible version can displace 150 W. They also can be integrated into a heat sink system that can handle a max heat flux of 350 W/cm^2. See Appendix E for more information on Heat Pipes.

We also considered a Thermal Pulse system that claims to regulate body temperature through thermal pulses. The technology is not well documented, and the system is made by Embr Labs.

Researching the refrigeration cycle, we found a company called Aspen Systems that creates miniature refrigeration compressors, as well as refrigeration systems. These compressors are small enough to fit in your hand and have impressive performance characteristics, displacing up to 360 W with the 1.4 cc version. The compressor can handle a variety of common refrigerants and weighs under two pounds. We have attached the technical specifications of the compressor in Appendix C. Aspen also produces a wide variety of thermal systems that we considered, including a custom Driver Cooling System. According to their website, it can displace 250 W at peak performance. We also considered direct expansion systems, which are the most compact form of a refrigeration system. Aspen does not directly link a specification sheet for this type of system.

We also looked into thermoelectric coolers, which have a high amount of cooling for low temperature differentials, no moving parts, and are easy to use. However, these coolers need a heat sink and require a lot of power.

3 Objectives

The problem statement has been updated to reference that our product must be compatible with the shirt that our sponsor will purchase separately. We have related the QFD to each specification in Section 3.4.

3.1 Problem Statement and Customer Needs

Club race car drivers need a way to keep their bodies cool during an extended racing period due to the high temperatures in the driver cabin. Currently, the only systems available are either cheap and inefficient or expensive and unreliable. Our aim is to make an affordable, lightweight product that effectively cools the driver, is interchangeable between most club race cars, and more reliable than the existing expensive system, which often fails after a couple uses. The product must also be compatible with the shirt provided by our sponsor.

The customer needs for the product are to keep the driver cool throughout a race and to have a durable product (approximately 100 hours lifespan), while having the prototype cost relatively cheap compared to the current high-end alternative. Stretch goals would include a higher lifespan, user adjustability for temperature, and vibration testing of the product. It is important for our product to be compatible with the shirt provided by Justin to size the pump and create proper fittings for the right tube diameter, 3/8 inch. The full list of Customer Needs/Wants can be viewed in Appendix A.

3.2 Boundary Diagram

We created boundary diagrams to visually illustrate the system in its operating environment, as shown in Figure 3. The cooling suit and heat exchanger are in blue, representing that it is within the system. The cooling line is shown in yellow and is viewed as a more critical component than the power line, shown in red. The driver is wearing the cooling suit and the heat exchanger is in the hollowed cockpit where the passenger seat would be located. Our project mainly deals with the heat exchanger unit, as the cooling suit is going to be purchased separately by our sponsor.

Figure 3. *Boundary Diagrams*

3.3 QFD Description

To characterize the voice of the customer, we used the method of Quality Function Deployment (QFD), which can be seen in Appendix B. The QFD allows us to list the customer's demanded qualities and quantify them into engineering metrics. The metrics have corresponding numerical targets and are weighted based on importance. We chose the qualities and metrics based on the interview with our sponsor and our own research. Existing product research, or benchmarking, is conducted for both the customer requirements and the engineering specifications and are rated on a 1-5 scale. We researched the Rini and CoolShirt Systems. While the Rini system is lightweight and able to keep the driver cool, it has a high cost and lacks durability. CoolShirt Systems is cheap and has a long lifespan, but it is heavy, not compact, and only cools if the ice is cold. The competitor ratings are found on the right under "Customer Ratings".

Along with benchmarking, the customer needs and wants and engineering metrics are shown in the QFD. The customer needs and wants are on the left under "Demanded Quality" and the engineering metrics are on the top labelled "Measures". Their needs helped us create the Specifications Table as shown in Table 2.

3.4 Specification Descriptions

Table 2. Specifications Table (*Potential vibes testing or other running tests)

Spec #	Specification Description	Target (units)	Tolerance	Risk	Compliance
1	Cooling Temperature	70°F*	Max	M	A, T
2	Longevity	100 hour life	Min	H	A, T*
3	Cost	$1,200	Max	M	A
4	Compactness	1 ft^3	Max	M	A, I
5	Current (Power)	6 Amps*	Max	L	T
6	Setup Time	5 min	Max	L	T
7	Weight	10 lb*	Max	L	T, S
8	User Interface	3 settings	Min	M	T, S

Compliance Key	Risk Key
A - Analysis	L - Low
T - Test	M - Medium
S -Similarity to Existing Designs	H - High
I - Inspection	

*We have updated these specifications with our new design. Our new power requirement is 30A max and new weight specification is 15 lb. We will still attempt to meet the 10 lb. maximum.

The Specifications Table shows the parameters and their corresponding target. Tolerance shows if the target is a maximum or minimum value. The risk column is our assessment of the risk of meeting the engineering target, and the compliance column signifies our compliance method.

The cooling temperature must remain low to keep the customer cool during driving. Therefore, it is one of the most important targets. The 70°F refers to the working fluid temperature that will be pumped in the system. The specification will be analyzed using heat transfer and thermodynamic analysis. We can test the temperature by measuring it before and after running the system for a given period of time. There is a medium risk because it might be difficult to get enough cooling from a relatively small system.

Longevity is another key specification, according to our QFD, due to it having a strong correlation with our product being durable and reliable. The specification may be analyzed using life analysis on key components, determining the amount of cycles completed until failure. We might possibly run vibrations testing and put our system on a shake table to extrapolate life. This specification is a high risk due to the nature of the analysis and testing. It is hard to guarantee the product will last as long as stated.

Cost is important to have customers interested in and purchase our product. It is also important for our sponsor due to budgetary constraints. The cost of $1200 in our QFD is for our final prototype, so most likely the manufacturing cost will be less due to purchasing in bulk. We can keep track of our costs in an Excel spreadsheet. The prices will be researched online, and we can contact companies for a price quote via email. The risk is medium because some of the components are expensive and there might be associated costs in manufacturing.

The compactness specification is important to universally fit in all racecar cabins. Its small size allows easier handling of the cooling unit for the customers. The compactness of our system can be measured using the dimensions of the components. We can also optimize the placement of the components within our system. The associated risk is medium due to the small space for our components.

The current specification is a maximum of 6 Amps because of limitations of drawing power from the car battery. The race car uses power from the car battery for other functions, and it would hinder the racer if too much of it is drawn into the cooling unit. The power can be checked by looking at the ratings of the power supply and by calculating power using a voltmeter. The risk is low since our power is coming from the car battery.

The setup time is an important aspect for the racer to keep a quick pace. For the setup time, we can test how long it takes to turn off the system, ensure no leakage, disconnect and reconnect the system, and turn the system on. This is a low risk because it is not difficult to have universal connectors for our hoses.

The racer and manufacturer both want a light system, to keep the race car light and to lower the costs and parts required for the system. The weight of the system can be measured on a scale. The weight can be compared to the Rini system, as it is our benchmark for weight. The risk is low due to the fact that our components will be small.

The user interface is a feature that goes above the customer's expectations and incentivizes them to purchase our product, at minimal additional cost for the manufacturer. We planned on having three varying settings now for simplicity, but there can be additional settings for future versions of the system. In our final prototype, we have a dial that can PWM the signal, creating virtually infinite settings within our maximum range. The user interface adjusts the temperature settings by varying the voltage. We can test the temperature while adjusting the voltage, using a voltmeter to verify the voltage. The risk is medium, as none of us are experts on electrical engineering. However, it should not be too difficult since there are available products for varying voltage settings.

4 Concept Design Development

Since our PDR presentation, we have gone with a TEC (thermoelectric cooling) solution.

We have added additional information to the Concept Development Process and Concept Selection Process sections to clarify our decision-making process and the different system-level concepts we came up with. We have also explained the Pugh Matrix and how we used it to decide on our concept. As most of the information was written when deciding whether to go with the refrigeration or TEC solution, some of the contents may not apply to our final prototype but are left in for transparency and to document a complete record of our design process. The section regarding TEC is 4.3.3.

4.1 Concept Development Process & Results

To begin our ideation, we had multiple brainstorming sessions. We used techniques such as brain-writing and SCAMPER in order to think more creatively and look at a problem from different perspectives. We broke up our end goal into a list of problems and held different ideation sessions for each of these problems. The main problems we identified were to cool the driver, reduce serviceability, extend life, and keep the maximum power supplied at 12V, 6A. Concepts we came up with included a vapor-compression cycle, similar to the Rini system, thermoelectric coolers, and some out-of-the-box ideas such as reducing the ambient temperature inside the cockpit by reducing the greenhouse effect from the windows. To reduce serviceability, we came up with ideas of using off-the-shelf parts to guarantee quality and to easy replacement them. To extend life, we came up with ideas of various housing and mounts or springs to dampen the vibrations to our cooling unit. For the vapor compression cycle, dampening the vibrations is more key due to the large number of moving parts. However, this is not as much of an issue with the TEC solution.

4.2 Concept Selection Process & Results

Our brainstorming sessions resulted in six possible system-level concepts to our problem statement. These include: Standard Refrigeration Unit, Enhanced Refrigeration Unit, Thermoelectric Cooling, Phase Change Materials, Ice-Box System, and Air-Air Cooling. The standard refrigeration unit is a basic vapor-compression cycle, and the enhanced refrigeration unit was an infeasible attempt to improve on the standard refrigeration cycle. The thermoelectric cooling solution uses thermoelectric coolers to cool the fluid. Phase change materials uses materials that absorb energy and change states. The ice-box system is similar to the CoolShirt solution and uses a pump in a chest filled with ice water. Air-air cooling was an attempt to cool the driver cabin simply using fans. See Appendix G for more detail.

We took these systems and compared them to our two competitors' products, The Rini and CoolShirt, using two Pugh Matrices, each with one of our competitors' models as a datum, which can be found in Table G.1 and G.2. The Pugh Matrix is a method to choose between a list of alternatives, using a ranking system for the most important criteria and comparing which solutions best fit the criteria. The datum refers to the baseline solution that we are comparing the other alternatives to. From these decision matrices, we chose two systems that we think can not only fulfill our customers' needs but are also feasible.

The standard refrigeration system and thermoelectric system are the two highest rated, feasible concepts. The enhanced refrigeration system was an idea to improve the efficiency of the refrigeration cycle by combining it with passive heat removal systems, such as heat tubes. After discussing this with Professor Jesse Maddren, we found the basis of the idea did not hold up. Furthermore, considering the thermoelectric cooling method, we found that while it would answer our reliability and cost requirements, we run into a problem with the power supply and being able to get a large enough temperature difference to adequately cool the fluid and, ultimately, the driver. However, due to budgetary constraints on one solution we found using the refrigeration cycle, we decided to analyze both the refrigeration cycle and thermoelectric cooling solutions.

4.3 Preliminary Analyses, Concept Models, and Proof-of-Concept Testing

When building our first concept model, we chose the packaging and placement of our components as our main point of study. We focused on the packaging of the components because the refrigeration system has been studied hundreds of different ways over many years; there is more than enough information for us to use. Since reliability, cooling, and size are important factors, it is important to understand the placement of the components to maximize each factor. With placement in mind, we chose two variables to study: pump location and airflow direction. The placement of refrigeration and thermoelectric cooling would vary and could be studied individually when we pick a final solution. We visually tested the concept model, and it sparked ideas towards placement and methods of fixing the system in the car.

Due to budgetary constraints on a promising solution, we decided to come up with a few concepts that we believe will meet the project goals. The solutions are the Aspen Systems Liquid Chiller Module, the Rigid Liquid Chiller Module and a thermoelectric cooling system. A full budget analysis of the four concepts can be seen in Appendix K.

4.3.1 Aspen Systems Liquid Chiller Module (LCM)

The original solution was the Aspen Systems Liquid Chiller Module (LCM). The LCM is a mini refrigeration unit that can be coupled with a water pump to cool water [Aspen Systems]. The module is compact, has a volume of 280 in^3, is lightweight (around 6 lb), and meets our cooling requirements. The LCM is essentially a refrigeration unit that has a cooling capacity of up to 400 W and can work in ambient temperatures seen in the racing environment. See Appendix H for the full specification sheet and drawings provided by Aspen Systems.

Along with this unit, we are planning to use an inline circulation pump. We have found two pumps with similar specifications and are waiting on vendor pricing to make a decision. The Aspen system does not come with a fan for the condenser in the unit, and we do not think we are going to add one in. We are planning to use the car's ducting to act as the fan. Our plan is to extend the car's system to face where the condenser is located on our system. This should ensure air circulation for the condenser. We are planning on using temperature-safe Polypropylene tubing to connect the pump to the suit and evaporator in the unit. We think that this tubing will be our best option, because it is safe up to 300 psi and 200 °F. To mitigate vibrations from the car affecting the system, we will be using vibration isolation mounts. These mounts come in a wide range of sizes and materials. We have preliminarily chosen a natural rubber isolation mount, but we need to perform a more detailed analysis to confirm this choice.

The full Aspen LCM unit can be seen in our CAD model below. The Aspen system is designed to run on a 24-volt power source, which is more than we could supply. We have contacted the company to see whether the system will still meet our needs using a lower power range. The Aspen system is also very expensive, coming in at $1150 each 100 units. Looking past the high pricing, we think it may be the highest quality option of our two refrigeration system models.

4.3.2 Rigid Liquid Chiller Module

The second option we came up with was the Rigid Liquid Chiller Module. The Rigid system is a lot like the Aspen in that it is a complete refrigeration system. It has a slightly larger volume at 380 in^3, but weighs less at around 5 lb. According to Rigid, the system can displace 360 W, should be able to work in our ambient conditions, and meets our power requirements. The system comes with a fan integrated onto the condenser, which will aid the cooling process. We are planning on using the same pump, piping and vibration mounting system. Both the Rigid and the Aspen units are modular and could be dropped into our current prototype. We are worried about the quality of the Rigid system, because of the pricing which is $168 each for 100 units. However, it looks like a good, cheap solution. Please refer to Appendix I for more details about the Rigid LCM.

4.3.3 Thermoelectric Cooling (TEC)

The third design was a thermoelectric cooling design. This design utilized three Peltier thermoelectric coolers and a cold plate to transfer heat from the water. Each of the Peltier coolers can displace 60-72 W of power. The coolers are compact units, and all three could fit on the 6" x 9" cold plate with ease. For this design, we are thinking of using the same inline pump that we would use for the refrigeration cycle designs. The main downside to this idea is that it exceeds our power demands. Each of the three coolers requires 12V, 5A. However, it is the cheapest option and with the addition of batteries could provide a great solution. Please see Appendix J for more details on our thermoelectric option.

Since our PDR, we have decided to that this solution was optimal. From our structural prototype tests (Chapter 7), we have found that it would be best to use four TEC units. More about the current solution will be addressed in future chapters.

4.4 Concept Functionality and How It Will Meet Our Project Goals

Earlier in our report we listed our project specifications and their potential completion risk in Table 1. Now that we have chosen three concepts to focus on, we modified the specification table to compare our designs to each other and our end target, which can be seen above in Table 3. Specifications such as Longevity, Setup Time, and User Interface require testing in order to get data, therefore they are labeled as “No Data” for now until we begin testing.

The Aspen LCM unit meets the Cooling Temperature, Compactness, and Weight targets while falling short for Cost and Power. The unit alone costs $1150 when ordering 100 units, leaving $50 to complete the rest of the system. Regarding power, we believe the unit can run within our voltage and current requirement with a slight reduction to performance. The Rigid LCM Unit currently meets all know targets. Concept CAD for the LCM unit is shown in Figure 4.

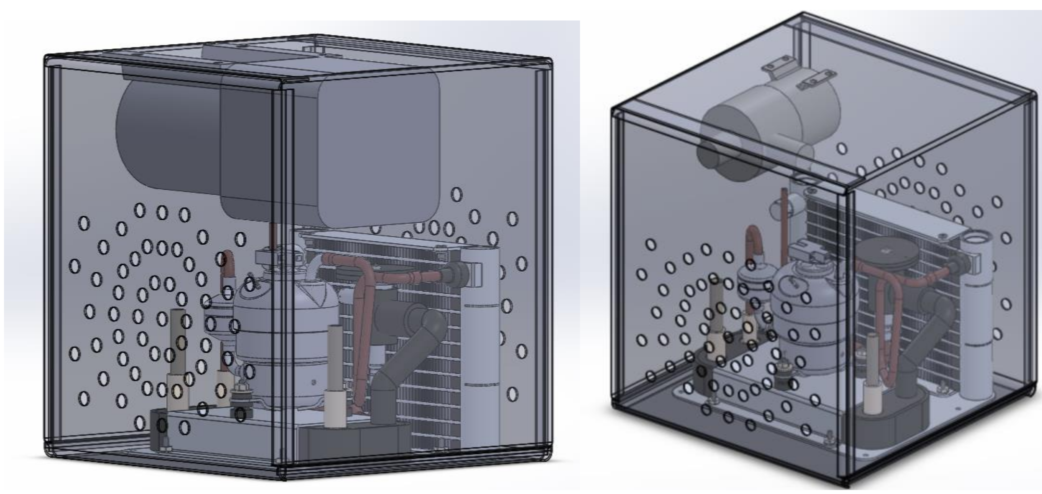

Figure 4. *LCM Concept CAD with Different Pump Choices*

4.5 Discussion of Risks and Unknowns with Current Concept

The Rigid LCM is similar to the Aspen LCM, as it uses a refrigeration cycle, but is from a different manufacturer and has different parts. It is much cheaper than the Aspen LCM and the quality of its parts is a concern. We would need to order the system to test its cooling ability and life. Table 3 shows how each of the solutions measure up to the specifications.

The thermoelectric cooling solution potentially meets life and size specifications but has issues with creating a large change in temperature and requires a larger power supply than provided through the car battery. It is unknown how we will wire the thermoelectric units and if we would need to provide our own power supply, specifically for this cooling system.

Building the refrigeration cycle ourselves leads to difficulty with handling the refrigerant. There are regulations for installing systems with refrigerant due to its hazardous low boiling point and its environmental hazards [9]. Also, building our own refrigeration cycle may be slightly out of our scope of work for this project.

There are associated risks with all the solutions. All ideas require a vibration dampening method to increase the lifespan of the product. They all need to include a mechanism which attaches the system to the car. This mechanism needs to have a significant factor of safety so the system does not detach during high impact situations. Once our mechanism method and cooling system is determined, we can proceed with vibrations testing to extrapolate data for life. Dr. Hemanth Porumamilla has agreed to help oversee our vibrations test.

Table 3. Specifications Table vs Concept Designs

Spec #	Specification Description	Target (units)	Aspen	Rigid	TEC
1	Cooling Temp	65°F	32-122°F	32-122°F	Up to -3°C
2	Longevity	100 hour life	ND*	ND	ND
3	Cost	$1,200	>$1,200	<$1,200	<$1,200
4	Compactness	1 ft^3	7.8x6.3x5.3 in	10.1x6.9x5.43 in	7x8x4 in
5	Power	12V, 6 A	24V, 6A	12V, 2.1A	12V, 30A
6	Setup Time	5 min	ND	ND	ND
7	Weight	10 lb	6 lb	5.1 lb	(1 lb) x4
8	User Interface	3 settings	ND	ND	ND
*ND = No Data		Meets Target		Does Not Meet Target	

5 Final Design

In this chapter we will be discussing our final design and the decisions/calculations that lead us to it. We will be discussing safety, maintenance and repair considerations as well as a detailed cost analysis of the first prototype. We have made some changes since our CDR report and will make these clear at the end of this section. After speaking with our sponsor we have updated our required power goals and will be moving forward with a thermos electric cooling design. We will be discussing the new changes and why we think this new design will succeed in the following chapters. Our final design is shown in Figure 5.

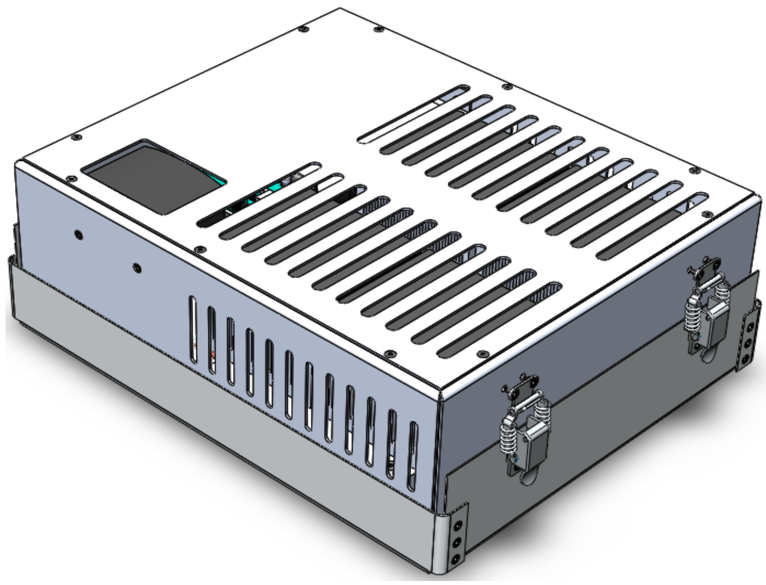

Figure 5. *Final Design*

5.1 Sub-Assemblies

Our final prototype consists of five distinct sub-assembly groups that all work together to accomplish our goal of creating an innovative driver cooling system. In this section we will be breaking down each of the sub-assemblies' functions, as well as explaining why we made the decisions we did. We have gone through numerous design iterations and believe that we have come up with a suitable configuration for creating a proof of concept model.

5.1.1 Housing Assembly

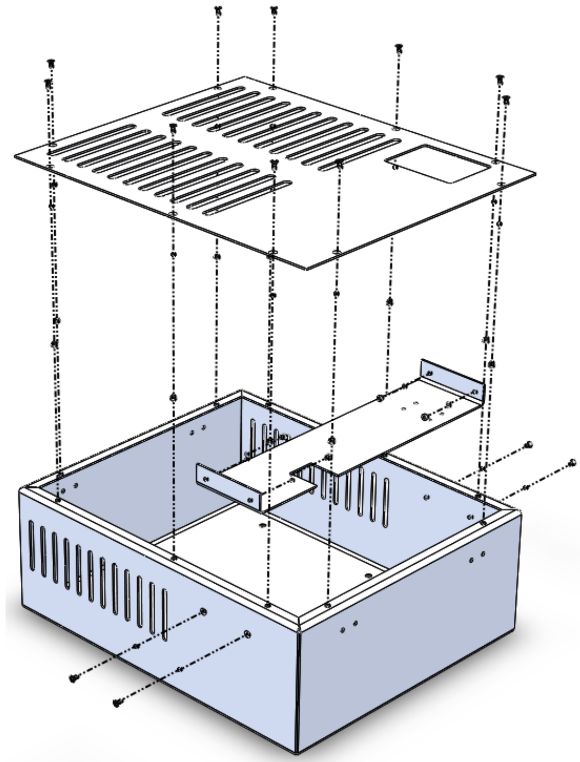

***Figure 6**. Exploded View of the Housing Assembly*

The housing assembly, Figure 6, is arguably the second most important system in our design. Its purpose is to protect the other sub-assemblies while allowing for enough air flow for optimum cooling. Housing was designed with ease of manufacturing in mind, and for this reason it is made of aluminum sheet metal. The assembly is comprised of two main pieces that will be formed from sheet metal, and hardware that will hold the two pieces together. The bottom of the housing is designed to be bent into a box shape, from a water jet cut piece of sheet metal. A water jet, bent shelf for electronics was added into the design after going over our CDR design with our sponsor. To save weight the sheet metal will be 1/16 in 5052-H32 aluminum. This will allow us to easily bend the sheet into the correct shape as well as allowing for acceptable strength. In choosing the material we were turned away from sheet steal because of its weight, and corrosiveness. With aluminum we chose 5052-H32 because it offered good strength and thermal conductivity for a reasonable price. 6061-T651 and 3003-H14 aluminum sheets were also considered.

To attach the two pieces of bent sheet metal together we will be using PEM nuts and flat head screws. PEM nuts are specifically created to be used in sheet metal. They are pressed into a hole in the sheet metal and allow for fasteners to be screwed into the sheet metal. We will be using 22 PEM nuts and 22 flat head screws to attach the two pieces together.

There was a challenge in creating this assembly because of the need for sufficient air flow and the need to protect the cooling assembly. The slots in the side of the housing were designed to be at the same height as the TEC heat sink modules to allow for air to escape the housing as quickly as possible. The top of the housing has slots that are directly above the cooling modules to allow for air to enter the box, and flow over the heat sinks. It also has enough space for a switch unit and space for a user interface to be integrated in for later revisions.

5.1.2 Mounting Assembly

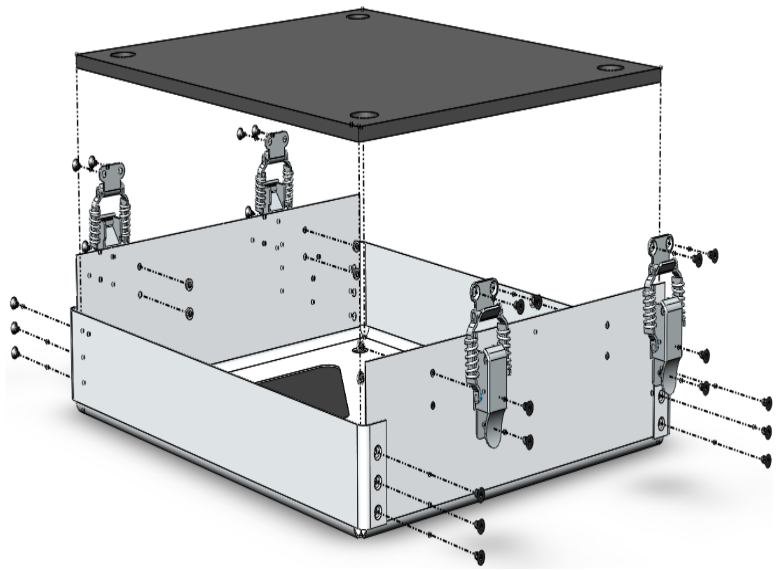

Figure 7. *Mounting Assembly Exploded View*

The mounting assembly, *Figure 7*, is simply there to attach the other assemblies to the car floor. This assembly's main piece is made from the same 5052-H32 aluminum sheet metal that the housing assembly is cut out of. The mount is designed to be water jet cut, and bent into shape. The latches will be fastened onto the bottom plate so that the sides may remain flush with the housing assembly. The user will be able to adjust the holes in the bottom of the mount with a hand held drill to allow for ease of attaching the mount to the car. We were worried about the housing assembly rattling on the mount, so we added a ¼ inch rubber mat into the design. This will also help with the vibrations from the car entering into the main assembly. We were also concerned about the structure as a whole, and there for added the corner brackets that will be fasted to the main mount body. All of the screws will be fastened into PEM nuts that will be pressed in before bending.

5.1.3 Cooling Assembly

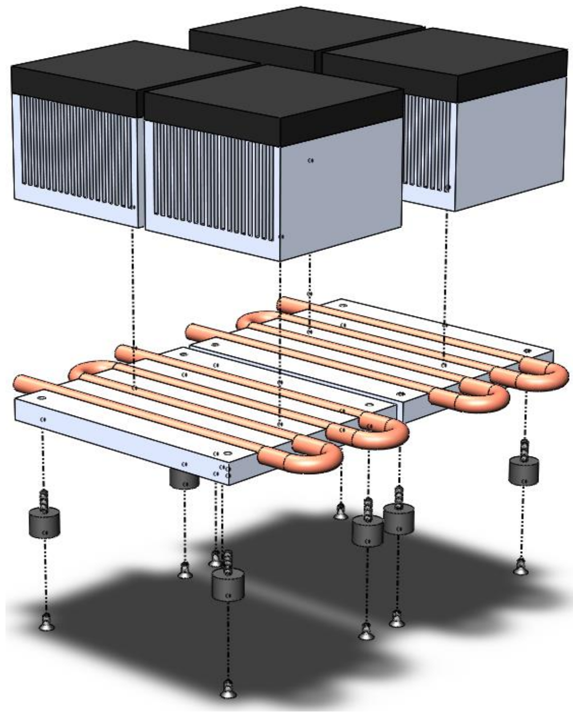

Figure 8. *Cooling Assembly Exploded View*

The cooling assembly, Figure 8, is the most important assembly in our final product. We designed the cooling assembly to utilize four thermoelectric cooling modules. Each module includes a 12V 6A Peltier cooler, an aluminum heat sink, and a 12V .5A fan. These modules are capable of reaching -3 degrees Celsius and removing up to 60 watts of heat per cooler. Using the data sheet of the Peltier modules, we concluded that at our worst conditions we will be able to reach our goal and testing confirmed that we were able to reach our water temperature goal. At a temperature differential of 40° C and the cooler being supplied 5A, each cooler can remove 30W, which would put us at 120W removed total. We plan on attaching the cold plates via thermal adhesive. This will create a permanent bond, and allow for the least amount of thermal resistance possible between the plate and the cooling module. We tested the thermal adhesives ability to hold a TEC unit to a block of aluminum in a simulated vibration environment that mimics what it would experience in a racecar. Our test results were positive and are expanded on in Section 7.

Our main way we will be exchanging heat will be through cold plates. This is a piece of aluminum with copper pipping through it, it is a simple yet effective piece of engineering. This cold plate will have water from a suit pumped through it, and will allow the coolers to remove heat from the water. We will talk about the specifics of the pump in a later section. The cold plate was planned to be custom made by an outside manufacturer. We reached out to four different companies. The cold plate will be mounted to the housing by neoprene standoffs. Due to time constraints, we ordered an off-the-shelf cold plate model.

A standoff is a piece of hardware that is male threaded on one side and female threaded on the other. The male side of the standoff will be screwed into the cold plate and the female side will attach to the bottom portion of the housing assembly through a M4 flat head screw. These standoffs will elevate the cold plate, and provide vibration dampening.

In order for our system to allow us to reach the coldest water temperatures, we have insulated the cold plate leaving only room for the TEC Units to attach. With the cold plate elevated by the standoffs, we were able to get insulation on all six of the sides of the cold plate. To insure the insulation does not come loose, we plan to use simple zip ties to secure it around the cold plate.

5.1.4 Pump Assembly

The pump assembly includes our pump, the pump mounting system, adapters and tubing. This system is relatively simple, but has an important job to do. We sized our pump using head loss calculations, accounting for all the minor and major losses we have in our system; these calculations can be seen in Appendix N. Through these calculations we found a pump that was suitable and will be purchasing it through a parts distributor. The pump selected is the Koolance PMP-500, and it seems to have a very respectable reputation online. We were fortunate enough to find a website that does extensive pump testing. Using their data, we were able to confirm that this pump is right for our application.

We will be using adapters to attach the pump to the cold plate. The pump's output diameter as well as the dimeter of the piping in the cold plate are 3/8 in. These adapters will be purchased from McMaster Car and will work perfectly. The tubing we chose to use is temperature safe santoprene plastic. The tubing is able to handle temperatures up to 275 °F which far exceeds our maximum temperature.

5.1.5 Electronics Assembly

The electronics assembly is our most difficult system to create, as none of us have a lot of experience with creating and wiring complex circuits. However, with this said we still have what we think is a viable solution. Our current solution is simple but meets the necessary criterion specified in our specifications table.

We will be wiring from the car's battery to our system. Since we are pulling a lot of power, to avoid shorting the car battery we will have a 40 Amp in-line fuse in the 8-gauge wire connecting our system to the battery. The positive side of the battery will run through the fuse and into the fuse box inside of our system. The fuse box is an automotive 6-way fuse box splitter. This will allow us to "set" the max amount of current that each of the six terminals will receive by selecting the appropriate size fuse. We will be connecting each of the Peltier coolers to its own fuse, leaving us with two left. We plan on wiring all of the fans in parallel and attach them to one fuse, which will allow them all to run at roughly the same speed. We then will have the pump running on the remaining fuse. We plan on keeping the fans and pump at the same power levels the whole time, and will vary temperature of the water through the Peltier coolers. The pump has been sized to run within a certain range of flow, and we do not want give the user the ability to steer outside this range.

Our coolers will be wired into a 6 way N-Channel MOSFET which will be connected to an Arduino. This set up will allow the driver to have temperature adjustability with the turn of a potentiometer. Through the use of the potentiometer, MOSFET and Arduino we will be able to PWM the Peltier modules, which will allow for adjustability of the coolers. The user can adjust the current levels to be lower, which will decrease the coolers efficiency and therefore raise the temperature. The all of the ground wires in the system will be connected together and grounded to a ground screw in the housing. The negative terminal will be attached to the ground screw therefore completing the circuit. The decision to go to a ground screw was crucial because it will allow all the devices to be on the same zero.

5.1.6 Design Changes After Critical Design Review (CDR)

Since our CDR report, we have spent most of our time manufacturing and testing our system. In doing so, we have occurred a few small errors and opportunities to improve our design. The main changes were to our Pump Assembly. We added a reservoir tank that goes before the inlet of the pump. This allows for easy filling of the system and removes air bubbles to increase the life of the pump. Furthermore our planned pump, the Danger Den Cpx Pro, is no longer available on the market. Fortunately, we were able to find a much better pump in the Koolance PMP-500. We were able to find flow data of this pump and various voltages which will be helpful down the road.

The rest of our design changes have been relatively small. In order to cut down cost and simplify manufacturing, we are no longer welding the latches to the mount but fastening them to the sheet metal using the same screws and PEM nuts that are used on the rest of the system. Our main housing now contains a few more holes to mount the reservoir tank, and the housing lid contains a cut out that serves as a window to view the status of the fuse box. If a fuse blows during operation, the corresponding LED next to it will turn red. Lastly, due to the high cost of buying a single custom cold plate, we switched to a design that uses two smaller, off the shelf cold plates. When purchasing the custom manufactured cold plates, the price dropped from over $1000 for an order of 1 to around $100 for an order off 100. We are still encouraging our design of a single custom cold plate when manufacturing in bulk, and our results from using two smaller TECs should mimic the cooling capacity of one larger unit.

5.2 Safety, Maintenance, and Repair Considerations

Safety is always a concern when working with electricity, and this is why we have taken the appropriate precautions to keep our users safe. The addition of a fuse box will allow us to not only protect the user but also the system itself. We were able to drop the amperage from 30A in one wire to a max of 6A per wire using this device. There are some pinch points with the latches, but nothing that we think can cause serious injury.

Maintenance and repair are aspects we will have to find out through customer trials. We are not sure what will fail or what will need keep up. We are thinking that the fans and the pump may be sources of repair or replacement. We can also foresee the latches maybe getting worn out and needing oil to loosen them up. After we perform some field tests, we will have a better understanding of what kind of maintenance and repair needs our system will require.

5.3 Cost Break Down

Our total predicted prototype cost is $815, and our final product cost is $706. A detailed cost analysis can be found in our Indented Bill of Materials (Figure 9), which can be viewed below; a more visible version is shown in Appendix Q. There are two final costs shown; the cost of making one prototype and the cost of making 100.

Indented Bill of Material (BOM)
Driver Cooling System

Part Number	Description				Vendor	Part Qty	Ind Cost	Final Product Cost	Purchasing Qty	Prototype Cost	Purchasing Link	Purchased?	Received
	Lvl0	Lvl1	Lvl2	Lvl3									
10000	Final Assembly												
		Housing											
10100			Cooling Assembly										
				M4 x .7 8mm Flat Head Screw - 2.5mm Allen	McMaster	8	$ 4.72	$ 0.38	1 Box	$ 4.72	Here	Yes	Yes
				Cold Plate	Mouser	2	$ 88.00	$ 176.00	2 Units	$ 176.00	Here	Yes	Yes
				Thermal Paste	Amazon	1	$ 7.50	$ 7.50	1 Tube	$ 7.50	Here	Yes	Yes
				TEC Units	Adafruit	4	$ 35.00	$ 140.00	4 Units	$ 140.00	Here	Yes	Yes
				Vibration Mount M4	McMaster	8	$ 2.12	$ 16.96	8 Units	$ 16.96	Here	Yes	Yes
				Fiberglass Insulation Strip	McMaster	1	$ 7.23	$ 7.23	1 Roll	$ 7.23	Here	Yes	Yes
				3M Dual Lock Velcro	Amazon	1	$ 11.49	$ 11.49	1 Roll	$ 11.49	Here	Yes	Yes
10200			Pump Assembly										
				M3 x .5 5mm Flat Head Screw - 2mm Allen	McMaster	4	$ 5.15	$ 0.21	1 Box	$ 5.15	Here	Yes	Yes
				Tubing	Fresh Water Systems	1	$ 25.00	$ 6.25	1 Roll	$ 25.00	Here	Yes	Yes
				Koolance Pmp-500 Pump	Koolance	1	$ 76.99	$ 76.99	1 Unit	$ 76.99	Here	Yes	Yes
				3/8" 90 Deg Adapters	McMaster	4	$ 8.05	$ 3.22	1 Box	$ 8.05	Here	Yes	Yes
				Rotary Elbow Barb Fitting 3/8"	Koolance	1	$ 5.49	$ 5.49	1 Units	$ 5.49	Here	Yes	Yes
				Straight Elbow Barb Fitting 3/8"	Koolance	1	$ 3.99	$ 3.99	1 Units	$ 3.99	Here	Yes	Yes
				Resevoir Tank		1	$ 30.00	$ 30.00	1 Units	$ 30.00		Yes	Yes
10300			Electronics Assembly										
				Arduino	Amazon	1	$ 10.90	$ 10.90	1 Unit	$ 10.90	Here	Yes	Yes
				Potentiometers	Amazon	1	$ 5.82	$ 5.82	1 Box	$ 5.82	Here	Yes	Yes
				16 Ga Wire Red 25ft	ProWire	1	$ 13.06	$ 13.06	1 Roll	$ 13.06	Here	Yes	Yes
				Fuse Box	Amazon	1	$ 8.23	$ 8.23	1 Unit	$ 8.23	Here	Yes	Yes
				Temp Sensors	Adafruit	2	$ 4.00	$ 8.00	2 Units	$ 8.00	Here	Yes	Yes
				M4 x .7 8mm Flat Head Screw - 2.5mm Allen	McMaster	4	$ 4.72	$ 0.19			Here	Yes	Yes
				Blade Fuses	Amazon	1	$ 7.99	$ 7.99	1 Box	$ 7.99	Here	Yes	Yes
				DT Connectors	ProWire	1	15.86	$ 15.86	1 Unit	$ 15.86	Here	Yes	Yes
				Mosfet Shield	Robot Shop	1	$ 16.45	$ 16.45	2 Unit	$ 32.90	Here	Yes	Yes
				Blade Connectors	McMaster	1	$ 4.11	$ 4.11	1 Unit	$ 4.11	Here	Yes	Yes
				22 Ga Wire Red 50ft	ProWire	1	$ 12.75	$ 12.75	1 Roll	$ 12.75	Here	Yes	Yes
				16 Ga Wire Black 25Ft	ProWire	1	$ 13.06	$ 13.06	1 Roll	$ 13.06	Here	Yes	Yes
				22 Ga Wire Black 50ft	ProWire	1	$ 12.75	$ 12.75	1 Roll	$ 12.75	Here	Yes	Yes
10400			Housing Assembly										
				3003 H14 1/16 in Aluminum Sheet Metal	Metals Depot	1	$ 35.92	$ 17.96	2 Unit	$ 71.84	Here	Yes	Yes
				M3 Pem Nuts	McMaster	30	$ 8.44	$ 12.66	2 Box	$ 16.88	Here	Yes	Yes
				M3 x .5 5mm Flat Head Screw - 2mm Allen	McMaster	10	$ 5.15	$ 0.52		$ 20.00	Here	Yes	Yes
10500		Mounting											
			Tight Hold Draw Latch		McMaster	4	$ 7.61	$ 30.44	4 Unit	$ 30.44	Here	Yes	Yes
			Rubber Mat		Amazon	1	$ 12.17	$ 12.17	1 Unit	$ 12.17	Here	Yes	Yes
			3003 H14 1/16 in Aluminum Sheet Metal		Metals Depot	1	$ 35.92	$ 17.96			Here	Yes	Yes
			M3 x .5 5mm Flat Head Screw - 2mm Allen		McMaster	8	$ 5.15	$ 0.41			Here	Yes	Yes
Totals						96		$706.99		$ 815.33			

Figure 9. *Indented Bill of Materials*

6 Manufacturing Plans

In this section, we will be discussing our manufacturing plan for our prototype. We will be going into detail on how each of our parts are made, modified, and how to assemble everything together. Now that we have finished the manufacturing and assembly, we have created Section 6.3, which gives advice on how to complete both tasks.

6.1 Manufacturing

We designed this prototype to involve as little manufacturing and modifying as possible.

With that said, we will only be manufacturing four parts from scratch: the housing top and bottom, the mount, and a shelf that goes inside the main housing and holds the Electronic Assembly. These four parts were designed to be cut using a water jet, and are able to fit on one single piece of 2ft x 4ft sheet aluminum. This will allow for less wasted material and lower costs. Also, with the use of a water jet machine we were able to introduce some complex designs that we would not have been able to do by hand. We also looked into using a 4ft by 4ft sheet of aluminum, which would save us more money in the long run. The water jet layout (Figure 10) can be seen below.

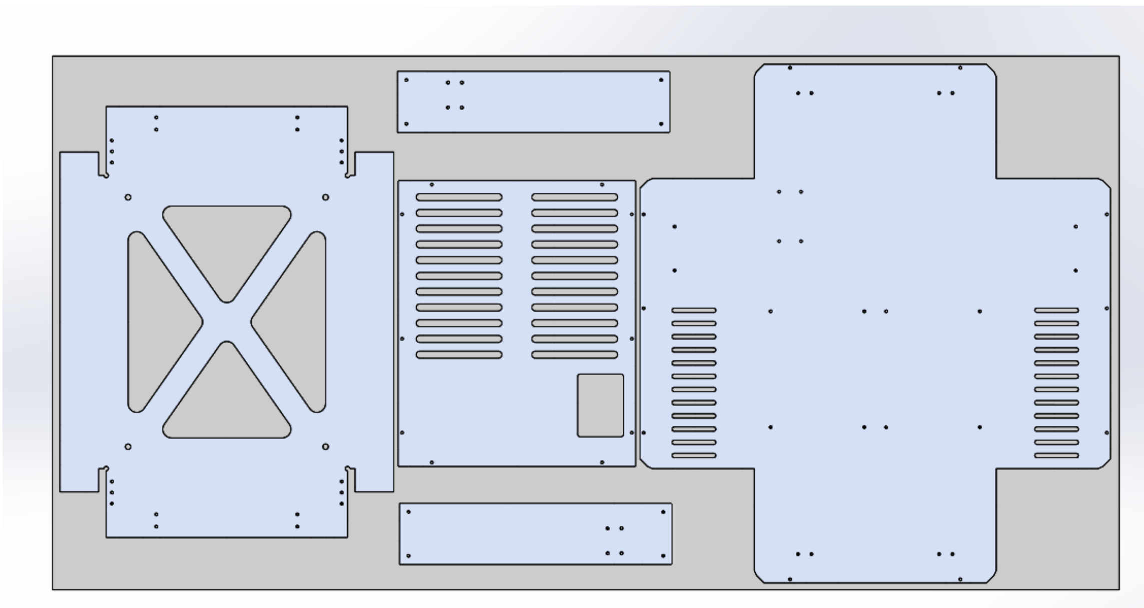

Figure 10. *Water Jet Layout, 2ft x 4ft*

After the parts have been cut, we will need to do some post processing. We will need to drill countersunk holes to allow for all the flat head screws to lay flat in. We will also need to press in the PEM nuts into the housing bottom before we bend the cutouts into their final shape. After these processes have been completed we can then begin bending the cutouts into their final forms using sheet metal tools in the Aero Hanger. For our first time, we expect this to take roughly 4-5 hours of manufacturing time, excluding water jet cutting time.

Once we assemble the sheets into their final forms, we will need to attach the latches to the mount piece. This will require us to simply screw them into the PEM nuts that have already been press fit in. This should not take more than 10 minutes.

The cold plate will require tapped holes and modified tube lengths. This means we have to drill into the plate and then tap it, and cut the entrance tubes to their respective lengths. Realistically this will take 2 hours, because of where the holes need to be drilled and the tolerances provided.

We will also need to cut our insulation to size, wrap it around the cold plate, and then cut out the openings for the TEC Units. This should take roughly 30 minutes.

Lastly, we will need to cut the rubber mats out of the roll of rubber we purchase that is large enough to make 8 mats. For our prototype we will cut out a mat using an x-acto knife, but when manufacturing in bulk this will be another water jet part. Pictures of the manufacturing can be seen in Figure 11.

Figure 11. *Our manufacturing process a) shows the water jetting of the sheet metal b) shows the drilling and tapping of the cold plates c) shows the post process drilling and deburring of holes in the sheet metal and d) shows the bending of the sheet metal*

6.2 Assembly

The system was designed to “plug and play.” Essentially, this means it’s designed to have easy placement of parts with minimal required tools to be able to run. This should, in theory, yield an easy assembly process. Once the mount, and housing pieces have been bent into shape and the other materials have been cut and tapped then all that is left to do is attach everything together.

We will start by screwing on the standoffs to the cold plates and then wrap them in insulation. After the insulation has the cuts for the TEC Units we will adhere the coolers to their respective position. Once this is finished we will fasten the cold plate onto the housing bottom. Next we will attach the pump and reservoir to the housing bottom, and then attach the adaptors and piping to both. We will then put the adapters on the cold plate and attach the piping to the adapter. We will then begin the wiring process. We will cut the wires to length and crimp on the appropriate connectors. We will attach the fuse box to the shelf with four flat head screws, and then attach all of the connectors to the fuse box. After this has been completed we will place the appropriate blade fuses in the fuse box, 10 amp fuses for the four TEC modules and 5 amp fuses for the fans and pump. We will then place the piping through the hole in the top of the housing, and begin fastening the top down. We will then attach the tops of the latches to the housing bottom. This will conclude the assembly of everything but the mount.

The Mounting Assembly only requires attaching the four latches with fasteners and inserting the rubber mat in the bottom. After those are complete, the rest of the system should fit right in. Figure 12 shows the assembly process.

a) b)

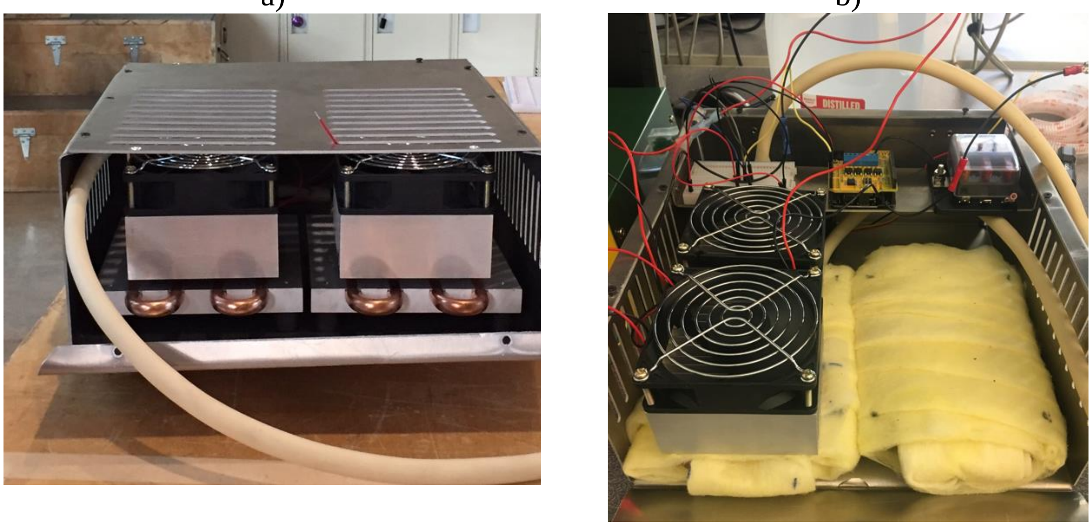

Figure 12. *Our assembly process a) shows our preliminary assembly before installing insulation and b) shows our assembly with an open lid to make the electronic and other interior assemblies visible. There are also only two TEC units shown.*

6.3 Manufacturing and Assembly Advice

While manufacturing and assembling our prototype, we can across a few difficulties and learned a few ways to not only make a better product but streamline the process. Our biggest bottleneck came through the water jetting process. The lead time to use a water jet is easily avoided when outsourcing for manufacturing and not using a student run machine. The most challenging part of the manufacturing was definitely the bending process. Bending with the correct bend radius specified in the CAD Model was impossible due to having only one manual bending machine in the Aero Hanger that bent with a singular radius. This caused our first attempt to have holes that did not line up in the main housing and we were only able to screw in approximately 85% of the screws. Also, the smaller bend radius of the machine made our mount housing smaller than intended and the system was not able to easily fit inside. The imprecision can be fixed by taking extreme care when bending as well as postponing the hole drilling until after the metal has been bent, which allows you to place the holes in their proper position. However, again when outsourcing manufacturing, the company should have machines that bend exactly to the specifications of the CAD Model, eliminating these problems.

7 Design Verification Plan (DVP)

Throughout the process of our design, we have used our specifications table as a reference for all important decisions. To help us ensure every specification target will be tested and proven, we created a Design Verification Plan, which can be found in Appendix P. Along with each of our specifications this table contains our planned tests, dates in which they will begin and be completed by, and results for completed tests.

7.1 Concept Prototype Tests

The first two specifications we tested were Numbers 3 and 4 on our DVP, Cost and Compactness, respectively. We were able to accomplish these during our construction of our Concept Prototype, Figure 4, back in October 2017. This test prototype was more aimed at representing our system using a refrigeration cycle, which was our main design at the time. However, our final design was not yet chosen, so we ensured it worked for Thermal Electric Coolers as well. This was simple because the TEC design is more efficient regarding cost and compactness.

The cost analysis involved listing out all major components and, conservatively, estimating the cost required for all parts and manufacturing. This of course included a miscellaneous cost for insignificant components we had not yet taken into consideration. Ultimately our estimated cost was far below our price cap and specification target of $1,200. Now that we have our final design set and know where and how we will get and put together each part, the final price comes out to $815, approximately one third of our goal. This is the confirmed price of our final prototype after manufacturing and testing.

Next, our compactness test involved putting together a packaging study. Essentially, we took all the parts listed out for the cost test and made sure they could fit inside set dimensions. From our Specifications Table, Table 1, our target size is 1 cubic foot, maximum. When putting together our Concept Prototype we figured we were able to fit all listed part within a 10” x 10” x 6” housing. Not only was this slightly conservative at the time, but we satisfied our goal by a decent margin. As our design evolved more components were added to include better functionality, this has brought our final design to a size of 0.46 ft^3. These dimensions are confirmed to be the size of our final prototype after manufacturing and testing.

7.2 Structural Prototype Tests

With our Structural Prototype we decided to test the first two specifications, Cooling Temperature and Longevity, respectively. These are the most involved tests, requiring more time and parts that the other tests.

Cooling Temperature was the test we were initially unsuccessful with and rescheduled. Our specification target is the ability for our system to bring the water temperature down to a temperature of 65°F. This idea behind this test was to start with a reservoir of 90 °F water and pump it through a cold plate that was being cooled by one of the thermoelectric units we will be using in our final design. There were two thermistors recording the water temperature, one before the water entered the cold plate and one after it exited. To move the water, we used the pump from the Ice Box System and to record the water temperature we used T-joints that connected two portions of piping and had a thermistor inserted and made water tight using a silicone sealant. This set up can be seen in Figure 13, below.

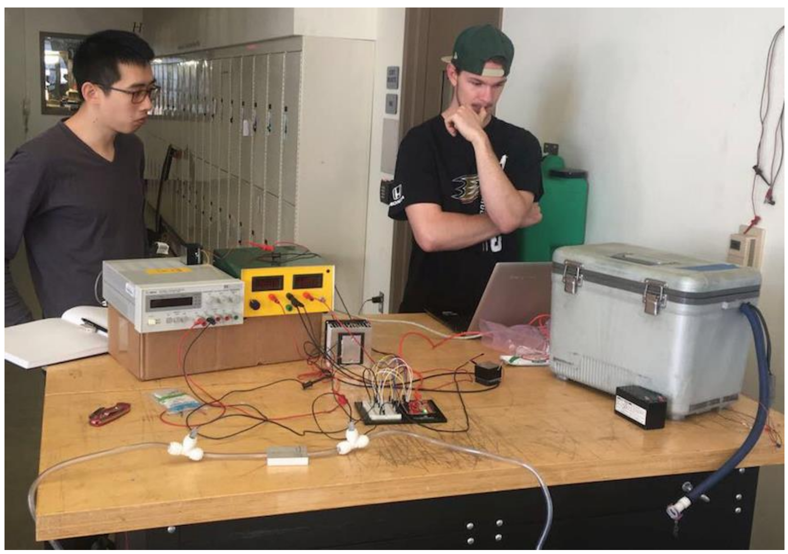

***Figure 13**. First Structural Prototype Test*

Our first run used no TEC Unit and functioned as a control, next we ran the test with the TEC Unit starting from an off position and increasing in cooling over time. Finally, we had one last run where we had the TEC Unit starting from steady state. When we initially planned the test, we hoped that the cold plate used would be the one used in our final design, unfortunately, due to a long lead time, this did not work out. Instead we used a small aluminum plate with a hole drilled through for the water to pass. During the test we realized, due to the small area of the aluminum block, that the water was not in the block for a long enough time to really feel the effects of the TEC Unit. This is what, ultimately, led to our test being inconclusive. To make up for this inconclusiveness, we are substituting the test with a heat transfer analysis and we will reattempt the test during our Final Prototype, when we will have the real cold plate. This test has since been completed using our final prototype and the results can be found in that section

This test, however, was not a complete failure; we were still able to obtain some valuable information. When using the TEC Unit, we were able to get the cold side down to a temperature of 3°C while not even supplying full power to the unit; this is very optimistic. Furthermore, even with the small makeshift cold plate, the TEC Unit was able to influence the water and increase the ΔT about 1.5°C from the control run. As insignificant as this sounds, it is quite impressive for the amount of time the water was in the aluminum block. In our Final Prototype, we will be using three more TEC Units and the water will be in the cold plate for a significantly longer duration.

Our next test analyzed the second specification: longevity. To perform this test, we obtained access to the shake table and focused on the thermal paste holding the TEC Units to the cold plate and the fans mounted to the heat sinks. We used accelerometer data of a racecar during a race, given to us by our sponsor, and shook each of these components at the frequency they will experience while in the car. For this test we used thermal adhesive, one TEC Unit, a DAQ system, and mounts for the shake table. We ran this test twice, shaking the adhered TEC Unit and aluminum plate combination for 30 minutes at a time. In each instance the adhesive held with no problems and the fan also operated smoothly. It was clear from the vibration simulation that the fans and thermal adhesive will operate without difficulty during a race.

7.3 Final Prototype Tests

With our Final Prototype we will test the four remaining specifications: Power, Setup Time, Weight, and User Interface. In addition, we will rerun the Cooling Temperature test with a slightly updated procedure and different components.

For Specification 5 and 7, Power and Weight, respectively, we just compared our system to the specification target to see if our Final Prototype meets their conditions, no real testing involved. For Power, we wanted our system to be able to run on approximately 12 Volts and 6 Amps. Unfortunately, this target was set when our main design option was a refrigeration cycle. Thermoelectric coolers require much more power and we did not meet this specification. This was discussed with our sponsor at the time of the design switch to thermoelectric cooling and he understands the failed result. For Weight, we weighed our Final Prototype and compared it to our specification target of 10 lb or less. Our prototype ended up weighing approximately 14 lb. However, we believe that this is due to our prototypes design and not our final suggested design to our sponsor. The use of one cold plate will reduce size and therefore weight. It will also reduce the amount of insulation needed and the amount of small parts such as standoffs, fasteners, PEM nuts, etc., however small of an impact that may have. Overall, we believe this will be at least 4 lb lighter than our prototype. If it is not, we suggest a thinner choice of aluminum sheet metal as we have noticed that 5052-H32 provides more than sufficient strength, durability, and protection to the interior assembly.

Specification 6, Setup Time, will include seeing how long it takes to prime the pump, latch in the system to the car, and hook up the cooling shirt. This needs to be done in under 5 minutes to meet the specification goal. We were unable to test our final prototype for this specification due to the fact that we did not have enough time or the possibility to do an in-car test. There are many factors that go into setting this system up in a car for a race and we could not simulate them without being in the environment. Specification 8, User Interface, requires our system to have 3 functioning, variable settings. Our final prototype has a potentiometer that controls the amount of amperage going to each of the 4 TEC Units. We have successfully run our system and ensured that it works correctly. Due to it being a nob that works continuously, we theoretically have an infinite number of cooling settings and have, therefore, met the specification target.

Finally, as mentioned before, due to the inconclusive nature of our first attempt, we reran the cooling test. This test is meant to verify that we can sufficiently cool water with our system. The target put on this specification was the ability to bring 90 °F water to 65 °F. Our test used our built final prototype and therefore used our installed pump, piping, cold plates, insulation, TEC Units, and electronics. Because we essentially used our whole prototype, this served as a functional test of our system as well, however, we only used two TEC Units and one cold plate due to restricted amount of power available. We first ran 90 °F water through our system with no TEC Units running to see how cool the water would get. This served as our control test and the water reached a steady state temperature of approximately 82 °F. Our next test used two TEC Units starting from room temperature, which is that they are not given the opportunity to cool down the cold plate until the system starts pumping the hot water. During this test we reached a water temperature of below 65 °F in around 23 minutes, therefore, meeting our specification target. And finally, we ran the test one more time allowing the TEC Units to cool down the cold plate for a few minutes before we started pumping the warm water through the system. This had a significant effect on our results as we were able to reach the same sub 65 °F temperature in 12 minutes, around half the time of the previous test. These tests are compared and shown below in Figure 14 These results are very optimistic as we were only using half of our cooling assembly and do not see the water getting much hotter that 90 °F during a race. This test, however did not take into consideration the higher environmental temperatures that will be experienced during a race; we had a boundary temperature of 72 °F during our tests. Furthermore, there is an uncertainty of +/- 0.5 °F due to the thermistor, however, this small of an uncertainty does not change the impact of the results.

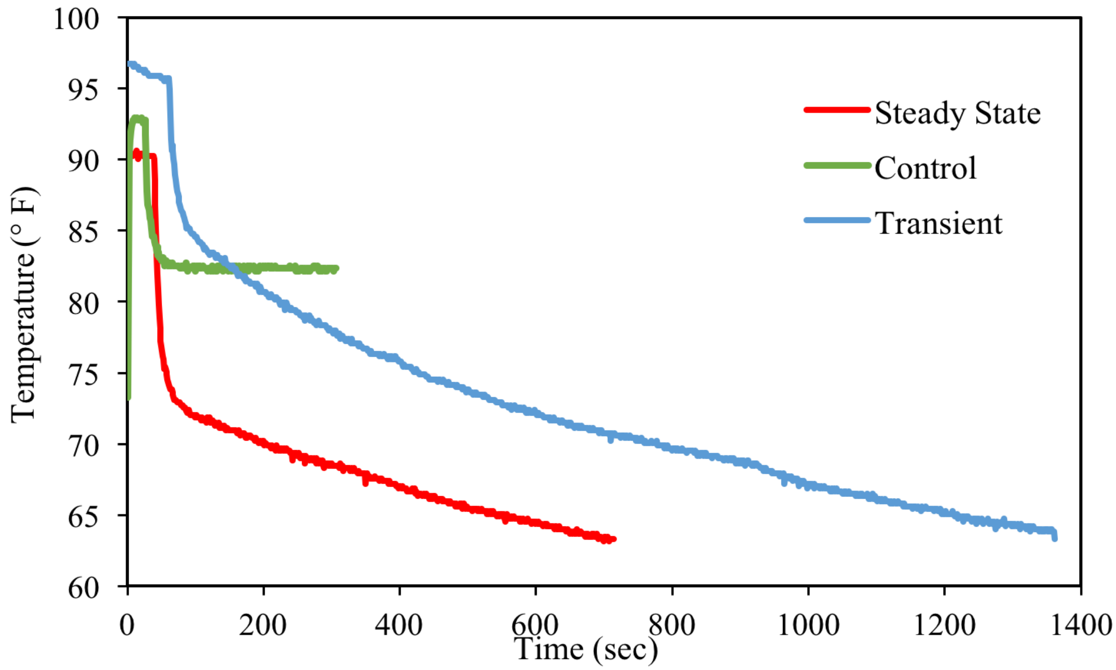

***Figure 14**. Data for our Cooling Test comparing how quickly each run was able to reach a water temperature of 65* °F.

7.4 Calculations

Some of our design decisions could not be tested and made more sense to verify through theoretical analysis. Appendix O contains the calculations we have currently done. When deciding on a safe way to latch our system to the car mount, we settled on using pull over latches from McMaster-Carr. Using accelerometer data given to us by our sponsor, we calculated the force the latches would experience from the g's recorded during a typical race. For normal racing conditions 2 latches would suffice, however, doing the same calculation for an estimated amount of force the latches would experience during a crash, we decided it safer to use 4 latches in our final design. This results in a conservative safety factor of 15.3 during normal racing conditions and a safety factor of 1.4 during a crash in which the latches experience 20 g.

The next design decision we verified through theoretical analysis was the Danger Den CPX Pro pump, and this was accomplished in a couple of ways. First, we found a review website that has done a thorough and in-depth analysis of our pump by testing it and taking it apart [14]. This has given us a lot of useful information and ultimately led us to focus on this particular pump. However, we cannot justify these findings. Next, we used an online head calculator as a quick check to make sure our pump falls in the operating range of our system [15]. We found we need about 6.2 ft of head and at 12 V and 1 GPM our pump is rated to do 11 ft. This check led us to perform our own analysis where we found that our system requires a pressure slightly less than 2.0 psi, and at the same rating as above the pump can do 4.8 psi. Overall from our analysis we have chosen to operate in range of 0.5 to 1.5 psi. As mentioned before the Danger Den Cpx Pro is no longer made and we had to switch to another pump. This pump has the same specifications, performance, and parts as the Cpx Pro, leaving our calculations still valid.

Lastly, due to our inconclusive first Structural Prototype Test, we have completed 1-D heat transfer analysis; our model and calculations can be seen in Appendix O. These calculations gave us insight into how we can increase our efficiency through changing our pipe diameter and total thickness in our cold plate. For more conclusive results regarding heat that can be removed from the water, we will be rerunning the first Structural Prototype Test on our Final Prototype, as mentioned above.

8 Project Management

We have updated the project management to reflect the final status on the project as of the FDR and Senior Project Expo. The task description has been updated. A new section has been included to show deviations from our original plan.

8.1 Method

Creating and maintaining a timeline has been vital to meeting our deadlines and ultimately delivering a final prototype. Below in Table 4 is the list of milestones we hit throughout the process. These provide a general outline of our schedule and will make sure we are staying up to date with our tasks.

Table 4. List of Key Deliverables

Key Deliverables	Expected Date of Completion
Preliminary Design Review (PDR)	11/14/17
Interim Design Review	01/16/18
Critical Design Review (CDR)	02/06/18
Manufacture & Test Review	03/13/18
Hardware/Safety Demo	04/26/18
Final Design Review (FDR)/Expo	06/01/18

All tasks that go into meeting these deliverables have been laid out in our Gantt Chart, seen in Appendix D. Our Gantt Chart was used to list the order of tasks, create dependencies, assign jobs, and keep a general schedule for our design process. This process includes Research, Ideation, Calculations, CAD Modeling, Prototyping, and Testing. A more detailed timeline and explanation of each step of this process can be seen in the Gantt Chart.

8.2 Task Description

The overall design process is listed below.

Research

We researched existing solutions (Rini, CoolShirt) and potential alternative solutions (thermoelectric cooling). We found four patents involving the Rini system. We initially decided on a refrigeration cycle solution, but our team decided to pursue thermoelectric cooling due to the low relative cost and fewer moving parts (only the pump), which increases the longevity of the unit.

Ideation

The ideation process included brainstorming solutions and ultimately choosing the best method based on our QFD, which includes the customer's needs and wants.

Calculations

Calculations will include heat transfer analysis, basic circuit analysis, pump sizing, and force calculations for the latches. The calculations have been completed as of this report (FDR).

CAD

A large part of our design process included creating a CAD model of our system. Our concept CAD is completed with the TEC solution, the cold plate, and manufacturing processes. It can be seen in our Drawing Package in Appendix L.

Prototyping

Similar to the CAD, our prototyping helped us find flaws in our system to fix and allowed us to find solutions. The first step is building a concept prototype, which will be at least partially functional. This process includes prototyping a key aspect of our chosen design concept. The purpose is to show our design has desired functionality, to prove the critical component works, and to highlight areas of difficulty that may come when building the full prototype.

The structural prototype has been completed, and we were able to test it in the vibrations lab. The test concluded that the cooling device would be able to withstand the g-forces associated with driving on the race track. Initially, the lead time on the cold plate was an issue for our final prototype. However, we bought off-the-shelf cold plate models instead of custom made ones, reducing the lead time to only two weeks instead of eight weeks.

The fully functioning prototype has been completed, allowing for testing to be done before submitting the FDR and presenting during Senior Project Expo.

Testing

To proceed with our tests, we needed to gather the necessary equipment. Most of the equipment specifically used for testing was borrowed or available for free on campus; the exceptions are the thermistors and a second Arduino to record temperature.

Our main testing involved measuring temperature change, where we used the thermistors and the additional Arduino. Vibrations testing has been done on our structural prototype in the vibrations lab per the DVP (Section 7). All the tests listed in the DVP have been completed with our functional prototype, except the setup time test. However, this test is low on the user priorities and goals for this project, and we estimate the setup time is not much longer than our desired time.

8.3 Deviations in Our Plan

Throughout our design process, we have had numerous changes and iterations that led to our final design. The first and largest deviation was changing our cooling solution from a refrigeration cycle to thermoelectric coolers. The change caused us to create a new CAD drawing and have two purchasing lists on hand, depending on which solution we chose.

There were not any other major deviations from our plan. However, there were multiple setbacks. The vibrations lab used an old computer, and it was difficult to figure out how to run our script, which delayed our vibrations test. The manufacturing was dependent on receiving the sheet metal and getting it cut with the waterjet, which were slightly behind schedule. Once the functional prototype was complete, we realized that the dimensions on our housing was off and would not fit the cold plates. Additionally, the housing did not fit into the mounting due to a larger than expected bend radius when bending the sheet metal. We had to use our extra sheet metal and manufacture another housing and mounting once we fixed the CAD. Because of the strict nature of our project's timeline, we did not have time to do additional testing, such as test running our project in an actual car on the racetrack.

9. Conclusion & Recommendations

We have been tasked with creating a cooling system for race car drivers to combat the high temperatures experienced for large durations at a time. Our goal is the design for the niche that was left by our two competitors, the Rini and CoolShirt Systems, which satisfies the price range and quality desired by club level race car drivers. To meet this goal, as well as satisfy the requirements set by our sponsor, we created a QFD House of Quality and a Gantt Chart to define the objectives of our project and set a scheduled timeline to keep us on track.

Our chosen solution uses TECs to cool a cold plate, which in turn cools the circulating fluid. Every part, including the TECs and the cold plate, was purchased, except for the housing and mounting of our system which we manufactured. The minimal amount of manufacturing saved us time, money, and allows easier maintenance with replaceable stock parts. The housing and mounting were initially made with wrong dimensions, and the housing was cut and remade.

All testing according to the DVP&R has been completed, except for setup time. Every test, except weight (14 lb from a required 10 lb), passed and met our requirements. The temperature test showed promising results, especially given the fact that only two TEC units out of four were running. The PWM setting on the Arduino is effective at changing the settings on the fan and TEC units.

Although our prototype is functional, further improvements can be made to the system. The dial to change the cooling settings can be moved from the box to the steering wheel or closer to the cockpit area with a different wiring schematic, giving the driver an easier time adjusting the settings. Code can be implemented to the Arduino to have user settings saved or fluctuate the PWM automatically, according to efficiency points of our TEC units and if power is needed for the race car. The weight of the system can be lessened with different materials, most likely a lower gauge aluminum sheet housing. However, decreasing the weight alone will not improve the efficiency or functionality of the system.

As it has hopefully been made clear TEC modules are very power hungry devices, but they get the job done. We were very happy to see how well the TEC modules did in our tests. We were able to get 98 deg F water to below 65 deg F in around 25 minutes with only half the system. This makes us optimistic that the system will indeed work the way we thought it would.

In the future we would recommend a couple key improvements to the system:

1st would be to look into higher efficiency Peltier modules, better fans and better heat sinks (pin fin). In talking to and industry professional at the senior project expo he recommended using heat pads as opposed to thermal paste or adhesive. He said that in his 30 years of electronics experience that they have been the best performers for interface heat transfer. He also told us that the best way he has found to remove heat using heat sinks was to blow air in parallel with the fins, not perpendicular as we have it now. This may not be feasible due to design constrains but it will be well worth looking into. Lastly, our research showed that there are higher efficiency Peltier modules and it may be beneficial to look into how much these high efficiency models make a difference. The physics department at Cal Poly has conducted research on Peltiers in the past and may know more about this topic.

2nd we would recommend looking into a different reservoir system and drainage system. We had a lot of trouble draining the system after we tested, most of the time we would have to blow water out of the tubes ourselves. Also, the current reservoir will fit in the system but will have a lot of trouble functioning properly without additional 90 deg pump connectors.

3rd we would recommend a different choice of piping, the piping we chose is quite frankly awful. It kinks every time we bend it which highly restricts the flow to the pump.

All in all this was a fun project where we learned a ton. We all want to thank you for being a great sponsor and helping us throughout the year. We hope that this proof of concept will help you bring this product to market in the future!

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Appendix A – Interview With Sponsor

9/24/17

FIRST MEETING WITH JUSTIN, SPONCER

TEMPERATURE

STANDARD COCKPIT TEMP ~ 100°F

@ AUSTIN ~ 145°F

AMP

6 AMP -> WHAT COMPETITOR USES

-> LIMIT FOR CHEAPER WIRE

SIZE

JUST SMALLER THAN ICE CHEST

IPHONE SIZE

* ASPEN COMPRESSOR ~ LOW NOISE, MINIATURE

LOOK INTO HEAT EXCHANGE PROBLEM

VIBRATION EFFECT

LIFE EXPECTANCY

AIM FOR 5 YEARS ~ 4 HOURS A MONTH AMATUER (THAT IS ABOUT A SEASON PRO)

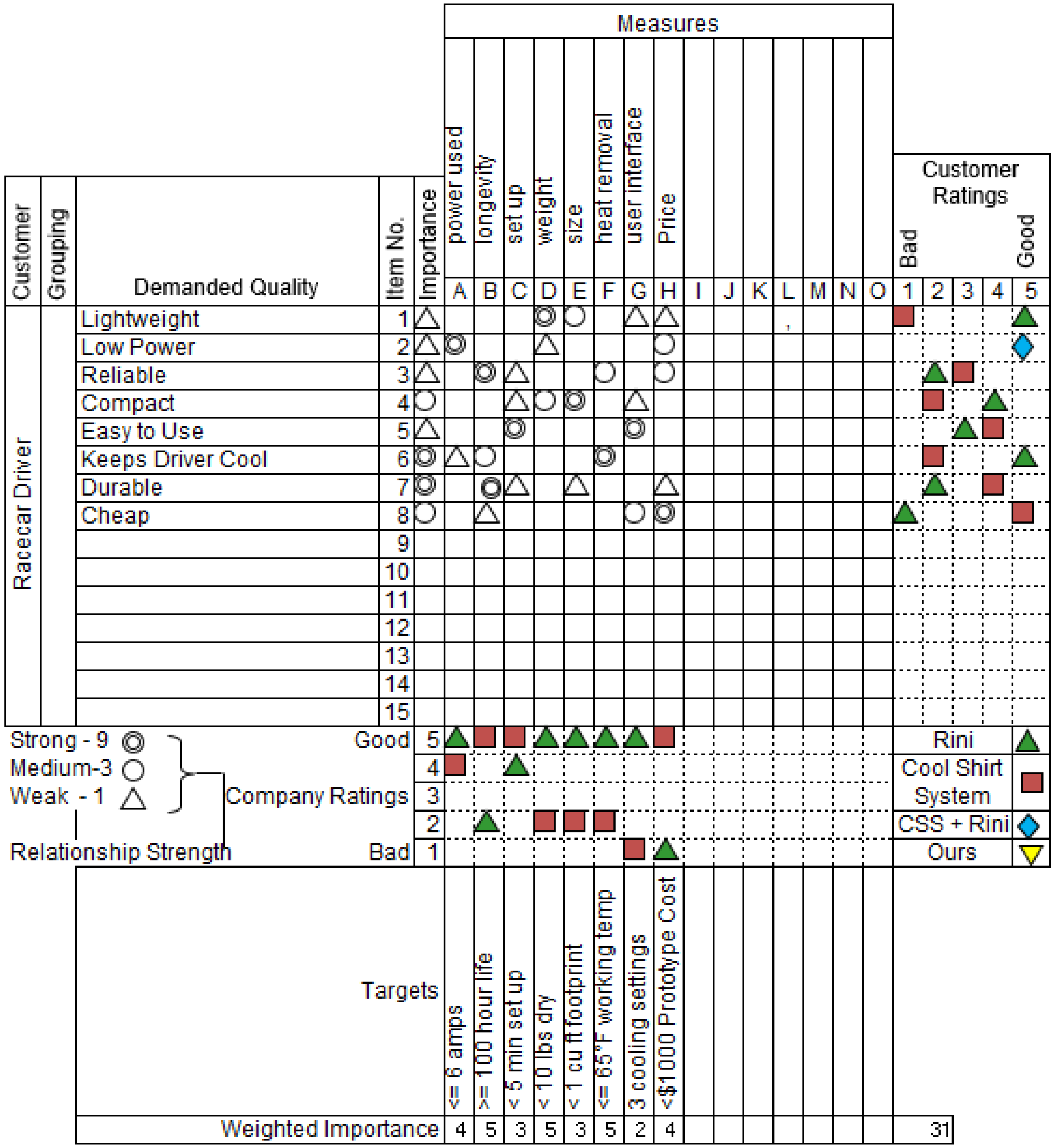
*PURCHASE MATERIALS IN DECEMBER (EARLIER THAN SCHOOL DATE)

↳ CHECK LEAD

Scope of Work

Project background information & sponsor interviews

Appendix B – QFD House of Quality



Appendix C – Benchmarking

Table C.1. Heat flux for different activities

Type of Activity	Mets	W/m^2
Resting	0.8	46.56
Seated	1.0	58.20
Light Activity	1.6	93.12
Medium Activity	2.0	116.40
Heavy Activity	3.0	174.60

Table C.2. Human heat generation during heavy activity

Body S.A (m^2)	Total Heat Generated (W)	Torso Heat (W)	Torso & Half Arms (W)	Torso & Full Arms (W)
1.30	226.98	81.71	102.14	122.57
1.40	244.44	88.00	110.00	132.00
1.50	261.90	94.28	117.86	141.43
1.60	279.36	100.57	125.71	150.85
1.70	296.82	106.86	133.57	160.28
1.80	314.28	113.14	141.43	169.71
1.90	331.74	119.43	149.28	179.14
2.00	349.20	125.71	157.14	188.57
2.10	366.66	132.00	165.00	198.00
2.20	384.12	138.28	172.85	207.42
2.30	401.58	144.57	180.71	216.85

Anatomic surface	% of total surface
Head and neck	9 = 9
Anterior trunk	2 x 9 = 18
Posterior trunk	2 x 9 = 18
Upper limbs	9 ea = 18
Lower limbs	18 ea = 36
Genitalia and perineum	1 = 1

Figure C.1. Rule of Nines

Appendix C – Benchmarking

COOLSHIRT SYSTEMS

Club-12 Driver Cooling System

Congratulations on your purchase of the world's finest Driver Cooling System

The COOLSHIRT Club-12 Driver Cooling System is the finest driver cooling system available today. Used by drivers in all levels of racing, this system delivers comfortable cooled water to the driver's shirt, keeping the driver more comfortable, safe, and mentally alert, as well as helping prevent heat exhaustion .

COOLSHIRT Personal Cooling Systems are manufactured in the USA and contain the highest quality components available. With proper installation and maintenance, your system will provide you with years of dependable service. ***Please inspect your purchase to ensure that your system contains the selected components listed below. If there are any discrepancies, please contact COOLSHIRT SYSTEMS customer service at 800-345-3176.***

Included with your system:

Quantity	**Part #**	**Description**
______ **1**	**CS-12**	**Club 12 Cooling Unit with 400 GPH internal pump**
______ **1**	**H-12-S**	**12-foot insulated water hose with quick disconnects**
______ **1**	**MA-16**	**Maintenance Additive (16 oz bottle)**

System Specifications:

Dimensions	***Cooling Time***	***Dry Weight***	***Power Required***
CS-12: 14"L x 9.5"W x 11"H	***3 Hours***	***4 lbs.***	***Water Pump: 2.5A, 12V***

Office : 800-345-3176 **Fax: 678-289-4325** **www.coolshirt.com**

Appendix C – Benchmarking

RINI TECHNOLOGIES

PERSONAL COOLING SOLUTIONS

407/359.7138 • www.rinitech.com

BENEFITS:

- Mitigates heat stress
- Reduces dehydration risk
- Enhances driving effectiveness
- Lightweight
- Continuous operation
- High efficiency

SYSTEMS SPECIFICATIONS:

- **Cooling:** 55°F Vest Temperature
- **Size:** 2.7" x 5.0" x 6.25"
- **Weight:** 4 lbs
- **Power Source:** 12V
- **Power Usage:** 6 amp
- **Built for Harsh Environments**
- **Contact:** info@rinitech.com

Personal Cooling System - Automotive

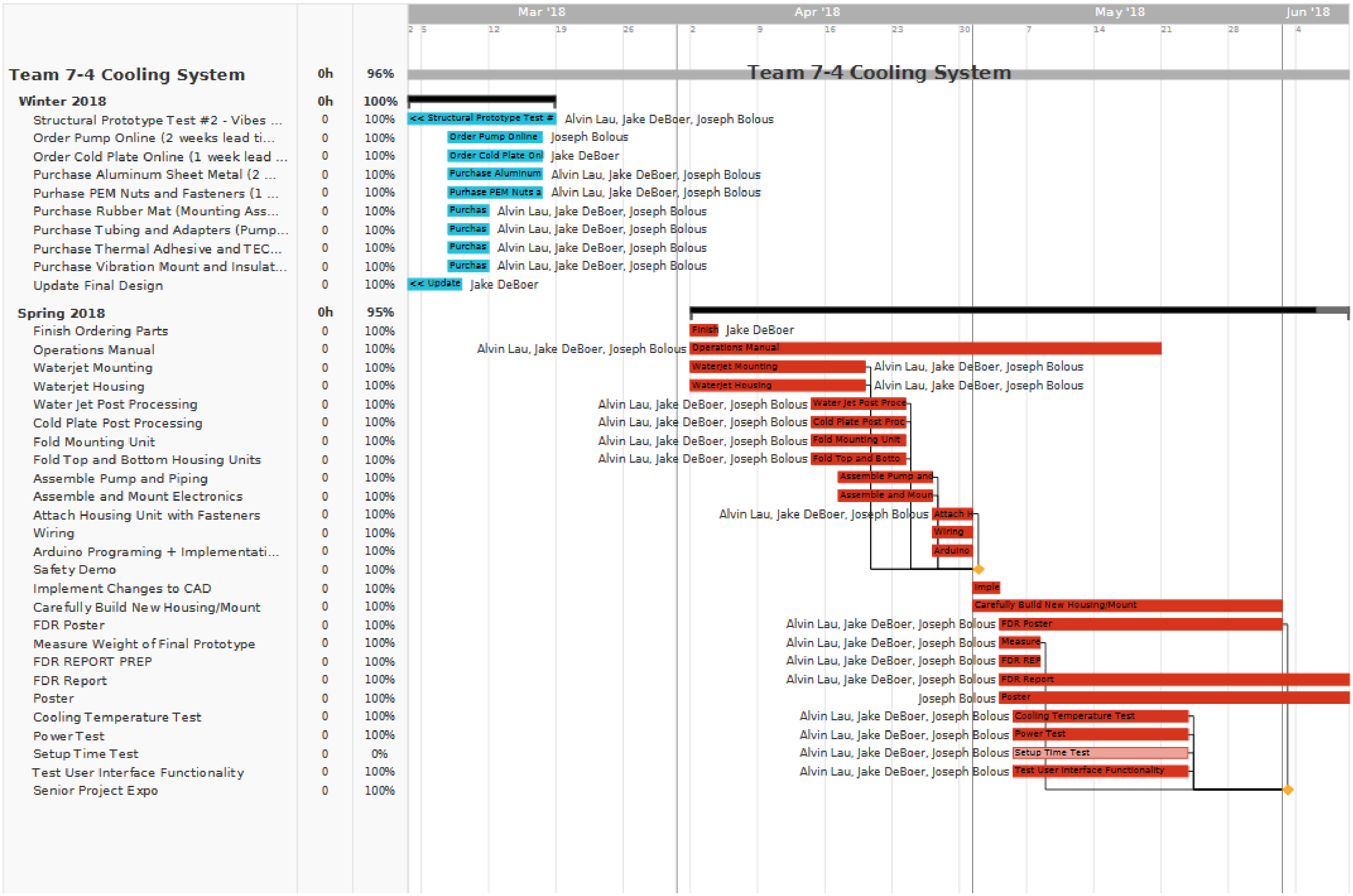
RINI Technologies' PCS-Auto is the smallest, lightest, and most effective Personal Cooling Solution available today. The PCS-Auto is powered via 12V and employs patented miniature refrigeration technology to continuously chill a flow of water to the Cooling Shirt. The PCS-Auto miniature cooling technology provides more heat transfer and is more efficient than air cooling or thermoelectric systems. The system can also be configured in a battery powered, backpack format, to cool the crew members.

Cooling Vest

Cooling Shirt

Cooling System

Appendix D – Gantt Chart

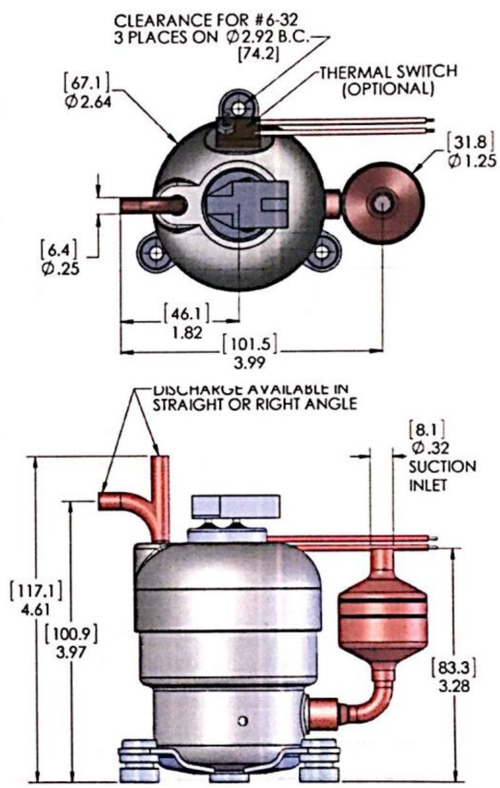


Appendix E – Specification Sheets for Possible Parts

Q-Series
Low Noise, Miniature, Rotary BLDC Refrigeration Compressors

ASPEN COMPRESSOR

Compressor Specifications	
Refrigerant	R134a / R404a / R410a / Others to be tested
Oil Type	Emkarate POE RL 68H
Oil Quantity	23cc Factory Charged
Motor / Drive	BLDC / Sensorless
Speed Range	2100 – 6500 RPM
Evaporator Temp. Range	-22~75°F (-30~24°C)
Max Condensing Temp.	160°F (71°C)
Max Discharge Temp.	265°F (130°C)
Max Ambient Temp.	130°F (54°C)
Max Dome Temp.	240°F (115°C)
Max Operating Pressure	350 psi (2.4 MPa)
Suction Port Size	0.25" ID Cup
Discharge Port Size	0.25" OD Tube
Analog Voltage Speed Command (Linear)	0 - .6 VDC = OFF .80 VDC: 2,300 RPM 4.5 VDC: 6,500 RPM
Cooling Capacity-ASHRAE T 1.4cc 1.9cc	R-134a R-404a 360 W W 455 W W
Noise Level @ 1 meter	~ 40 dBA
Weight 1.4cc 1.9cc	~ 900g ~ 925g



Compressor Ordering Guide

Q_-_ _-_1__

- **0 – Without Thermal Overload Switch**
- **1 – With Thermal Overload Switch**
- **0 – Standard Compressor**
- **1 – UL Approved Compressor**
- **4 – Straight Discharge Tube**
- **5 – Right Angle Discharge Tube**
- **12 – 12 VDC**
- **24 – 24 VDC**
- **48 – 48 VDC**
- **4 – 1.4cc**
- **9 – 1.9cc**

Sample Order # Q4 - 24 - 5111
Description – **1.4cc compressor**
24 Volt
Right angle discharge
UL approved
With Thermal Overload Switch

Compressor Application Notes:

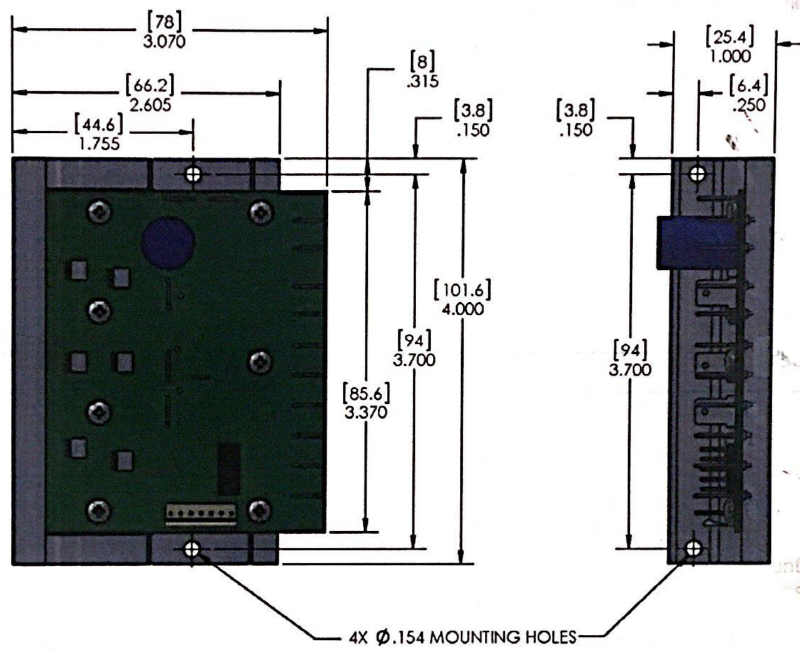
1. Compressor is supplied with 23cc Emkarate RL68 POE oil. Addition oil will be required if operating compressor in systems with long tubes, large heat exchangers or internal surfaces that can trap oil and prevent adequate return to the compressor.
2. Recommended airflow over compressor is 1 meter/sec.

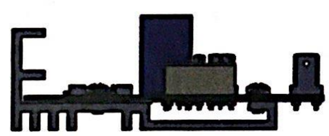
Aspen Compressor, LLC 24 St. Martin Drive, Marlborough, MA 01752 ☎508-380-7048 508-480-0328
web: www.aspencompressor.com email: info@aspencompressor.com

December, 2013

Appendix E – Specification Sheets for Possible Parts

ASPEN High Capacity Compressor Drive Board





Maximum Drive Board Current	
Drive Type	Max Current (A)
12V	10A or 15A - User selectable
24V	10A or 15A - User selectable
48V	7A or 8A - User selectable

Compressor Drive Application Notes:

1. Drive Board is conformally coated, however, care should be taken to prevent operation in corrosive or wet environments. Drive board is thermally protected, however, airflow over the drive board and heat sink is highly recommended.
2. Maximum current to the compressor is automatically limited by the drive board by reducing the compressor speed as the current approaches set limits. See table on the left for user selectable current limits for the drives.

Aspen Compressor, LLC 24 St. Martin Drive, Marlborough, MA 01752 ☎508-380-7048 508-480-0328
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Appendix E – Specification Sheets for Possible Parts

THERMACORE
Thermal Management Solutions

TECHNICAL DATA SHEET

Flexible Heat Pipe and Flexible Heat Pipe Cold Plate

For improved aerospace thermal control with a need for freedom of movement, minimum weight and maximum reliability, Thermacore's custom flexible heat pipes (Figure 1) are an advanced heat pipe technology that provides an ideal solution.

These flexible heat pipes give design engineers the freedom to:

- Specify moving actuators, and remote terminals.
- Maintain thermal controls in rugged and demanding environments.
- Use as building blocks for innovative systems to meet emerging aerospace challenges.
- Vibration and isolation tested

In fact, Thermacore's flexible heat pipes have been qualified for use in military aircraft — specifically, for cooling electronics on the **More Electric Aircraft**, and the **All Electric Aircraft**.

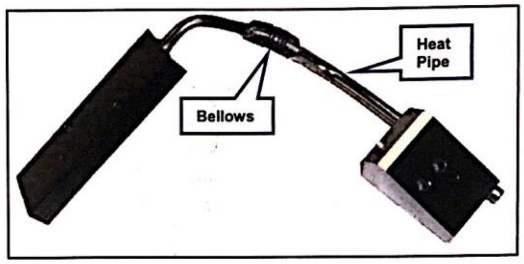

Figure 1 – Flexible Heat Pipe

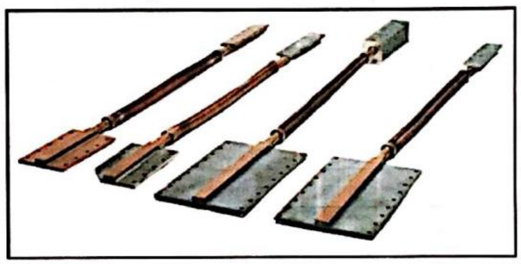

Figure 2 – Flexible Heat Pipe Cold Plate

Flexible Heat Pipe Cold Plate (FHPCP)

Thermacore's Flexible Heat Pipe Cold Plate (FHPCP) (Figure 2), available in four configurations, solves cooling problems with a cold plate that transfers electronic heat to the most convenient heat sink via a flexible heat pipe. The flexibility allows relative motion between the heat sink and the component to be cooled — increasing durability and mean time between failures.

Key Features and Benefits

- Aircraft Level Vibration Tested: Met shock and acoustic noise design requirements, and test procedures for the aircraft equipment
- Thermal-Cycled Tested: Freeze/Thaw from -55°C to 135°C
- Bellows Flex Fatigue Tested to Over 5 million cycles with No Signs of Failure
- Shock Tested for Cooling Missile Avionics

Critical Need Application

- Vibration Isolated Heat Sources
  - Optical Sensors
  - Radar Amplifiers
- Assemblies that Require Relative Motion
  - Deployable Radiators
  - Electro-Mechanical Actuators
  - Molding/Tooling
- Challenging "Fit-Up" with Tolerance Stack-Up Issues
  - Complex, Multiple-Part Assemblies
  - Difficult to Assemble, Constrained Spaces

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Appendix E – Specification Sheets for Possible Parts

THERMACORE
Thermal Management Solutions

TECHNICAL DATA SHEET

How Can Heat Pipes Be Made Flexible?

Heat pipes are made flexible by inserting a bellows section between the evaporator heat input section, and the condenser heat output section. Flexible heat pipes are made from a wide range of metal materials, and use a variety of working fluids, depending on the application.

Flexible heat pipes can be installed in either gravity-aiding, or against-gravity orientations. The against-gravity orientation is possible because of Thermacore's proprietary flexible wick structures, which are used to return the working fluid to the evaporator section. The cold plate portion attaches to the surface to be cooled, and the other end attaches to the heat sink. The flexible section allows for ease of installation, and it accommodates any relative motion between the heat source and the heat sink. The condenser region can be cooled by air cooled fins, like many other Thermacore products.

Specifications – Flexible Heat Pipe Cold Plate	
Length	Up to 30 in.
Design Power	Up to 150 Watts
Weight	Typically less than 2 lbs.
Cold Plate Size	Up to 5" x 8" x 3/16" Solid Al
Heat Sink Attachment	Customer Specified
Working Fluid	Water
ΔT at 150 Watts	Typically Less Than 4 °C

References from Thermacore's Web Site:

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Appendix E – Specification Sheets for Possible Parts

AAVID THERMACORE

TECHNICAL DATA SHEET

Embedded Heat Pipe Heat Sink

Aavid Thermacore's embedded heat pipe heat sink solutions are two-phase heat transfer devices that allow spreading of heat along the length of a heat pipe embedded within a heat sink (Figure 1). The heat pipes take "hot spots" on the heat sink base, and transport the heat across the base for more efficient cooling, maximizing airside fin efficiency. The heat pipes incorporate sintered powder wick structures that provide high-heat flux heat dissipation capability (>300 Watts/cm^2), and improves thermal performance of up to 20%, compared to a solid aluminum or copper based heat spreader. Its smaller size improves system packaging, and provides quieter operation through less air flow. Minimal design effort is required because a metallic-based heat spreader can be changed to an embedded heat pipe sink without altering the geometry of the original design.

Options to Attach the Heat Pipes to the Base

The heat pipes can be mounted to the heat sink base. The first option is to embed the heat pipes into gun-drilled holes, using Aavid Thermacore's unique expansion process that gives the heat sink a very efficient metal-to-metal thermal interface. The heat pipes can also be directly soldered (lead-free, high and low temperature) into the grooves on the heat sink base surface, which provide an excellent, low thermal resistance interface with the heat sources. In more cost sensitive applications, Aavid Thermacore uses a thermally conductive adhesive film, which covers the epoxy joint evenly throughout the surface. The heat pipes can also be integrated into the "hot face" of the heat sink for direct contact to the heat wall.

Key Features and Benefits

- Industry Leading Thermal Performance
- Over 40 years of life and reliability testing
- Able to withstand increased internal freeze-thaw and thermal shock ranging from -50° to 200°C)

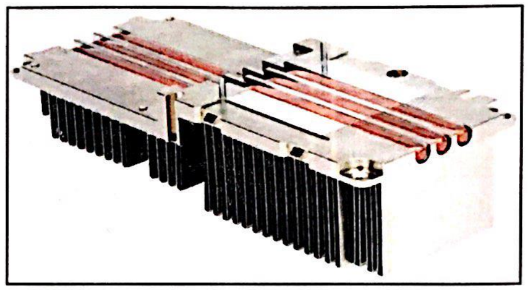

Figure 1 – Embedded Heat Pipe Heat Sink

Specifications – Embedded Heat Pipe Heat Sink	
Sizes	Custom sizes, application specific
Options	Various Shapes (Square, L-shaped, Rectangular)
Heat Pipe Options	Expanded, Soldered or Thermal Epoxy
Wall Material	High Purity Copper
Working Fluid	Water
Wick	Sintered Copper Powder
Maximum Heat Flux	300 Watts/cm^2

Critical Application Need

- Military Power Electronics Cooling:
  - IGBTs, MOSFETs, TWTs, and Thyristers
  - Transmitter/Receiver Modules
  - Transporting Heat to Liquid-Cooled Rails
- Telecom Communications: RF Amplifiers
- Low-Profile Applications
- Computer CPU, and GPU Cooling:
  - Desktop, Laptop, and Servers

Aavid Thermacore, Inc.
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Lancaster, PA 17601-4794 USA
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www.thermacore.com and www.aavid.com

US007010936B2

(12) **United States Patent**
Rini et al.

(10) **Patent No.: US 7,010,936 B2**
(45) **Date of Patent: Mar. 14, 2006**

(54) **METHOD AND APPARATUS FOR HIGHLY EFFICIENT COMPACT VAPOR COMPRESSION COOLING**

(75) Inventors: **Daniel P. Rini**, Orlando, FL (US); **Louis Chow**, Winter Park, FL (US); **H. Randolph Anderson**, Clermont, FL (US); **Jayanta Sankar Kapat**, Oviedo, FL (US); **Bradley Carman**, Orlando, FL (US); **Brian Gulliver**, Orange City, FL (US); **Jose Mauricio Recio**, Parkland, FL (US)

(73) Assignee: **Rini Technologies, Inc.**, Oviedo, FL (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **10/625,014**

(22) Filed: **Jul. 22, 2003**

(65) **Prior Publication Data**

US 2004/0129018 A1 Jul. 8, 2004

Related U.S. Application Data

(60) Provisional application No. 60/413,056, filed on Sep. 24, 2002.

(51) **Int. Cl.**
F25B 39/04 (2006.01)

(52) **U.S. Cl.** **62/507**; 165/154

(58) **Field of Classification Search** 62/506, 62/507; 165/154–156
See application file for complete search history.

(56) **References Cited**

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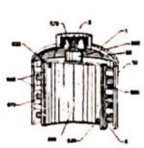
(Continued)

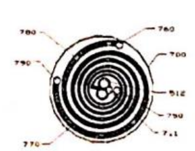
Primary Examiner—William E. Tapolcai
(74) *Attorney, Agent, or Firm*—Saliwanchik, Lloyd & Saliwanchik

(57) **ABSTRACT**

The subject invention pertains to a method and apparatus for cooling. In a specific embodiment, the subject invention relates to a lightweight, compact, reliable, and efficient cooling system. The subject system can provide heat stress relief to individuals operating under, for example, hazardous conditions, or in elevated temperatures, while wearing protective clothing. The subject invention also relates to a condenser for transferring heat from a refrigerant to an external fluid in thermal contact with the condenser. The subject condenser can have a heat transfer surface and can be designed for an external fluid, such as air, to flow across the heat transfer surface and allow the transfer of heat from heat transfer surface to the external fluid. In a specific embodiment, the flow of the external fluid is parallel to the heat transfer surface. In another specific embodiment, the heat transfer surface can incorporate surface enhancements which enhance the transfer of heat from the heat transfer surface to the external fluid. In another specific embodiment, an outer layer can be positioned above the heat transfer surface to create a volume between the heat transfer surface and the outer layer through which the external fluid can flow.

63 Claims, 14 Drawing Sheets





US007318325B2

(12) **United States Patent**
Rini et al.

(10) **Patent No.: US 7,318,325 B2**
(45) **Date of Patent: Jan. 15, 2008**

(54) **METHOD AND APPARATUS FOR HIGHLY EFFICIENT COMPACT VAPOR COMPRESSION COOLING**

(75) Inventors: **Daniel P. Rini**, Orlando, FL (US); **Louis Chow**, Winter Park, FL (US); **H. Randolph Anderson**, Clermont, FL (US); **Jayanta Sankar Kapat**, Oviedo, FL (US); **Bradley Carman**, Orlando, FL (US); **Brian Gulliver**, Orange City, FL (US); **Jose Mauricio Recio**, Parkland, FL (US)

(73) Assignee: **Rini Technologies, Inc.**, Oviedo, FL (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **11/343,431**

(22) Filed: **Jan. 31, 2006**

(65) **Prior Publication Data**

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Related U.S. Application Data

(62) Division of application No. 10/625,014, filed on Jul. 22, 2003, now Pat. No. 7,010,936.

(60) Provisional application No. 60/413,056, filed on Sep. 24, 2002.

(51) **Int. Cl.**
F25B 39/04 (2006.01)

(52) **U.S. Cl.** **62/507**; 165/154

(58) **Field of Classification Search** 62/506–507; 165/154–156, 148, 166

See application file for complete search history.

(56) **References Cited**

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CH 106 312 A 1/1925
(Continued)

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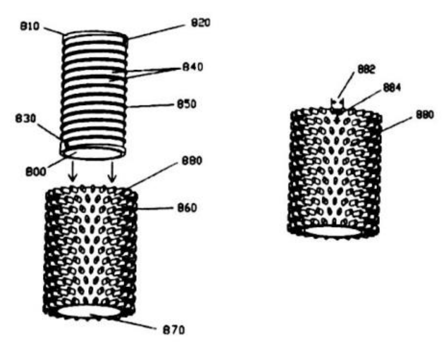
(Continued)

Primary Examiner—William E. Tapolcai
(74) *Attorney, Agent, or Firm*—Saliwanchik, Lloyd & Saliwanchik

(57) **ABSTRACT**

The subject invention pertains to a method and apparatus for cooling. In a specific embodiment, the subject invention relates to a lightweight, compact, reliable, and efficient cooling system. The subject system can provide heat stress relief to individuals operating under, for example, hazardous conditions, or in elevated temperatures, while wearing protective clothing. The subject invention also relates to a condenser for transferring heat from a refrigerant to an external fluid in thermal contact with the condenser. The subject condenser can have a heat transfer surface and can be designed for an external fluid, such as air, to flow across the heat transfer surface and allow the transfer of heat from heat transfer surface to the external fluid. In a specific embodiment, the flow of the external fluid is parallel to the heat transfer surface. In another specific embodiment, the heat transfer surface can incorporate surface enhancements which enhance the transfer of heat from the heat transfer surface to the external fluid. In another specific embodiment, an outer layer can be positioned above the heat transfer surface to create a volume between the heat transfer surface and the outer layer through which the external fluid can flow.

32 Claims, 14 Drawing Sheets



US007942642B2

(12) **United States Patent**
Rini et al.

(10) **Patent No.: US 7,942,642 B2**
(45) **Date of Patent: May 17, 2011**

(54) **METHOD AND APPARATUS FOR HIGHLY EFFICIENT COMPACT VAPOR COMPRESSION COOLING**

(75) Inventors: **Daniel P. Rini**, Orlando, FL (US); **Louis Chow**, Winter Park, FL (US); **H. Randolph Anderson**, Clermont, FL (US); **Jayanta Sankar Kapat**, Oviedo, FL (US); **Bradley Carman**, Orlando, FL (US); **Brian Gulliver**, Orange City, FL (US); **Jose Mauricio Recio**, Parkland, FL (US)

(73) Assignee: **Rini Technologies, Inc.**, Oviedo, FL (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **12/495,279**

(22) Filed: **Jun. 30, 2009**

(65) **Prior Publication Data**

US 2010/0071389 A1 Mar. 25, 2010

Related U.S. Application Data

(60) Continuation of application No. 11/963,669, filed on Dec. 21, 2007, which is a continuation of application No. 11/343,431, filed on Jan. 31, 2006, now Pat. No. 7,318,325, which is a division of application No. 10/625,014, filed on Jul. 22, 2003, now Pat. No. 7,010,936.

(60) Provisional application No. 60/413,056, filed on Sep. 24, 2002.

(51) **Int. Cl.**
F04B 49/06 (2006.01)
F04B 35/04 (2006.01)
F01C 1/02 (2006.01)

(52) **U.S. Cl.** **417/53**; 417/410.3; 418/61.2

(58) **Field of Classification Search** 417/44.1, 417/410.3, 53; 416/61.1–61.3
See application file for complete search history.

(56) **References Cited**

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(Continued)

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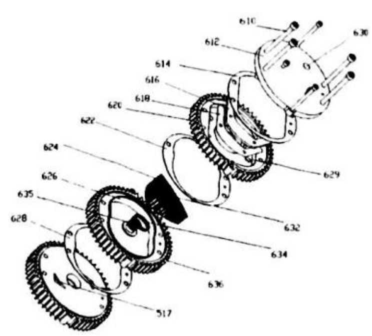
(Continued)

Primary Examiner — Charles G Freay
(74) *Attorney, Agent, or Firm* — Saliwanchik, Lloyd & Eisenschenk

(57) **ABSTRACT**

The subject invention pertains to a method and apparatus for cooling. In a specific embodiment, the subject invention relates to a lightweight, compact, reliable, and efficient cooling system. The subject system can provide heat stress relief to individuals operating under, for example, hazardous conditions, or in elevated temperatures, while wearing protective clothing. The subject invention also relates to a condenser for transferring heat from a refrigerant to an external fluid in thermal contact with the condenser. The subject condenser can have a heat transfer surface and can be designed for an external fluid, such as air, to flow across the heat transfer surface and allow the transfer of heat from heat transfer surface to the external fluid. In a specific embodiment, the flow of the external fluid is parallel to the heat transfer surface. In another specific embodiment, the heat transfer surface can incorporate surface enhancements which enhance the transfer of heat from the heat transfer surface to the external fluid. In another specific embodiment, an outer layer can be positioned above the heat transfer surface to create a volume between the heat transfer surface and the outer layer through which the external fluid can flow.

40 Claims, 14 Drawing Sheets



US008024942B2

(12) **United States Patent**
Rini et al.

(10) **Patent No.:** **US 8,024,942 B2**
(45) **Date of Patent:** **Sep. 27, 2011**

(54) **METHOD AND APPARATUS FOR HIGHLY EFFICIENT COMPACT VAPOR COMPRESSION COOLING**

(75) Inventors: **Daniel P. Rini**, Orlando, FL (US); **Louis Chow**, Winter Park, FL (US); **H. Randolph Anderson**, Clermont, FL (US); **Jayanta Sankar Kapat**, Oviedo, FL (US); **Bradley Carman**, Orlando, FL (US); **Brian Gulliver**, Orange City, FL (US); **Jose Mauricio Recio**, Parkland, FL (US)

(73) Assignee: **Rini Technologies, Inc.**, Oviedo, FL (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 766 days.

(21) Appl. No.: **11/963,669**

(22) Filed: **Dec. 21, 2007**

(65) **Prior Publication Data**

US 2010/0293993 A1 Nov. 25, 2010

Related U.S. Application Data

(60) Continuation of application No. 11/343,431, filed on Jan. 31, 2006, now Pat. No. 7,318,325, which is a division of application No. 10/625,014, filed on Jul. 22, 2003, now Pat. No. 7,010,936.

(60) Provisional application No. 60/413,056, filed on Sep. 24, 2002.

(51) **Int. Cl.**
F25B 39/04 (2006.01)

(52) **U.S. Cl.** **62/507**; 62/508

(58) **Field of Classification Search** 62/507–508, 62/505, 506, 426, 314, 414, 419; 165/183–184; 29/890.038; 454/15, 141, 201
See application file for complete search history.

(56) **References Cited**

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CH 106 312 A 1/1925
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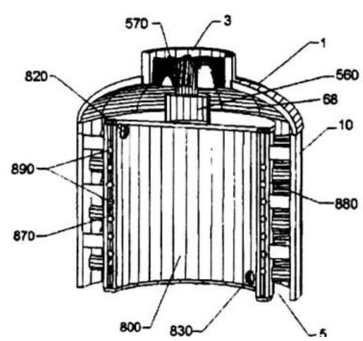
Li, Q. et. al. "Heat Transfer and Pressure Drop Characteristics in Rectangular Channels with Elliptic Pin Fins" *International Journal of Heat and Fluid Flow*, 1998, pp. 245-250; vol. 19.
(Continued)

Primary Examiner — Mohammad Ali
(74) *Attorney, Agent, or Firm* — Saliwanchik, Lloyd & Eisenschenk

(57) **ABSTRACT**

The subject invention pertains to a method and apparatus for cooling. In a specific embodiment, the subject invention relates to a lightweight, compact, reliable, and efficient cooling system. The subject system can provide heat stress relief to individuals operating under, for example, hazardous conditions, or in elevated temperatures, while wearing protective clothing. The subject invention also relates to a condenser for transferring heat from a refrigerant to an external fluid in thermal contact with the condenser. The subject condenser can have a heat transfer surface and can be designed for an external fluid, such as air, to flow across the heat transfer surface and allow the transfer of heat from heat transfer surface to the external fluid. In a specific embodiment, the flow of the external fluid is parallel to the heat transfer surface. In another specific embodiment, the heat transfer surface can incorporate surface enhancements which enhance the transfer of heat from the heat transfer surface to the external fluid. In another specific embodiment, an outer layer can be positioned above the heat transfer surface to create a volume between the heat transfer surface and the outer layer through which the external fluid can flow.

23 Claims, 14 Drawing Sheets



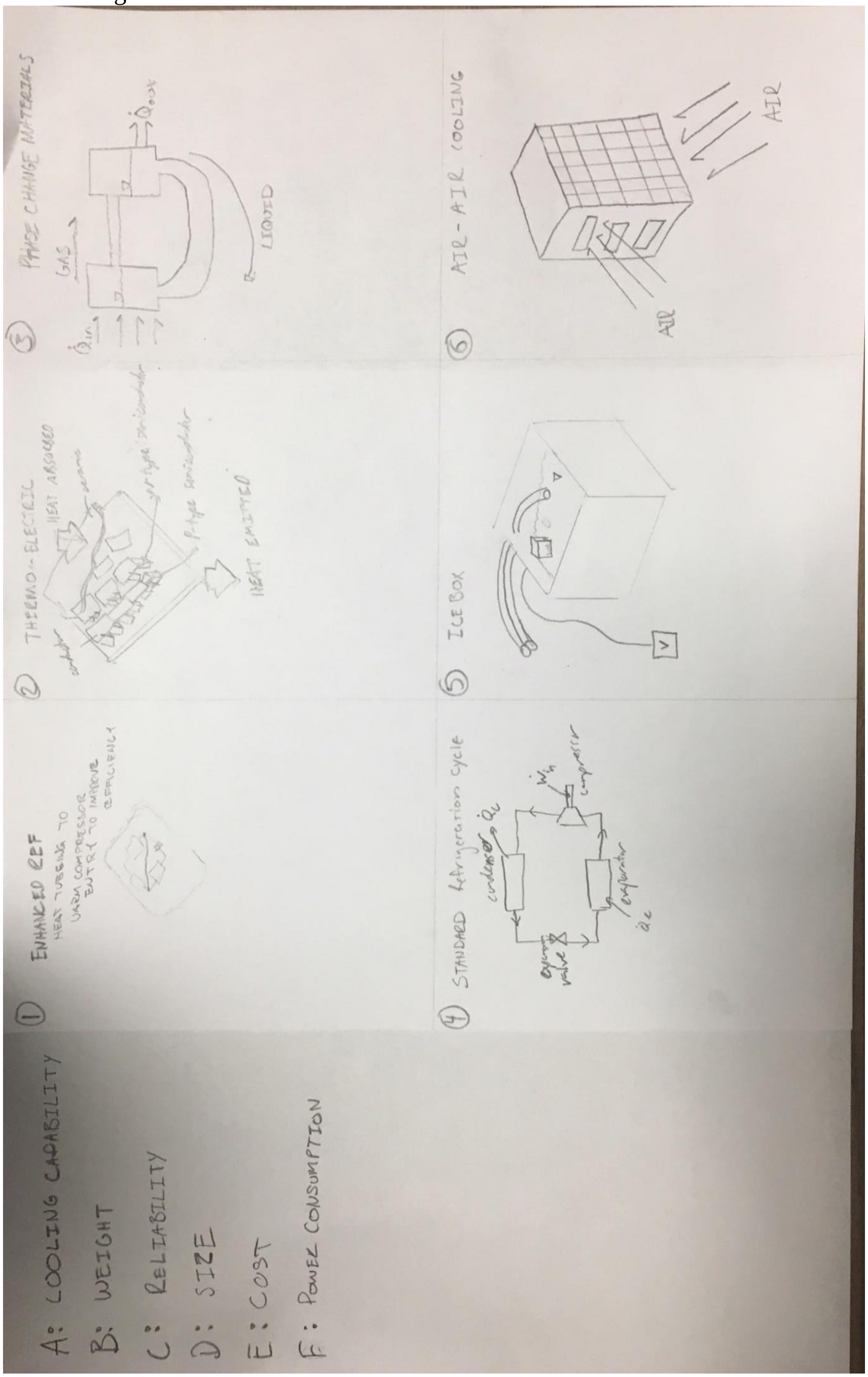


Figure G.1. Chosen concepts to analyze using the Pugh Matrix

Appendix G – Pugh Matrices

Table G.1. Pugh Matrix using the Cool Shirt Ice Box system as a datum

Datum with Ice Box

Concept/Criteria	Enhanced REF	TEC	Phase Change	Standard REF	Ice Box	Air-Air
Cooling Capability	+	+	+	S	Datum	-
Weight	+	+	S	+	Datum	+
Reliability	-	+	?	-	Datum	+
Size	+	+	?	+	Datum	-
Cost	-	-	-	-	Datum	-
Power Consumption	S	-	S	S	Datum	S
Total	+1	+2	0	+1	Datum	-1

Table G.2. Pugh Matrix using the Rini Refrigeration Cycle as a datum

Datum with Rini

Concept/Criteria	Enhanced REF	TEC	Phase Change	Standard REF	Ice Box	Air-Air
Cooling Capability	+	-	?	Datum	-	-
Weight	S	+	-	Datum	-	-
Reliability	S	+	?	Datum	+	+
Size	S	+	-	Datum	-	-
Cost	-	+	S	Datum	+	+
Power Consumption	+	S	S	Datum	+	S
Total	+1	+3	-2	Datum	0	-1

Appendix H – Concept 1: Aspen Liquid Chiller Module (LCM)

Figure H.1. Components of the Aspen LCM Unit

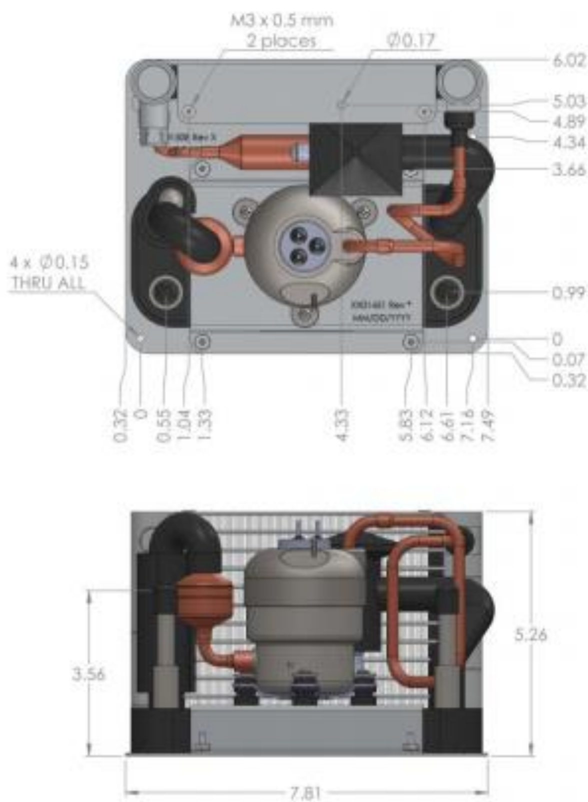


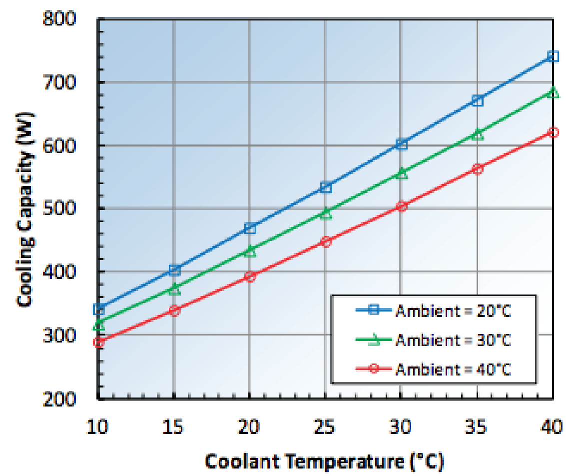
Figure H.2. Dimensions of the Aspen LCM Unit

Appendix H – Concept 1: Aspen Liquid Chiller Module (LCM)

Technical Data

Cooling Capacity	See graph to right
Compatible Fluids	Water, Glycol/Water Mixtures
Coolant Temperature	0°C to 50°C (32°F to 122°F)
Maximum Power Draw	360 Watts (at 24 V)
Voltage	22-32 VDC (24 V nominal)
Maximum Current	15 Amps
Noise	<40 dBA
Weight	2.7 kg (6.0 lbs) (including drive board)
Dimensions	199 x 161 x 134 mm (7.8 x 6.3 x 5.3 in) (L x W x H)
Orientation	Must operate within 30° of flat
Operating Ambient Temperature	0°C to 50°C (32°F to 122°F)
Storage Temperature	-20°C to 50°C (-4°F to 122°F)
Refrigerant	R-134a

Performance Curves



Note: All results above obtained with water as the working coolant at a coolant flow of 2 L/min flow and with 150 cfm of air over the condenser.

Figure H.3. Technical Data for the Aspen LCM Unit

Appendix I – Concept 2: Rigid Liquid Chiller Module (RLCM)

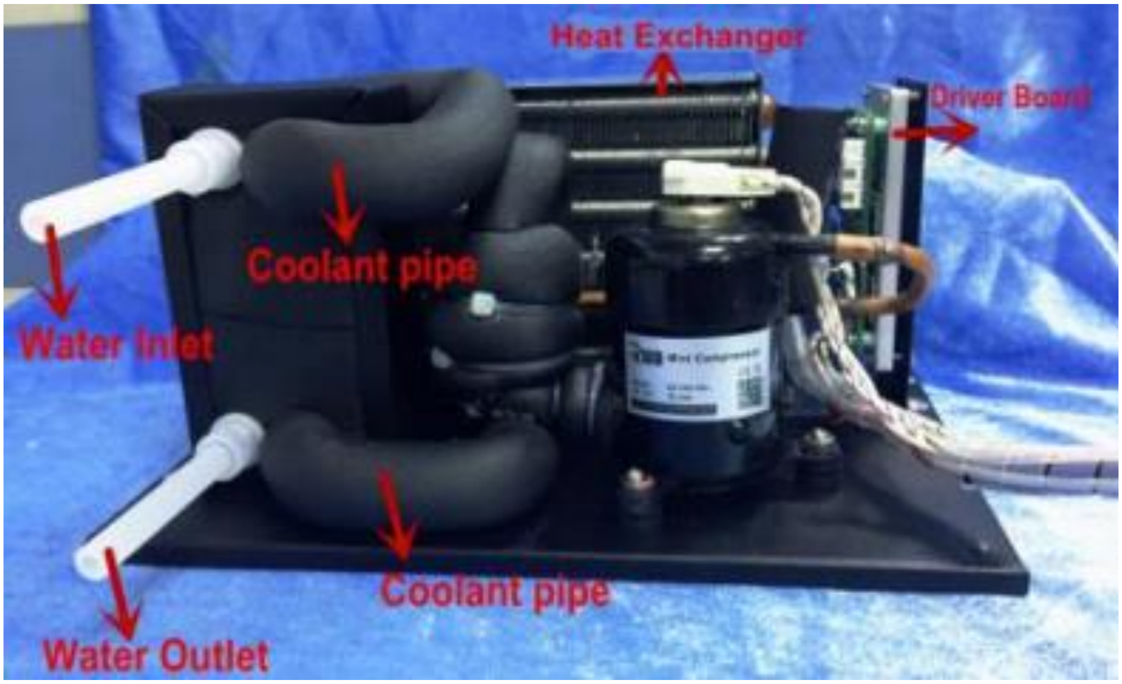


Figure I.1. A picture of the Rigid Liquid Chiller Module Unit

Appendix I – Concept 2: Rigid Liquid Chiller Module (RLCM)

Table I.1. Technical Data for the RLCM

Model Name	DV1910E-P
DC Compressor Model	QX1901VDL
Refrigerant	R134a
Rated Voltage	12V
Voltage Range	9 V - 16 V
Start-up Voltage	9V
Start-up Current	2.1 A
Max Current	10 A
Cooling Capacity	360 W
Capillary Tube	Φ2 * 0.8 m
Condenser	450 W
Evaporator	Φ8 * 1.8 m
Fan Voltage	12V @2550rpm
N.W	5.1lbs/2.3 Kgs
Control Panel	Variable Frequency Controller
External Dimension	257x175x138mm / 10.1x6.9x5.43" inch

Appendix I – Concept 2: Rigid Liquid Chiller Module (RLCM)

Table I.2. More parameters for the RLCM

Item	Standard	Overload	Note
Discharge Pressure	< 1.7MPa	< 2.2MPa	Compressor will be overloaded protection when temp reaches 105° degree
Suction Pressure	0.1 - 0.3Mpa	0.1 - 0.3Mpa	
Compression Ratio	< 6	< 8	
Discharge Temp	84° degree	105° degree	
Start-up Pressure	Only when system's high-low pressure under balance can operate compressor（Compressor has this built-in setting）		
Max Tilt Angle	40° Degree		
Oil Type & Amount	Type: POE68# Amount: 25cc		
Compressor Protection	Controller Automatic Protection		
Motor Data	PM Brushless DC Motor		
Noise	52dB		

Appendix J – Concept 4: Thermoelectric Cooling Unit (TEC)

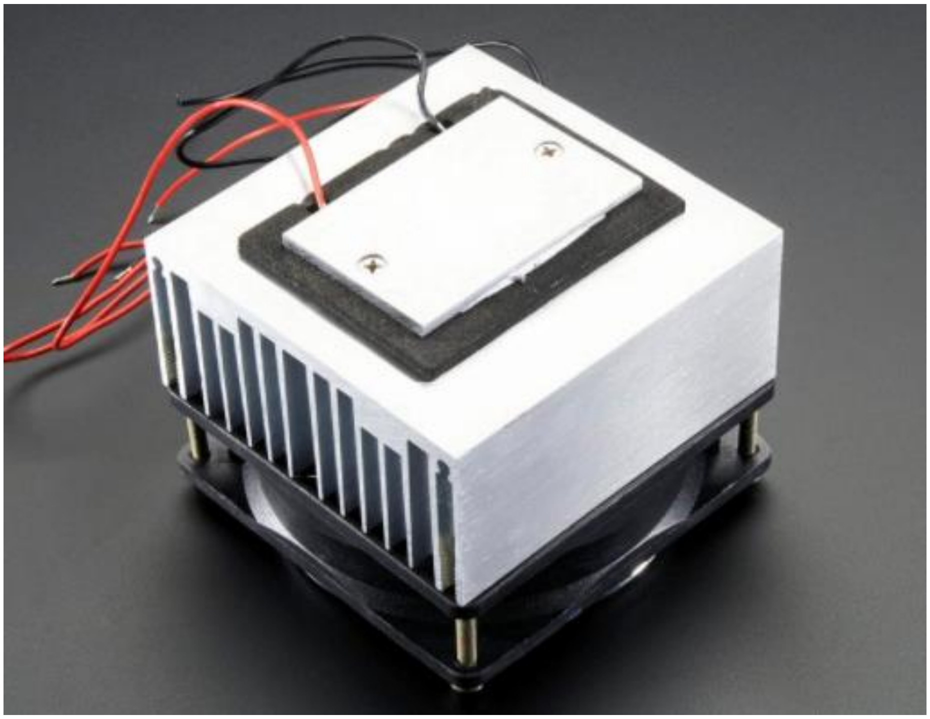


Figure J.1. Picture of the Thermoelectric Cooling Unit. The unit is made up of a heat sink with a thermoelectric cooler mounted on top.

Appendix J – Concept 4: Thermoelectric Cooling Unit (TEC)

TECHNICAL DETAILS

- The Peltier Module is 40mm x 40mm / 1.6" x 1.6"
- The aluminum plate is 40mm x 60mm / 1.6" x 2.4"
- The heat-sink is 90mm x 90mm / 3.5" x 3.5"
- The whole assembly is approximately 78mm / 3.1" tall
- Wire Length: 280mm / 11"
- Weight: 455g
- Wattage: 60W nominal (12V * 5A), 72W max

Figure J.2. Technical Data for the Thermoelectric Cooling Unit

Appendix J – Concept 4: Thermoelectric Cooling Unit (TEC)

Figure J.3. Picture of Cold Plate
Cold plate with water running through it that gets placed on top of TEC configuration

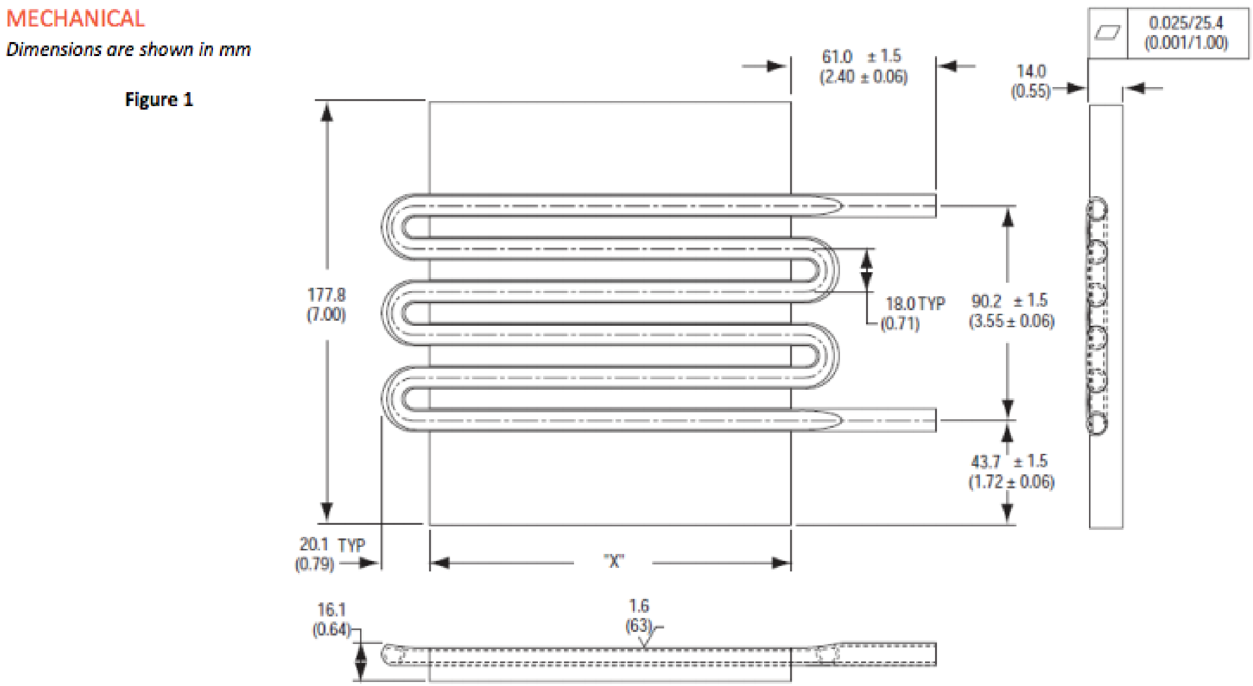


Figure J.4. Cold Plate Dimensions

Appendix J – Concept 4: Thermoelectric Cooling Unit (TEC)

PERFORMANCE – 6 PASS

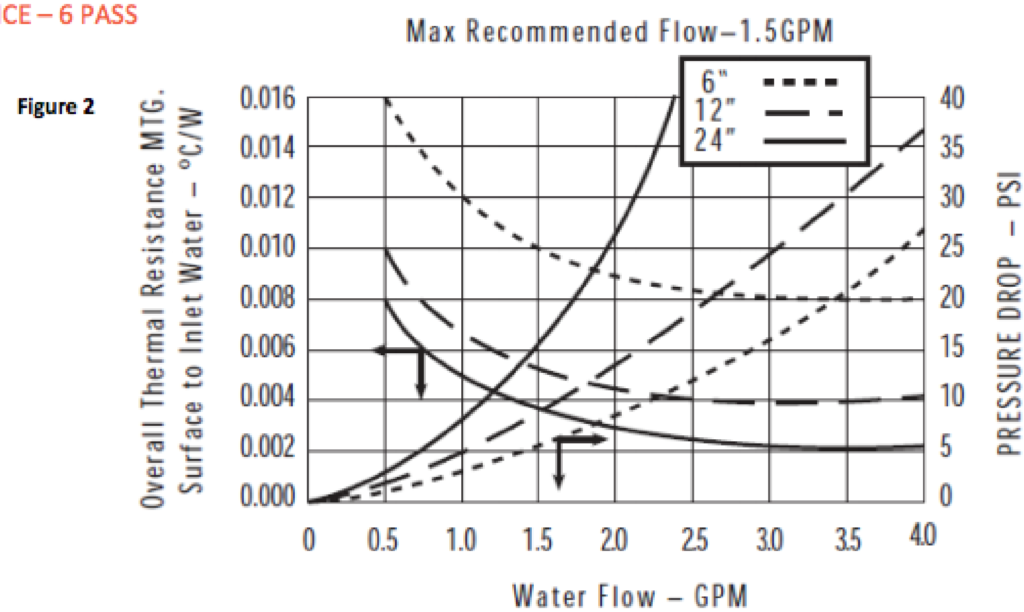


Figure J.5. Performance plot for cold plate

Table J.1. Miscellaneous cold plate information

HI-CONTACT™ PRODUCT SPECIFICATIONS

Property	Details
Plate Details	Extruded Aluminum
Tube Material	Copper 9.5mm O.D. x 1.24mm wall
Standard Finish	Unfinished
Epoxy	Aluminum Filled - High Thermal Conductivity

Measurement	mm	in
Width	177.8	7
Thickness	15.24	0.55

Appendix K – Budget Analysis of Concept Designs

Table K.1. Tentative Budget for ASPEN System. Highlighted items priced for 100 units.

Design 1 - Aspen LCM			
Part	**Price**	**Quantity of part / Unit**	**Price of part /unit**
Aspen LCM Unit	$1,150.00	1.00	$1,150.00
v100 Vib units	$2.44	8.00	$19.52
2'x2' 22 GA Gal sheet	$13.76	1.00	$13.76
Pump	$30.50	1.00	$30.50
Electronics	$50.00	1.00	$50.00
Connectors	$4.28	2.00	$8.56
Thermal Piping - 500 ft	$205.00	0.02	$4.10
Misc	$50.00	1.00	$50.00
Totals		**15.02**	**$1,326.44**

Table K.2. Tentative Budget for Rigid System. Highlighted items priced for 100 units.

Design 2 -Rigid LCM			
Part	**Price**	**Quantity of part / Unit**	**Price of part /unit**
Rigid LCM Unit	$168.00	1.00	$168.00
v100 Vib units	$2.44	8.00	$19.52
2'x2' 22 GA Gal sheet	$13.76	1.00	$13.76
Pump	$30.50	1.00	$30.50
Electronics	$50.00	1.00	$50.00
Connectors	$4.28	2.00	$8.56
Thermal Piping - 500 ft	$205.00	0.02	$4.10
Misc	$50.00	1.00	$50.00
Totals		**15.02**	**$344.44**

Table K.3. Tentative Budget for Thermoelectric Cooling. Highlighted items priced for 100 units.

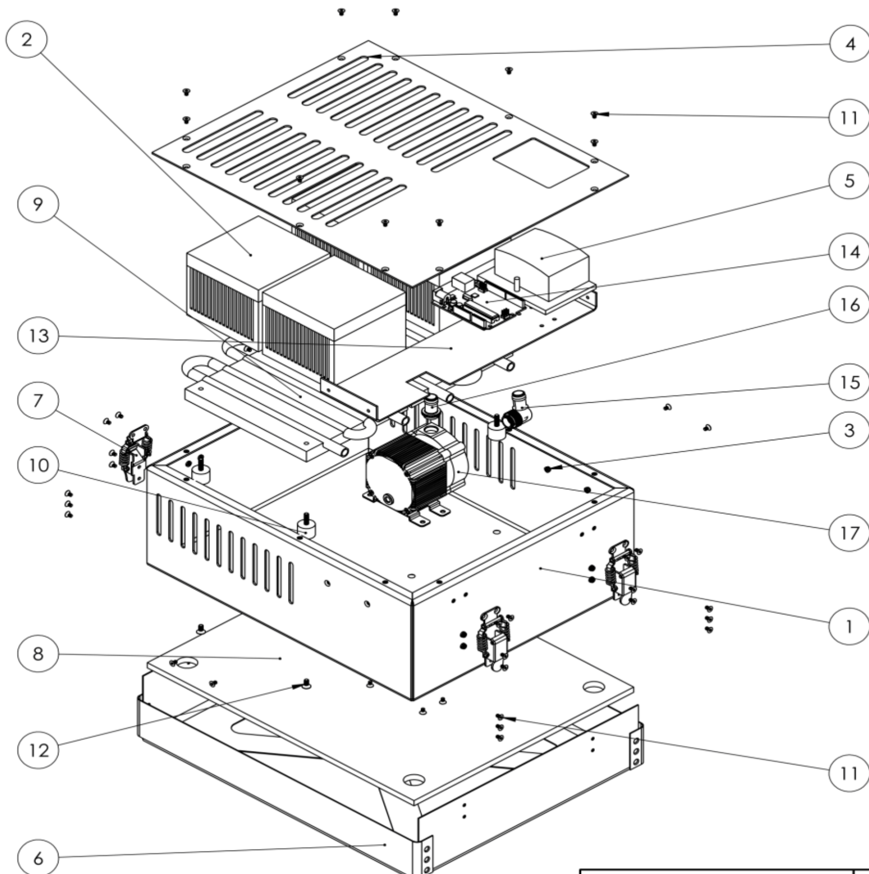
Design 3 -Thermoelectric			
Part	**Price**	**Quantity of part / Unit**	**Price of part /unit**
Peltier Cooler+ HS + Fan	$27.96	3.00	$83.88
Aavid Cold Plate	$39.51	1.00	$39.51
v100 Vib units	$2.44	8.00	$19.52
Electronics	$50.00	1.00	$50.00
Connectors	$4.28	2.00	$8.56
2'x2' 22 GA Gal sheet	$13.76	1.00	$13.76
Pump	$30.50	1.00	$30.50
Thermal Piping - 500 ft	$205.00	0.02	$4.10
Misc	$50.00	1.00	$50.00
Totals		**18.02**	**$299.83**

Appendix L – Indented Bill of Materials

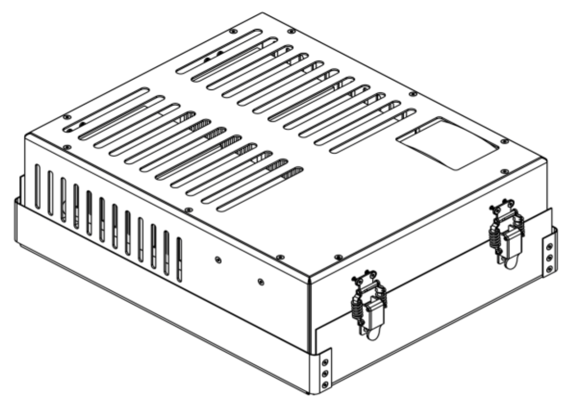
Indented Bill of Material (BOM)
Driver Cooling System

Part Number	Description				Vendor	Part Qty	Ind Cost	Final Product Cost	Purchasing Qty	Prototype Cost	Purchasing Link	Purchased?	Received
	Lvl0	Lvl1	Lvl2	Lvl3									
10000	Final Assembly												
		Housing											
10100			Cooling Assembly										
				M4 x .7 8mm Flat Head Screw - 2.5mm Allen	McMaster	8	$ 4.72	$ 0.38	1 Box	$ 4.72	Here	Yes	Yes
				Cold Plate	Mouser	2	$ 88.00	$ 176.00	2 Units	$ 176.00	Here	Yes	Yes
				Thermal Paste	Amazon	1	$ 7.50	$ 7.50	1 Tube	$ 7.50	Here	Yes	Yes
				TEC Units	Adafruit	4	$ 35.00	$ 140.00	4 Units	$ 140.00	Here	Yes	Yes
				Vibration Mount M4	McMaster	8	$ 2.12	$ 16.96	8 Units	$ 16.96	Here	Yes	Yes
				Fiberglass Insulation Strip	McMaster	1	$ 7.23	$ 7.23	1 Roll	$ 7.23	Here	Yes	Yes
				3M Dual Lock Velcro	Amazon	1	$ 11.49	$ 11.49	1 Roll	$ 11.49	Here	Yes	Yes
10200			Pump Assembly										
				M3 x .5 5mm Flat Head Screw - 2mm Allen	McMaster	4	$ 5.15	$ 0.21	1 Box	$ 5.15	Here	Yes	Yes
				Tubing	Fresh Water Systems	1	$ 25.00	$ 6.25	1 Roll	$ 25.00	Here	Yes	Yes
				Koolance Pmp-500 Pump	Koolance	1	$ 76.99	$ 76.99	1 Unit	$ 76.99	Here	Yes	Yes
				3/8" 90 Deg Adapters	McMaster	4	$ 8.05	$ 3.22	1 Box	$ 8.05	Here	Yes	Yes
				Rotary Elbow Barb Fitting 3/8"	Koolance	1	$ 5.49	$ 5.49	1 Units	$ 5.49	Here	Yes	Yes
				Straight Elbow Barb Fitting 3/8"	Koolance	1	$ 3.99	$ 3.99	1 Units	$ 3.99	Here	Yes	Yes
				Resevoir Tank		1	$ 30.00	$ 30.00	1 Units	$ 30.00		Yes	Yes
10300			Electronics Assembly										
				Arduino	Amazon	1	$ 10.90	$ 10.90	1 Unit	$ 10.90	Here	Yes	Yes
				Potentiometers	Amazon	1	$ 5.82	$ 5.82	1 Box	$ 5.82	Here	Yes	Yes
				16 Ga Wire Red 25ft	ProWire	1	$ 13.06	$ 13.06	1 Roll	$ 13.06	Here	Yes	Yes
				Fuse Box	Amazon	1	$ 8.23	$ 8.23	1 Unit	$ 8.23	Here	Yes	Yes
				Temp Sensors	Adafruit	2	$ 4.00	$ 8.00	2 Units	$ 8.00	Here	Yes	Yes
				M4 x .7 8mm Flat Head Screw - 2.5mm Allen	McMaster	4	$ 4.72	$ 0.19			Here	Yes	Yes
				Blade Fuses	Amazon	1	$ 7.99	$ 7.99	1 Box	$ 7.99	Here	Yes	Yes
				DT Connectors	ProWire	1	15.86	$ 15.86	1 Unit	$ 15.86	Here	Yes	Yes
				Mosfet Shield	Robot Shop	1	$ 16.45	$ 16.45	2 Unit	$ 32.90	Here	Yes	Yes
				Blade Connectors	McMaster	1	$ 4.11	$ 4.11	1 Unit	$ 4.11	Here	Yes	Yes
				22 Ga Wire Red 50ft	ProWire	1	$ 12.75	$ 12.75	1 Roll	$ 12.75	Here	Yes	Yes
				16 Ga Wire Black 25ft	ProWire	1	$ 13.06	$ 13.06	1 Roll	$ 13.06	Here	Yes	Yes
				22 Ga Wire Black 50ft	ProWire	1	$ 12.75	$ 12.75	1 Roll	$ 12.75	Here	Yes	Yes
10400			Housing Assembly										
				3003 H14 1/16 in Aluminum Sheet Metal	Metals Depot	1	$ 35.92	$ 17.96	2 Unit	$ 71.84	Here	Yes	Yes
				M3 Pem Nuts	McMaster	30	$ 8.44	$ 12.66	2 Box	$ 16.88	Here	Yes	Yes
				M3 x .5 5mm Flat Head Screw - 2mm Allen	McMaster	10	$ 5.15	$ 0.52		$ 20.00	Here	Yes	Yes
10500		Mounting											
			Tight Hold Draw Latch		McMaster	4	$ 7.61	$ 30.44	4 Unit	$ 30.44	Here	Yes	Yes
			Rubber Mat		Amazon	1	$ 12.17	$ 12.17	1 Unit	$ 12.17	Here	Yes	Yes
			3003 H14 1/16 in Aluminum Sheet Metal		Metals Depot	1	$ 35.92	$ 17.96			Here	Yes	Yes
			M3 x .5 5mm Flat Head Screw - 2mm Allen		McMaster	8	$ 5.15	$ 0.41			Here	Yes	Yes
Totals						96		$706.99		$ 815.33			

Appendix M – Complete Drawings Package

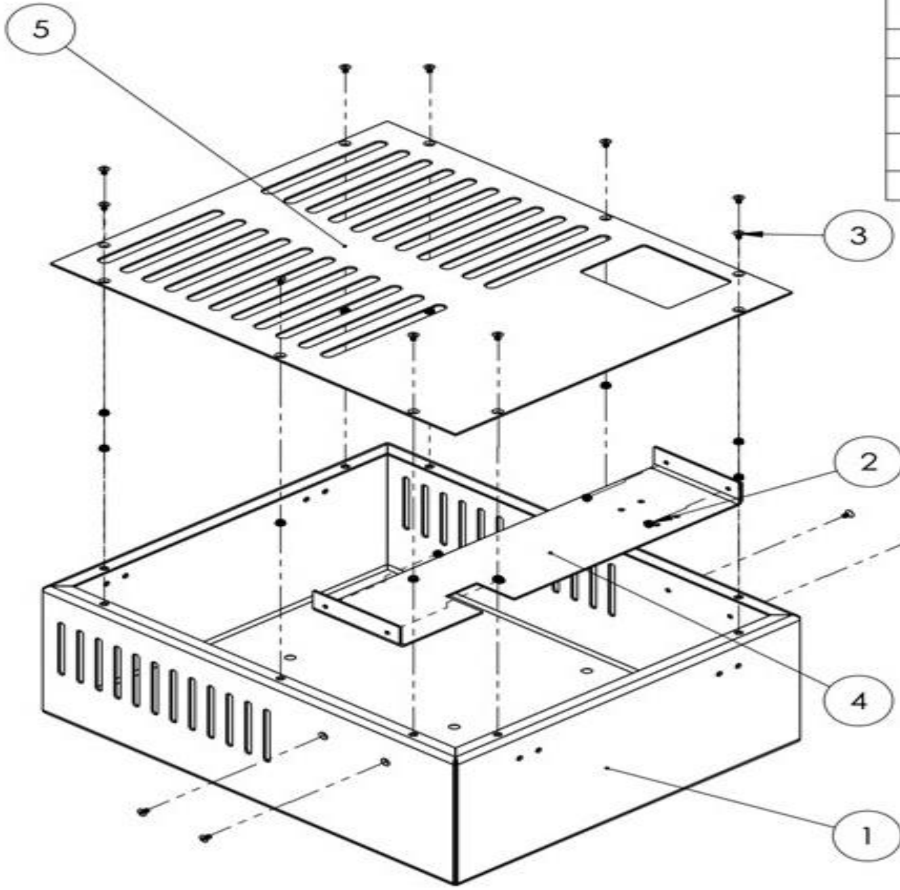


ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	10401	HOUSING BOTTOM	1
2	10103	TEC MODULE	4
3	94100A110	M3 PEM NUT	58
4	10402	HOUSING TOP	1
5	OLS PSZACCEPS051H	OLS 6 FUSE FUSE BLOCK	1
6	10500	HOUSING MOUNT	1
7	1734A270	DRAW SPRING LATCH	4
8	10501	RUBBER MAT	1
9	10100	COLD PLATE	2
10	9241K420	VIBRATION MOUNT M4	8
11	91294A125	M3 X .5 5MM FLAT HEAD SCREW	58
12	91294A188	M4 X .7 8MM FLAT HEAD SCREW	8
13	10400	SHELF	1
14	Arduino UNO	ARDUINO	1
15	10204	PUMP ROTARY ELBOW	1
16	10205	PUMP STRAIGHT CONNECTION	1
17	10202	KOOLANCE PMP-500	1



Cal Poly Mechanical Engineering	Lab Section:	D.C.S SYSTEM	Title: DCS COOLING ASSEM		Drwn. By: JAKE DEBOER
ME 430 - SPRING 2018	Dwg. #: 1	Nxt Asb:	Date: 6/1/18	Scale: 1:3.75	Chkd. By: ME STAFF

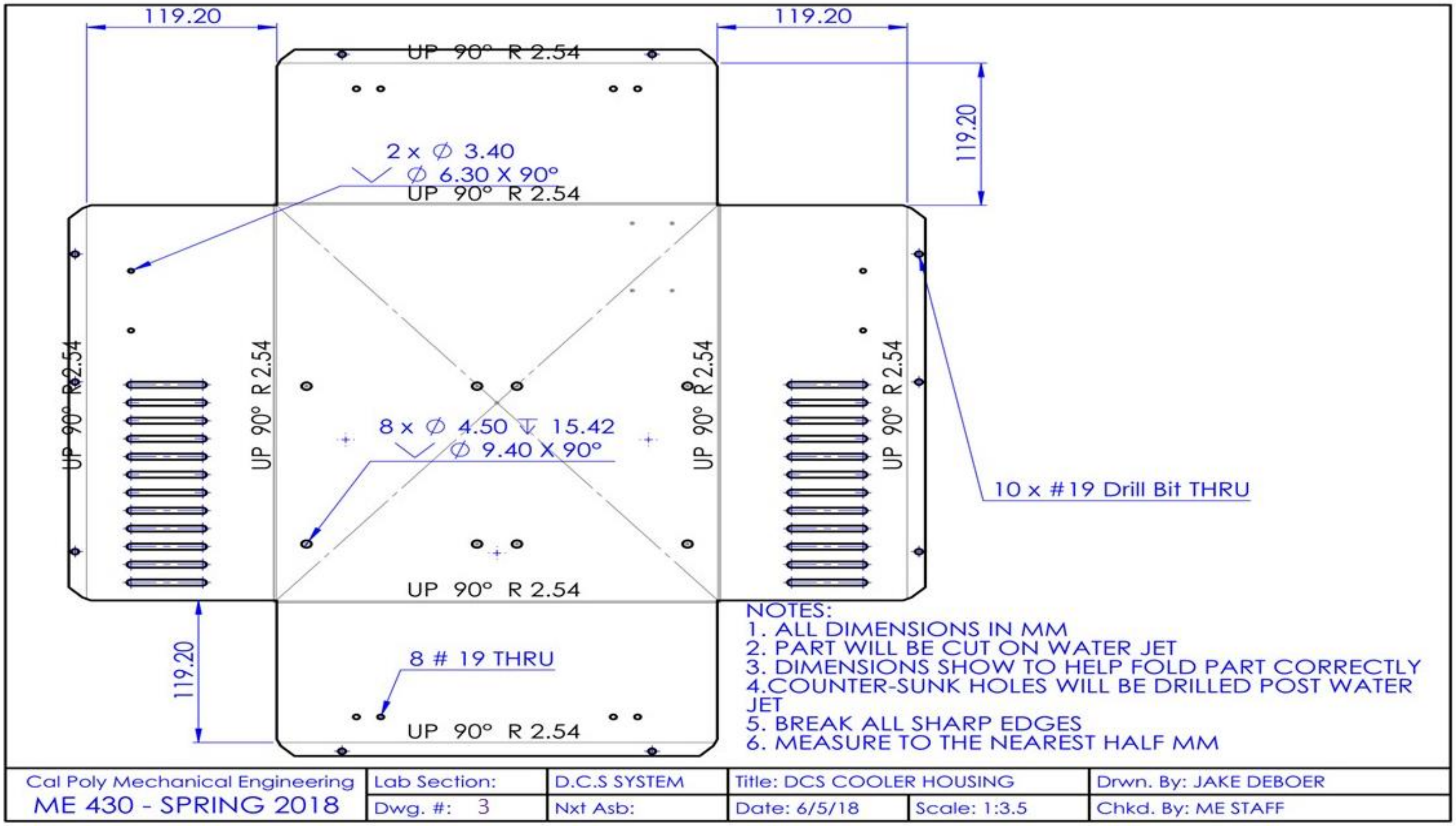
Appendix M – Complete Drawings Package



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	10401	HOUSING BOTTOM	1
2	94100A110	M3 PEM NUTS	14
3	91294A125	M3 X .5 5MM SCREW	14
4	10400	SHELF	1
5	10402	HOUSING TOP	1

Cal Poly Mechanical Engineering	Lab Section:	D.C.S SYSTEM	Title: HOUSING ASSEMBLY		Drwn. By: JAKE DEBOER
ME 420 - SPRING 2018	Dwg. #: 2	Nxt Asb:	Date: 6/1/18	Scale:1:4	Chkd. By: ME STAFF

Appendix M – Complete Drawings Package



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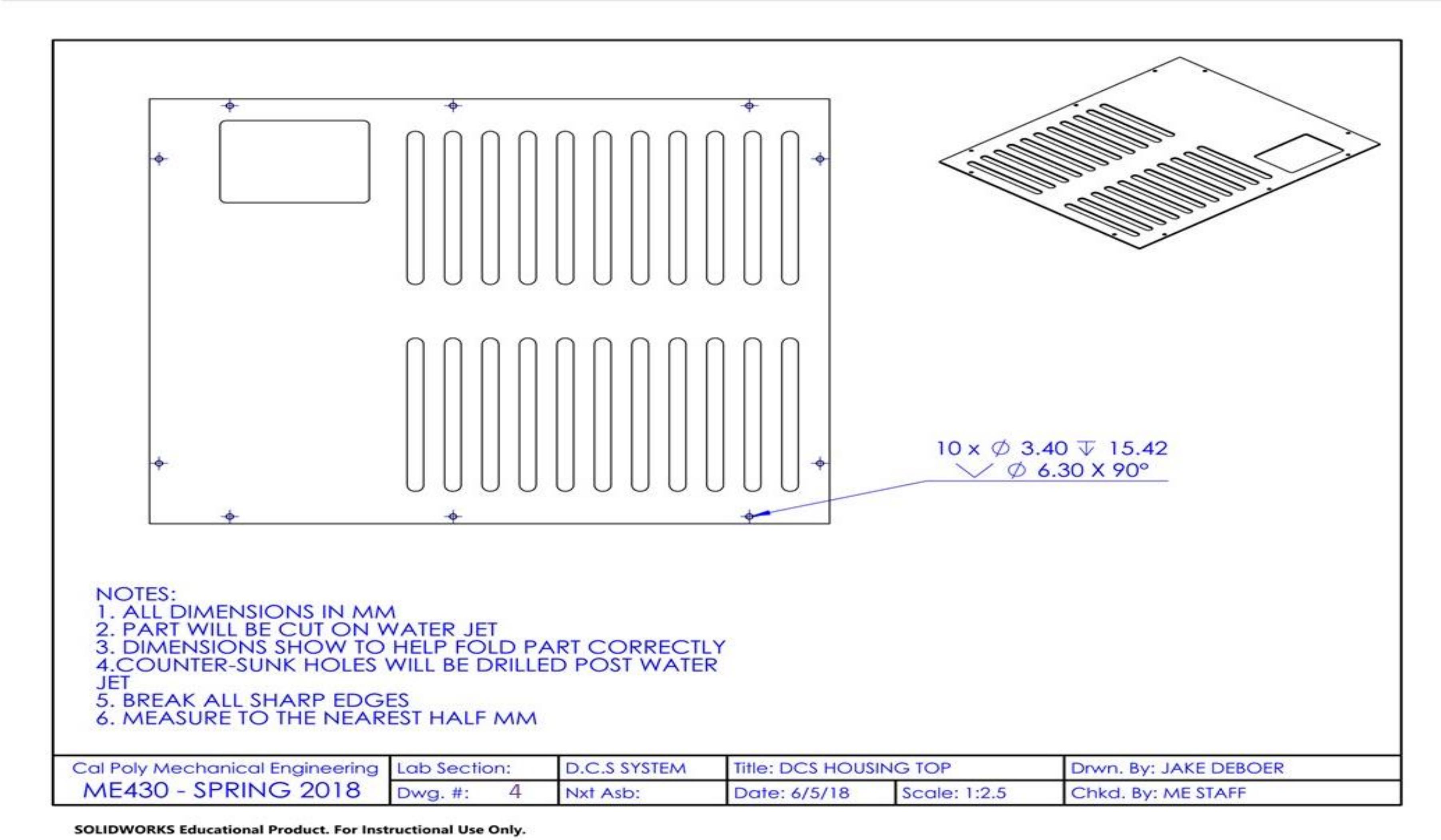
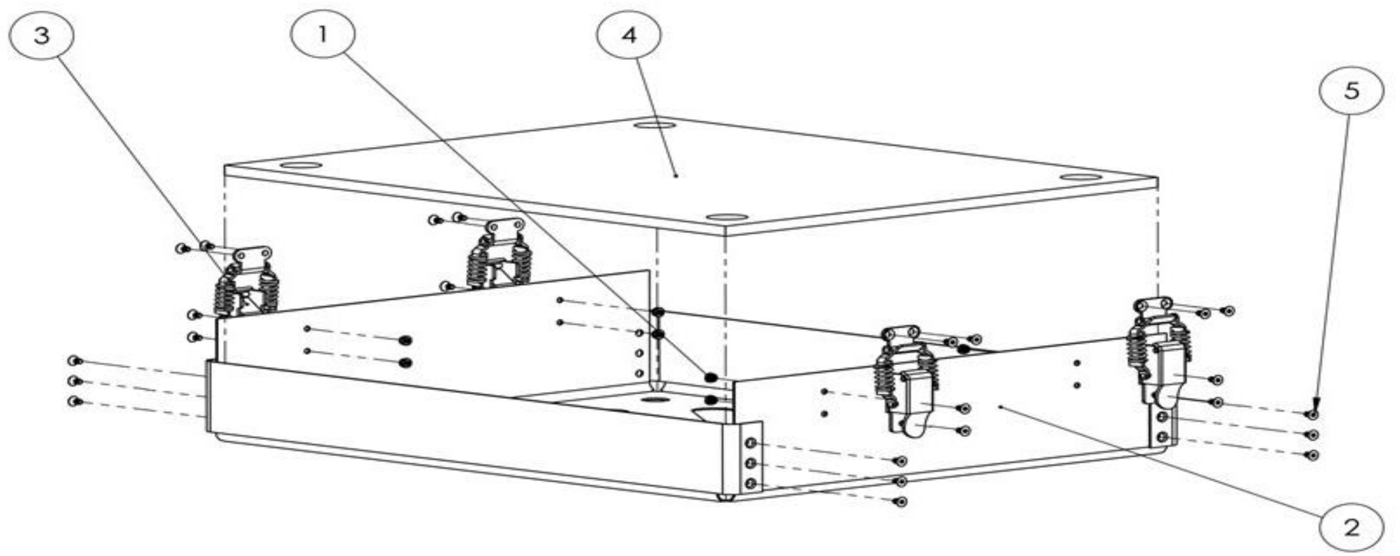
Appendix M – Complete Drawings Package



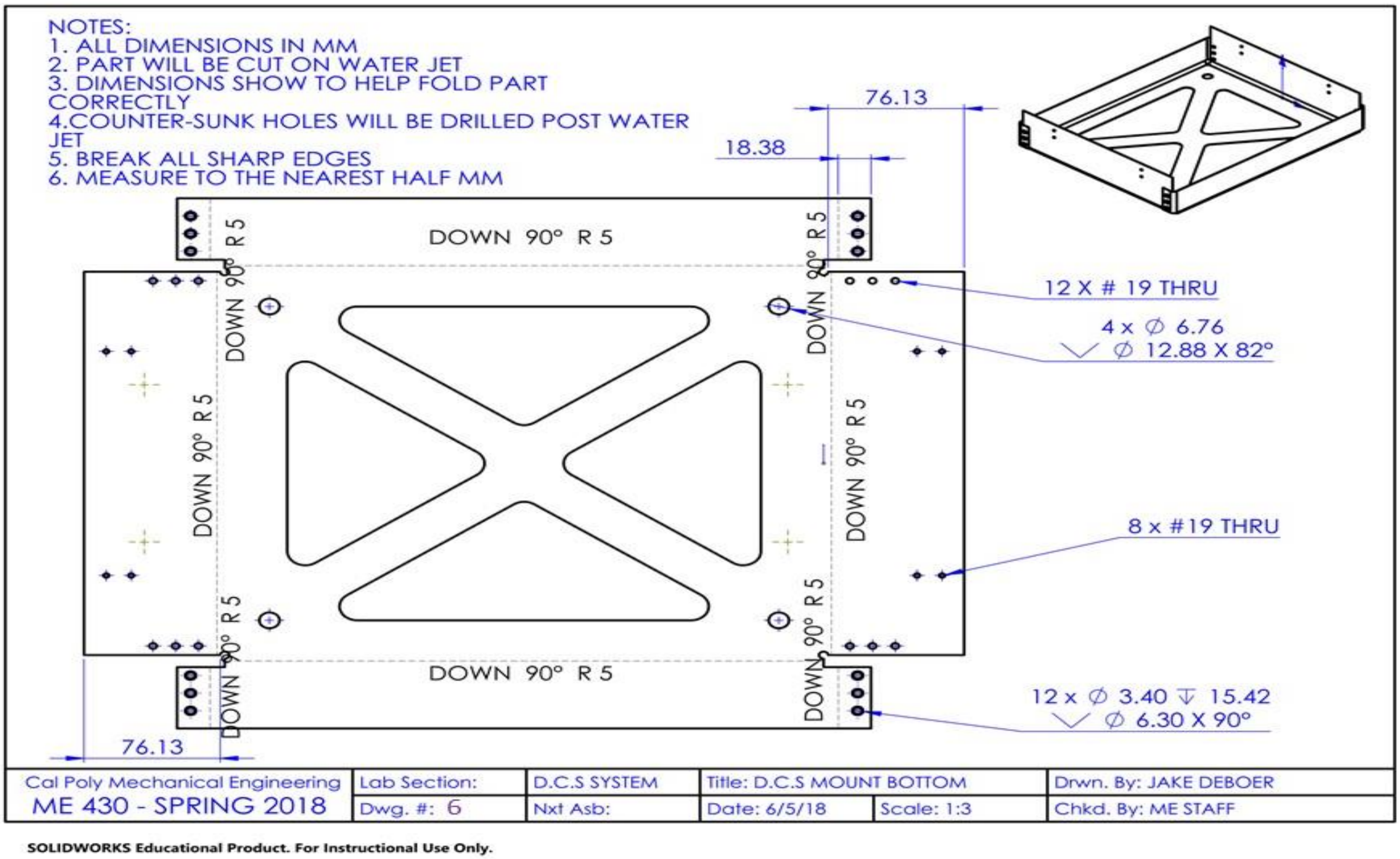
Appendix M – Complete Drawings Package

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	94100A110	M3 PEM NUT	20
2	10500	MOUNT	1
3	1734A270	TIGHT HOLD LATCH	4
4	10501	RUBBER MAT	1
5	91294A125	M3 X .5 5MM SCREW	28

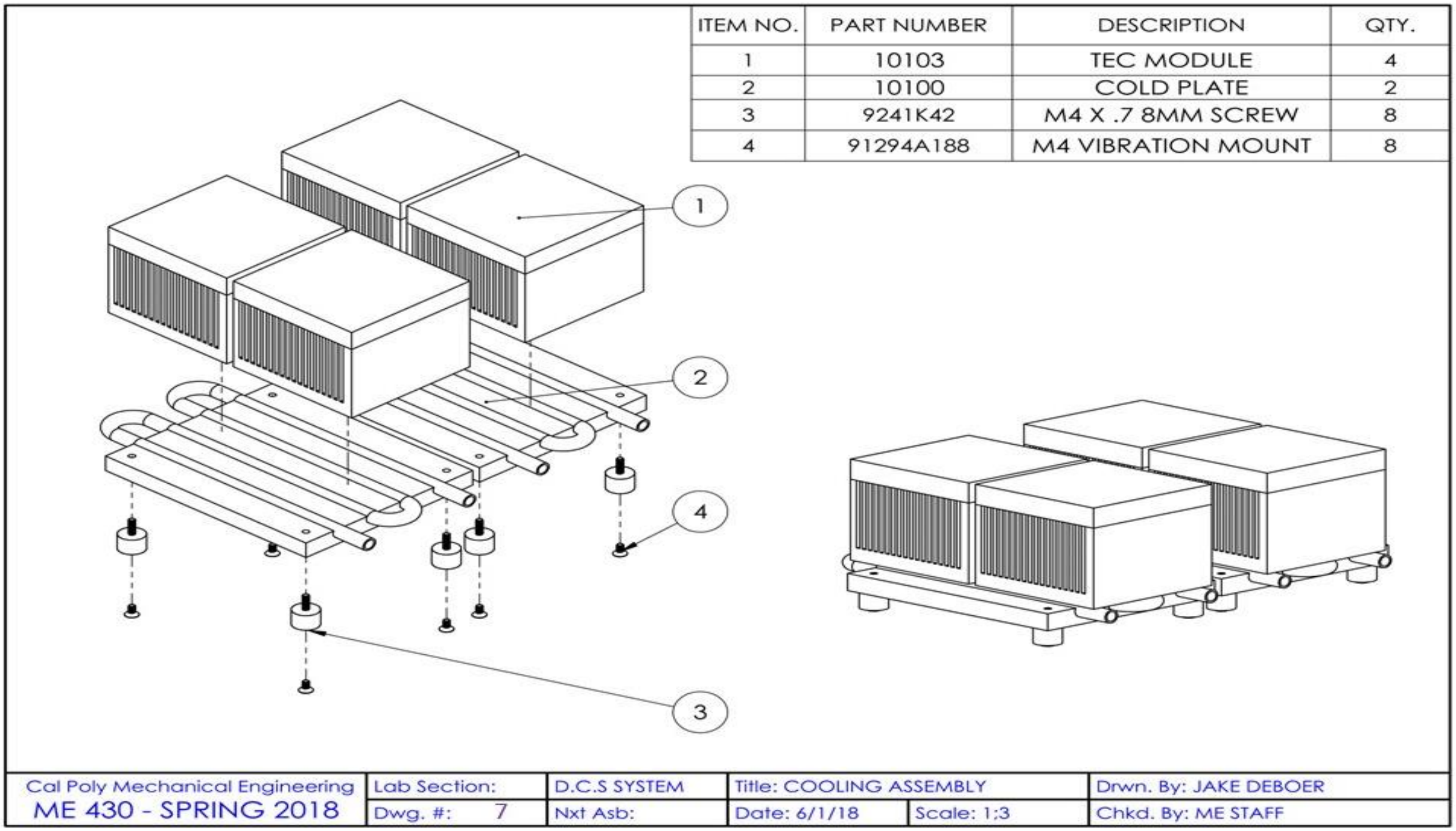


Cal Poly Mechanical Engineering	Lab Section:	D.C.S SYSTEM	Title: MOUNTING ASSEMBLY		Drwn. By: JAKE DEBOER
ME 430 - SPRING 2018	Dwg. #: 5	Nxt Asb:	Date: 6/1/18	Scale: 1:3	Chkd. By: ME STAFF

Appendix M – Complete Drawings Package



Appendix M – Complete Drawings Package



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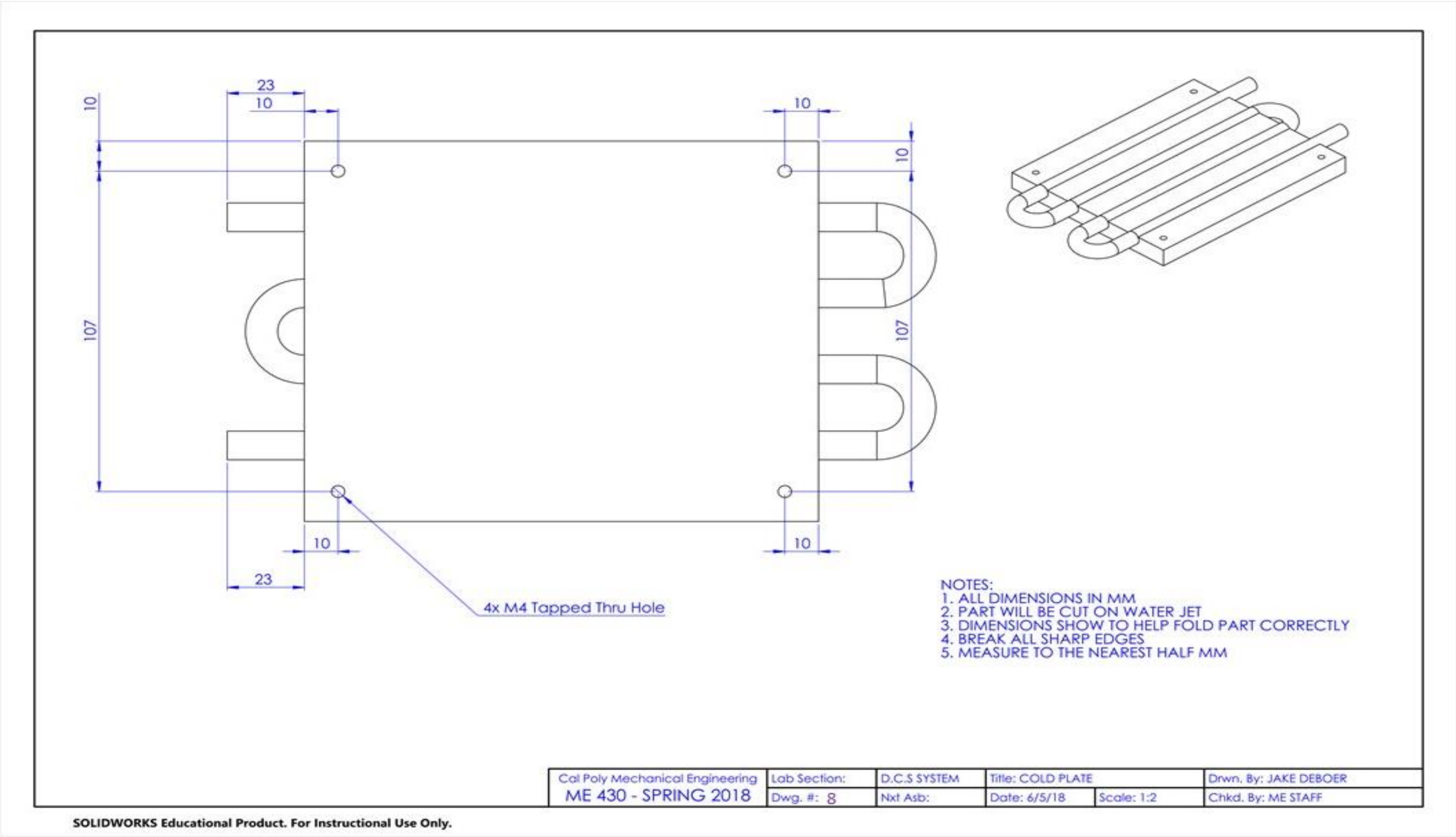
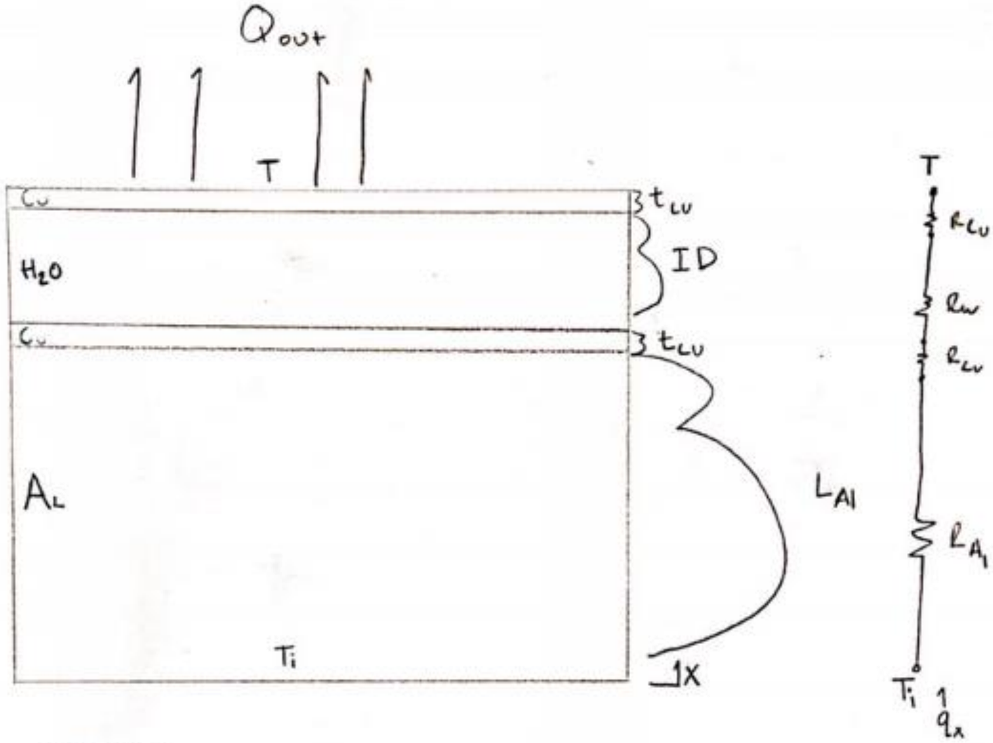
Appendix M – Complete Drawings Package



DRIVER COOLING SYSTEM 1-D HEAT TRANSFER MODEL – COLD PLATE



ASSUMPTIONS:

- 1-D CONDUCTION
- CONSTANT Q OUT
- ADIABATIC INSULATION
- CONSTANT PROPERTIES
- RADIATION IS MINIMAL
- PERFECT CONTACT
- FULLY DEVELOPED, LAMINAR FLOW

$$Q_{out} = \frac{T_i - T}{R_{tot}}$$

$$R_{tot} = \sum \frac{L}{KA} + \sum \frac{1}{hA}$$

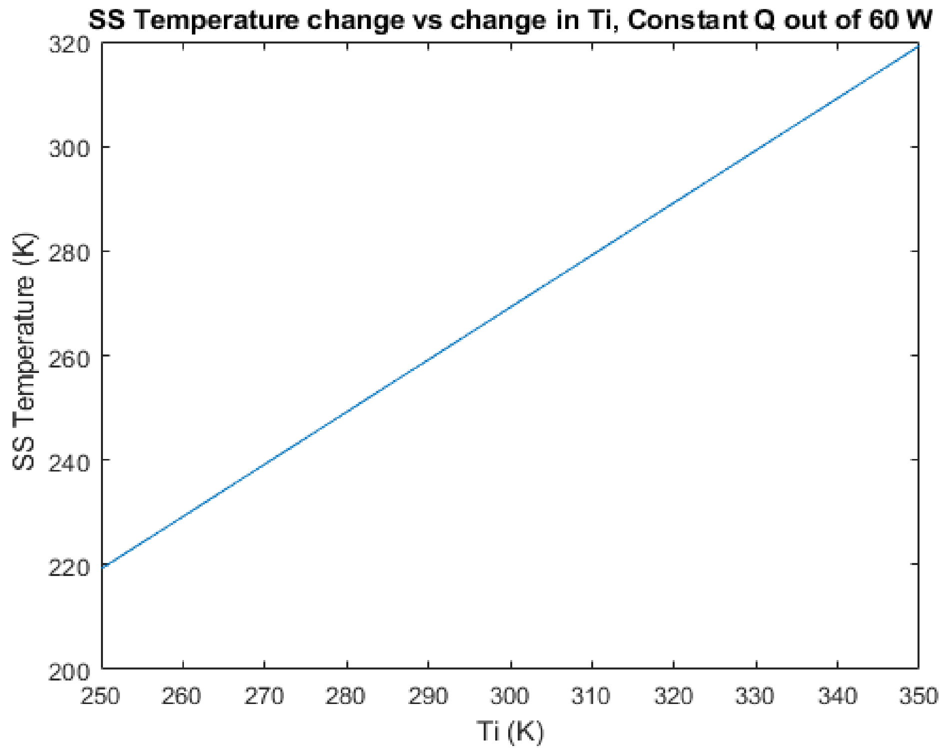
DCS Cold Plate Calcs

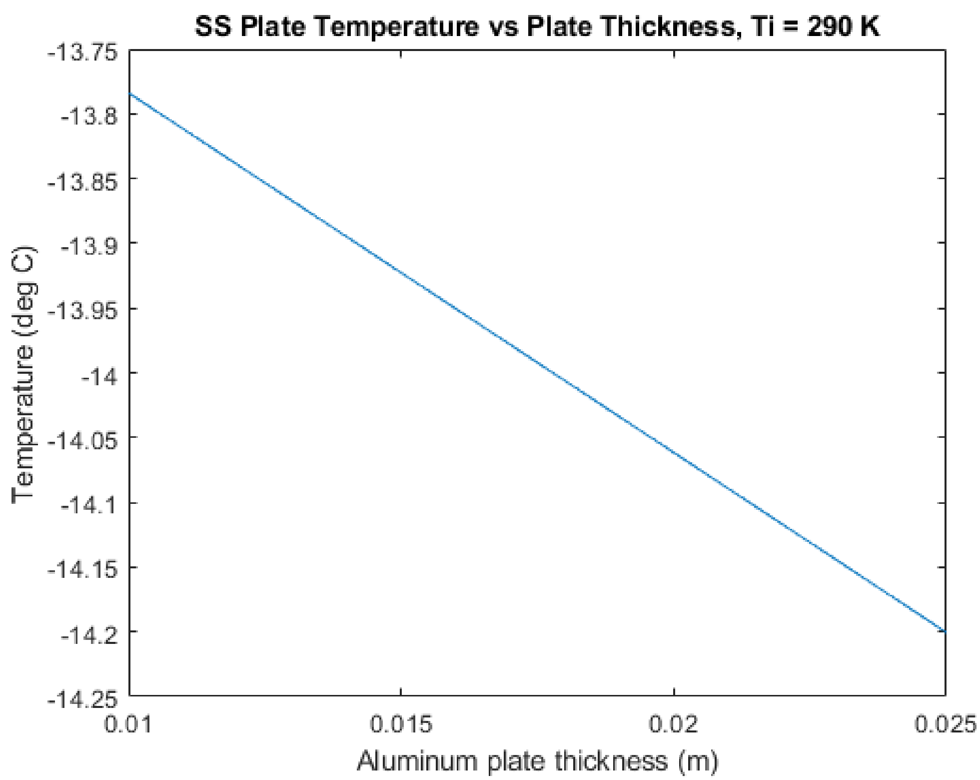
```
% Jake DeBoer
% ME 429
% 9495008129 jakedeboer16@gmail.com

% goal create a 1 D model to investigate pipe size and thickness

close all; clear all;

gtl = 3.785; %gallons/m to L/m
Q = 2 * gtl* 10^-3; % flow rate, m^3/min, the 10^-3 is for l to m3
insq_msq = 0.00064516; ; %in^2 to m^2.
D_cu = .5; % ID of copper pipe (in)
A_cu = 1/4 * (D_cu)^2 * pi * insq_msq; % area of the 1/2 ID pipe in the cold plate (m2)
V_cu = Q / A_cu * 1/60; % (m/s)
dyn_visc_h2o = 8.93 *10^-3;

L_al = .01; % length of aluminum (m)
t_cu = .002; %thickness of copper pipe (m)
L_h2o = D_cu * .0254; %diameter h20 (m)
A = 4* (.04 * .06); % cooler area (m^2)
q_out = 60; %constant heat flow out (W)
Ts = 3 + 273; % constant surface temp (K)
Ti = 290;% initial temp (K)

k_cu = 400 ; % thermal conductivty of cu (W/mK)
k_al = 225 ; %thermal conductivity of al (W/mK)
k_h2o = .598 ; % Thermal conductivty of H2O @ 65 deg F (~290K) (W/mK)

%assuming fully defined flow...
Re = (1000 * V_cu * (D_cu) * .0254)/ (dyn_visc_h2o); %Re of 1/2 pipe

%(laminar flow)

Nud_q = 4.36; %nusslet number for constant heat flux and laminar flow
Nud_t = 3.66; %nusslet number for constant Ts and laminar flow

h_t= (Nud_t * k_h2o) / (D_cu * .0254); %heat transfer coeficient for const Ts (W/mK)
h_q = (Nud_q * k_h2o) / (D_cu * .0254); %heat transfer coeficient for const q out (W/mK)

Rt_q = ( L_al/(k_al * A) + 1/(h_q*A) + 2 * ( t_cu/(k_cu*A))); %total resistance for
constant q out (W/K)
Rt_t = ( L_al/(k_al * A) + 1/(h_t*A) + 2 * ( t_cu/(k_cu*A))); %total resistance for
constant Ts (W/K)

% solve for surface temp if 60 W removed
T = Ti - 60 * Rt_q; %K
%solve for q out if Ts = 3 deg c
q = (Ti - Ts)/Rt_t; % W/m2
```

Sweeps

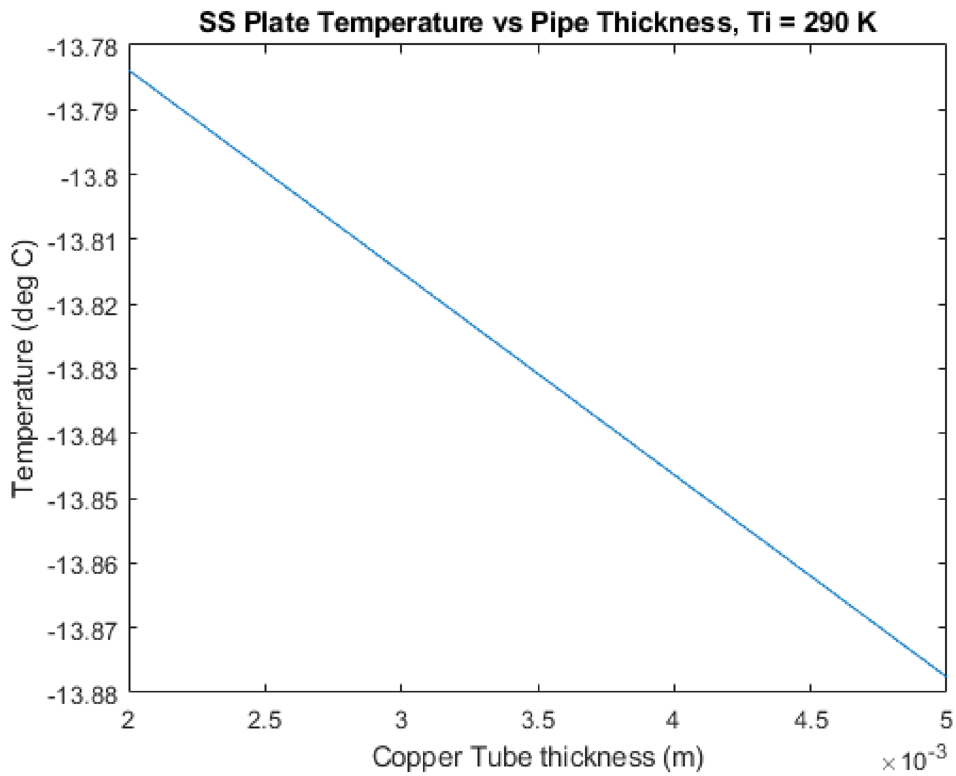
```
Ti_v = 250:5:350;
T_v = Ti_v - 60 * Rt_q; %C
figure;
plot(Ti_v,T_v);
xlabel('Ti (K)'); ylabel(' SS Temperature (K)');
title('SS Temperature change vs change in Ti, Constant Q out of 60 W');


L_al_v = .01:.001:.025; % length of aluminum (m)
t_cu_v = .002:.0001:.005; %thickness of copper pipe (m)

Rt_q_al = ( L_al_v./(k_al * A) + 1/(h_q*A) + 2 * ( t_cu/(k_cu*A))); %total resistance for
constant q out (W/K)
Rt_q_cu = ( L_al/(k_al * A) + 1/(h_q*A) + 2 * ( t_cu_v ./ (k_cu*A))); %total resistance
for constant q out (W/K)

T_al = Ti - 60 * Rt_q_al - 273; %C
figure;
plot(L_al_v,T_al);
xlabel('Aluminum plate thickness (m)'); ylabel('Temperature (deg C)');
title('SS Plate Temperature vs Plate Thickness, Ti = 290 K');

T_cu = Ti - 60 * Rt_q_cu - 273; %C
figure;
plot(t_cu_v,T_cu);
xlabel('Copper Tube thickness (m)'); ylabel('Temperature (deg C)');
title('SS Plate Temperature vs Pipe Thickness, Ti = 290 K');
```

Appendix N – Final Analysis (Heat Transfer, Latches, Pump)





Appendix N – Final Analysis (Heat Transfer, Latches, Pump)



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DRIVER COOLING SYS   2/8/18   JOSEPH BOLOUS   1/2

LATCH CALCULATION

- MAX G'S EXPERIENCED WHILE DRIVING DURING A RACE:

$\rightarrow G's_{MAX} = 1.83g$ (FROM DATA GIVEN TO US BY OUR SPONSOR)

- MAX MASS OF UNIT:

$W_{max} = 10\ lb \quad W = mg \quad g = 32.2\ ft/s^2$

$m = W/g \rightarrow m = 10\ lb_f / 32.2\ ft/s^2$

$\rightarrow m = 0.311\ \frac{lb_f \cdot s^2}{ft} \cdot \frac{ft \cdot lb_m}{s^2 \cdot lb_f} \rightarrow m_{max} = 0.311\ lb_m$

- MAX POUNDS FORCE OUR LATCH WILL EXPERIENCE:

$F = ma \quad m_{max} = 0.311\ lb_m \rightarrow m_{max} = 0.311\ \frac{lb_f \cdot s^2}{ft}$

$a_{max} = 1.83 \cdot 32.2\ ft/s^2 \rightarrow a_{max} = 58.9\ ft/s^2$

$F = (58.9\ ft/s^2)(0.311\ \frac{lb_f \cdot s^2}{ft}) \rightarrow \boxed{F = 18.3\ lb_f}$

- ESTIMATED G'S EXPERIENCED DURING A RACECAR CRASH:

$\rightarrow G's = 20g$

- POUNDS FORCE OUR LATCH WILL EXPERIENCE DURING A CRASH:

$F = ma \quad m_{max} = 0.311\ lb_m \rightarrow m_{max} = 0.311\ \frac{lb_f \cdot s^2}{ft}$

$a = 20 \cdot 32.2\ ft/s^2 \rightarrow a = 644\ ft/s^2$

$F = ma \rightarrow F_{crash} = (0.311\ \frac{lb_f \cdot s^2}{ft})(644\ ft/s^2)$

$\rightarrow \boxed{F_{crash} = 200\ lb_f}$

Appendix N – Final Analysis (Heat Transfer, Latches, Pump)

DRIVER COOLING SYS | 2/8/18 | JOSEPH BOLOUS | 2/2

- LATCHES ARE SPEC'D TO HOLD 70-100 lb_f EACH

- DURING NORMAL RACING CONDITIONS THE LATCHES WILL EXPERIENCE A MAXIMUM OF 18.3 lb_f

$$\#L = F_{MAX}/F_{LATCH} \rightarrow \#L = \frac{18.3\ lb_f}{70\ lb_f} = \underline{0.26\ \text{LATCHES}}$$

∴ ROUNDING UP, ONE LATCH WILL SUFFICE, HOWEVER WE NEED AT LEAST TWO TO HOLD BOTH SIDES

→ FOR NORMAL RACING CONDITIONS, WE NEED AT LEAST TWO LATCHES

- DURING A RACECAR CRASH THE LATCHES CAN EXPERIENCE A FORCE OF 200 lb_f

$$\#L = F_{CRASH}/F_{LATCH} \rightarrow \#L = \frac{200\ lb_f}{70\ lb_f} = \underline{2.85\ \text{LATCHES}}$$

∴ WE NEED 3 LATCHES, FOR DESIGN PURPOSES WE WILL USE AN EVEN NUMBER OF LATCHES

⟹ FINAL DESIGN: 4 LATCHES

SAFETY FACTOR

CRASH: $n_{CRASH} = \frac{F_{LATCHES}}{F_{CRASH}}$ $\quad F_{LATCHES} = 4 \cdot \underbrace{70\ lb_f}_{\text{CONSERVATIVE END}} \rightarrow F_{LATCHES} = 280\ lb_f$

$F_{CRASH} = 200\ lb_f$ @ 20 G's

$$\rightarrow n_{CRASH} = \frac{280\ lb_f}{200\ lb_f} \rightarrow \boxed{n_{CRASH} = 1.4}$$

DRIVING: $n_{DRIVE} = \frac{F_{LATCHES}}{F_{MAX}}$ $\quad F_{MAX} = 18.3\ lb_f$

$$\rightarrow n_{DRIVE} = \frac{280\ lb_f}{18.3\ lb_f} \rightarrow \boxed{n_{DRIVE} = 15.3}$$

ASSUMPTIONS:

- FORCES APPLIED NORMALLY TO LATCHES
- n_{CRASH} IS USEING AN ACCELERATION OF 20 G'S

DCS Head Loss Calcs

```
% Jake DeBoer
% ME 429
% 9495008129 jakedeboer16@gmail.com

close all;
%goal to calcualate head loss across the entire system to size pump

gtl = 3.785; %gallons/m to L/m
gpm = 2; % flow rate in gpm
Q = gpm * gtl* 10^-3; % flow rate, m^3/min, the 10^-3 is for l to m3
insq_msq = 0.00064516; ; %in^2 to m^2.
D_pl = 3/8; %in ID of plastic pipe
D_cu = .5; %in ID of copper pipe

A_pl = 1/4 * (D_pl)^2 * pi * insq_msq; %area of the 3/8 ID pipe in suite
V_pl = Q / A_pl * 1/60; % m/s
A_cu = 1/4 * (D_cu)^2 * pi * insq_msq; %area of the 1/2 ID pipe in the cold plate
V_cu = Q / A_cu * 1/60; % m/s

dyn_visc_h2o = 8.93 *10^-3;
Re1= (1000 * V_pl * (D_pl) * .0254)/ (dyn_visc_h2o); %Re of 3/8 pipe
Re2= (1000 * V_cu * (D_cu) * .0254)/ (dyn_visc_h2o); %Re of 1/2 pipe

AR1 = A_pl/A_cu; %area ratio for expansion/contraction
DR = (D_pl)/(D_cu);

Kl = (1-(D_pl^2)/(D_cu^2))^2; % colorado state minor loss pdf for expansion/contraction
K_90 = .3;
K_180 = .2;
Kc = .2;

fpl = 64/Re1; %laminar flow friction factor
fcu = 64/Re2; %laminar flow friction factor

hlm_90_pl = K_90 * V_pl^2 / 2 * 1000; %Pa headloss minor for the 90 deg bends in pipe
hlm_180_pl = K_180 * V_pl^2 / 2 * 1000; %Pa headloss minor for the 180 deg bends in pipe

hlm_90_cu = K_90 * V_cu^2 / 2 * 1000; %Pa headloss minor for the 90 deg bends in cold plate
hlm_180_cu = K_180 * V_cu^2 / 2 * 1000; %Pa headloss minor for the 180 deg bends in cold
plate

hlm_exp_cu = Kl * V_cu^2 / 2 * 1000;
hlm_con_cu = Kc * V_cu^2 / 2 * 1000;

hl_cu = fcu * (1.27/(D_cu * .0254)) * (V_cu^2/2) * 1000; % Pa major losses in the cold
```

plate 1.27 m of straight pipe

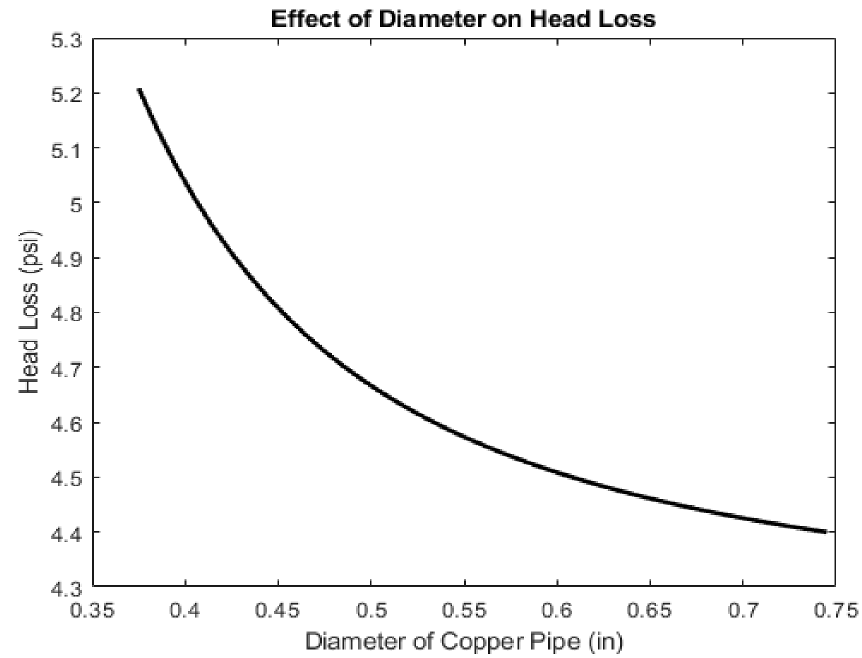
```
hl_pl = fpl * (144/D_pl) * (V_pl^2/2) * 1000; % Pa major losses in the cold plate 12ft
(144 in) of straight pipe

hl_t = hl_cu + hl_pl + (20 * hlm_180_pl) + (6* hlm_180_cu) + (4*hlm_90_cu) +(4*hlm_90_pl)
+ hlm_exp_cu + hlm_con_cu;
Pa_psi = 0.000145038;
hl_t_psi = hl_t * Pa_psi;
disp(hl_t_psi);
```

```
4.6666 psi
```

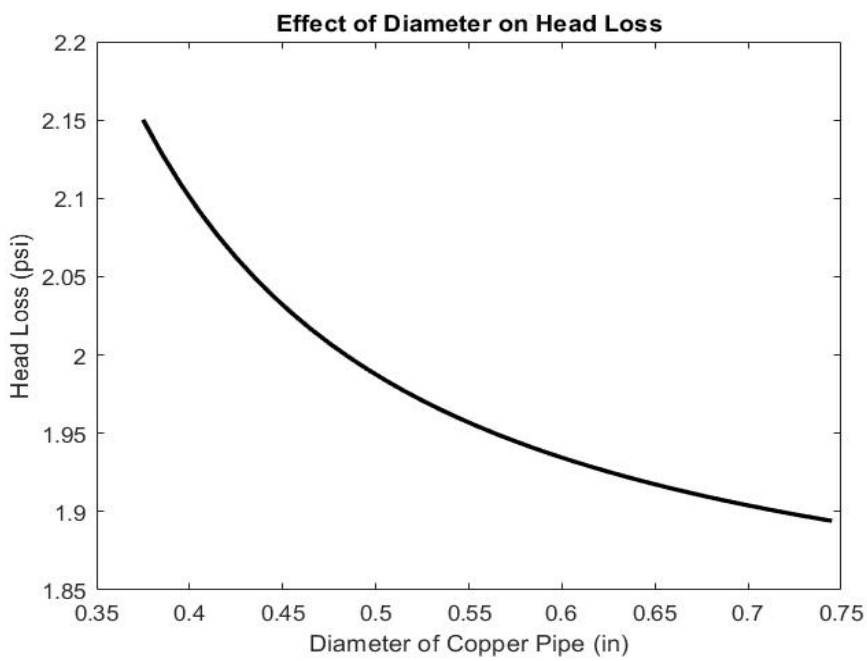
Changing the diameter of the copper tubing

```
D_cu_v = .375 : .01 :.75;
A_cu_v = 1/4 * (D_cu_v).^2 * pi * insq_msq; %area of the 1/2 ID pipe in the cold plate
V_cu_v = (Q ./ A_cu_v) .* 1/60; % m/s
Kl_v = (1-(D_pl^2)./(D_cu_v.^2)).^2;

hlm_90_cu_v = K_90 * V_cu_v.^2 / 2 * 1000; %Pa headloss minor for the 90 deg bends in
cold plate
hlm_180_cu_v = K_180 * V_cu_v.^2 / 2 * 1000; %Pa headloss minor for the 180 deg bends in
cold plate

hlm_exp_cu_v = Kl * V_cu_v.^2 / 2 * 1000;
hlm_con_cu_v = Kc * V_cu_v.^2 / 2 * 1000;

hl_cu_v = fcu .* (1.27./(D_cu_v .* .0254)) .* (V_cu.^2/2) * 1000; % Pa major losses in
the cold plate 1.27 m of straight pipe

hl_t_v = hl_cu_v + hl_pl + (20 * hlm_180_pl) + (6* hlm_180_cu_v) + (4*hlm_90_cu_v)
+(4*hlm_90_pl) + hlm_exp_cu_v + hlm_con_cu_v;
hl_t_psi_v = hl_t_v * Pa_psi;

figure;
plot(D_cu_v,hl_t_psi_v,'k', 'linewidth',2);
xlabel('Diameter of Copper Pipe (in)'); ylabel('Head Loss (psi)');
title('Effect of Diameter on Head Loss');
```

Appendix N – Final Analysis (Heat Transfer, Latches, Pump)

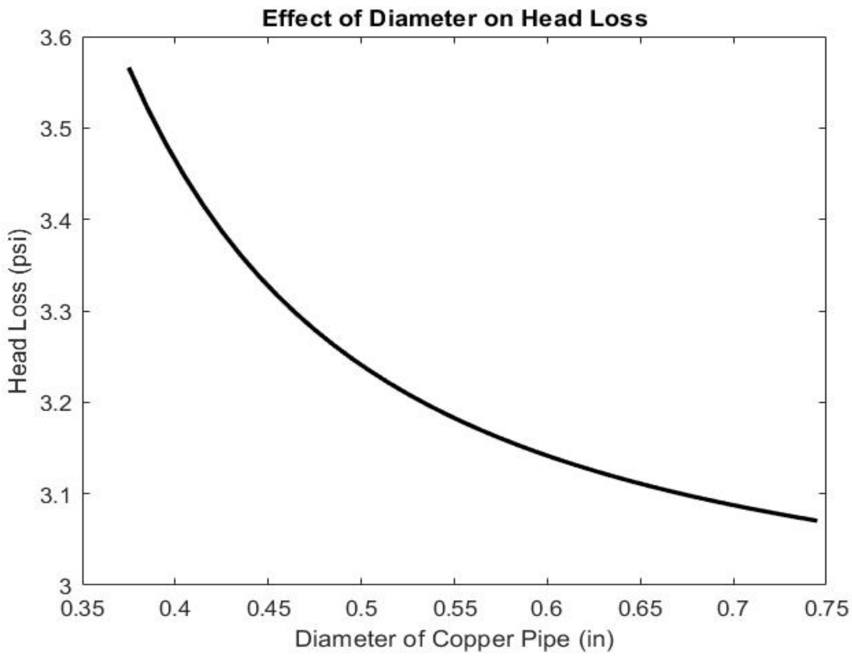


Matlab Figure 1. Head loss vs Pipe Diameter @ 2 gpm



Matlab Figure 2. Head loss vs Pipe Diameter @ 1 gpm

Appendix N – Final Analysis (Heat Transfer, Latches, Pump)



Matlab Figure 3. Head loss vs Pipe Diameter @ 1.5 gpm

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Appendix N – Final Analysis (Heat Transfer, Latches, Pump)

DRIVER COOLING SYS 2/11/18 JOSEPH BOLOUS 1/2

PUMP VERIFICATION – DANGER DEN CPX PRO

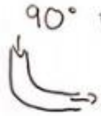
LOSSES:

180° RETURN BENDS

$K_L = 0.2$

x 20 FOR SHIRT
x 6 FOR COLD PLATE
26

90° ELBOWS



$K_L = 0.3$

x 4 FOR SHIRT
x 2 FOR COLD PLATE
6

90° FITTINGS

$K_L = 0.31$ x 2 FOR COLD PLATE

VELOCITY:

PUMP FUNCTIONS BEST AT 2GPM
(MARTIN'S LIQUID LAB, PUMP REVIEW)

- 3/8" PIPING $\rightarrow A = \pi\left(\frac{3}{16}\right)^2 in^2 = \underline{0.11 in^2}$

$V = Q/A \quad Q = 2GPM \cdot \frac{0.002228\ ft^3/s}{1GPM} \rightarrow Q = 0.058\ ft^3/s$

$\rightarrow \underline{Q = 100\ in^3/s}$

$V = \frac{100\ in^3/s}{0.11\ in^2} = \underline{\underline{909\ in/s}}$

- 1/2" PIPING $\rightarrow A = \pi\left(1/4\right)^2 in^2 = 0.20\ in^2$

$V = \frac{100\ in^3/s}{0.20\ in^2} = \underline{\underline{500\ in/s}}$

DRIVER COOLING SYS | 2/11/18 | JOSEPH BOLOUS | 2/2

HEAD LOSS:

$$* \; h_{L_{minor}} = \sum K_L \frac{V^2}{2g}$$

$$\cdot \; h_{L_{minor,180^\circ bends}} = \underbrace{\left[20\times\left(0.2\,\frac{(909\,in/s)^2}{2(386.4\,in/s^2)}\right)\right]}_{SHIRT} + \underbrace{\left[6\times\left(0.2\,\frac{(500\,in/s)^2}{2(386.4\,in/s^2)}\right)\right]}_{COLD\ PLATE}$$

$$= 4277\,in + 388\,in = \underline{4665\,in}$$

$$\cdot \; h_{L_{minor,90^\circ bend}} = \left[4\times\left(0.3\,\frac{(909\,in/s)^2}{2(386.4\,in/s^2)}\right)\right] + \left[2\times\left(0.3\,\frac{(500\,in/s)^2}{2(386.4\,in/s^2)}\right)\right]$$

$$= 1283\,in + 194\,in = \underline{1477\,in}$$

$$\cdot \; h_{L_{minor,90^\circ fitting}} = 2\times\left(0.31\,\frac{(500\,in/s)^2}{2(386.4\,in/s^2)}\right)$$

$$= \underline{201\,in}$$

$$\rightarrow h_{L_{minor}} = h_{L_{180^\circ}} + h_{L_{90^\circ B}} + h_{L_{90^\circ F}}$$

$$= 4665\,in + 1477\,in + 201\,in \Rightarrow \underline{h_{L,minor} = 6343\,in}$$

$$* \; h_{L_{major}} = f\,\frac{L}{D}\,\frac{V^2}{2g} \qquad f = 0.01 \text{ FOR PLASTIC TUBING}, \quad L \approx 12\,FT = 144\,in$$

$$h_{L_{major}} = 0.01\,\frac{144\,in}{(3/8)\,in}\,\frac{(909\,in/s)^2}{2(386.4\,in/s^2)} \Rightarrow \underline{\underline{h_{L,major} = 4106\,in}}$$

$$* \; h_L = h_{L,major} + h_{L,minor} = 4106\,in + 6343\,in$$

$$\Rightarrow \boxed{h_L = 10450\,in}$$

ASSUMPTIONS:

- FULLY DEVELOPED FLOW
- STEADY STATE
- INCOMPRESSIBLE FLOW
- NEGLECT MAJOR LOSSES IN COLD PLATE
- FRICTION FACTOR IN PLASTIC TUBING, $f = 0.01$

Appendix O – Safety Hazard Checklist and FMEA

DESIGN HAZARD CHECKLIST

Team: DRIVER COOLING SYSTEM Advisor: ROSSMAN Date: 1/4/18

Y	N	
☐	☒	1. Will the system include hazardous revolving, running, rolling, or mixing actions?
☐	☒	2. Will the system include hazardous reciprocating, shearing, punching, pressing, squeezing, drawing, or cutting actions?
☐	☒	3. Will any part of the design undergo high accelerations/decelerations?
☐	☒	4. Will the system have any large (>5 kg) moving masses or large (>250 N) forces?
☐	☒	5. Could the system produce a projectile?
☐	☒	6. Could the system fall (due to gravity), creating injury?
☐	☒	7. Will a user be exposed to overhanging weights as part of the design?
☒	☐	8. Will the system have any burrs, sharp edges, shear points, or pinch points?
☐	☒	9. Will any part of the electrical systems not be grounded?
☐	☒	10. Will there be any large batteries (over 30 V)?
☐	☒	11. Will there be any exposed electrical connections in the system (over 40 V)?
☐	☒	12. Will there be any stored energy in the system such as flywheels, hanging weights or pressurized fluids/gases?
☐	☒	13. Will there be any explosive or flammable liquids, gases, or small particle fuel as part of the system?
☐	☒	14. Will the user be required to exert any abnormal effort or experience any abnormal physical posture during the use of the design?
☐	☒	15. Will there be any materials known to be hazardous to humans involved in either the design or its manufacturing?
☐	☒	16. Could the system generate high levels (>90 dBA) of noise?
☐	☒	17. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, or cold/high temperatures, during normal use?
☐	☒	18. Is it possible for the system to be used in an unsafe manner?
☐	☒	19. For powered systems, is there an emergency stop button?
☐	☐	20. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

For any "Y" responses, add (1) a complete description, (2) a list of corrective actions to be taken, and (3) date to be completed on the reverse side.

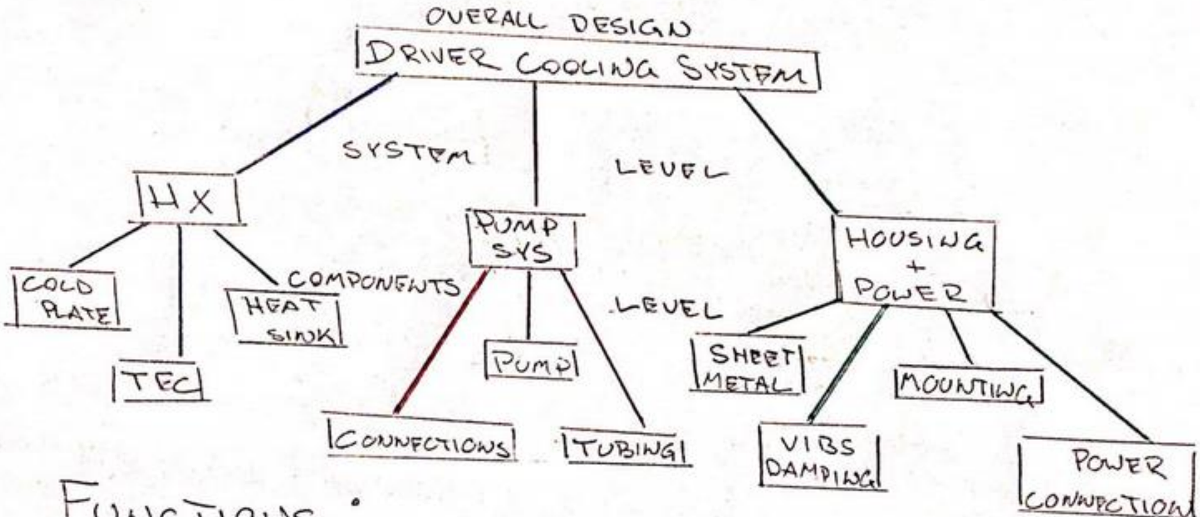
Appendix 0 – Safety Hazard Checklist and FMEA

Description of Hazard	Planned Corrective Action	Planned Date	Actual Date
SHEET METAL HOUSING MAY HAVE SHARP EDGES/PINCH POINTS	FILE DOWN EDGE DURING MANUFACTURING PROCESS	3/15/18	

FMEA

11/29

DESIGN TREE:



FUNCTIONS:

SYSTEM LEVEL

HX → COOL FLUID

PUMP SYS → MOVE FLUID

HOUSING + POWER → CONTAIN/ PROTECT SYSTEM → SUPPLY POWER TO RUN SYS

COMPONENT LEVEL

COLD PLATE → EXPOSE MOVING FLUID TO COLD
TEC → CREATE ΔT TO COOL FLUID
HEAT SINK → REMOVE HEAT FROM SYS

PUMP → APPLY PRESSURE TO MOVE FLUID
TUBING → GUIDE MOVING FLUID
CONNECTIONS → CONNECT TUBING

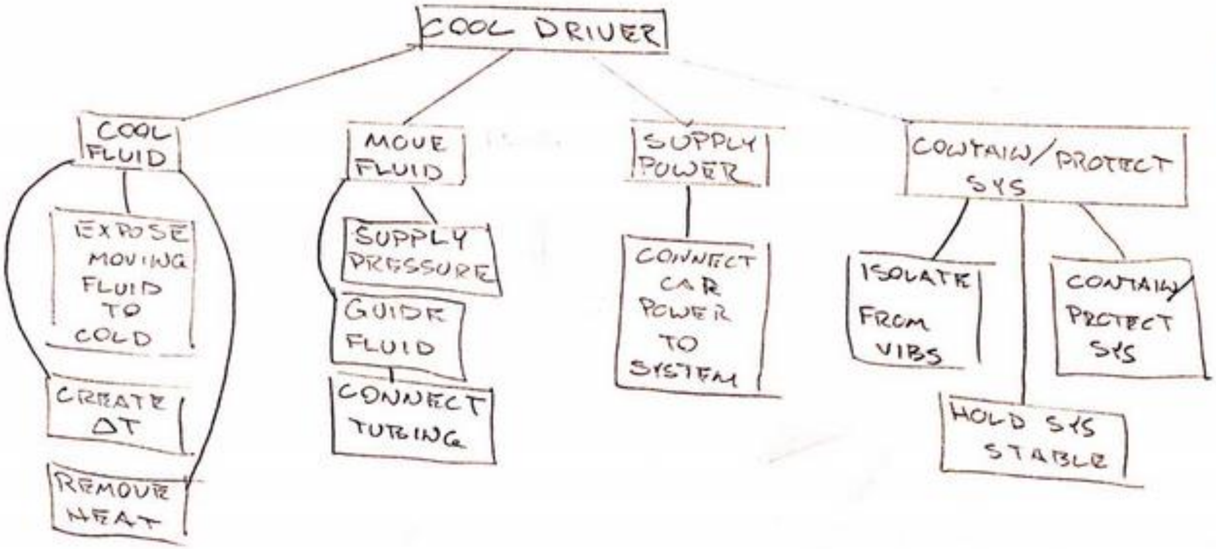
SHEET METAL → CONTAIN/ PROTECT SYS
VIBS DAMPING → ISOLATE SYS FROM VIBS
MOUNTING → HOLD SYS STABLE
POWER CONNECTIONS → CONNECT CAR POWER TO DEVICES

OVERALL DESIGN

DRIVER COOLING SYSTEM → COOL DRIVER

11/29

FUNCTION TREE:



DEFINE FAILURES:

OVERALL DESIGN

COOL DRIVER → DOESN'T COOL DRIVER

SYSTEM FAILURES

COOL FLUID → FLUID DOESN'T COOL SUFFICIENTLY OR TOO SMALL OF ΔT
MOVE FLUID → FLUID GETS STUCK OR NOT ENOUGH PRESSURE/SPEED
SUPPLY POWER → CONNECTIONS FAIL/ OR NOT ENOUGH POWER
CONTAIN/PROTECT SYS → SYSTEM BREAKS OR BECOMES LOOSE

COMPONENT FAILURES

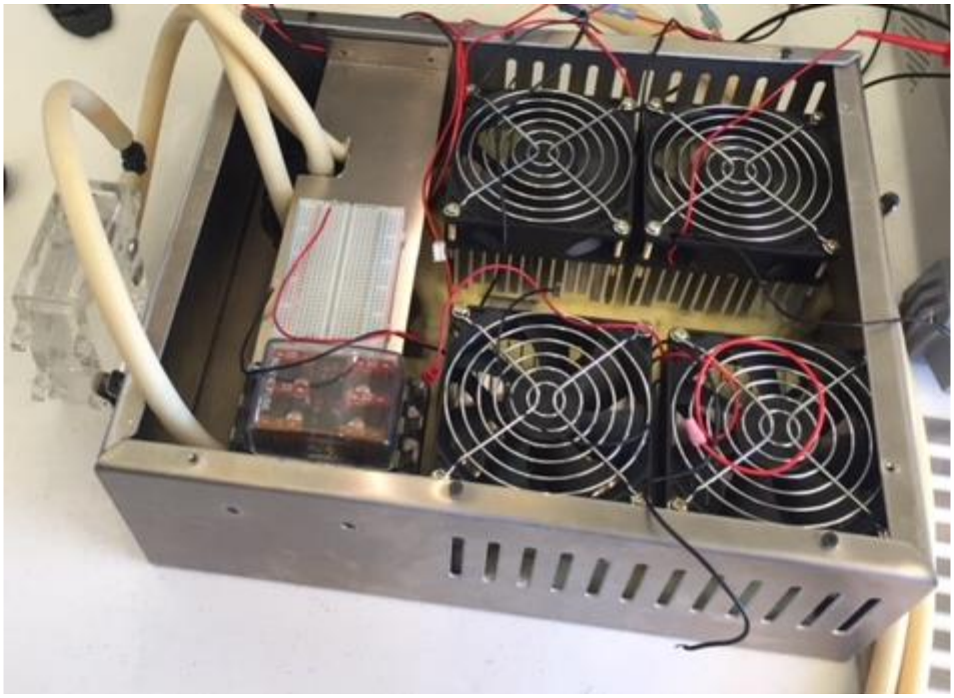
EXPOSE FLUID TO COLD → NO CONTACT TO TEC OR NOT ENOUGH HEAT TRANSFER
CREATE ΔT → FLUID ISN'T COOLED ENOUGH
REMOVE HEAT → NOT ENOUGH HEAT IS REMOVED
SUPPLY PRESSURE → FLUID ISN'T PUSHED W/ SUFFICIENT VELOCITY
GUIDE FLUID → FLUID CANNOT MOVE PROPERLY THROUGH TUBING
CONNECT TUBING → FLUID LEAKS
CONNECT CAR POWER → POWER ISN'T SUPPLIED TO SYSTEM
ISOLATE FROM VIBS → NOT ENOUGH ISOLATION
HOLD SYS STABLE → SYS NOT STABLE ENOUGH
CONTAIN/PROTECT SYS → NOT CONTAINED OR PROTECTED

Appendix P – Design Verification Plan and Report

Senior Project DVP&R														
Last Update: 05/31/18		Team: Driver Cooling System	Sponsor: Justin Jang			Description of System: Heat exchanger, using Thermal Electric units, to remove heat from water being pumped through the system				DVP&R Engineer: Joseph Bolous				
										TEST REPORT				
Item No	Specification #	Test Description	Acceptance Criteria	Test Responsibility	Test Stage	SAMPLES		TIMING		TEST RESULTS			NOTES
						Quantity	Type	Start date	Finish date	Test Result	Quantity Pass	Quantity Fail	
1	Cooling Temp	Structural Prototype Test #1: We will pump water through an aluminum block, acting as a cold plate, and measure how much heat can be removed from the water using one TEC Unit.	Finished system should be able to bring water temperature to 65°F	Jake	SP FP	x3	SUB	2/4/2018 5/3/18	2/4/18	We were able to bring 90 °F water to 65 °F in 12 minutes using only half our system (two TEC Units)	3/3	0/3	We ran one control test where without the coolers the water reached a steady state of 82 °F.
2	Longevity	Structural Prototype Test #2: We are testing the portions of our system that we believe are most likely to fail on a shake table to simulate the environment our system will be under.	100 hour life	Joseph	SP	2x3	COMP	2/4/18	3/15/18	Both the thermal adhesive and fan went through the vibration simulation with any problem	2/2	0/2	Thermal Paste and Fan
3	Cost	Verified Through Inspection	$1,200	All	CP	x1	SYS	10/20/17	10/24/17	$815	1/1	0/1	We are currently well below the price cap
4	Compactness	Test that all components can fit into a 1 ft^3 housing.	1 ft^3	Jake	CP	x2	SYS	10/20/17	10/24/17	0.46 ft^3	2/2	0/2	We are currently well below the size limit
5	Power	Will be verified by testing our final prototype when built and through analysis before the prototype is built.	12V, 6A	Alvin	FP	x3	SYS	5/3/18	5/31/18	30 Amps	0/1	1/1	Spoke with sposor and removed Power specification
6	Setup Time	Will be verified by testing our final prototype when built.	5 min	Joseph	FP	x3	SYS	5/3/18	Incomplete				Were not able to accurately test for set-up time with out an in car test
7	Weight	Verified Through Inspection	10 lbs	All	FP	x1	SYS	5/3/18	5/10/18	14 lb	0/1	1/1	Suggustions for solution given to sponsor and in FDR
8	User Interface	Will be verified by testing our final prototype when built.	3 settings	Alvin	FP	x3	SYS	5/3/18	5/10/18	> 3 settings	1/1	0/1	The nob to change cooling is continuous so we technically have infinite cooling settings

Appendix Q – Operator's Manual

Operator's Manual



Cooling System

Important: Before using this product, the user should read this Operator's Manual to familiarize themselves with the operation and safety hazards of the Cooling System.

Safety Warnings:

- **The Cooling System uses high current**
  - Do not attach to or remove from car power while car is running
  - Do not attach to or remove from car power if in-line power switch is on
  - Do not unplug from car power while Cooling System is running
  - Do not use Cooling System with a power source other than the car battery or equivalent sources
  - While in operation, refrain from putting the power cord in an area with potential of getting wet or pulled out
  - Do not run if there are any exposed wires

- **The Cooling System can cause injury if not secured properly**
  - Do not use in a high-speed environment if the cooling box is not properly secured to the cooling mount (refer to Mounting Section in How-To)
  - Do not use in a high-speed environment if the cooling mount is not properly secured to car (refer to Mounting Section in How-To)
  - Avoid using product if not wearing proper safety equipment (helmet, gloves, fire retardant clothing, etc.)

- **There may be sharp edges and pinch points on the cooling box housing and the mounting**

How-To:

- **Mounting**
  - The mounting must first be installed in order to secure the Cooling System
    - The mounting is installed on the floor of the car and must be close enough so that the hoses connect to the driver's suit
    - Mount must be secured with a rigid connection; all 4 fasteners must be used and drilled into the car body
    - It must be mounted in an area that is horizontal and box must be installed upright (do not install on the roof)
    - Mount must be checked for secure installation before every use to make sure fasteners have not become loose

- **Housing**
  - Make sure the box is properly inserted into the mount
  - Use all four latches and secure the box to the mount
  - Give one last check to make sure a latch was not missed and box is held tightly

- **Power Connection**
  - Insert power connection to control panel (follow instructions from Safety Warning section)

- **Cooling Suit Connection**

- Once the box and mount are secured and the user is inside the vehicle wearing the cooling suit, connect the cable from the suit to the one coming from the box using the quick connect plug
    - This quick connection can be used to quickly disconnect driver from the system to timely switch drivers, in case of a crash, or other emergency

- **Pump**
  - Pour DI water into the reservoir and run the system until there are no air bubbles in the tubing and the reservoir

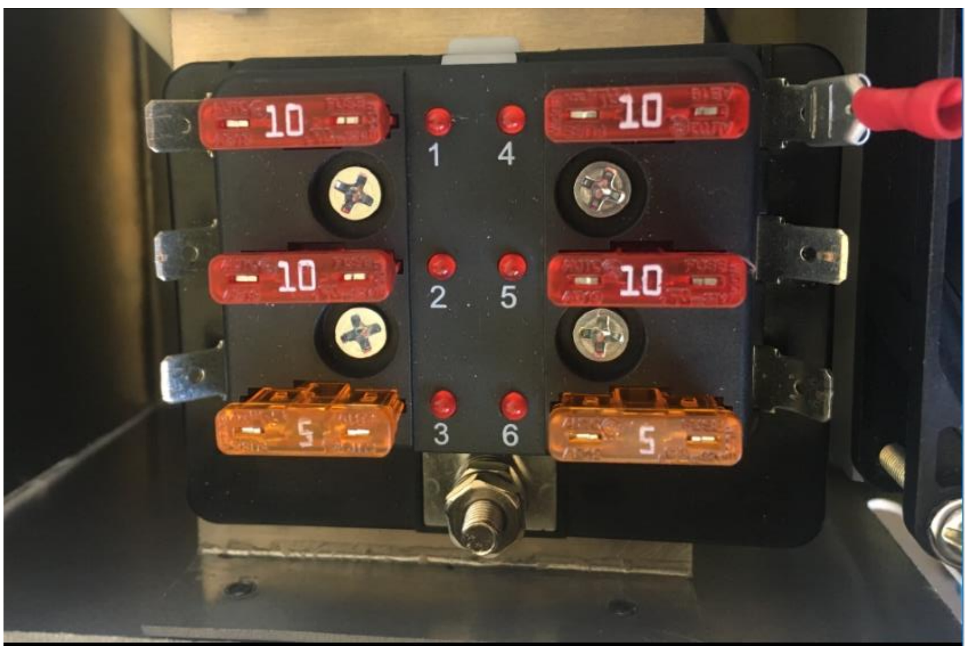
- **Operation**
  - Once the power and suit cables are properly connected, the car may be turned on
  - Now that the car is running, the Cooling System may be turned on using the in-line power switch found in the power cord
    - This switch should be conveniently placed next to the driver, in case there is a need for emergency shut off
  - The dial on the box can be used while driving to increase and decrease cooling of the system to the preference of the driver
    - Be sure to only use this dial if 100% sure it will not reduce focus on driving
    - DO NOT use dial during a time that can increase risk of crashing or impede safety to driver or anyone else

- **Shut Off**
  - When car is no longer in motion, shut down procedure may begin
  - Turn cooling dial all the way to the left
  - Turn in-line power switch to the off position
  - Disconnect cooling suit from system

Set Up:

To begin using your Cooling System, you will first need to attach the Cooling System mount to the floor of your car. To do this you will need to drill four holes using the mount as a template. The measured holes will ensure that the product fits nice and snug. Once the holes have been drilled, place the mount on the floor of the car and bolt the mount down.

Next, you will need to wire the system into your car. Please do so when the car is turned off, be aware that this can be dangerous, and please refer to the safety warnings above. To wire your device, you will need 8-gauge automotive wire. Attach one end to your car's ECU/battery and then connect the other end to the fuse box inside of the box. The positive wire will have a 40 Amp in-line fuse connected to it, and the negative wire will be screwed into our housing and grounded with the other negative wires of our system. To access the fuse box, you will need to remove the top cover by removing the 10 screws on the top of the product. Once the top cover is removed, you can easily attach the wire to the fuse box. Note: this will now arm the system when the car is on. Please make sure that the temperature knob is to the left most position and that the car is off when you have the top removed.

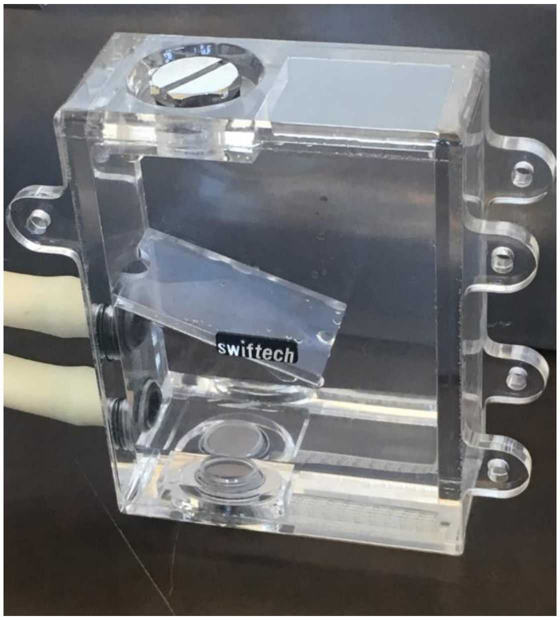


Fuse Box

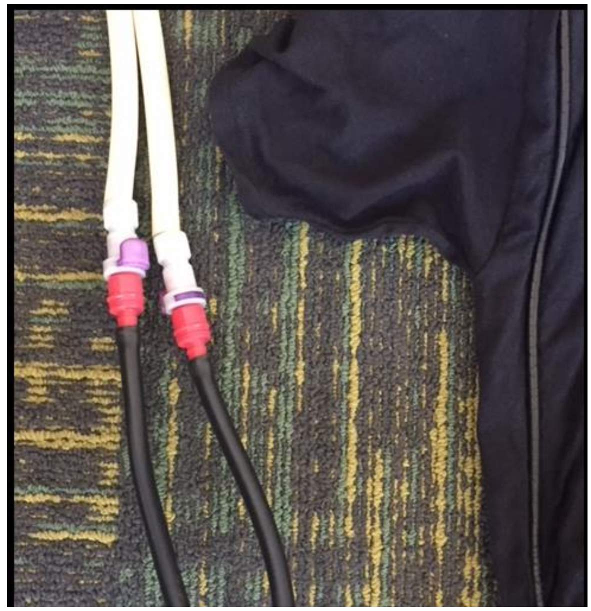
With the top still removed it is advised that you now attach the cooling system to the mount. To do this you will need to place the housing inside the mount and fasten all four latches down, this will ensure a snug fit and that the system will stay put while driving the car.

After the system has been locked down, reattach the top of the housing. Make sure not to pinch any wires or hoses for this will hurt system performance. When everything is reattached, you will need to prime the system by pouring in DI water into the reservoir. This requires you pouring water into the reservoir while the pump is running, so that water may flow through the entire system. Make sure that the Cooling System is attached to the

CoolShirt for this process, it will close the system and allow the pump to be primed. This has a medium risk associated with it, use a funnel and be careful not to spill water on any electronics. Once this is done, re-cap the reservoir. Next, turn the system on and run until all the bubbles are out of the suit, add more water if necessary. Turn the system off, disconnect the hoses and reattach to the system and suit. You are now ready to go race and stay cool!



Pump Reservoir



Shirt-System Connection

Maintenance:

Once the system is installed, there is little active maintenance required. Ensure that only DI water is used and that all the water is removed from the system when it is out of use. The mounting and cooling unit can be left in the car once it is installed. Make sure that tubes are not pinched, and water does not spill on the electronics.

Replacing or Repairing Parts:

If the electronics are not working, it may be caused by a broken fuse. Open the housing and check the lights on the fuse box; red indicates a broken fuse. Remove the broken fuse and replace with a new one. Almost all the parts except for the housing and mounting are off-the-shelf products that can be found in hardware stores and can be replaced and repaired by the consumer.