Final Design Review Report

Vaccine Cooler for the Global Poor

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May 31st, 2019

Statement of Confidentiality

The complete senior project report was submitted to the faculty coach/advisor and sponsor. The results of this project are of a confidential nature and will not be published at this time.

Statement of Disclaimer

Abstract

Cal Poly physics professors Peter Schwartz and Nathan Heston approached the Solar Freeze team with the problem that remote communities in Africa have limited access to modern-day medicine or vaccines. They suggested that we try and design a cooling device that can keep vaccines cold for multiple days at a time while the medicine is transported to remote villages. Currently, there are vaccine cooler products on the market, but most of them are very expensive or lack portability. Peter and Nate have tasked the Solar Freeze team to come up with a less expensive solution that is also portable and can handle the harsh environments of Africa. Due to the fact that Peter and Nate have done extensive research and laboratory experiments with using a solar panel to power thermo-electric coolers, they suggested that a thermo-electric cooler should be used to keep the cooler cold. The Solar Freeze team's goal is to design a solar-powered vaccine cooler that utilizes thermo-electric coolers to freeze a phase change material and keep vaccines at optimal temperature.

In the following Design Report document, the Solar Freeze team will discuss how a portable vaccine cooler would be beneficial to poorer communities in Africa. In the Background section, the results of our extensive research will be discussed including existing products, current patents, and interviews with the sponsor. The Objectives section will cover the scope of the problem that the Solar Freeze team is trying to solve which includes a problem statement, Quality Function Deployment (QFD), and risk analysis. The Concept Design chapter will cover idea development, decision matrices, and potential risks and issues. In the Final Design chapter, a complete description of the final design including 3D models, supporting calculations, and cost analysis will be discussed. The Manufacturing Plan chapter will have in-depth descriptions of how procurement, manufacturing, and assembly of all the parts and subsystems. The Design Verification Plan chapter will cover the testing specifications, verification tests, and testing facilities and equipment. In the Project Management section, project timeline and key deliverable tables discussed. Lastly, the Conclusion will wrap up the document and suggest a potential plan for moving forward.

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1. Introduction

The Vaccine Cooler for the Global Poor is a senior project with a team that consists of four senior mechanical engineering students at California Polytechnic State University. The communications lead is Cody Volk who has an interest in solar panel technology. Our manufacturing lead is Cooper Gibson who has an interest in sustainable energy and improving the quality of life in developing countries. Our testing lead is Ben Larson who has an interest in applying his engineering studies in real world applications. Our hardware lead is Eilbron Younan who is looking forward to working with Peltier technology and making a difference in the world.

2. Background

The background section will discuss customer research the team performed, research on existing products, and research on patents for similar devices.

2.1 Customer Research

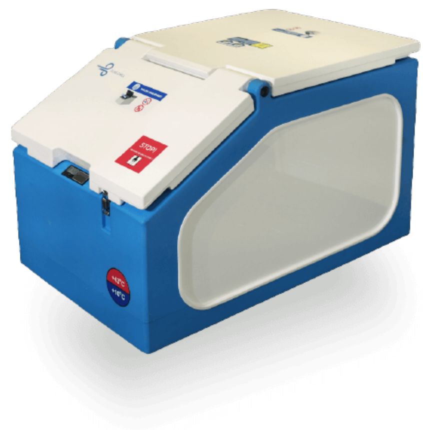
Three distinct types of background research were focused on during the initial research stage: customer research, product research, and technical research. Customer research involved the team familiarizing itself with quality of life in Africa, and the needs/wants of a clinic hoping to transport vaccines to remote villages. Product research involved researching current solutions on the market in order to determine how commercial products solved similar problems. Technical research was primarily centered on existing patents and how specific components work.

After meeting multiple times with Peter Schwartz and Nathan Heston, the Solar Freeze team had a good idea of what type of customer they were trying to build a vaccine cooler for. In the poorer communities of Africa the electricity may only be on intermittently for a few hours at a time. For this reason it is very important that the vaccine cooler can run using a solar panel. The cooler must also be small and portable enough to fit on the back of the motorcycle as that is one of the most common methods of transportation between villages. This means that the Solar Freeze team must be aware, when designing the cooler, of the bumps and vibrations that occur while riding on a motorcycle and how fragile glass vial vaccines are. Parts of Africa's climate are very hot, dry, and dusty. The cooler must be designed to handle hot surroundings and must not be affected by dust. The cooler must also be easy to maintain in poor communities as it is likely that they do not have access to specialized parts or skilled workers if the cooler were to breakdown.

2.2 Product Research

Table 1 summarizes the product research completed by the Solar Freeze team. In completing our research of similar products on the market, a few common observations and insights were made that will help guide our initial design phase. Firstly, a lot of commercially available solar refrigeration units are large and meant for storage of large quantities of vaccines at the clinic itself. There are not many portable solar-driven coolers designed with the intent of transporting vaccines far distances to remote villages. Also, the solar coolers that are available are incredibly expensive, often times costing upwards of $3000.

Table 1. Existing products that solve similar problems.

Product: Sure Chill [1] **Pros:** Portable, stays cool for long time, powered by renewable energy **Cons:** Bulky, difficult to attach to motorcycle, expensive **Functionality:** Water surrounds a Sure Chill refrigeration compartment. When it has power, the water cools and forms ice above the compartment leaving only water at four degrees cooling the contents. When the power is switched off, the water warms and rises while the ice begins to melt, keeping only four-degree water cooling the contents of the compartment [1].	
Product: Solar Chill [2] **Pros:** Solar powered, stays cool for long time, powered by solar power, accurately stays at 4 ℃, 12 days of constant cooling. **Cons:** Heavy, not portable, expensive **Functionality:** Solar power, generated by solar panels, runs a direct drive compressor. The compressor powers the refrigerant cycle creating an ice-bank. The power of the sun is essentially stored in an “ice battery”. The cold temperature is transferred from the ice-bank to the storage cabin [2].	

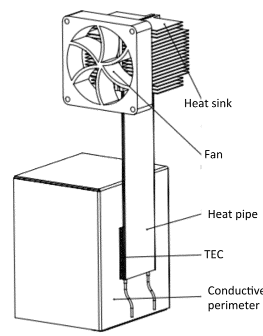
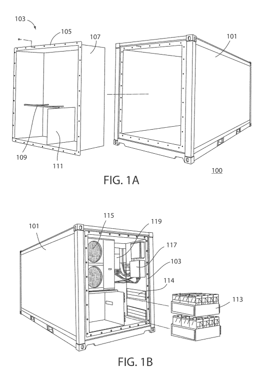
Product: Sundanzer BFRV55 [3] **Pros:** Stays cool for long time, powered by renewable energy, can store hundreds of vaccine vials, maintains idea internal temperature for 4 days in an environment of 43 ℃. **Cons:** Heavy, not portable, expensive **Functionality:** Direct solar-driven cooler, with no internal batteries. Conventional refrigerator components.	
Product: Isobar [4] **Pros:** Lightweight, portable, stays cool for long time **Cons:** Expensive **Functionality:** A mix of ammonia and water is heated in a lower pressure vessel, causing the ammonia to vaporize and separate from the water. It remains trapped in the upper chamber by a valve until the cooling effect is needed. The device is then flipped over, causing the chemicals to recombine and give a cooling effect [4].	
Product: Indigo [5] **Pros:** Lightweight, portable, stays cool for long time **Cons:** Difficult to recharge, expensive **Functionality:** The vessel is a liquid nitrogen (a doubled-walled bottle with vacuum insulation that is much like a thermos), with multi-layer insulation technology (aka: the material that protects spaceships from extreme temperatures). It functions as an ultra-insulated cooler [5].	

Table 1. cont.

2.3 Technical Research

Table 2 summarizes five patents that are integral to the functionality of the solar cooler. Our goal is to design a cooler that is driven by the thermo-electric cooling effect of Peltier technology. A Peltier is a thermo-electric cooler that works when DC current flows through small, doped semiconductors that are arranged in series between two ceramic plates. One side of the Peltier heats up while the other side cools down. Usually, heat is dissipated through a heat sink or some type of circulating water system. This creates the desired temperature on the cold side of the Peltier [6]. Peltiers are an appealing option when deciding how to effectively cool a vaccine transport cooler due to their low cost, no moving parts, and durability. For example, a generic single Peltier module costs around $6, and was shown to effectively cool 80 grams of water from 25 °C to 0 °C into solid ice in 50 min [7]. This informed the team that they could use direct solar-driven Peltier(s) to create an adequate cooling environment for vaccines.

Table 2. Related technical patents.

Patent Title	Patent Number	Patent Description	Drawing
Mobile Thermoelectric Vaccine Cooler With a Planar Heat Pipe	US20160003503A1	A portable medical refrigerator cooled with a thermoelectric device connected to a heat sink. Also utilizes a planar heat pipe to efficiently transfer heat out of the cooling chamber. [8]	
Backpack for use with a Portable Solar Powered Refrigeration Box and Water Generator	US20180106509A1	A solar powered portable refrigeration unit with an insulated chamber for storing perishable goods. Contains batteries and an inverter to convert DC voltage to AC voltage. Also contains a stand-alone water generation unit for converting atmospheric moisture to potable water. [9]	

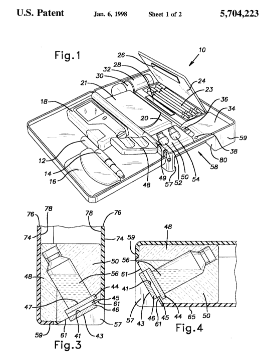
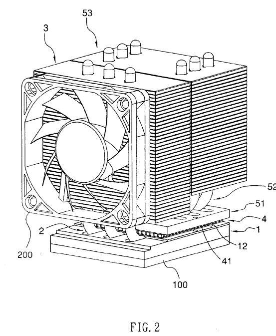
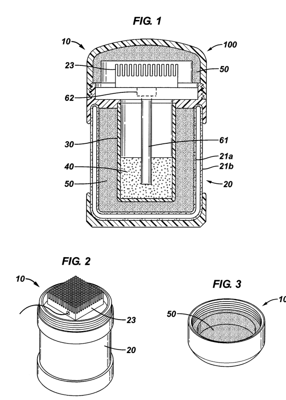
Thermoelectric Medicine Cooling Bag	US5704223A	Medicine cooling bag cooled by a Peltier heat pump. Vials of medicine are tilted to maximize heat transfer efficiency. The heat pump has both a cold plate and heat sink and is powered by an internal battery. [10]	
Two Stage Radiation Thermoelectric Cooling Apparatus	US6880346B1	Two stage thermoelectric cooling apparatus for cooling electrical components. First stage pre-cools the electronic device in order to lower the temperature to level the TEC can efficiently cool. Residual heat is dissipated out the back of the device using a heat pipe and radiator. [11]	
Medical Travel Pack with Cooling System	US20090049845A1	Device incorporates a thermoelectric cooler inside an insulated cooler. TEC is in contact with a freezable phase change material. When disconnected the phase change material provides passive cooling inside the container while medical material is transported. Not solar powered, is intended for short trips in between charges. [12]	

Table 2. cont.

One strategy to maintain a vaccine cooler at its desired temperature is to use ice packs. Ice packs are effective due to the large amounts of energy it takes to cause a phase change from solid to liquid. If the phase change temperature is the same temperature that the cooler needs to be maintained at, ice packs can be effective. Since most vaccines must be kept between 2-8 ℃, only certain types of ice packs would work. For example, water has a phase change temperature of 0 ℃ which is too cold for a vaccine cooler, so other phase change materials have been investigated. Organic phase change materials (PCMs) manufactured by Rubitherm have a phase change temperature of 5℃, are non-toxic, and have consistent performance over thousands of heating and cooling cycles [13].

In addition to product and patent research, it was important to understand certain industry standards that will guide the safety of our design. In terms of industry standards, the World Health Organization has very strict vaccine regulations. For example, the maximum acceptable fully loaded weight of a vaccine box should not exceed 55 lbf, if being lifted by one worker. Also, the universal safety standard for transporting vaccines is to maintain a temperature of between 2-8℃ for 7.48 hours at a surrounding temperature of 43℃ [14]. Our plan is to use this standard as the main focus for the performance of our cooler in order to meet and surpass it, as there is a lot of uncertainty in transporting vaccines to remote villages in Africa.

3. Objectives

People in Africa do not have access to reliable electricity need a way to safely and effectively transport vaccines, with the ability to maintain optimal temperatures of 2-8°C for up to 1 day at a time.

Figure 1 below shows the boundary diagram for this project. Components that are inside the dotted line are ones that we can control. These will have strict specifications and be entirely designed by us, while the components outside the dotted line are components that should be accounted for, but not necessarily designed for.

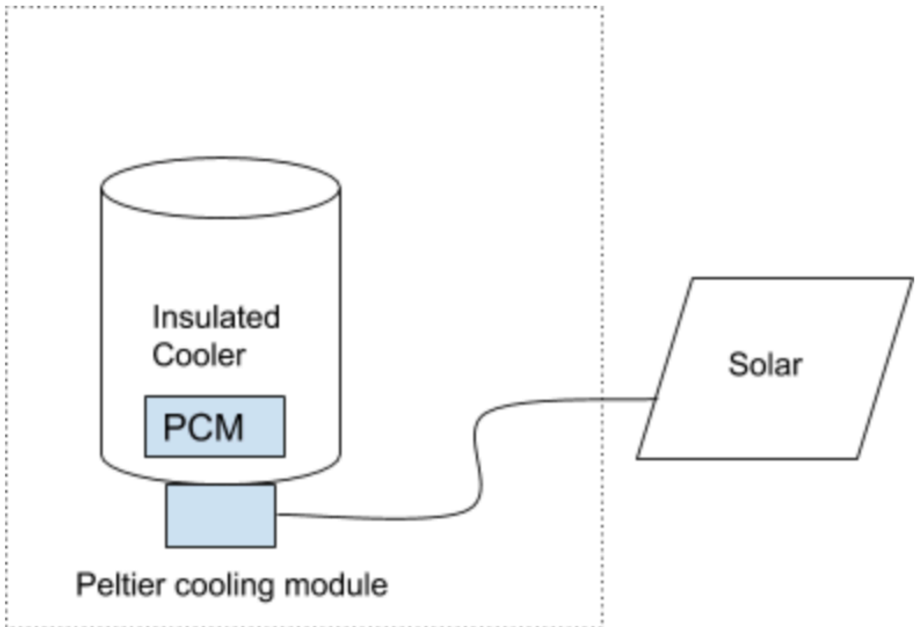


Figure 1. Boundary diagram showing scope of project design.

3.1. Design Considerations (Needs and Wants)

The customer's needs for this project are that the cooler is to be portable and lightweight, and should not require more than one adult in order to handle it. Due to the lack of stability of power grids in Africa, this cooler needs to be powered by off-grid electricity. The cooler needs to be durable and require little to no maintenance, encouraging the solid-state technology of Peltiers to be the main method of cooling the device.

After talking extensively to Peter Schwartz and Nate Heston about the type of environment and possible uses of a vaccine cooler, the Solar Freeze team outlined a list of possible needs and wants which can be seen in Table 3 below. The most important needs are maintaining the optimal temperature of the vaccines and keeping that temperature for days at a time because if a vaccine spends too much time at a non-ideal temperature, it loses its potency. Many of the "wants" are intended to be included in the team's vaccine cooler but are not absolutely essential to the final product.

Table 3. Possible needs and wants for vaccine cooler.

Need	Want
Maintains optimal temperature	Cheap
Safely transports vaccines	Aesthetically pleasing
Portable	Easy to operate
Has off-grid power option	Durable
Stays operational for up to 1 days	Can be connected to regular outlet
Minimal maintenance	

3.2. Quality Function Deployment (QFD)

To assure that they are solving the correct problem with the proper specifications, the Solar Freeze team created a QFD to compare their specifications to the specification of existing products. The QFD takes key elements such as who, what, how, how much, and testing categories and compares them with each other. The primary purpose of the QFD is to obtain a measurable set of engineering specifications. The Solar Freeze team's QFD can be seen in Appendix A. For example, the "who" or different customers of a vaccine cooler was compared to "what" or different requirements that the vaccine cooler fulfilled. Depending on who the customer was, they would value each requirement differently. The different requirements that the vaccine cooler fulfilled were also compared to the testing categories and evaluated for relevance. Rudimentary values for each testing category were established. Other products on the market were then compared to our standards and evaluated for how well they did. Using this QFD, it is our goal to design a vaccine cooler that meets our standards and scores better than the competition.

3.3. Specifications and Risk Assessment

The Solar Freeze team came up with parameters and requirements for each of the engineering specifications for the vaccine cooler and listed them in Table 4. These engineering specifications are only estimates from extensive research and will likely change when tests are performed. The only specification that is set is the optimal temperature specification of 2-8 ℃, which was determined from World Health Organization parameters. Tolerances of each of the requirements were estimated. In order to assess the amount of risk regarding each specification, levels of risk were assigned using high risk (H), medium risk (M), and low risk (L). The higher the risk, the more important that parameter is to the end product. For example, maintaining the optimal temperature for the required time period is crucial since the vaccine will lose potency if ideal temperature range is not maintained. Parameters such as weight and dimensions were given low risk because these parameters are not set in stone and can be changed as needed. Compliance methods or how each parameter will be tested were also determined for each parameter including testing (T), analysis (A), inspection (I) and similarity to existing designs (S). For example, maintaining the optimal temperature must be determined by testing with thermocouple, while the dimensions can be determined by inspection. Since the Solar Freeze team does not yet know how the vaccine cooler will be kept cold, the engineering specifications were kept as broad as possible.

Table 4. Engineering specifications.

Spec. #	Parameter	Requirement	Tolerance	Risk	Compliance
1	Optimal Temperature	2-8 ℃	± 0℃	H	T
2	Number of Vaccines Capacity	50 vials	Min	L	T, A
3	Weight	Under 100 lbs.	Max	L	I
4	Cost	$200	Max	M	A
5	Lifespan	3 years	Max	L	S
6	Dimensions	2ft x 2ft x 2ft	Max	L	A, I
7	Power Consumption	100 Watts	Max	M	T, S
8	Time to Reach Optimal Temperature	3.5 hours	± 3 hours	M	T, A
9	Time of Maintaining Optimal Temperature	12 hours	Max	H	T

4. Concept Design

The concept design chapter will discuss the team's idea development process, initial sketches, concept models developed, decision matrices, and the chosen final concept.

4.1. Idea Development

To begin the idea development stage the team identified four main functions of the cooler. The four functions were determined as: cool vaccines, transport vaccines, charge cooler, and withstand heat. The team held multiple ideation sessions to create as many ideas as possible. Three separate brainstorming strategies were deployed during the sessions including traditional brainstorming, the SCAMPER technique, and brainwriting. Traditional brainstorming consists of each member contributing ideas over a set time period. SCAMPER stands for substitute, combine, adapt, modify, put to another use, eliminate, and reverse. It utilized by asking questions about existing products in order to develop creative ideas for developing new products. Finally, brainwriting consists of each team member writing ideas in a notebook for three minutes. At the end of three minutes, each team member passes their notebook to someone else, and another session begins. After everyone has written in each available notebook, results are shared, resulting in the development of new ideas. In Table 5 below, the strategy used is listed alongside the corresponding function. The results are shown in each subsequent column. The team was encouraged by faculty advisor, Dr. Eileen Rossman to keep even the craziest ideas throughout the process to spark creative and original thought.

Table 5. Ideation techniques.

Transport Vaccines (Traditional Brainstorming)	**Cool Vaccines (SCAMPER)**	**Charge Cooler (Traditional Brainstorming)**	**Withstand Heat (Brainwriting)**
· Existing Cooler · Autonomous Helicopter · Back of motorcycle · Backpack · Teleportation · Amazon prime · Drones · ATV · Car · Elephant · Horse	**S:** Ice Packs, thermal battery **C:** Freezer, Solar Panels **A:** Adapt to surrounding temp **M:** Dry Ice **P:** Use for food **E:** Minimize Weight, Insulation **R:** Cooker, Oven	· Solar power · Peltier · Battery · Wall outlet · Nuclear · Hydro · Gravity · Wind · Sun · Ocean · River powered · Human powered · Elephant powered	· Vacuum sealed cooler · Styrofoam insulation · Local African insulation · Water bath · Always pump out heat to keep cool · Change climate of Africa to 2-8 C · Vacuum and material insulation

· Camelback · Sniper/cannon · Flat earth map – straight shot · AT-AT · Jason Bourne · Vacuum chamber · Insulated bag · Yeti · Crate · Bank vacuum tube · Heely's		· Bike powered · Electricity · Gas · Propane · Generator · Hamster · Fly · Laser · Clean coal · Hand crank · Magnets · Thermal magnets	· Pump heat out using stacked Peltiers · Place cooler in a cooler in a cooler · Reflective outer coating for solar heat · Phase change substance of 2-8 C · Cover device with thermal blanket

During and after the brainstorming sessions, the members of the team drew sketches to communicate their more inspired concepts. Figure 2 depicts a top view of a concept cooler with a simple Peltier-driven cooling set up.

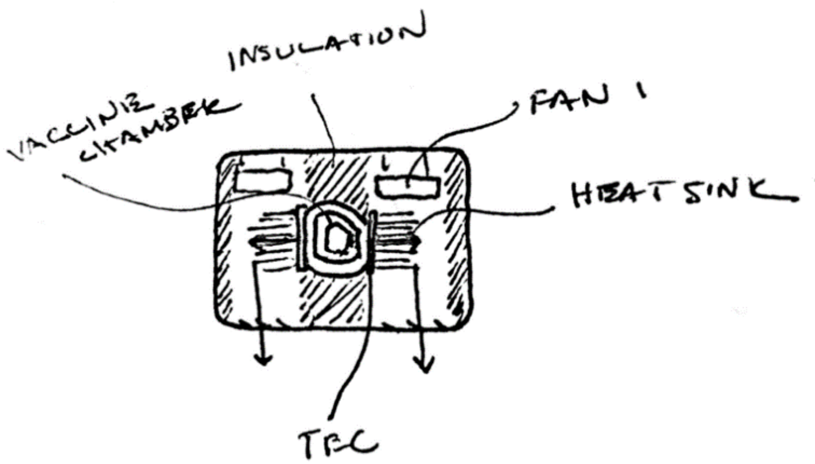


Figure 2. Concept cooler with two heat sinks and fans.

The concept cooler in Figure 2 is cooled by two Peltiers with the hot side on a heat sink and the cold side in contact with an aluminum housing. The heat sinks are kept cooled by two DC fans that blow air through the fins to dissipate heat. Holes in the sides of the cooler would allow the hot air to escape to the ambient air. The following concept in Figure 3 utilizes water instead of air to cool the hot side of a Peltier to capitalize on the high specific heat capacity of water.

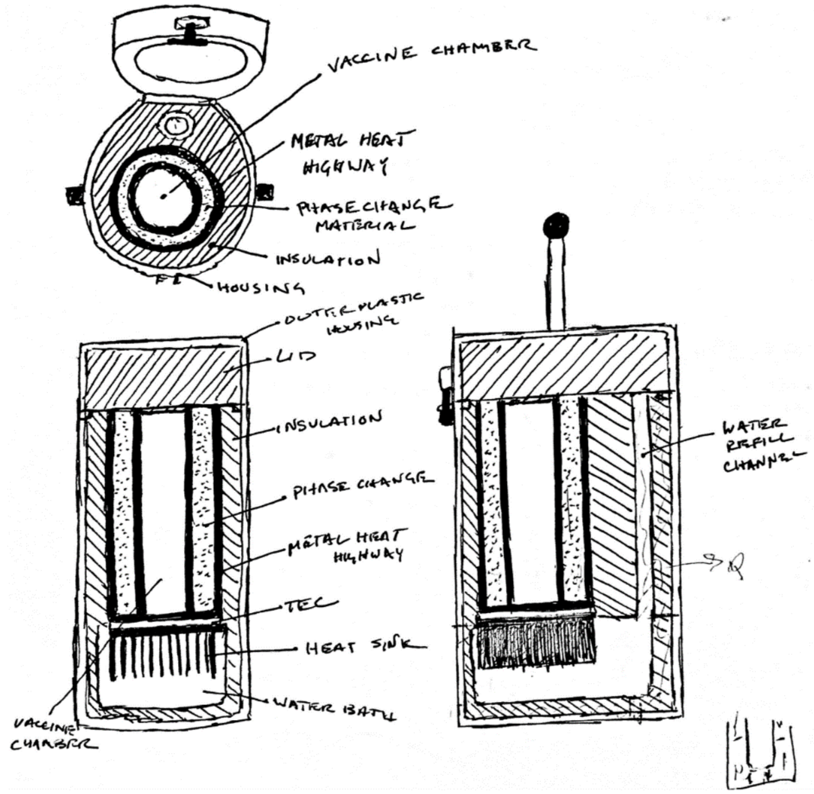


Figure 3. Concept cooler with Peltier, phase change material, and heat sink inside a water bath.

The concept in Figure 3 is cooled by a Peltier with its hot side connected to a heat sink which sits in a water bath. Once the system has run completely through (i.e. the phase change material is completely frozen), the water bath will be hot from absorbing energy and can be dumped out to release the unwanted heat. The cold side cools an aluminum chamber with a phase change material inside. Once the phase change material is frozen it acts as a thermal battery to keep the vaccine chamber cool while the Peltier is off. Another cooler concept created during the brainstorming sessions is portrayed in Figure 4.

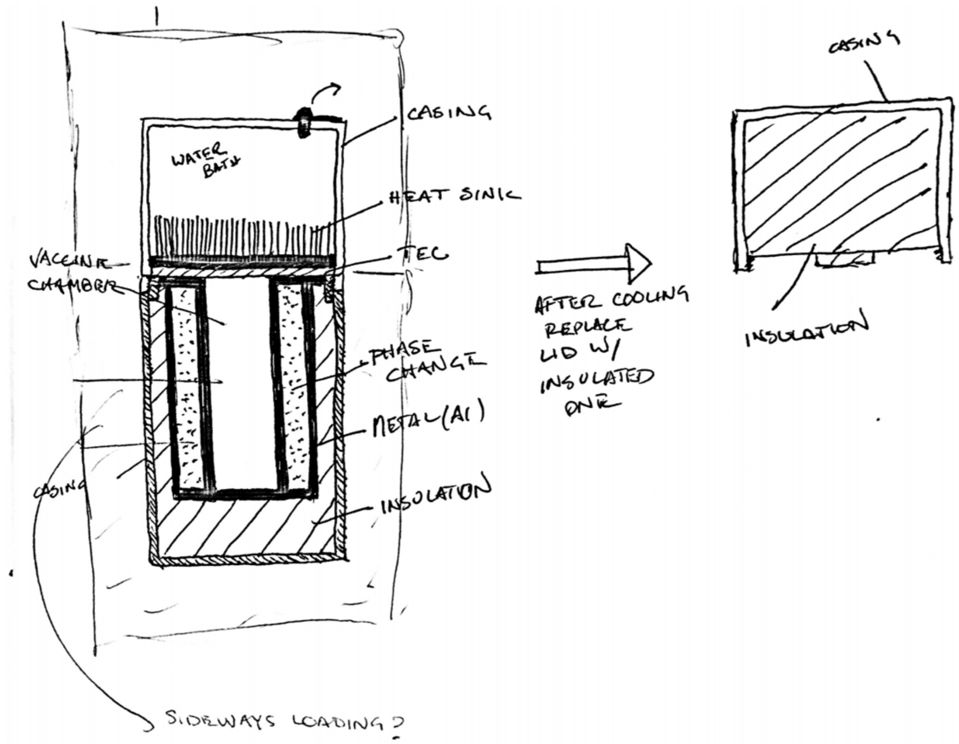


Figure 4. Concept cooler with heat sink and water bath on top.

The cooler in Figure 4 is another cooler concept which utilizes Peltier technology coupled with a phase change material. The heat sink and water bath are flipped to be on top of the vaccine chamber in order maximize cooling efficiency since heat has the tendency to travel up. The water can be dumped after use to get rid of the unwanted energy within the system. The concept also has a second lid that is more heavily insulated that replaces the water bath lid when not in use.

The above featured concept sketches were some of the many drawn by the team during the ideation stage. Using the list of ideas in conjunction with the sketches, the team put together four separate Pugh matrices for each function. The matrices took the top ideas from each session and weighed them against each other to more narrowly select the most viable solutions. The Pugh matrices can be viewed in Appendix C at the end of the document.

4.2. Concept Models

Table 6 below depicts the concept models generated prior to the preliminary design review presentation. These models were made from easily adaptable materials such as cardboard, aluminum foil, and tape, and are not fully functional. They only represent potential design directions set forth by the team.

Table 6. Concept Models

Concept Model	Description	Picture
#1 Tall Boy	Tall, rectangular cooler design for ample room for vaccines. Solar panel and removable lid on top.	
#2 The Separator	Rectangular cooler design. Has inner lattice design to hold vaccines securely.	
#3 Jack in the Box	Cooler within a cooler design. Maximizes insulation potential. Uses air gap between coolers as a thermal insulator.	
#4 Two Face	Cooler design with two interchangeable lids. When the Peltier is not running, lids will be switched to limit heat transfer.	

#5 The Nuclear Core	Cylindrical cooler design. Peltier and heat sink located on top of cooler. Phase change material along the sides of the vaccine chamber. Insulation on the outside of the phase change material layer.	

4.3 Decision Matrix

The team selected the top three to six concepts from each Pugh matrix and created a Morphological matrix to assemble multiple creative and viable solutions. The matrix serves as a way to combine function concepts into distinctly different products and can be found in Appendix D.

The five system concepts were entered into a decision matrix (Appendix D) to weigh how they perform against each other. The specifications taken from the QFD were used to evaluate how each system satisfied critical criteria. The engineering needs were weighted by importance against themselves. It was found that the most critical criteria of the cooler would be maintaining the optimal operating temperature and it is the only criteria that earned a weight of 5. The next most important criteria were found to be cost, power consumption duration of charge, and portability each receiving a weight of 4. The system model were rated on a scale of 1-5 for how they fulfilled each criteria. Then the ratings were multiplied by the weight of importance for the criteria. The final scores are at the bottom of the matrix and are the sums of the weighted rating values.

The totals in the matrix show that system Concept 1 outscored the rest of the designs which utilized a Peltier coupled with a phase change material. The second best design was Concept 2 which used a backpack, Peltier and phase change material. The cooling device would be stored in an existing cooler style body and use Styrofoam insulation similar to current cooler models available.

4.4 Selected Concept

The Solar Freeze team has made many iterations and design changes since the beginning of the project. The current design as presented during the Critical Design Review can be seen below in Figure 5 and will be discussed in further detail in Chapter 5: Final Design. To see a previous design iteration, specifically the design at the time of the Preliminary Design Review (11/16/18) view Appendix H.

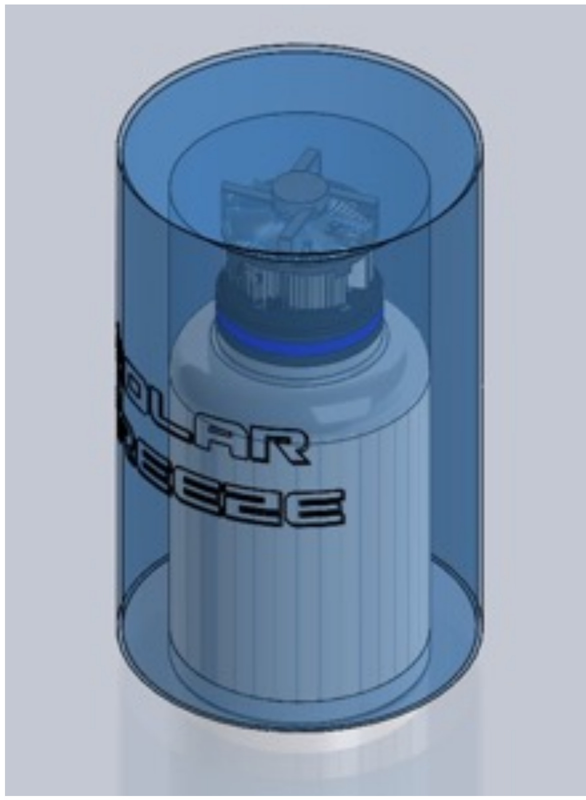


Figure 5. Concept of final design.

4.5 Potential Issues/Risks

One of the biggest issues involved with a vaccine cooler is keeping the vaccines at the optimal temperature so they retain their effectiveness. Limiting the heat transfer into the cooler will be one of the biggest challenges the Solar Freeze team will face. The team will also face challenges with the Peltier. The hot side of the Peltier must be very securely pressed to the heat sink otherwise heat will not dissipate efficiently enough. The cold side of the Peltier must also be securely attached to the heat pipes so they can work efficiently. Attaching and figuring out the optimal design of the heat pipes in the phase change material chamber will likely be tricky. Using the Peltier to fully freeze the phase change material will also be a challenge. Extensive testing needs to be done to get a better sense of these issues and what will be done to combat them.

The Design Hazard Checklist in Appendix G goes over the expected risks that will be present with our design. Due to the fact that our project is design to have no moving parts, only three of the design hazards are applicable to the Solar Freeze's project. Sturdy handles will be installed to make transportation easier. One design hazard on the checklist that needs to be considered is that there will be electrical systems used that will not be grounded. But, the amount of current running from the solar panel to the Peltier is small enough that it will not be harmful. The last design hazard that the team will need to consider is the exposure to extreme weather conditions. The vaccine cooler must be designed to withstand the high temperatures and harsh conditions such as dust or wind in Africa.

5. Final Design

This chapter discusses the overall system description, detailed subsystem description, specific part descriptions, and an ideal usage schedule. After this chapter, the reader should have a very good idea of how each part works in each subsystem and how the overall system runs.

In the following chapter, two versions of the final design will be discussed: first, the final design as of the Critical Design review on February 7th, 2019 and second, the final design as of the Final Design Review on May 31st, 2019. The second final design will reflect a design that has been iterated and improved on based off of hours and hours of testing. This is the design that was presented at the Senior Project Expo on May 31st, 2019.

5.1 CDR Design: Overall System Description

The vaccine cooler system consists of a vacuum flask used as an outer chamber for insulating the vaccines and cooling system, along with a thermoelectric cooling system consisting of a heat sink and fan, Peltier, and phase change material (PCM) chamber. Also included is an insulation cover for operation when the Peltier is not being powered, as well as temperature controller that notifies the user when to plug into the solar panel to power the Peltier. Since the capability of the plastic lid to insulate heat will be defected after alterations, the insulation cover protects the critical junction from allowing heat into the vaccine chamber. The PCM chamber houses a non-toxic, biodegradable phase change material which acts as a thermal battery in order to maintain the vaccine chamber at 4.5 ℃. In order to minimize heat transfer from the environment to the vaccine chamber, nylon fasteners are used to attach each system together. A full exploded view of the complete assembly can be seen in Figure 6 below.

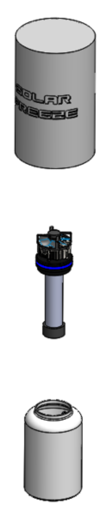


Figure 6. Exploded view of complete assembly. From top to bottom: Insulation Cover Assembly, Heat Transfer Assembly, and Vaccine Chamber Assembly.

5.2 Detailed Subsystem Descriptions

In the following section, each subsystem of the vaccine cooler will be discussed in detail. The function of each part will be described along with justification for the design direction through analysis and testing.

5.2.1 Vaccine Chamber

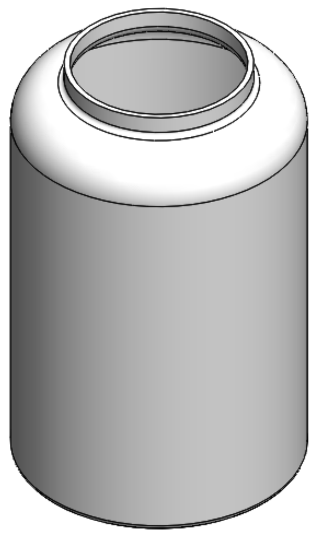


Figure 7. CAD rendering of vaccine chamber.

The vaccine chamber is a vacuum-insulated, RTIC one gallon flask that is used to hold and transport the vaccines, as seen in Figure 7. Due to the temperature sensitivity of the vaccines, this component needs to be well-insulated and reliable. A vacuum-sealed flask was chosen over other types of insulation because of how effective it is at limiting heat transfer. From the specifications provided by RTIC Products, the one gallon flask is able to keep ice at 0 ℃ for 24 hours. Upon further simple testing, it was found that the flask was able to hold a half gallon of ice for 22 hours, thus validating the claims made by RTIC and providing design verification for the component. The full detailed drawing of this part can be found in Appendix M: Drawing Package, part number SF101010.

Six steel cup hooks are adhered to the inside of the gallon jug 8 inches up from the bottom using epoxy. These six evenly spaced hooks are used in conjunction with mesh bags to hold the vaccines in an organized array out of the path of the phase change chamber down the center of the system. The bags are small enough that they can be lifted out of the 4 in opening of the gallon jug. The bags also serve as an organization method for separating vaccines by type and size. The full assembly drawing of this subsystem can be found in Appendix M: Drawing Package, part number SF101000.

5.2.2 Heat Transfer Assembly

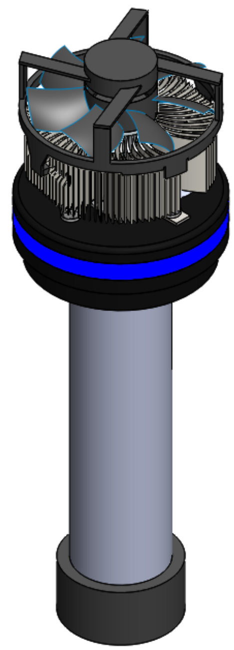


Figure 8. CAD rendering of heat transfer assembly.

The heat transfer assembly pictured above in Figure 8 is the driving system of the design. At the core is the Peltier thermoelectric cooler which draws heat out of a phase change material and dissipates it to the air through a heat sink and fan. The heat sink, fan and aluminum phase change chamber are secured to the container lid using nylon bolts, screws and nuts. An LED indicator strip wraps around the cap to signal the temperature of the vaccines to the operator. Refer to Appendix M: Drawing Package, part number SF102000 for an assembly drawing of the system.

5.2.2.1 Phase Change Material Container

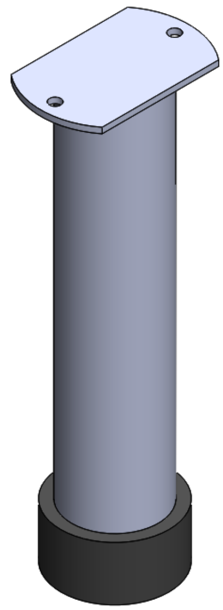


Figure 9. CAD rendering of PCM container.

The phase change material container is a 9” long, 1.5” diameter aluminum pipe that is filled with phase change material and is capped at the top by the cold side plate and at the bottom with a rubber end cap as seen above in Figure 9. The rubber end cap is bought off the shelf and has a screw-driven binding to tighten the fitting. The cold side of the Peltier is in contact with cold side plate featured as the part at the top of Figure 9. Heat is removed from the cold side plate and then the PCM container walls. As the temperature decreases, the PCM freezes as heat is drawn out radially. When the PCM is frozen, it will act as a thermal battery for the system, or an “ice pack”. This thermal battery maintains the internal temperature of the vaccine chamber at the ideal temperature of 4.5 °C. When the Peltier is not in use, the PCM in the container slowly melts because it is absorbing thermal energy that is leaking into the chamber. Even when it is melting, the PCM maintains the internal temperature of the vaccine chamber. The phase change material chosen is manufactured by a company called Vericor Medical. It is non-toxic and biodegradable with a melting point of 4.5°C. For the full detailed drawing of the PCM container, refer to Appendix M: Drawing Package, part number SF102020.

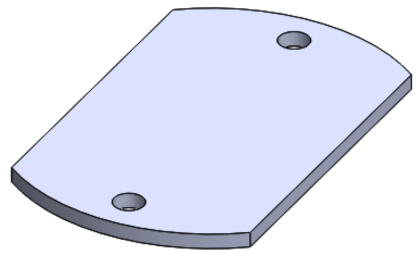


Figure 10. CAD rendering of cold side plate.

The purpose of the cold side plate is to be in contact with the cold side of the Peltier. The plate is made from 6061 aluminum. The material was chosen for its excellent thermal conductivity and common use in industry for heat transfer applications. The CAD rendering can be seen above in Figure 10. The plate was analyzed using a 3-D transient heat transfer model in MATLAB. The plate was initially set at ambient temperature (30°C), then a 4.5°C boundary condition was set on the top of the plate to provide a simple model for the Peltier. All other faces were assumed to be insulated since they are located inside the vacuum flask. It was found that at steady state, there was only a 0.16 °C temperature difference between the top and bottom plates, validating the geometry and material choice for the cold side plate. The transient results can be seen in Figure 11 below for t = 1 min and t = 10 min (steady state) seen from left to right. The full code can be seen in Appendix F: MATLAB code for 3D Thermal Modeling. For the full detailed drawing of the cold side plate, refer to Appendix M: Drawing Package, part number SF102021.

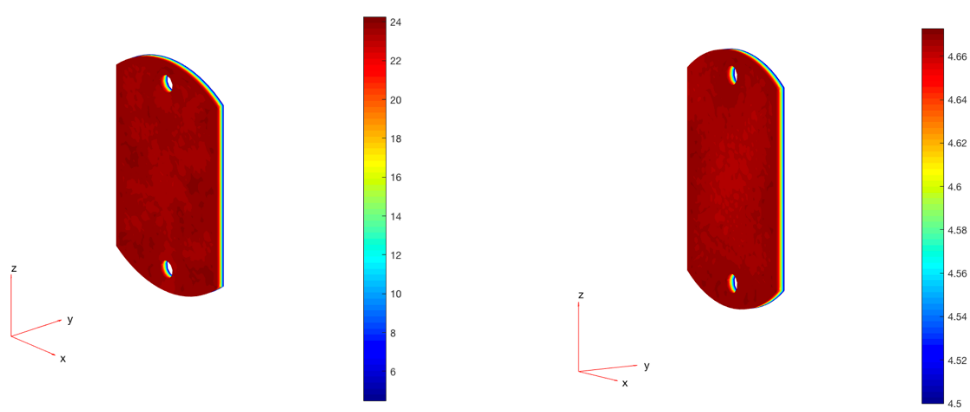


Figure 11. Transient analysis for cold side plate at t = 1 min and t = 10 min.

5.2.2.2 Cap

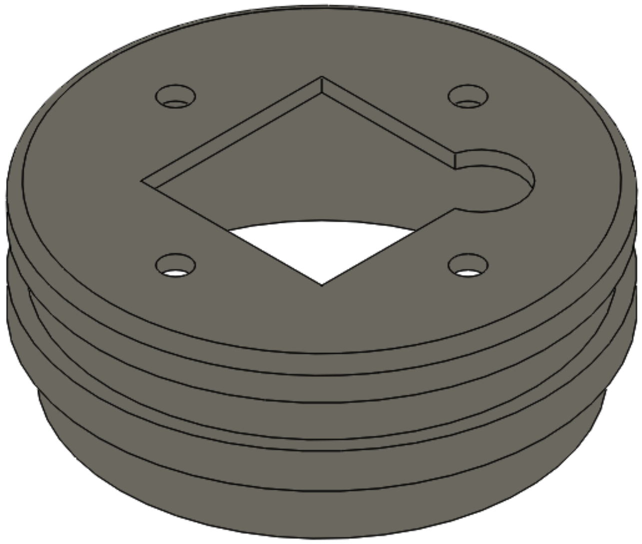


Figure 12. CAD rendering of cap.

The cap is the threaded cap that comes standard with the RTIC one gallon vacuum jug. It is modified to act as the "base" for the entire heat transfer assembly. The cold side plate of the phase change chamber is attached to the bottom of the cap via two nylon bolts in the holes seen above in Figure 12. The cold plate will sit flush with the inside of the top of the cap. The other two circular holes in the lid are used to secure the heat sink/fan. The Peltier sits in the square hole of the lid and is squished between the heatsink and phase change chamber. Thermal paste is used on both sides of the Peltier to maximize thermal efficiency. Refer to Appendix M: Drawing Package for an exploded view of the heat transfer assembly and detailed drawings of the cap.

Note: The three quarter circle hole on the right side of the cap in Figure 12 is where the water spout was located. This hole is covered up and well insulated to prevent unwanted heat transfer.

Due to the many modifications done to the cap, measures were taken to properly insulate it. Nylon bolts are used to fasten the cold side plate and heat sink to the cap because they have a thermal conductivity of about 800 times less than aluminum bolts. A rubber O-ring is included in the purchase of the one gallon jug that is used to effectively minimize heat transfer through the threads that connect the lid to the vacuum chamber.

5.2.2.3 Peltier

The proposed design will rely on a Peltier to cool and maintain the vaccine chamber between 2 and 8 °C. Peltiers consist of small rectangular ceramic plates with doped semiconductors sandwiched between them. When a voltage is applied between electrical junctions of a Peltier, current flows through them, causing heat to be removed at one junction and deposited at the other. In this sense, a Peltier is a solid-state active heat pump that uses electrical energy to achieve a desired cooling effect. Due to the lack of moving parts or refrigerant, small profile, very long life, and low cost, Peltiers prove to be an attractive method of cooling for this application. On top of this, Nate Heston and Peter Schwartz have shared their research data from the summer of 2018 where solar-driven Peltiers were used to effectively cool water in order to produce ice. This research provided us with performance characteristics of Peltiers at varying current levels, different configurations (i.e. stacked), and fluctuating temperature differences. Important parts of their research are included in Appendix E: Peltier Data.

Figure 13. TEC 12715 Peltier module.

Figure 13 depicts the Peltier model that will be used to transfer heat from the PCM chamber, effectively cooling the inner chamber to a temperature of 4.5 °C. After about 0.001 in. of thermal paste is applied to both sides of the Peltier device and excess paste is removed, the heat sink and fan will be attached to the hot side of the Peltier, and bolted down with an adequate mounting pressure of 25-100 psi. This mounting pressure will be measured with torque wrenches and will help to minimize the contact thermal resistance of the Peltier. In order to pull an estimated 20 W of heat out of the system as calculated in Appendix E: Peltier Data, the Peltier must be ran at 8.08 V and 8.25 A to achieve an optimal COP. This configuration draws 66.66 W out of the solar panel, which is possible with a 100W solar panel, even during non-peak hours.

5.2.2.4 Heatsink and Fan

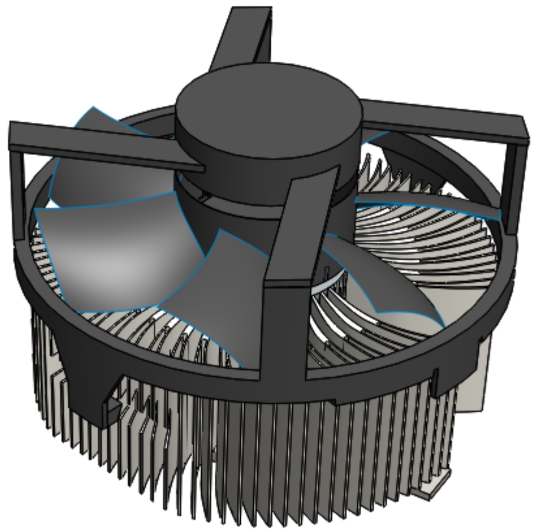


Figure 14. CAD rendering of heatsink and fan.

One of the most important aspects of the vaccine cooler design is the method used to dissipate heat from the hot side of the Peltier. If heat cannot be dissipated quick enough, the Peltier could possibly short out or become inefficient. If the Peltier is not working properly, the phase change material will not freeze and the vaccines will spoil. Research and calculations were done involving some type of water bath that would be utilized to cool the Peltier but in the end it was decided that a fan and heatsink combination system would be most effective and appropriate for the design.

The chosen fan and heatsink is a LGA Socket 1155 Intel CPU Cooler and can be seen above in Figure 14. According to calculations in Appendix N: Hand Calculations, this fan and heat sink combination device can dissipate heat at a rate of 163 Watts which is adequate for the design. The heatsink with be secured firmly to the holes in the cap via nylon bolts (See Appendix M: Drawing Package for an exploded view of how the two components line up). Small slots were machined out of the fins using the Dremel tool (See Chapter 6.2.5 for more in-depth manufacturing instructions) for which the nylon bolts will sit.

5.2.2.5 LED Temperature Indicator Lights

Maintaining ideal temperatures is a crucial component in the vaccine cooler. A series of digital LEDs will be wrapped around the circumference of the vaccine cap. Incorporating a 360 degree indicator light configuration allows the end user to be aware of the status of the cooler from any angle of observation. This system is composed of a microcontroller, waterproof temperature sensor, LED light strip as previously mentioned above, and a rechargeable power bank that supplies power to the system as depicted in Figure 15 below. The LED lights will be controlled by an Arduino Nano that will output a signal to illuminate either red, green or blue light depending on the input signal from the temperature sensor. The waterproof temperature sensor is mounted on the inside of the chamber where the vaccines are housed during transport. The microcontroller is compact enough to secure on top of the cap, and the power bank will be secured on the top of the heatsink. The microcontroller is programed to illuminate the LED strip with a blue hue when the temperature inside the chamber is 2 °C or less. When the end user observes the blue color, this indicates that the chamber is ready be filled with vaccines and begin the transport journey.

In the event of the internal chamber is at a temperature between 3 and 6 °C, the microcontroller will output and signal the RGB LED strip to deactivate the blue hue and activate a green hue. The green color signifies that the vaccines are at optimal temperature and no action is required from the end user. When the internal temperature reaches 7 °C, microcontroller will activate the LED strip with a red color indicating to the user that the vaccines are reaching upper limit temperatures and the Peltier needs to be plugged back into a power source immediately. Once the internal temperature reaches 8 °C, the red ring of LEDs will start to pulse to generate a sense of urgency from the end user for the Peliter to be plugged into a power source. Once the upper limit of 8 °C is surpassed, and the RED LED strip is illuminated for more that 10 minutes, the vaccines have lost their potency and need to be discarded. Refer to Appendix K for the microcontroller code and flowchart.

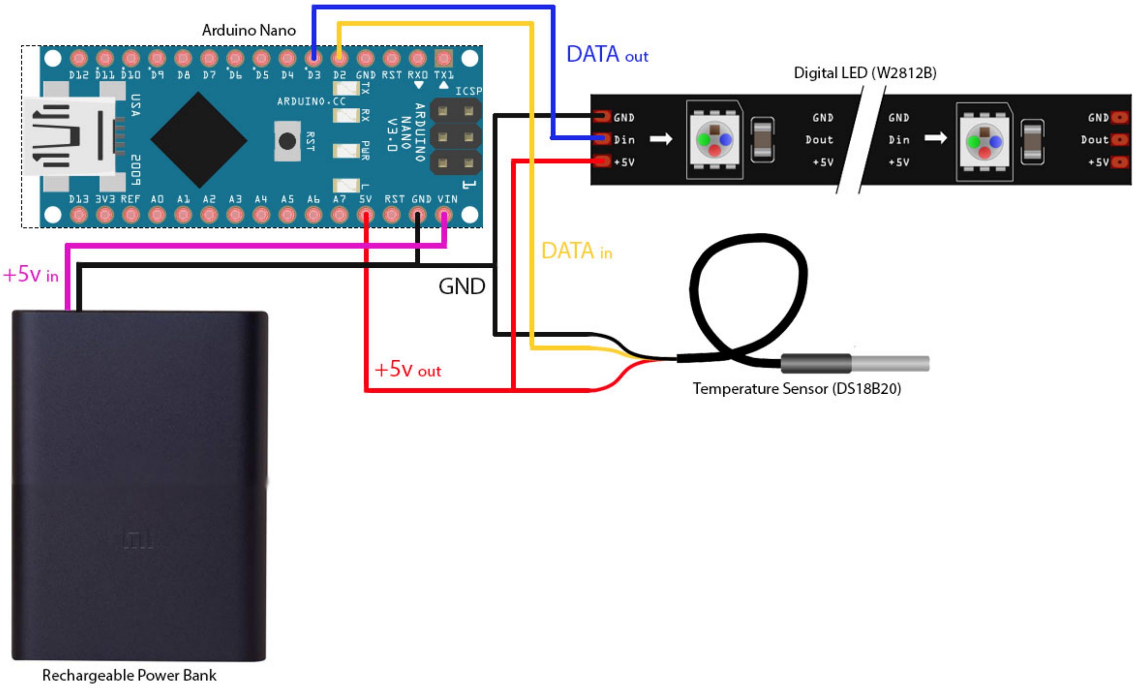


Figure 15. Circuit diagram of LED temperature indication system.

5.2.3 Insulation Cover Assembly

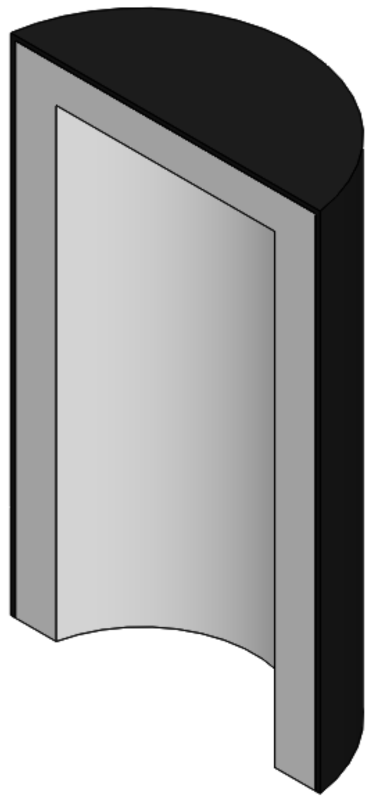


Figure 16. CAD rendering of insulation cover.

The insulation cover, seen above in Figure 16, will be used when the Peltier-driven cooling system is not running to limit the heat transfer into the vaccine chamber. Due to the multiple modifications done to the cap of the vacuum flask, heat transfer will be more likely to travel through the cap. This heat transfer is not a problem when the Peltier is running but when it is not, measures need to be taken to limit the heat transfer into the vaccine chamber. The insulation cover will limit the heat transfer by eliminating any heat transfer via convection through the cap.

The outer surface of the insulation cover is an 9" diameter acrylic cylinder capped on one end. 1" thick strips of FOAMULAR® extruded polystyrene insulation are glued to the inside of the cylinder. These strips sit flush with each other creating a good insulation seal. The insulation cover will slide over the top of the vaccine cooler and fit snugly with an interference fit.

5.3 FDR Design: Overall System Description

The second final design is similar to first final design in the sense that the team is still trying to accomplish the goals in the same fashion. A Peltier is still used to cool a phase change material which is held in a PCM container and located inside of the vaccine chamber, and the PCM still acts as a thermal battery. A heatsink and fan is still used to remove heat from the system and an insulation cover is still used to limit the heat seepage into the vaccine chamber when not running. Design changes include changes to the PCM container, cold side plate, cap, and insulation cover. These changes will be discussed in the following sections. See Figure 17 below for an exploded view of the modified design.

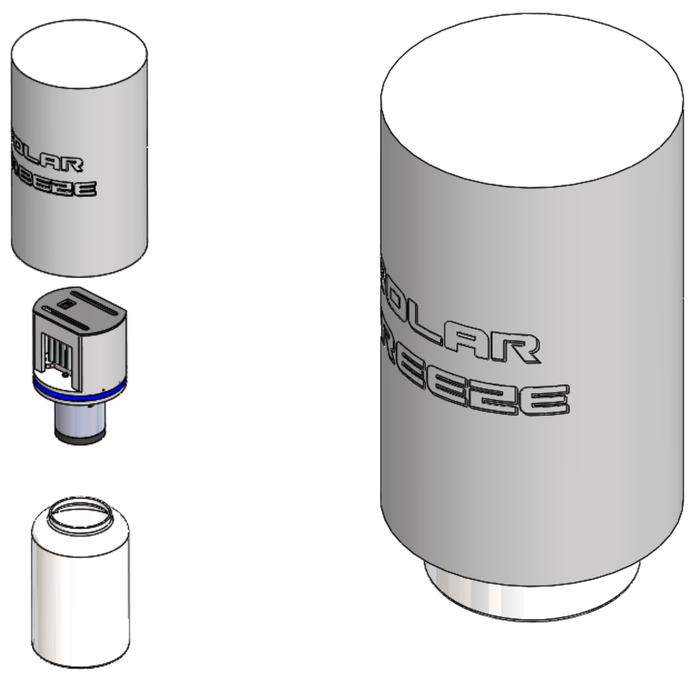


Figure 17. Exploded view of modified complete assembly. From top to bottom: Insulation Cover Assembly, Heat Transfer Assembly, and Vaccine Chamber Assembly.

5.3.1 Modified Heat Transfer Assembly

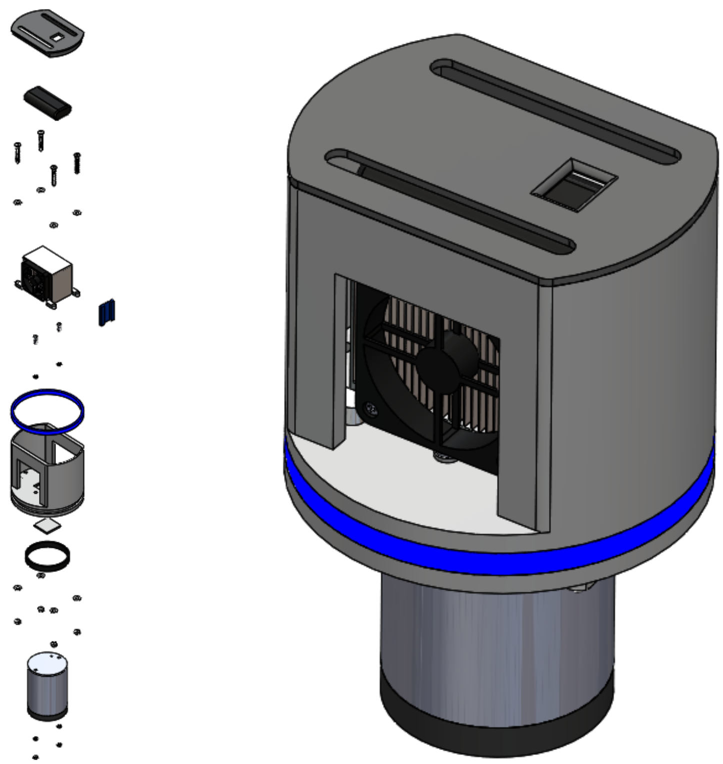


Figure 18. CAD rendering of modified heat transfer assembly.

As it can be seen in Figure 18 above, the heat transfer assembly has been modified primarily to be able to dissipate more heat from the system and freeze the PCM in less time. This has been accomplished through a new heat sink, shorter and wider PCM container, and 3D printed cap to enclose the heat sink and fan. A detailed description of design changes for each component can be found below.

5.3.1.1 Modified PCM Container

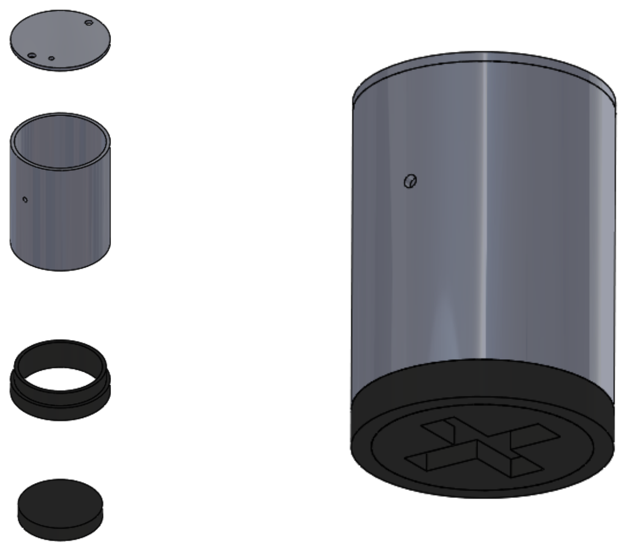


Figure 19. CAD rendering of modified PCM container.

As seen in Figure 19 above, the PCM container has been modified from the original long, slender design to a shorter and wider PCM chamber. The chamber was made from 3” aluminum pipe and is 4” long. A threaded ABS plumbing cap was epoxied to the end of the pipe in order to fill the chamber with PCM and keep it sealed during operation. Also The design was changed so that the aspect ratio of the cylinder was closer to 1:1 in order to facilitate improved heat transfer throughout the cylinder. Furthermore, aluminum metal shavings were loosely added to the inside of the PCM chamber in order to adequately freeze the entire PCM. Without these aluminum shavings, the center of the PCM is not able to freeze completely in under 3 and half hours.

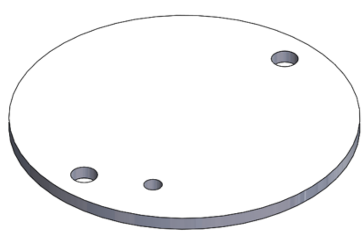


Figure 20. CAD rendering of modified cold side plate.

As seen in Figure 20 above, the cold side plate was modified to fit the new PCM container and allow enough room to mount the PCM chamber and cold side plate to the underside of the modified cap. The cold side plate was made from a 3.25” circular aluminum plate and is 0.25” thick. Two through holes were drilled on the cold side plate in order to allow it to be mounted to the underside of the modified cap. One through hole was drilled on the cold side plate to accommodate a temperature probe. For detailed dimensions and hole locations, refer to Appendix M.

5.3.1.2 Modified Cap

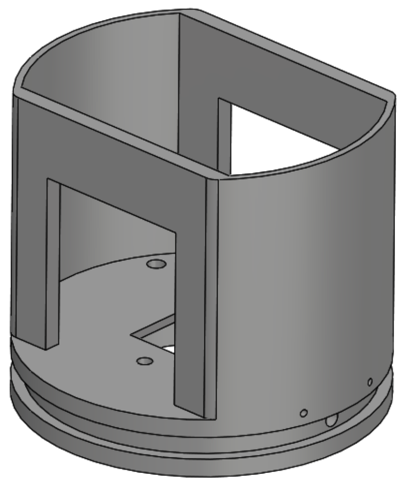


Figure 21. CAD rendering of modified cap.

As seen in Figure 21 above, the cap was modified from the CDR design in order to accommodate a larger heat sink, and provide adequate housing for the Arduino Nano and wired connections. The cap consists of two components: the housing itself, and a snap-fit lid that attaches to the top of the housing.

5.3.1.3 Modified Heatsink and Fan

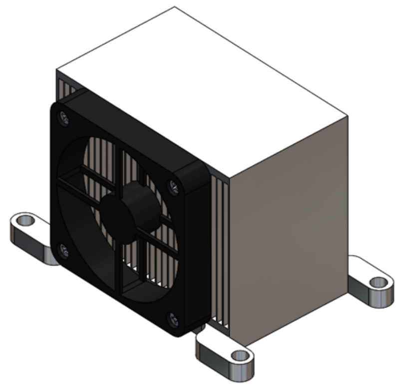


Figure 22. CAD rendering of modified heatsink and fan.

As seen in Figure 22 above, the heatsink and fan were completely changed in order to dissipate more heat and improve the heat transfer out of the PCM chamber. The heat sink was upgraded from a LGA Socket 1155 Intel CPU Cooler, typically used in desktop computer applications, to a copper-core HP dc5700s with integrated copper heat pipes. The improved thermal conductivity of copper and the introduction of heat pipes to quickly dissipate heat improved the cooling capabilities of the system.

5.3.2 Modified Insulation Cover Assembly

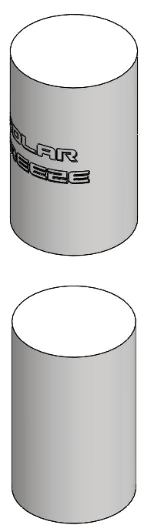


Figure 23. CAD rendering of modified insulation cover.

As seen in Figure 23 above, the insulation cover was changed in order to better insulate the system when the cooler is in transit. Styrofoam was selected for its low thermal conductivity of 0.01 W/m-K, and was press fitted into a white, plastic housing in order to supply 1.5 inches of insulation all around the vacuum flask.

5.4 Ideal Usage Schedule

The solar-powered Peltier-driven vaccine cooler can be used wherever there is adequate sunlight. The ideal way to use the cooler is to set it up in the morning, then let it charge for 3 hours until the PCM is completely frozen and the LED indicator is blue. Unplug the solar panel and transport the vaccines, making sure the LED indicator remains green for the duration of travel. The design will give the user about 12 hours of travel time. Once the LED turns red, it means that it is time to plug the solar panel back in and refreeze the PCM. This process will continue until the vaccines have reached their final destinations

6. Manufacturing

The manufacturing chapter covers the procurement of materials, the step by step manufacturing plan for each part, and the assembly plan. All of the materials are easily obtainable and have short order lead times. Every part can be manufactured in the Mustang 60 machine shop or other shop locations on Cal Poly's campus.

6.1 Procurement

The list of every part or material needed can be found in the Bill of Materials in Appendix M. Most parts can be found on Amazon or another online retailer. Smaller parts such as bolts, washers, and nuts can be purchased at local hardware store such as Home Depot. To obtain many heatsinks and fans for which can be tested, the Solar Freeze team has reached an agreement with the local computer recycling company, Achievement House Inc., to receive free heatsinks and fans. Partnering with Achievement House Inc. has been a huge benefit to the team as now they can experiment on fans and heatsinks without fear of running out of funds.

6.2 Manufacturing Plan

The following section will go through step by step instructions of how to manufacture each part of the vaccine cooler and prepare it for assembly. All of the following manufacturing processes were completed at the Cal Poly Mustang 60 machine shop or the Hangar machine shop. The current design does not call for any outsourcing of manufacturing other than a weld which was completed by welding Professor Kevin Williams. Refer to Appendix M: Drawing Package for drawings and dimensions to aid in the manufacture of each individual part.

6.2.1 Cold Side Plate

The cold side plate is a 0.25” thick circular aluminum plate. The name cold side plate comes from the fact that it is in contact with the cold side of the Peltier and will be cold. The part itself is purchased as a 0.5” thick, 3.25” diameter plate from McMaster. The manufacturing that is required it to step down the thickness of the plate to 0.25” , and drill the holes for mounting to the cap.

1. Use the mill to trim down the thickness of the aluminum plate from 0.5” to 0.25”.
2. Using drill press, drill four 11/64” holes into the plate. Two holes will be on each side. See drawings in Appendix M for hole location dimensions. Four corresponding holes will be drilled into the cap later. Two of these holes will be where the nylon bolts are used to attach the cold side plate to the bottom of the cap. The other two holes are for thermocouples to monitor the internal temperature of the phase change material.

Figure 24. Solar Freeze team member Cody Volk using the mill to precisely trim down the thickness of the aluminum cold side plate.

6.2.2 PCM Chamber

The phase change material chamber consists of an aluminum pipe and a plastic end cap. Manufacture as follows:

1. Using the metal chop saw, cut the 3” diameter aluminum pipe to a length of 4”.
2. Mount the RectorSeal 3” plastic drain cap on a manual lathe.
3. Using a turning tool, remove the plastic flange so that the entire cap is a cylinder with 3” outer diameter.
4. Measure 2” inward from the threaded cap and clearly mark with ink.
5. Turn the diameter of this 2” section to 2.89” so that it will fit inside the aluminum pipe.
6. Flip the part around in the lathe. Use a parting tool to remove the excess material that has not been turned.
7. File/ sand edges so that the cap is smooth.
8. Mix epoxy and apply generously to inside of aluminum pipe as well as outside of end cap. Spread epoxy up the end cap about 0.5”.
9. Attach parts and allow 20 minutes for epoxy to set.

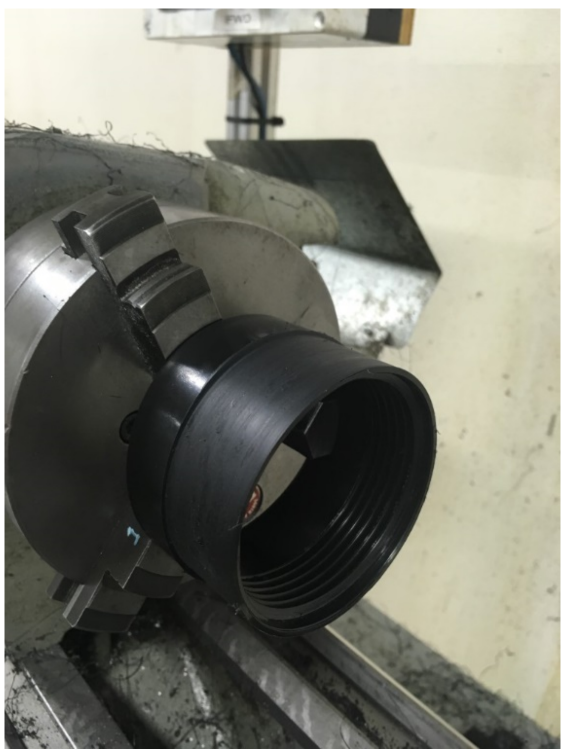


Figure 25. Threaded cap mounted on a manual lathe.

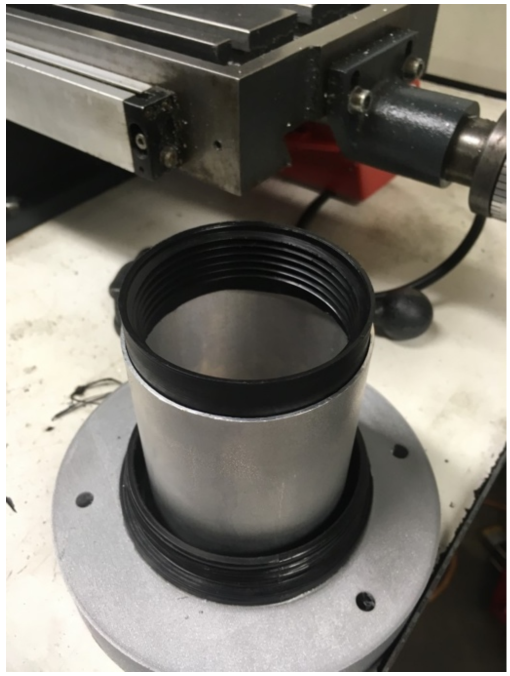


Figure 26. Assembled PCM chamber with plastic threaded cap.

6.2.3 PCM Chamber and Cold Side Plate

It is important that the phase change material chamber and the cold side plate have good thermal connection as this is where the heat will be transferring through. Manufacture as follows:

1. Using the lathe, face the edge of the 3” aluminum pipe so it is level. The pipe needs to be able to sit flush on the cold side plate to ensure good thermal contact.
2. Add a small chamfer to the outside diameter of the 3” aluminum pipe. This will make the welding process easier.
3. Welding Professor Kevin Williams was contacted and agreed to assist the team in welding the PCM chamber to the cold side plate. The 3” aluminum pipe was centered on the aluminum plate and welded. It is important that this weld is water-tight as this chamber will be holding the phase change material and any leakage would be a large concern.
4. Once the weld is completed, a small hole will be drilled on the side of the PCM container for a temperature probe. This probe will run from the micro-controller, through the cold side plate and into the PCM chamber, and out of the PCM chamber into the vaccine chamber so it can measure the air temperature there.
5. The hole is 11/64 in diameter and is drilled 1.5 in from the top of the chamber. See Appendix M for the exact location in the drawing.

6.2.4 Cap

The cap of the one-gallon vacuum chamber is 3D printed in order to accommodate the Peltier and heat sink assembly. This was done through Engineering Sandbox. The fully dimensioned drawings for the cap can be found in Appendix M. The only further manufacturing required for the cap is to drill the required holes to mount the heat sink, as well as the temperature probes. The hole locations can be found in Appendix M.

6.2.5 Heatsink

The heatsink and fan combo utilized in this project is a copper-core HP dc5700s heat sink. This CPU cooler has a rectangular four-hole bracket that is designed to securely fix the large and heavy heatsink to the motherboard. This is an off-the-shelf part, and only one manufacturing process needs to be completed on the heatsink.

1. Add a strip of Velcro to the top and side of the heatsink. Place a corresponding strip of Velcro on the battery and the micro-controller.

6.2.6 Cooling Fan

The cooling fan utilized in this project is a single speed cooling fan out of a Cisco 2900 series network router. This fan has a two-pin connector that is designed to plug into a motherboard. This connector has a back and brown wire. Assemble as follows:

1. Using wire cutters, cut both wires near the connector that plugs into the motherboard.
2. Unwind the two wires to separate them from one another.
3. Using wire strippers, strip off the insulation ends of the wires.
4. Using a crimping tool, crimp on terminals to easily connect and disconnect the fan from the solar panel.
5. Using 4 screws, fasten the fan to the heatsink making sure the label of the fam is up against the heatsink to ensure proper air flow to maximize cooling effect.

Figure 27. Cooling fan attached to the heatsink on top of the cap.

6.2.7 Vaccine Chamber

The vaccine chamber is a one-gallon vacuum sealed flask. No manufacturing was completed that could potentially have damaged the vacuum seal of the walls of the flask. Vaccines will be stored in Ziploc bags and placed at the bottom of the vaccine chamber. Additional padding can be added to protect the vaccine vials if needed.

6.2.8 Insulation Cover

When the system is not running, it is important that any heat transfer from the environment into the vaccine chamber is minimized so that the phase change material container remains frozen for as long as possible. An insulation cover will be used to limit the heat transfer into the vaccine chamber through the cap. The insulation cover will be made from large 1-inch-thick sheets of Styrofoam and a white plastic trashcan.

1. Place the vacuum flask down on a sheet of Styrofoam and outline the base in order to draw the inner circle for the insulation.
2. Locate the center of the circle, and use a compass to add 1.5 inches to the radius of the inner circle.
3. Cut out the insulation ring and use this as a template for all other cuts.
4. Measure and cut out an additional 10 rings.
5. Epoxy the rings concentric with one another and let set overnight.
6. Now use the template and only trace the outer diameter circle on the sheets of Styrofoam.
7. Cut out 4 of these circles and lay them stacked on top of one another inside the white trashcan.
8. Next, stack the epoxied rings on top so ensuring that the top-most ring is flush with the lid of the trashcan.
9. The fit between the Styrofoam and trashcan should be very snug, ensuring that the vaccine cooler can be covered and uncovered without the Styrofoam itself coming out.

6.2.9 LED Indication System

The contents that will be carried in the vacuum flask are sensitive to temperature and require to be within a specific temperature range. An LED indicator system will give the end user a visual of the current status of the cooler. An Arduino mini controller will collect data from temperature probe and output a signal to a digital LED strip wrapped along the perimeter of the cap of the vacuum flask. This system is composed of the following: Arduino controller, temperature sensors, LED light strip, 5v battery power pack, and 3 pairs of 14-gauge wire leads to make connections from the controller to each component. Assemble as follows:

1. Secure Arduino controller to the side of the heatsink with Velcro and 3D printed holder.
2. Secure battery pack on top of the heatsink with Velcro.
3. Spice and join the black wire from the LED strip, temperature sensor, and Ground on controller board to the negative terminal of the power pack.
4. Splice and join the Din contact point on the LED strip to D2 contact point on the controller.
5. Splice and join the yellow data wire on the temperature sensor to D3 contact point on the controller.
6. Splice and join the +5v contact point on the LED strip, red wire from the temperature probe, and +Vin on the controller to the positive terminal of the battery pack.
7. Turn on power pack and the LED Indication System will power on and illuminate a hue from the LED strip.

6.3 Assembly

Once the parts are manufactured, the assembly can begin. The assembly is relatively simple as it will only require the insertion and tightening of bolts. Assemble as follows:

1. Secure the cold side plate and the welded phase change material container to the cap using two nylon bolts, washers, and nuts. The thermocouple should be inserted into the phase change material container and run out to its location in the vaccine chamber. The thermocouple should be kept as near to the middle as possible.
2. Add thermal paste to both sides of the Peltier to improve thermal conductivity. Place the Peltier into its dedicated rectangular cut out on the cap.
3. Attach heat sink to cap using bolts, washers, and nuts into corresponding holes. Make sure the bottom of the heat sink is flush with the Peltier. Tighten the bolts down appropriately until the connection is snug.
4. Stuff the PCM chamber full with scrap aluminum shavings from a lathe. Be sure to thoroughly wash the shavings first. See Figure 29. below to see the PCM chamber and the aluminum shavings.

5. Fill the phase change material chamber with PCM (about 250 mL) and use the threaded cap to seal the chamber so no PCM leaks out. Add 4-6 layers of plumber's tape to the threads of the cap before screwing it closed. Tighten the cap as much as possible to prevent leakage of PCM.
6. Insert PCM container assembly into the vaccine chamber. Tighten cap until secure.
7. Velcro battery pack and micro controller to heatsink.
8. Connect wires as described in section 6.2.9

Overall, the vaccine cooler is not a difficult device to manufacture and can be completed by a person with basic machining skills in the machine shop. The estimated manufacture time is eight hours not including the time needed to 3D print parts.

Figure 28. Attaching the cold side plate to the cap using nylon bolts.

Figure 29. PCM container with aluminum metal shavings from a lathe.

6.4 Future Recommendations for Manufacturing

In future manufacturing of the vaccine cooler system, the Solar Freeze team recommends following the steps outline above in Chapter 6, and referring to the drawings as needed in Appendix M.

7. Design Verification Plan

In this chapter the following will be discussed: design specifications that need to be met, testing facilities, testing instructions, and test results.

7.1 Design Specifications

In this section each individual design specification that needs to be met will be discussed independently. Discussion will include how each specification is met and the level of importance of meeting that specification.

7.1.1 Optimal Temperature

The most important design specification that needs to be achieved is maintaining the internal temperature of the vaccine chamber between 2-8 ℃. One Peltier will need to be able to freeze the entire phase change material while charging. The next iteration will be powered by a power supply and data will be recorded with multiple thermocouples with one in the vaccine chamber, one in the phase change material, and one at the heat sink. The full design will be tested to ensure that the cooler is safe for vaccines.

Once the phase change material is frozen, a test will be conducted to see how long the cooler will be able to keep the vaccines between 2-8 ℃. To do this, thermocouples will be placed in the vaccine chamber and the data will be recorded for the duration of one charge. Because the heat transfer calculations are very complex, this design specification will only be verified through testing.

7.1.2 Vaccine Capacity

Currently, the design can hold 50 vaccine vials in the mesh bags hanging from hooks on the inner wall of the vaccine chamber. This number could change depending on design considerations. Ultimately, since each vaccine will already be at 2-8 ℃ before entering the cooler, maximizing the number of vaccines the cooler will actually help to prolong the time that the vaccine chamber will remain within the optimal temperature range. The team will test this through simple fit tests with standard vaccine vials.

7.1.3 Weight

The sponsors, Peter Schwartz and Nate Heston, gave a weight specification that the device must weigh less than 100 lbs. The current design weighs 15 lbs. without vaccines and is far below the design restriction. With vaccines it is estimated that the total weight will only increase by 5 to 10 lbs. This specification will be tested by using a scale.

7.1.4 Cost

A chart displaying the cost of each part along with the total cost can be found in the Bill of Materials in Appendix M. As per the cost specification, the total cost of the vaccine cooler should not exceed $200. Currently, the device is over budget by approximately $166. This cost includes the solar panel, heat sink, and PCM, all of which have been acquired free of cost. Without taking these into account, the cooler is under budget by $14. Design decisions were made to attempt to lower the total overall cost. While cost is an important specification, designing a vaccine cooler that works is more important. Once the device works (meets other design specifications), steps were taken to optimize the design so the cost will not be so high. This specification will be tested by compiling a list of prices of each part and comparing it to the specified budget.

7.1.5 Lifespan

The specified lifespan for the vaccine cooler is about three years. The current design will last the duration of that time period as the PCM is rated at 1000 freeze/melt cycles assuming the cooler is being charged once a day. Potential issues could arise with the fan and Peltier if they are not maintained properly. The vaccine chamber, cold side plate, PCM container, and heatsink are made of durable materials and will have no issues lasting three years. This specification is dependent on the lifespan of the phase change material. The phase change material company, Vericor, listed the lifespan of its phase change material as 1,000 cycles of freezing and melting.

7.1.6 Dimensions

According to the dimension specification, the device must fit in a 2' x 2' x 2' cube. The current design has a 6" circular base and is 14.9" tall which fits easily inside a 2' x 2' x 2' envelope. This specification is important because the vaccine cooler must be portable as it will be travelling extensively and can be tested via inspection of measurements.

7.1.7 Power Consumption

Currently, the design consumes about 80.4 Watts to run the Peltier and 6 Watts to power the fan. The maximum power consumption specified is 100 Watts. Power consumption is limited to the wattage of the solar panel that is used to power the device. It is important that the vaccine cooler is designed so that a single solar panel can power the device. The LED indicator system has a separate battery and provides a current on the milliamp scale, making its power consumption negligible. This specification can be measured using the equipment in the Ice Lab. The Ice Lab will be discussed more in-depth in section 7.2 Testing Facilities.

7.1.8 Charge Time

Charge time, or the time it takes for the Peltier to freeze the phase change material and lower the temperature of the vaccine chamber to the optimal temperature, is specified to be 3.5 hours. The initial test of the vaccine cooler suggested that the charge time would be about 8 hours (Discussed in Section 7.3 Completed Tests). Design optimization steps were taken to bring the charge time down. Charge time is important as the vaccine cooler can only be charged when the sun is out. The lower the charge time is, the more mobile the vaccine cooler can be. This specification can be tested using thermocouples placed inside of the PCM container and a stopwatch.

7.1.9 Duration of Maintaining Optimal Temperature

This engineering specification refers to how long the frozen PCM can maintain the optimal temperature inside of the vaccine cooler. The team's specification is to have the device maintain the optimal temperature for a period of 12 hours. This specification can be tested in the Ice Lab using thermocouples and a Data Acquisition device (DAQ).

7.2 Testing Facilities

The sponsors, Peter Schwartz and Nate Heston, have a designated "Ice Lab" (building 52 room D13) where they have been running tests on Peltiers and how they can be used to freeze water. The Solar Freeze Team has full access to the lab and all of its equipment. Equipment includes thermocouples, power supplies (simulates solar panel), sinks, and a variety of useful tools such as screwdrivers and hot glue guns. This lab adequately meets the team's testing needs.

7.3 Completed Tests

A variety of tests were completed to prove that the vaccine cooler could comply with the set engineering specifications. The first test completed was a proof of concept test proving that the team's goals were achievable. Following tests proved more specifics of the design.

7.3.1 Proof of Concept Test

The Solar Freeze Team first completed a proof of concept test on their structural prototype. Figure 30 below depicts the test taking place. Using the equipment in the lab, the team was able to use the Peltier to cool 250 grams of water by about 14 ℃ in 70 minutes to remove about 14,000 Joules. The temperature of the hot side of the Peltier remained relatively constant. This proved that the Peltier was capable of cooling the temperature of water at about an average rate of 1 ℃ every five minutes. It also showed that the fan heatsink combination was capable of dissipating the heat at a fast enough rate to maintain the Peltier efficiency.

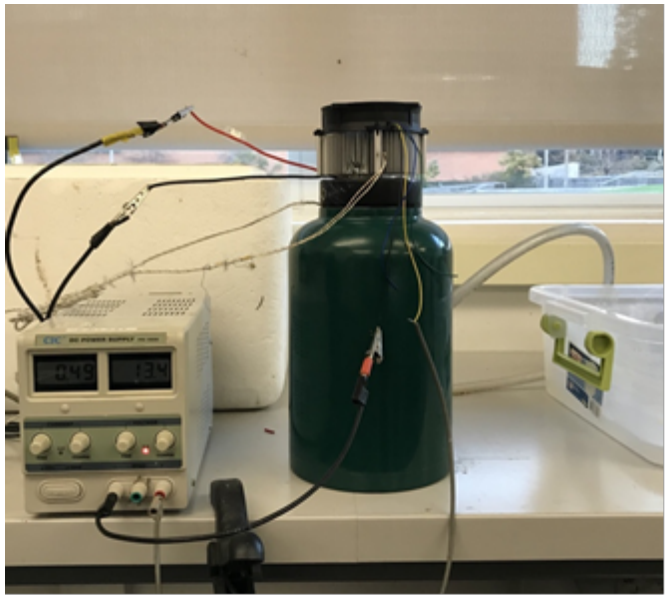


Figure 30. Testing the structural prototype while connected to a power supply and thermocouples in the Ice Lab.

To see the table of the temperature data along with a corresponding graph, view Appendix I: Design Verification Plan. After further calculations which can be seen in Appendix J: Testing Calculations, it was determined that the system removed about 3.5 Watts from the water in the phase change material container. At this rate, it would take about 8.3 hours to completely freeze the water in PCM container. This is assuming the Peltier maintains the level of efficiency that it had been achieving thus far. Further tests were completed in order verify the design. These tests will be covered in the next section.

7.3.2 Testing Process: Freezing the PCM

Outlined below is the step by step description of the testing process that was completed to fully "charge" or freeze the PCM. The equipment required for testing include: two power supplies, connector wires, three type K thermocouples, temperature readout display, timer, and thermal paste. This test procedure assumes the Peltier-driven vaccine cooler is already completely assembled as described in Chapter 6: Manufacturing.

1. Attach the wires of the Peltier and fan to the power supplies. The fan power supply should be set at 12 volts and 0.2 amps. The Peltier power supply should be set at 12 volts and 6.5 amps.
2. One thermocouple, T2, should already be in place inside the PCM chamber. The second thermocouple, T3, is placed in between the fins of the heatsink. The end should be touching the core of the heatsink and running to the temperature readout display. The third thermocouple, T1, is placed inside the vaccine chamber. This thermocouple will be monitoring the air temperature inside the vaccine chamber.

3. Record the starting temperatures of all three thermocouples. Also record atmospheric pressure and temperature.
4. Turn on the power supplies and start the timer. Record the temperature readings every three minutes for the first 30 minutes. This provides an accurate temperature versus time measurement as the PCM drops from room temperature to its freezing point of around 6 ℃. This should take between 21-27 minutes. The heatsink temperature should remain constant between 33-36 ℃.
5. Once the PCM temperature reaches about 6 ℃ and at 30 minutes, begin taking data points every five minutes. The PCM temperature will stay steady at 6 ℃ while the air temperature inside the chamber will continue to slowly drop.
6. After approximately 2 hours and 40 minutes, or 160 minutes, the PCM will be completely frozen.

The team completed a series of “charging” tests over multiple days to get a general understanding of how the process worked. A few of these tests were stopped early before the PCM was completely frozen in order to observe the results.

Figure 31. Freezing or “charging” testing configuration setup with fan/heat sink system and Peltier connected to power supplies.

Test Results:

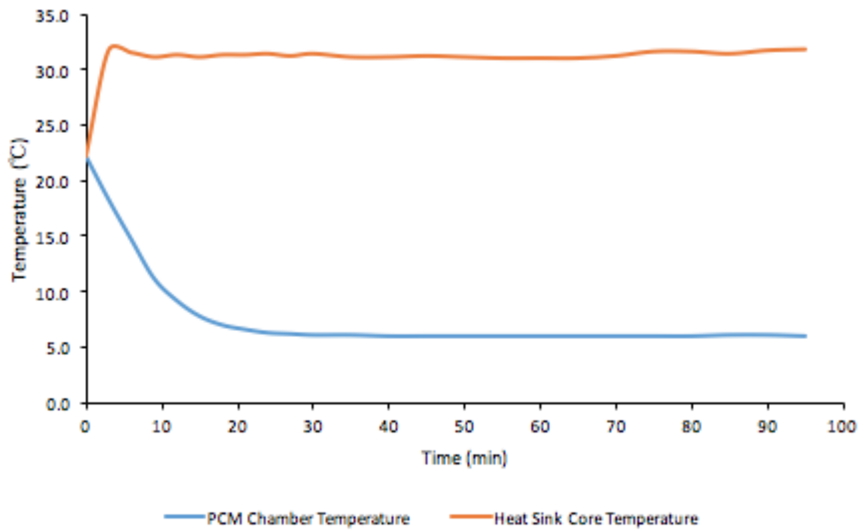


Figure 32. Temperature vs time for PCM freezing test performed on May 2nd 2019.

It can be seen in Figure 32 that the PCM began to undergo a phase change but did not phase change completely. The team wanted to categorize the air temperature inside the flask itself, so a third thermocouple was added to the system and a new test was conducted on May 7th.

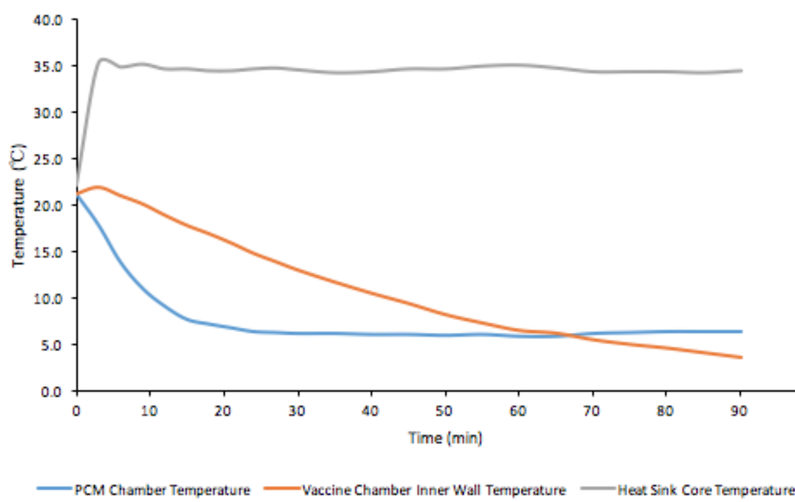


Figure 33. Temperature vs time for PCM freezing test performed on May 7th 2019.

In Figure 33 the team observed the temperature of the vaccine chamber drop below the PCM chamber temperature, while the PCM was still undergoing a phase change. They decided to end the test at 90 minutes in order to observe the freezing profile of the PCM and determine potential methods of optimization.

Figure 34. Partially frozen phase change material inside PCM container after 90 minutes of "charging".

Figure 34 depicts the freezing profile of the PCM after the 90-minute mark of the freezing test performed on May 7th 2019. The team concluded that the PCM froze completely on the walls of the PCM chamber, creating a large thermal resistance and a barrier for further heat transfer. Furthermore, the PCM chamber started to gradually increase in temperature at the 80-minute mark, indicating that the Peltier was unable to pull more heat out of the system, and that heat was transferring back into the PCM chamber. After much deliberation and consultation with multiple Cal Poly professors, the team decided that the simplest, cheapest, and most effective way to improve the thermal conductivity of the PCM chamber was to introduce scrap aluminum shavings to the chamber before filling it with PCM. Another test was then performed in order to support this theory.

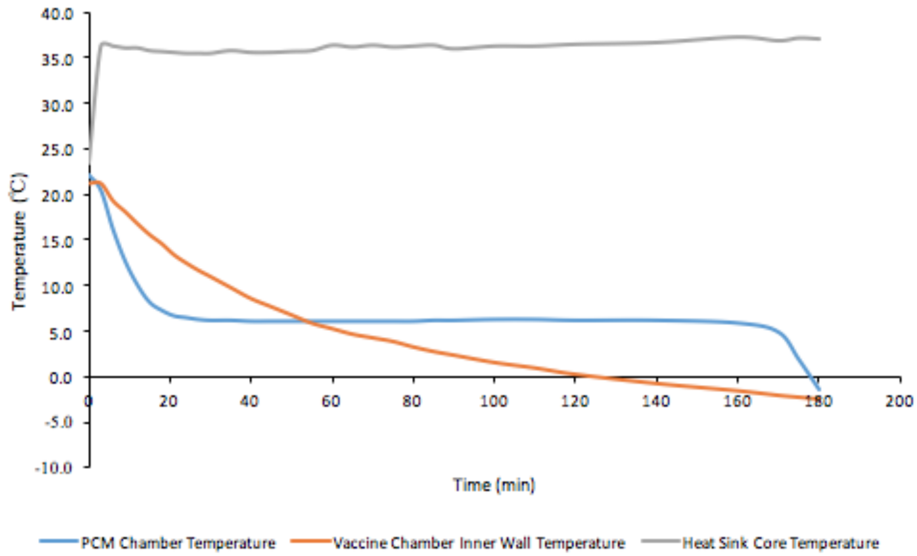


Figure 35. Temperature versus time for test with metal shavings in PCM container on May 14th.

As seen in Figure 35, the PCM was able to freeze completely in 2 hours and 40 minutes, validating the introduction of aluminum shavings as a method of increasing heat transfer. After the PCM chamber was frozen entirely, the team opened the lid of the flask and kept it open for 60 seconds in order to simulate loading vaccines. Once 60 seconds had passed, the lid was sealed and the temperature inside the flask was recorded at 2 ℃, the lower limit of the acceptable range.

7.3.3 Uncertainty Analysis

In any experiment, there is inherent uncertainty involved with the equipment and methods selected for measuring desired quantities. In this case, the team observed potential sources of error in the accuracy of the thermocouple itself, an uncertainty based on the resolution of the temperature readout device, and uncertainty due to measurement noise. For the test on May 14th, total uncertainty in temperature measurement for each thermocouple during the phase change was calculated from tabulated uncertainties for type K thermocouples, visual inspection of the resolution of the temperature readout, and a statistical analysis for a sample size of 30 measurements. For a temperature range of 0-200℃, type K thermocouples have a standard accuracy of ±2.2℃. The temperature readout device reported to the nearest 0.1℃, introducing an uncertainty of ±0.05℃. Finally, a population standard deviation was found for each population of temperature measurements (populated by thermocouple 1 through thermocouple 3). By dividing these standard deviations by the square root of the sample size, an uncertainty due to measurement noise was found for each respective thermocouple. The uncertainties were then combined using a root sum square technique, since each uncertainty had the same units (℃).

Table 8. Summary of uncertainties due to measuring devices

Readout Resolution [±℃]	
U_{read}	0.05
Type K standard tolerance [±℃]	
U_{TK}	2.2

Table 9. Statistical analysis and summary of total uncertainty for each thermocouple

Standard Deviations [℃]		
T1	T2	T3
7.16	4.57	2.33

Measurement Uncertainty [℃]		
T1	T2	T3
1.31	0.84	0.42

Total Uncertainties [±℃]		
T1	T2	T3
2.56	2.35	2.24

As summarized in Table 8 and Table 9, the calculated uncertainties in temperature measurement for thermocouples T1, T2, and T3, respectively are ±2.56℃, ±2.35℃, and ±2.24℃.

Table 10. Summary of PCM freezing results

Test Date	Duration (min)	Final PCM Temp. (℃)	Final Vaccine Chamber Temp. (℃)	Average Heatsink Temp. (℃)	Total Wattage (W)
5/2	110	6.1	N/A	31.1	57.4
5/7	90	6.4	3.5	33.9	68.5
5/14	180	-1.4	-2.5	35.8	80.4

Table 10 summarizes the important results from the PCM freezing test. It should be highlighted that although the last test in Table 10 shows temperatures that are lower than the coldest acceptable temperature to maintain vaccine potency (2℃), the vaccine chamber will still be able to function as intended. As the chamber is opened and loaded with vaccines, some heat will leak in and raise the inside temperature by a few degrees Celsius. It was found that at 21.6 ℃ ambient temperature, the inner flask temperature will raise by 3.5 ℃ in 60 seconds. This provides confidence that after charging the cooler and loading the vaccines, the inner temperature will be within the desired constraints.

7.3.4 Testing Process: Duration of Charge

Outlined below are the steps that should be taken to test to see if the "charged" frozen PCM maintains the temperature criteria for the engineering specification of 12 hours. This test took place in the Ice Lab, a relatively temperature-controlled environment.

1. Ensure that the phase change material is completely frozen in the PCM container. Check the temperature of the thermocouple inside of the PCM chamber. Make sure it is under 0 ℃.
2. Disconnect the vaccine cooler from the power supply. Place the insulation cover over the top of the vaccine cooler. Connect the thermocouple to a data acquisition device (DAQ) and begin recording. The DAQ should record the temperature once every five minutes.
3. Stop the recording of the DAQ after 24 hours.
4. Take the SD card out of the DAQ and access the data from it using a computer. Plot the temperature versus time data in Excel.
5. The time taken to melt the PCM can be estimated from the plot.

Test Results:

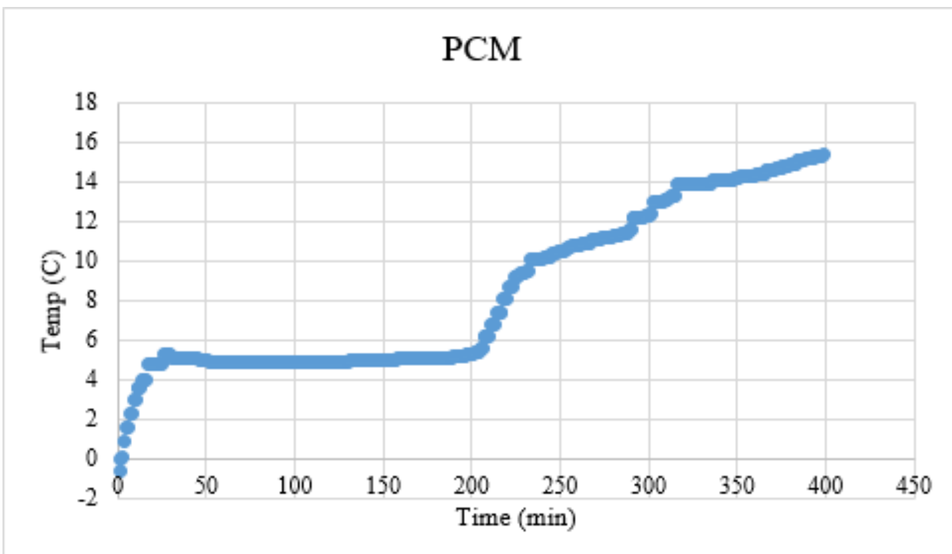


Figure 36. Temperature of the PCM as a function of time.

As it can be seen in Figure 36 above, the phase change material only stayed within the optimal temperature for vaccines for about 220 minutes or about 3.7 hours. Unfortunately, this does not meet the team's specified charge duration.

7.3.5 Testing Process: Heat Seepage Into Vaccine Chamber

Outlined below are the steps to test the heat seepage into the vaccine chamber. The heat seepage into the vaccine chamber is an important result to know because it directly effects how long the frozen PCM charge will last. This test took place in the Ice Lab, a relatively temperature-controlled environment.

1. Create an ice bath of water and ice in a separate container. Allow time for the water to reach 0 ℃.
2. Pour 1 liter of 0 ℃ water into the vaccine chamber (vacuum-sealed flask). Make sure there are no ice cubes inside of the flask.
3. Insert a thermocouple into the vaccine chamber. Make sure it is submerged in the water.
4. Seal the vaccine chamber with the cap which includes the PCM container, heatsink, and fan. Slide insulation cap over the top.
5. Connect thermocouple to the DAQ and begin recording. Come back after 16-24 hours and retrieve the SD card from the DAQ. Plot and observe data in Excel.
6. Heat seepage can be calculated by taking the change in temperature of the water and finding the amount of energy needed to cause this change over the set time period. See hand calculations in Appendix O.

Test Results:
At the conclusion of this test and corresponding hand calculations it was determined that the heat seepage into the vaccine chamber was about 0.62 Watts. This test was supposed to give the team a good idea of the heat seepage into the PCM chamber but the team does not feel that this is an accurate representation of the heat seepage. This is due to the fact that in order for heat to transfer into the water in the above test, it must first travel through the insulation cap, then the Peltier, then the PCM chamber, then the air inside of the vaccine chamber, and finally to the water. But in reality for the actual system, heat will only be transferring through the insulation cap, then the Peltier, and finally into the PCM chamber. This process encounters a lot less heat transfer resistance as it does not need to transfer through air.

In Table 11 below, the engineering specifications that were decided upon at the beginning of the project and if they are met are shown. As you can see, eight of the nine engineering specifications were met. Meeting these specifications was determined through hours of testing the system.

Table 11. Engineering specifications.

Spec. #	Parameter	Requirement	Specification Met?
1	Optimal Temperature	2-8 ℃	Yes
2	Number of Vaccines Capacity	50 vials	Yes
3	Weight	Under 100 lbs.	Yes
4	Cost	$200	Yes
5	Lifespan	3 years	Yes
6	Dimensions	2ft x 2ft x 2ft	Yes
7	Power Consumption	100 Watts	Yes
8	Time to Reach Optimal Temperature	3.5 hours	Yes
9	Time of Maintaining Optimal Temperature	12 hours	No

7.3.6 Potential Future Tests

The only test that is yet to be completed is to test the vaccine cooler in the harsh environmental, off-grid, conditions of Africa that it was designed for. Obviously, it is not realistic for a senior project team to travel to Africa to test the project so knowing how it would perform in the African backcountry hooked up to a solar panel is impossible. As per the engineering specification, a 100-Watt solar panel is required to power the vaccine cooler system. The total power consumption of the system is only 80.4 Watts so using a 100-Watt solar panel will be sufficient even if there is not direct sunlight.

7.4 Design Optimization

The vaccine capacity has increased due to the reduction in size of the PCM chamber from previous iterations. The chamber is designed to have a 1:1 diameter to depth ratio which is optimal for heat transfer. The weight of the cooler has increased due to the addition of 3D printed electrical mounting brackets and heat sink housing. However, the additional weight from the new 3D printed parts is small compared to the overall cooler weight. The cost of the cooler has been reduced due to part searching for better prices. This project is mostly designed on off-the-shelf parts and there are many supplies offering competitive prices. With a charge time of 2.7 hours, the initial specification charge time of 3.5 hours was easily met. The lower time was achieved by improving the welds between the PCM chamber and the cold side plate and adding aluminum shavings to the PCM chamber. The lower charge time was also achieved by utilizing a heat sink that has copper heat pipes embedded in a copper core in order to increase overall heat transfer.

7.5 Recommendation for Future Work

At the conclusion of the testing, the Solar Freeze Team believes that although they have achieved their goals of creating an off-grid vaccine cooler that adheres to advisor-designated specifications, there is potential room for further testing/design. One thing that could be investigated is the use of cylindrical pin fin heat sinks on the cold side of the Peltier in order to vastly improve the ability of heat to be taken out of the PCM. While the team utilized aluminum shavings to accomplish this, a heat sink would be far more effective and could help to improve the efficiency of the Peltier module. Furthermore, there is room to scale up this type of cooler so that it can transport more vaccines. One could investigate the possibility of using multiple Peltiers in different configurations in order to achieve a greater cooling effect. Finally, the possibility of utilizing a different insulation material for the insulation cover could be investigated in order to keep the vaccines within the desired range for longer. For example, with more funds and manufacturing equipment, a double-vacuum walled insulation cover could be manufactured in order to drastically lower the convective and conductive heat transfer through the cover. This would prolong the amount of time that the cooler can be in transport without the need to stop and charge for 3 hours.

8. Project Management

This project has been completed after one full academic year of design, manufacturing, and testing. Key deliverables and corresponding due dates that were met throughout the year are listed below in Table 12. The project management and design process followed throughout this project worked well, but there were certain aspects of the project that could have been managed/designed better. For example, a huge success for the team was being able to freeze the entire PCM in under three and a half hours, with the entire system consuming less than 100 watts. A failure in the design, however, was that after charging, the system only maintained the acceptable temperature range for approximately three hours. Too much time was spent designing and ensuring that the PCM would freeze, with not enough time allocated to ensuring that the cooler would be able to maintain temperature. The team should have broken up into two sections that worked collaboratively and in tandem with one another: one team to tackle freezing the PCM, and one team to work on the insulation and maintaining temperature. This way, both teams would have been able to work quickly and efficiently, with inputs from all team members, in order to improve time management.

Table 12. Timeline of deliverables

Key Deliverables	Due Date
Scope of Work	10/19/18
Preliminary Design Review	11/15/18
Interim Design Review	1/17/19
Critical Design Review	2/7/19
Manufacturing & Test Review	3/14/19
Hardware/Safety Demo	4/25/19
Final Design Report	5/30/19
EXPO	5/31/19

Overall the team worked very well together. Utilizing the Gantt Chart, deadlines were met, presentations and reports were turned in on time. The only delay the team suffered was having to delay their CDR report and presentation by one week. Despite this, the team was able to make up for the lost time and were soon back on track.

9. Conclusion

This document outlines the final design for a portable solar-powered vaccine cooler aimed at satisfying the needs of third world countries along with the objectives that will ensure efficient progress in accordance with the project plan. While all specifications set forth at the beginning of this project were not entirely met (including the important specification of maintaining temperature for 12 hours at a time), the team would by no means consider this project a failure. This project highlighted the ability of using a Peltier to effectively cool a system in a manner that consumes a little more power than a standard light bulb. It also highlighted the potential that phase change materials have for thermal storage. Also, with the increased availability of double-walled vacuum flasks and their desirable insulation properties, the project provided insight into the possibility of using these for vaccine transport instead of typical Styrofoam coolers used today. A big area where the project struggled was maintaining the vaccine temperature once fully charged. This was due to the fact that a large portion of the design process was focused on making sure the Peltier would be able to remove heat from the PCM, freeze it entirely, and cool the vaccine chamber to the specified temperature. Towards the end of the project, the insulation cover was put together with not enough design or calculations to ensure that it would work effectively. If the team was to do the project over again, they would budget their time more appropriately in order to accommodate the design and implementation of the insulation cover. This aspect was overlooked as not as important as getting the PCM to freeze entirely (a difficult feat in and of itself), but it should have gotten far more attention than it did. Also, the team decided that the insulation cover could only really be tested after the entire assembly was assembled and functioning properly. After further reflection, the team realized that this was not entirely accurate, and likely contributed to a bottleneck in testing. The team should have implemented more tests earlier in the design process as 'proofs of concept' for certain components. For example, the insulation cover could have been constructed and tested as soon as the vacuum flask was bought. The team could have put the flask inside a freezer and monitor the temperature until it was in the desired range. Then, the heat leakage could have been calculated into the flask through the insulation cover and modifications or redesigns could have been performed appropriately.

9.1 Next Steps

For next steps in the design process, the team recommends exploring different insulation options for the insulation cover in order to extend the duration that the PCM can stay frozen. Also, reconfiguring the location and quantity of PCM as well as the quantity of Peltier modules could improve the performance of the system by introducing more thermal storage capability.

10. References

[1] “Sure Chill.” *Sure Chill*, www.surechill.com/.
[2] “The Solution: Solarchill Technology.” *Solarchilltests Webseite!*, www.solarchill.org/english/the-solution/.
[3] “Solar Powered Medical Refrigerator, 55 Liters.” *SunDanzer*, sundanzer.com/product/bfrv55/.
[4] “ISOBAR | Mobile Vaccine Delivery.” *ISOBAR | Mobile Vaccine Delivery*, isobar.org.uk/.
[5] Gates, Bill. “Can This Cooler Save Kids from Dying?” *Gatesnotes.com*, www.gatesnotes.com/Health/The-big-chill.
[6] How Do Thermoelectric Coolers (TEC) Work? (n.d.). Retrieved from https://www.marlow.com/how-do-thermoelectric-coolers-tecs-work
[7] “Summer 2018.” *Sharedcurriculum*, sharedcurriculum.peteschwartz.net/summer-2018-3/.
[8] US20160003503A1 - Mobile Thermoelectric Vaccine Cooler with a Planar Heat Pipe." Google Patents. Google. 24 Jan. 2019 <https://patents.google.com/patent/US20160003503A1/enq=Pipe&oq=Mobile%2BThermoelectric%2BVaccine%2BCooler%2BWith%2Ba%2BPlanar%2BHeat%2BPipe>.
[9] “US20180106509A1 - Backpack for Use with a Portable Solar Powered Refrigeration Box and Water Generator.” *Google Patents*, Google,patents.google.com/patent/US20180106509A1/enq=Generator&oq=Backpack%2Bfor%2Buse%2Bwith%2Ba%2BPortable%2BSolar%2BPowered%2BRefrigeration%2BBox%2Band%2BWater%2BGenerator.
[10] “US5704223A - Thermoelectric Medicine Cooling Bag.” *Google Patents*, Google, patents.google.com/patent/US5704223A/enq=Bag&oq=Thermoelectric%2BMedicine%2BCooling%2BBag.
[11] “US6880346B1 - Two Stage Radiation Thermoelectric Cooling Apparatus.” *Google Patents*, Google, patents.google.com/patent/US6880346B1/en?oq=US6880346B1.
[12] “US6880346B1 - Two Stage Radiation Thermoelectric Cooling Apparatus.” *Google Patents*, Google, patents.google.com/patent/US6880346B1/en?oq=US6880346B1.
[13] “Rubitherm GmbH.” *German*, www.rubitherm.eu/en/index.php/productcategory/organische-pcm-rt.
[14] “10 Facts on Immunization.” *World Health Organization*, World Health Organization, 17 Apr. 2018, www.who.int/features/factfiles/immunization/en/.

11. Appendices

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Appendix B: Gantt Chart
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Appendix O: Source Code for Temperature Indication System
Appendix P: Heat Seepage Hand Calculations
Appendix Q: Operators Manual
Appendix R: Risk Assessment

Appendix A: Quality Function Deployment

Correlations	
Positive	+
Negative	−
No Correlation	

Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼

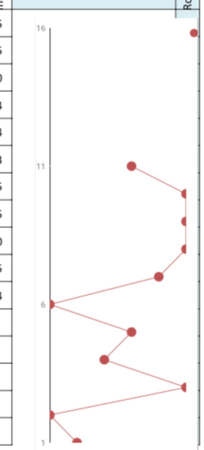
QFD House of Quality

Project: Solar Ice for Vaccine Refrigeration

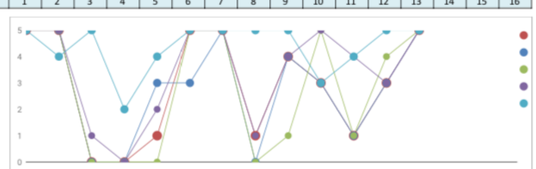
Revision Date: 10/16/18

Row #	Weight Chart	Relative Weight	Clinic	Vaccine Administrator	Non Profit		Maximum Relationship	WHAT: Customer Requirements (Needs/Wants) / HOW: Engineering Specifications (Tests)	Optimal temperature (2-8 degre	Number of vaccines it can hold	Weight	Cost	Drop height fully loaded	Fatigue	Lifespan	Dimensions	Power consumption	Time to reach ideal temperature	Vibration on motorcycle	Amount of maintence	Thermal performance				Sure Chill	Solar Chill	SunDanzer BFRV55	Isobar	Indigo
								Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16					
								Direction of Improvement	▲	▲	◇	▼	◇	▲	▲	◇	▼	▼											
1	IIIII	12%	10	10	10		9	Safely transport vaccine	○	▽	○	○	●	○	▽	▽	▽	▽	●		○				1	4	1	5	5
2	IIII	9%	7	10	7		9	Portable	▽	○	●	○	○	○	○	●	▽	▽	○						0	1	0	5	5
3	III	8%	3	10	7		9	Off grid power	▽	▽	▽	●				○	●	○	▽	▽	○				5	5	5	4	0
4	IIII	8%	5	10	7		9	Durable		○	○	○	●	●	●	○			○	○					2	5	2	2	4
5	IIII	9%	7	10	7		9	Easy to maintain				▽		○	○	○	○			●					3	2	5	1	4
6	IIII	9%	7	7	10		9	Cheap	▽	○	○	●	○	○	●	▽	○	○	○	○	○				0	2	0	0	3
7	IIII	9%	7	10	7		9	Easy to operate		▽	▽	▽		○		▽		○	○	●					4	4	4	3	5
8	IIIII	12%	10	10	10		9	Maintains optimal temperature	●	●	▽	○		○	○	○	○	●	○	▽	●				5	4	5	5	5
9	II	6%	7	3	5		9	Compatable with 120v outlet	▽	▽	▽	▽			▽	▽	●	○							5	0	0	0	0
10	IIIII	12%	10	10	10		9	Stays operational for up to 5 days	●	▽	▽	○	○	○	○	▽	○	●		▽	●				5	5	4	5	5
11	III	6%	5	1	10		3	Aesthetically pleasing			▽	○	○			▽	▽		○	▽					3	3	0	4	4
12		0%																											
13		0%																											
14		0%																											
15		0%																											
16		0%																											

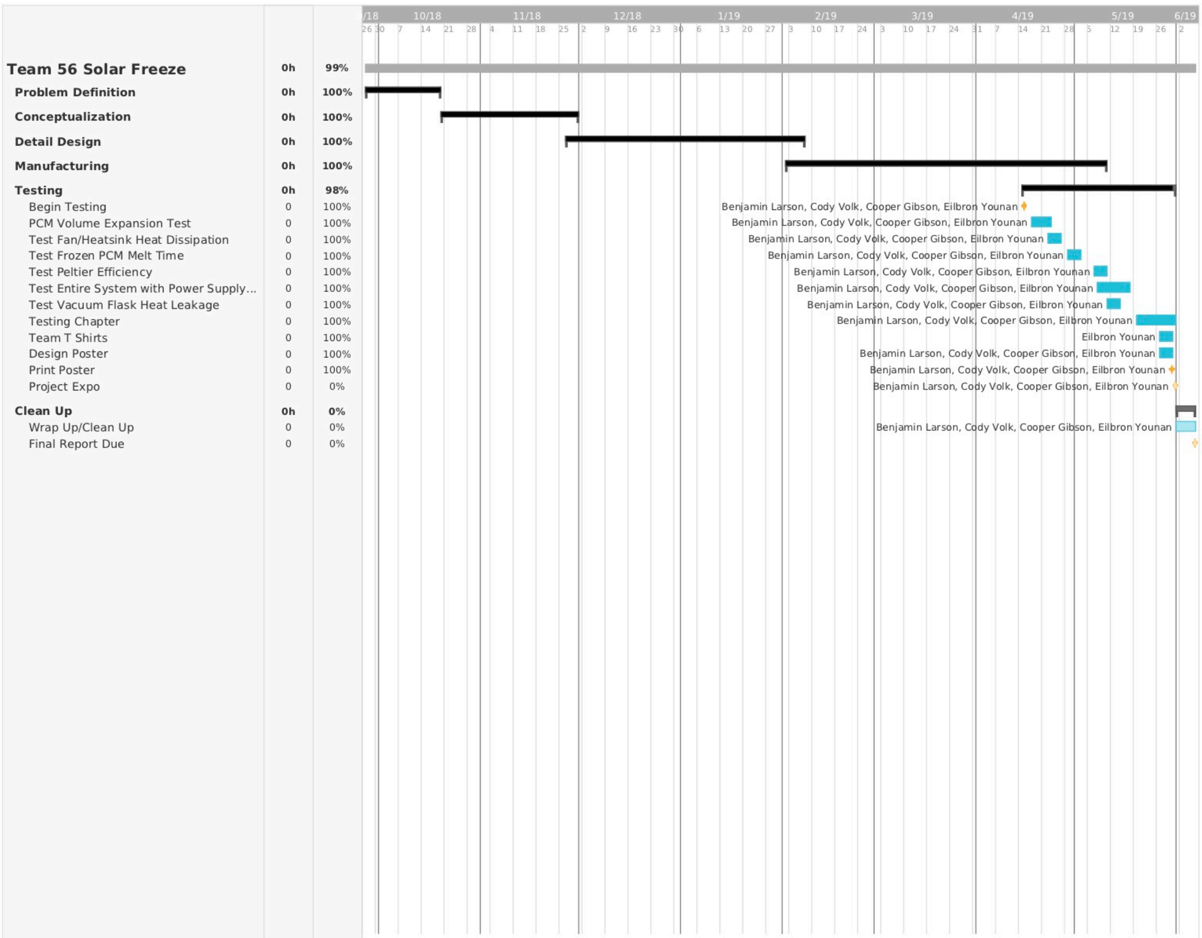
WHO: Customers — NOW: Curr. Products



HOW MUCH: Target Values	4 degrees C	200 vaccines	20 lbs	100-500$	3 feet	100 villages	3 years	2' x 2' x 2'	50-100 watts	12 hours	Not effected	Minimal	3-4 days			
Max Relationship	9	9	9	9	9	9	9	9	9	9	9	9	9			
Technical Importance Rating	276.4	231.5	223.3	351.9	289.4	291.3	301.8	247.6	273.8	326.4	274.3	256.4	294.8			
Relative Weight	8%	6%	6%	10%	8%	8%	8%	7%	8%	9%	8%	7%	8%			
Curr. Products: Sure Chill	5	5	0	0	1	5	5	1	4	3	1	3	5			
Curr. Products: Solar Chill	5	5	0	0	3	3	5	0	4	3	1	3	5			
Curr. Products: SunDanzer BFRV55	5	5	0	0	0	5	5	0	1	5	1	4	5			
Curr. Products: Isobar	5	5	1	0	2	5	5	1	4	5	4	3	5			
Curr. Products: Indigo	5	4	5	2	4	5	5	5	5	3	4	5	5			
Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16



Appendix B: Gantt Chart



Appendix C: Pugh Matrices

Table C.1. Pugh Matrix for Cooling Vaccines Function.

Concepts / Criteria	Refrigeration Cycle (Datum)	Single Peltier	Two Peltiers	PCM Only	Peltier and PCM
Temperature	S	-	-	-	-
Speed	S	+	+	-	+
Cost	S	+	+	+	+
Weight	S	+	+	+	+
Efficiency	S	-	-	-	-
Power Required	S	+	+	+	+
Sum	0	2	2	0	2

Table C.2 Pugh Matrix for Withstanding Heat

Concepts / Criteria	Existing Cooler (Datum)	Modified Cooler	Vacuum Sealed Cooler	Styrofoam Cooler	Metal Cooler	Cooler Using Local Insulation (straw)
Cost	S	-	-	+	-	+
Weight	S	-	S	+	-	-
Quality of Insulation	S	+	+	S	-	+
Maintains Optimal Temp	S	+	+	-	-	+
Duration	S	+	+	-	+	S
Size	S	S	S	S	S	-
Sum	0	1	2	0	-3	1

Table C.3 Pugh Matrix for Dissipating Heat

Concepts / Criteria	Aluminum w/Copper Core	Aluminum Block	Copper Heat Sink	Copper w/Heat Pipes	Aluminum w/Heat Pipes
Speed	S	-	+	+	+
Cost	S	+	-	-	-
Duration	S	+	+	+	+
Maintains Temp	S	-	+	+	+
Weight	S	+	-	-	-
Sum	0	1	1	1	1

Table C.4 Pugh Matrix for Transporting Vaccines

Concepts / Criteria	Existing Cooler	Backpack	Vacuum Sealed Container	Insulated Bag	Cooler Pants
Cost	S	-	-	+	-

Weight	S	+	-	+	+
Portability	S	+	S	S	+
Strength	S	-	+	-	-
Capacity	S	-	S	-	-
Sum	0	-1	-1	0	-1

Appendix D: Decision Matrices

Table D.1 Morphological matrix.

	System Concepts					
Function	1	2	3	4	5	6
Transport Vaccines	Existing Cooler	Backpack	Vacuum sealed	Insulated bag	Cooler pants	
Cool Vaccines	Compressor freezer	One Peltier	Two Peltiers	Phase change material	Peltier and Phase change	
Charge Cooler	Wall plug in	Solar	Hand Crank	Gas	Pre cooled	
Withstand Heat	Existing cooler	Modified cooler	Vacuum sealed	Styrofoam	Metal	Local Insulation

From the matrix above the team drew lines from function concept to function concept to uncover original system combinations. Below is a list of five system concepts that were used in a final decision matrix.

1. Transport – Existing cooler
Cooling – Peltier with phase change material
Charging – Solar
Withstand Heat – Styrofoam

2. Transport – Backpack
Cooling – Peltier with phase change material
Charging – Solar
Withstand Heat – Styrofoam insulation

3. Transport – Insulated bag
Cooling – Phase change material
Charging – Precooled phase change from freezer
Withstand Heat – Styrofoam insulation

4. Transport – Vacuum chamber
Cooling – Peltier with phase change material
Charging – Wall plug in
Withstand Heat – Vacuum sealed chamber

5. Transport – Existing cooler
Cooling – Two Peltiers
Charging – Solar

Withstand Heat – Local insulation

Table D.2 Decision Matrix

Criteria	Weight	1		2		3		4		5	
Operate at optimal temp	5	5	25	2	10	2	10	4	20	2	10
Vaccine Capacity	3	4	12	2	6	2	6	3	9	4	12
Weight	3	2	6	5	15	5	15	2	6	3	9
Cost	4	3	12	4	16	4	16	1	4	4	16
Drop Height	2	3	6	3	6	2	4	3	6	3	6
Fatigue/ uses	1	4	4	3	3	2	2	4	4	2	2
Lifespan	1	4	4	3	3	2	2	4	4	2	2
Dimensions	2	3	6	4	8	4	8	4	8	2	4
Power Consumption	4	2	8	3	12	3	12	2	8	2	8
Time to reach ideal temp	3	2	6	2	6	3	9	3	9	1	3
Vibration on moto	1	4	4	4	4	3	3	3	3	3	3
Duration of one charge	4	4	16	2	8	2	8	3	12	2	8
Portability	4	3	12	5	20	4	16	3	12	2	8
TOTALS			121		117		111		105		91

Appendix E: Peltier Data

TEC1-12715 Datasheet

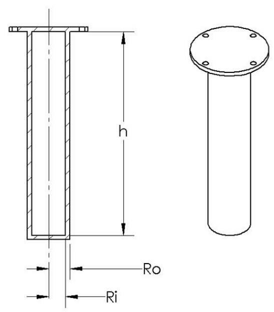
No.	Items	Symbol	Parameter	Condition
1	Max. Operating Tem.	T	＜90℃	
2	Max. Cooling Power	Qmax	136	Vacuum testing Tem Th=30℃
3	Tem. Difference Max	△Tmax	70	Vacuum testing Tem Th=30℃
4	Input Voltage Max	Vmax	15.4	Vacuum testing Tem Th=30℃
5	Max. Current	Imax	15.0	Vacuum testing Tem Th=30℃
6	Resistance	R	0.75±0.05	Ambient Tem Th=25℃
7	Parallel		≤0.05 ㎜	
8	Lines		20AWG	

Included in this appendix is a table of specifications for the TEC 12715 Peltier module, as well as sample calculations and graphs that helped guide the design decisions regarding Peltier operating conditions and heat sink thermal resistance. Also included is the excel spreadsheet from which basic heat transfer calculations can be found. The total amount of heat required to cool the chamber and freeze the PCM is

Recorded as *Q_cool* in the spreadsheet.

Phase Change Material			
VeriCor Med Material			
Spec Heat	*c*	2	[kJ/kg-°C]
Density	*ρ*	997	[kg/m^3]
Latent heat	*H_f*	334	[kJ/kg]
Freezing temp	*T_freeze*	4.5	[°C]
Mass	*m*	0.67842756	[kg]

PCM Housing Specifications			
1060 Aluminum			
Inner pipe height	*h*	0.15	[m]
Outer pipe height	*h_o*	0.155	[m]
Inner radius	*R_i*	0.038	[m]
Outer radius	*R_o*	0.05	[m]
PCM Volume	*V_pcm*	0.00068047	[m^3]
Housing volume	*V_h*	0.00051422	[m^3]
Density	*ρ_h*	0.0027	[kg/m^3]
Spec heat	*c_h*	0.9	[kJ/kg-°C]



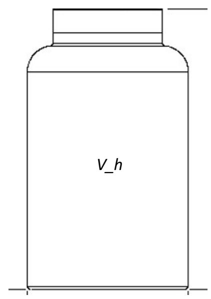
Vaccine Chamber Cooling		
Q_air	0.079753531	[kJ]
Q_PCM	267.9788869	[kJ]
Q_PCMhousing	3.81111E-05	[kJ]
Q_total	268.06	[kJ]
Q_cool	**19.65**	[W]
t_cool	14400	[s]

Heat Losses		
Q_rad	1.03216903	[W]
Q_fan	3	[W]
Q_total	4.03216903	[W]

Q_cool is the total amount of energy to remove from the air in the chamber, PCM material, and PCM housing to cool the system to the desired temprature. It is assumed that the cooling takes about 4 hours to complete.

Assuming that the vaccuum flask eliminates conduction and convection, leaving radiation as the only method of heat transfer. Assume also that nylon fasteners provide little heat transfer and thus will not be categorized as losses. *Q_fan* is the heat leakage when the insulation cover is placed over the fan and the solar panel is disconnected. Q_total is the worst case heat transfer when the system is completely closed off.

Vaccine Housing Specifications			
Stainless Steel			
Volume	*V_h*	0.00378541	[m^3]
Air volume	*V_a*	0.00259073	[m^3]
Ambient temp	*T_ia*	35	[°C]
Final air temp	*T_fa*	0	[°C]
Spec heat of air	*c_v*	0.718	[kJ/kg-°C]
Density of air	*ρ*	1.225	[kg/m^3]
Mass of air	*m_a*	0.00317364	[kg]
Surface area	*A_s*	0.152	[m^2]
Boltzman constant	*σ*	5.67E-08	[W/m^2-°K^4]
Emissivity	*ε*	0.075	[]



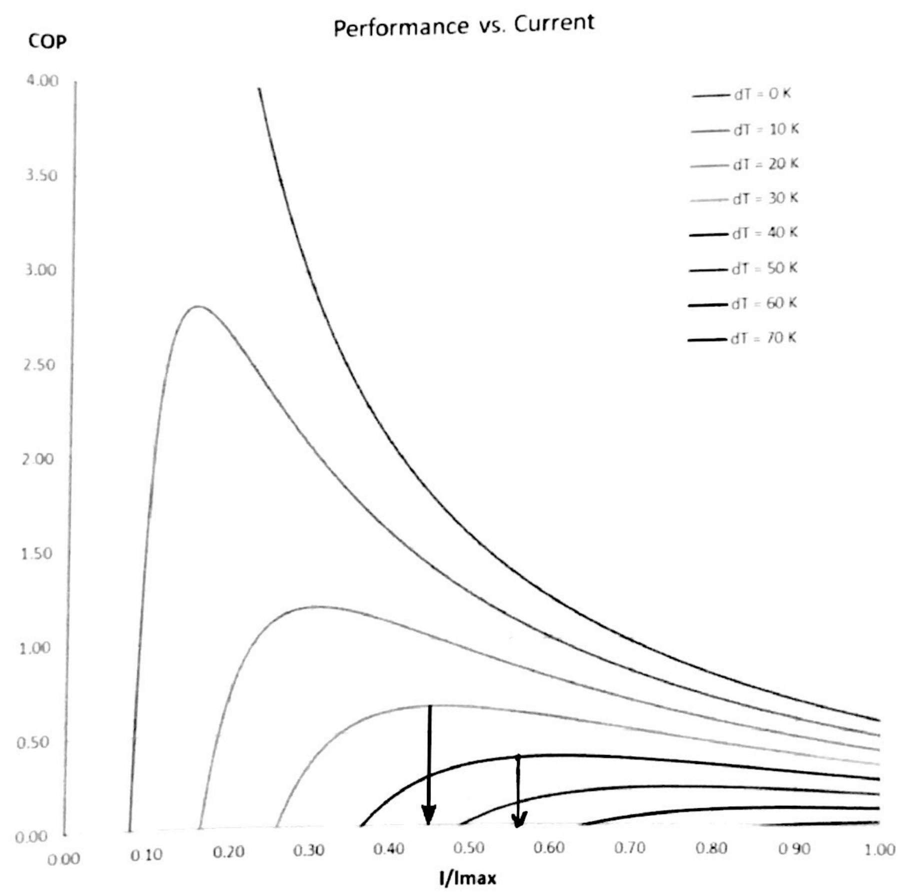
Estimate Heat Loads and Define Temperatures

We assume an object with a heat load of $\mathbf{Q_C = 10\ W}$ to be cooled to zero degrees Celsius. ($T_O = 0$ °C) Let's say that the room temperature is 25 °C and the heat sink temperature T_S is expected at 30 °C. Thus, the temperature difference between the cold side and the hot side of the Peltier element dT is 30 K. It's important to remember that it would be incorrect to calculate dT as difference between ambient air temperature and desired object temperature.

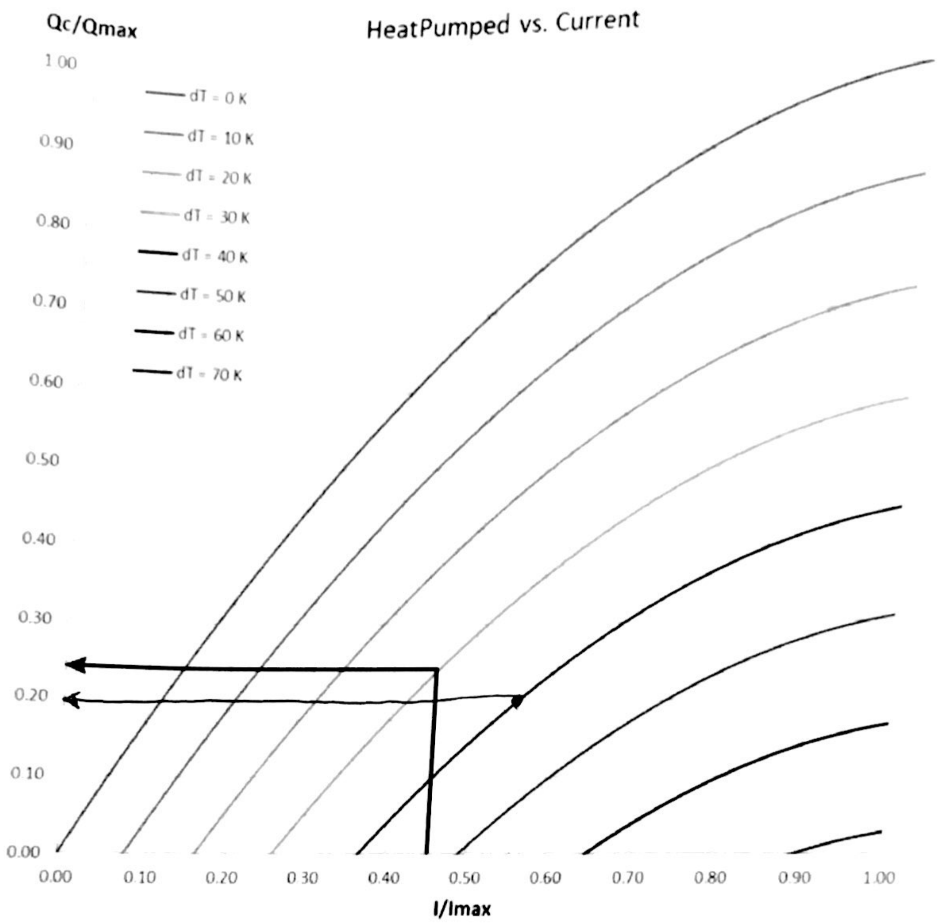
Choosing a Peltier/ TEM Module

Our goal is to find a Q_{max} that is large enough to cover the needed Q_C and yields the best COP.

In the *performance vs. current graph* we locate the maximum of the dT = 30 K curve at a current of $\mathbf{I/I_{max} = 0.45}$. In general, this ratio should not be higher than 0.7.



Using that factor for the current we find in the *heat pumped vs. current graph* the value $\mathbf{Q_C/Q_{max} = 0.25}$ for the given temperature difference dT = 30 K and relative current of 0.45.



Now we can calculate the Q_{max} for the Peltier element. $\mathbf{Q_{max}} = Q_C / 0.25 = 10\ W / 0.25 = \mathbf{40\ W}$

In the *performance vs. current graph* we find **COP = 0.6** for our previously read out I/I_{max}. This allows us to calculate $\mathbf{P_{el}} = Q_C / COP = 10\ W / 0.6 = \mathbf{16.7\ W}$.

Peltier element manufacturers offer a wide range of elements. In their product line we look for an element with a Q_{max} of 40 W. As we have a temperature difference of dT = 30 K, a single stage Peltier element is sufficient.

As an example, we choose a Peltier element with Q_{max}=41 W, dT_{max}=68 K, I_{max}=5 A and V_{max}=15.4 V.

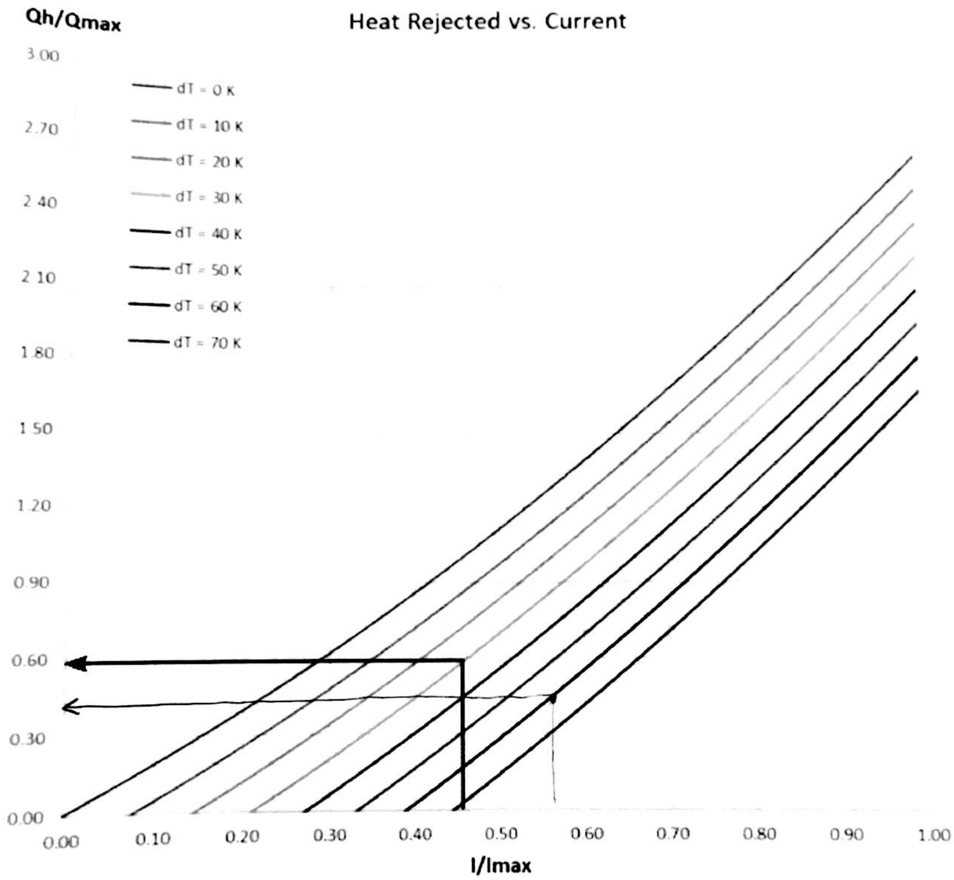
The operating current and voltage are calculated as follows:
$\mathbf{I} = I_{max} * (I/I_{max}) = 5\ A * 0.45 = \mathbf{2.25\ A}$
$\mathbf{V} = P_{el} / I = 16.7\ W / 3.83A = \mathbf{7.42\ V}$

Choosing a TEC Controller

Based on the calculated values, we choose a TEC controller TEC-1091 with 4 A output current and 21 V output voltage. It's good to add some design margin by choosing a TEC controller with higher than required output current. Later, when the performance of the system is well known, another controller with less performance may be sufficient.

Heat Sink

To find a heat sink for the Peltier element, we need to know the required thermal resistance of the heat sink. In the *heat rejected vs. current graph* we find **Q_h / Q_{max}=0.6** for our chosen current and dT. Thus, $Q_h = Q_{max} * 0.6 = 41\ W * 0.6 = 24.6\ W$.



Calculation of the heat sink thermal resistance:

$R_{thHS} = \Delta T_{HS} / Q_h = 5\ K / 24.6\ W =$ **0.2 K/W**

We need a heat sink with a thermal resistance smaller than 0.2 K/W.

The above calculations are a first estimation of the parameters for a thermoelectric cooling system. Testing of a real system and iterating through the design steps is necessary to determine optimal system parameters.

heat flux

OPTIMAL PELTIER CALCULATIONS:

ASSUME: HEAT LOAD OF 20 W COOLED TO 4.5°C

$T_{amb} = 30°C$ AND $T_{HEATSINK} \approx 40°C$ (THRU FORCED CONVECTION)

so $dT = 40 - 4.5 = 35.5°C$

From performance vs. current graph: $I/I_{max} = 0.55$

From heat pumped vs. current graph: $Q_c/Q_{max} = 0.20 \rightarrow Q_{max} = 20/.2 = 100W$

From heat rejected vs. current graph: $Q_h/Q_{max} = 0.42 \rightarrow Q_h = 42W$

From performance vs. current, $COP = 0.30$

so $P_{el} = Q_c/COP = 66.67W$

From TEC datasheet: $Q_{max} = 136W$

$I_{max} = 15.0A$

$V_{max} = 15.4V$

so then: Operating conditions:

$I = I_{max} \cdot (I/I_{max}) = 15.0A(0.55) = 8.25A$

$V = P_{el}/I = 8.08V$

Choosing a heat sink:

$R_{th,HS} = \Delta T_{HS}/Q_h = 10/42 = 0.238 K/W$

Choose a heat sink with a thermal resistance of less than 0.24 K/W.

Appendix F: MATLAB Code For 3D Thermal Modeling

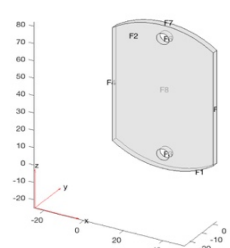
Contents


```
%This script will simulate the transient 3D Model for the PCM chamber.
```

Aluminum Plate 3D conduction

```
%Importing coldside plate into workspace
close all
thermalmodel = createpde('thermal','transient');
importGeometry(thermalmodel,'Coldsideplate.stl');
pdegplot(thermalmodel,'FaceLabels','on','FaceAlpha',0.5)
axis equal

%Setting thermal conductivity of entire system for aluminum. Note that
%this model is being used to validate the use of aluminum on the cold
%side of the Peliter. Essentially, all sides will be insulated (under the
%lid of the vacuum flask) except the Peltier side is modeled at a constant
%temperature (choose 4.5C).

% Specifying Properties of Aluminum 6061
k = 175;
cp = 0.9;
rho = 2710;

thermalProperties(thermalmodel,'ThermalConductivity',k,'SpecificHeat',cp,'MassDensity',rho)
% Setting initial conditions as ambient temp.
thermalIC(thermalmodel,30)
% Specifying BC as "Peliter" maintaingin 4.5C. (Not realistic, but since we
% are checking the conductivity of the aluminum plate, it will be ok).

thermalBC(thermalmodel,'Face',8,'Temperature',4.5);

generateMesh(thermalmodel);
tlist = 0:100:10000; %5000 second run time
R = solve(thermalmodel,tlist);
figure
pdeplot3D(thermalmodel,'ColorMapData',R.Temperature(:,4))
```

```
ans =

  ThermalMaterialAssignment with properties:

             RegionType: 'cell'
               RegionID: 1
    ThermalConductivity: 175
            MassDensity: 2710
           SpecificHeat: 0.9000


ans =

  GeometricThermalICs with properties:

             RegionType: 'cell'
               RegionID: 1
     InitialTemperature: 30
```



Appendix G: Design Hazard Checklist

Team: Solar Freeze		Advisor: Dr. Eileen Rossman		Date: 11/14/18

<u>Y N</u>

N 1. Will the system include hazardous revolving, running, rolling, or mixing actions?

N 2. Will the system include hazardous reciprocating, shearing, punching, pressing, squeezing, drawing, or cutting actions?

N 3. Will any part of the design undergo high accelerations/decelerations?

N 4. Will the system have any large (>5 kg) moving masses or large (>250 N) forces?

N 5. Could the system produce a projectile?

N 6. Could the system fall (due to gravity), creating injury?

N 7. Will a user be exposed to overhanging weights as part of the design?

N 8. Will the system have any burrs, sharp edges, shear points, or pinch points?

Y 9. Will any part of the electrical systems not be grounded?

N 10. Will there be any large batteries (over 30 V)?

N 11. Will there be any exposed electrical connections in the system (over 40 V)?

N 12. Will there be any stored energy in the system such as flywheels, hanging weights or pressurized fluids/gases?

N 13. Will there be any explosive or flammable liquids, gases, or small particle fuel as part of the system?

N 14. Will the user be required to exert any abnormal effort or experience any abnormal physical posture during the use of the design?

N 15. Will there be any materials known to be hazardous to humans involved in either the design or its manufacturing?

N 16. Could the system generate high levels (>90 dBA) of noise?

Y 17. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, or cold/high temperatures, during normal use?

N 18. Is it possible for the system to be used in an unsafe manner?

N 19. For powered systems, is there an emergency stop button?

N 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.

Description of Hazard	Planned Corrective Action	Planned Date	Actual Date
The current running from the solar panel to the Peltier will not be grounded.	The current is low enough that it is not dangerous and does not need to be grounded.	N/A	
During normal use in Africa, the cooler will be exposed to temperatures of up to 35 degrees Celsius.	Every aspect of the cooler will be designed with this temperature in mind.	All year	

Appendix: H

The selected concept at the time of the Preliminary Design Review used Peltier technology together with a phase change material. Research indicated that a height to width ratio of 1:1 would yield the best cooling efficiency of the phase change material. Figure 18 below shows a labeled section view of the selected design which incorporates a Peltier TEC, an aluminum housing, phase change material, heat pipes, and a heat sink in a water bath.

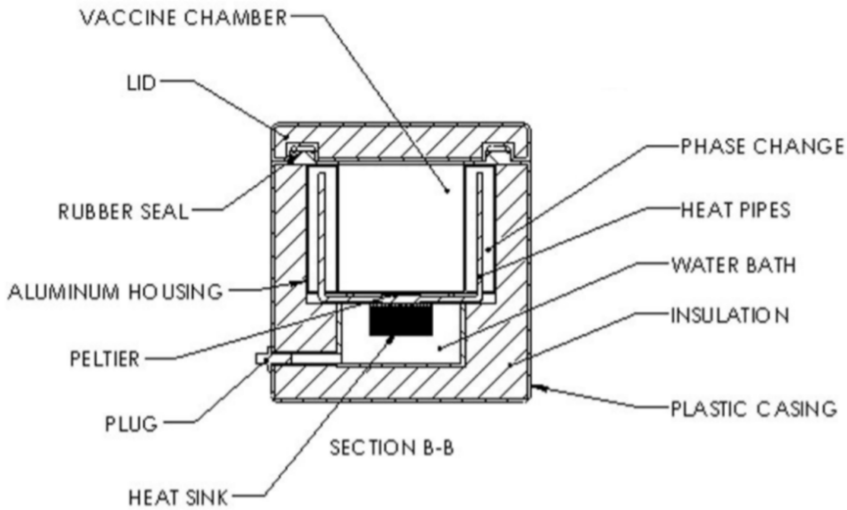


Figure 19. Labeled concept model section view

The large hatched areas above represent the insulation inside the cooler. It was found that there would need to be at least 5 cm of high grade Styrofoam insulation around every component inside the cooler. A plastic outer housing shields the inside from impacts and everyday wear. Figure 19 below shows a 3D section view of the design.

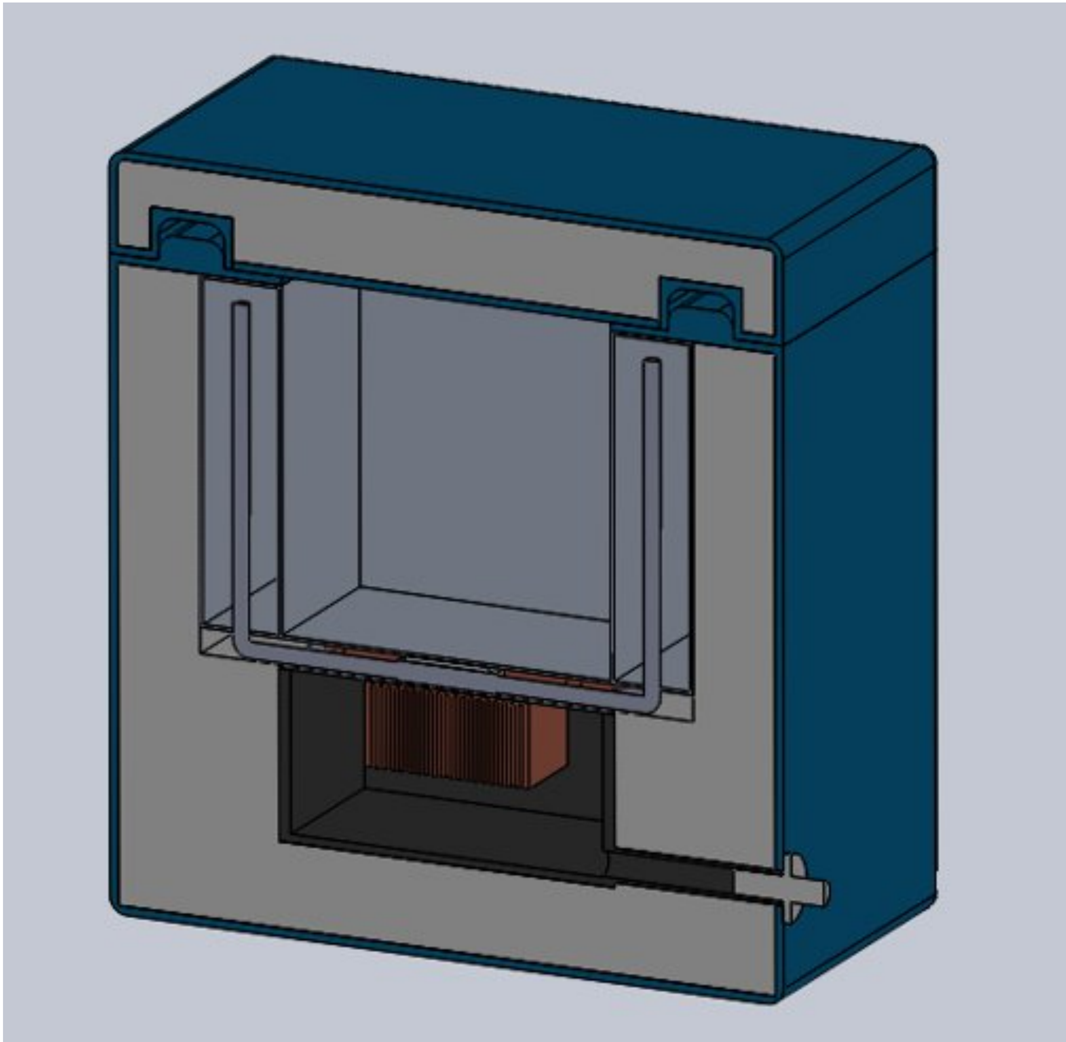


Figure 19. Isometric concept model section view.

The cubical design features an inner vaccine chamber with dimensions of 20 cm x 20 cm x 20 cm (8000 cm^3). Smaller vaccine coolers on the market feature a vaccine capacity of 6000 to 8000 cubic cm. The vaccine chamber is surrounded phase change material encased in an aluminum housing. Both the lid and main body of the cooled are filled with a minimum insulation thickness of 5 cm. The lip inside the lid contains a rubber seal to limit the amount of heat leak into the system from the lid/body junction. Figure 20 below shows a front view and section view with preliminary dimensions that were used throughout analysis attached in the appendices.

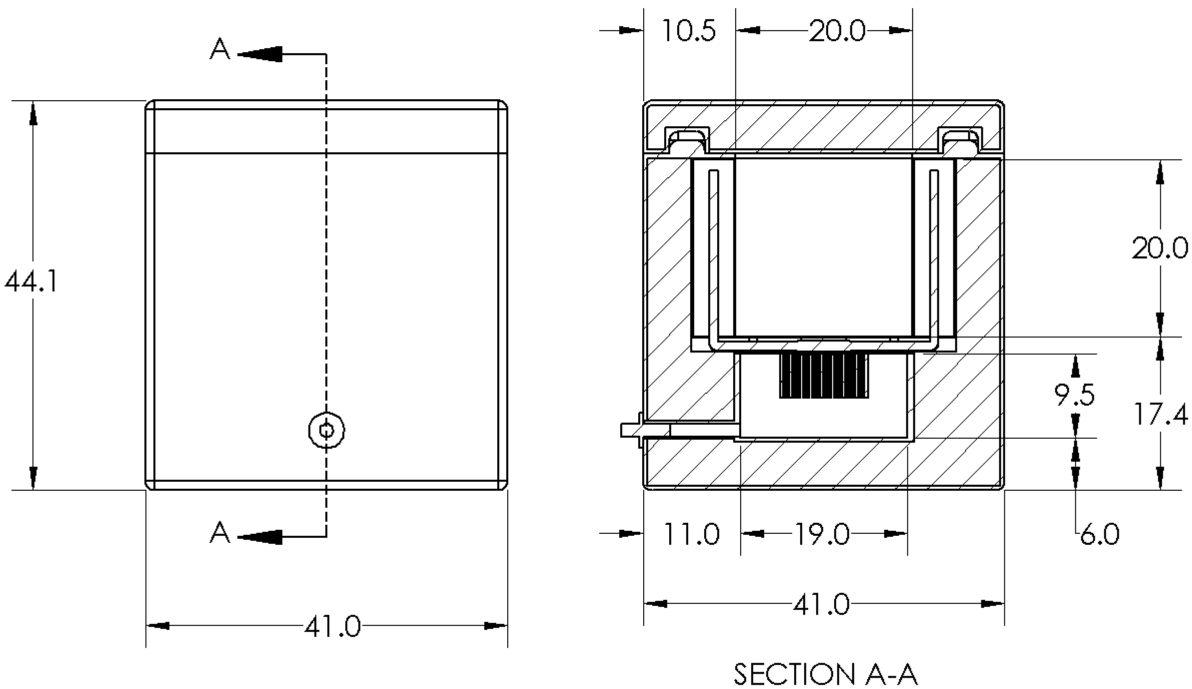


Figure 20. Concept model section view with preliminary dimensions.

The hot side of the Peltier is thermally connected to a heat sink while the cold side is connected to a heat pipe array and the metal aluminum phase change housing. After the system has ran, the phase change material will be completely solid and the hot water bath can be emptied via a release spout and replaced with cooler water.

After further research and calculations, Solar Freeze Team realized that this design was not feasible and decided to head in a different design direction.

Appendix I: Design Verification Plan

Senior Project DVP&R

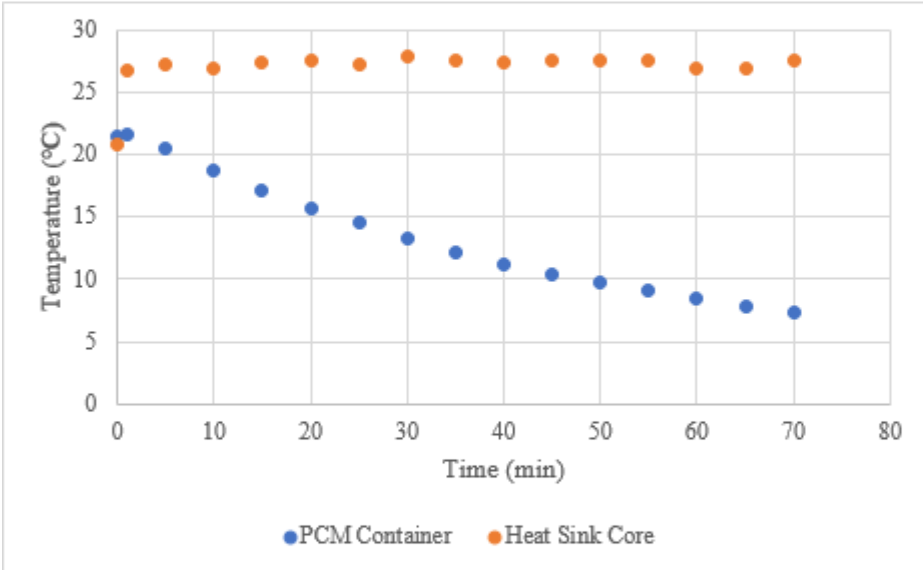
Date: 5-31-19	Team: Solar Freeze	Sponsor: Peter Schwartz	Description of System: Peltier-driven Vaccine Cooler	DVP&R Engineer: Ben Larson

TEST PLAN										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	Optimal Temperature	Test to see if the frozen PCM container keeps the air in the vaccine chamber at the optimal temperature.	2-8 deg C	Eilbron	SP, FP	1	Sys	4/6/19	4/10/19	2-8 deg C	inside 2-8 deg C	outside 2-8 deg C	Pased.
2	Vaccine Capacity	Visual inspection.	50 vials	Cooper	FP	1	Sys	4/12/19	4/13/19	> 50	> 50	< 50	Passed.
3	Weigth	Use scale to measure weight of device.	under 100 lbs	Ben	FP	1	Sys	4/18/19	4/20/19	15 lbs	< 100 lbs	> 100 lbs	Passed.
4	Cost	Sum up cost of parts	under $200	Cody	FP	1	Sys	4/22/19	4/24/19	186$	< 200$	> 200$	Passed.
5	Lifespan	Can not test lifespan. Manufacturer specification says 3,000 freeze/melting cycles of PCM. Estimate about 5 years.	1 year	Cooper	FP	1	Sys	N/A	N/A	N/A	N/A	N/A	N/A
6	Dimensions	Visual inspection.	2ft x 2ft x 2ft	Ben	FP	1	Sys	4/28/19	4/30/19	1ft x 1.5ft x 1ft	< 2ft x 2ft x 2ft	> 2ft x 2ft x 2ft	Passed.
7	Power Consumption	When Peltier is running, read power supply display for power consumption.	100 Watts	Eilbron	FP	1	Sys	5/4/19	5/10/19	80.4 Watts	< 100 Watts	< 100 Watts	Passed.
8	Time to Reach Optimal Temperature	Connect Peltier to power supply. Monitor temperature using thermocouples placed inside of PCM container. Time with stopwatch.	4 hours	Cody	FP	1	Sys	5/14/19	5/18/19	3 hours	<3.5 hours	> 3.5 hours	Passed.
9	Time of Maintaining Optimal Temperature	Once PCM container is fully frozen, seal vaccine chamber and start timer.	1 day	Ben	FP	1	Sys	5/18/19	5/22/19	3.7 hours	> 12 hours	< 12 hours	Failed.

Confirmation Prototype Test Results:

	Atm Temp (℃)	Atm Hum (%)	Peltier	Fan
Controls:	19	49	9.24 V, 6A, 60 W	13V, 0.5A max rpm
			TEC 15-127	Intel 1155 Socket LGA

Time (min)	PCM Container (℃)	Heat Sink Core (℃)
0	21.5	20.8
1	21.6	26.7
5	20.5	27.2
10	18.7	27
15	17.2	27.4
20	15.7	27.5
25	14.6	27.2
30	13.3	27.9
35	12.2	27.6
40	11.2	27.4
45	10.4	27.5
50	9.7	27.6
55	9.1	27.5
60	8.5	27
65	7.9	27
70	7.3	27.5


30
25
20
15
10
5
0
Temperature (ºC)
0
10
20
30
40
50
60
70
80
Time (min)
PCM Container
Heat Sink Core

Appendix J: Testing Calculations

Test #1 in Ice Lab

Fan: 13 V, 0.5 A

Weight: 1.235 kg (post-leak)

250 mL water (about)

Atomosphere: T = 19 °C, 49% hum

Peltier: 9.24 V, 6A — 60 Watts

127-15 TEC
- max rated: 15 A
- amount of semi conductors

Time (s)	PCM Container (°C)	Heat sink core (°C)
0	21.5	20.8
60	21.6	26.7
5 min	20.5	27.2
10 min	18.7	27.0
15 min	17.2	27.4
20 min	15.7	27.5
25 min	14.6	27.2
30 min	13.3	27.9
35 min	12.2	27.6
40 min	11.2	27.4
45 min	10.4	27.5
50 min	9.7	27.6
55 min	9.1	27.5
60 min	8.5	27.0
65 min	7.9	27.0
70 min	7.3	27.5

Calcs

$q = mC\Delta T$

- $\Delta T = 21.5 - 7.3 = 14.2\ °C$
- $C = 4.186\ \frac{J}{g°C}$
- $m = 0.25$ Liter $= 250$ g

$q = (250g)(4.186\frac{J}{g°C})(14.2°C)$

$q = 14{,}860.3\ J$

$Q = \frac{14{,}860.3\ J}{(70\ min)(60\ \frac{s}{min})} = 3.538\ W$ achieved during experiment

Finding total q (Joules)

$q = mC\Delta T + m H_{fusion}$

$q = (250g)(4.186\frac{J}{g°C})(21.5°C) + (250g)(334\frac{J}{g})$

$q = 22{,}499.8J + 83{,}500J$

★ $q = 106{,}000\ J$

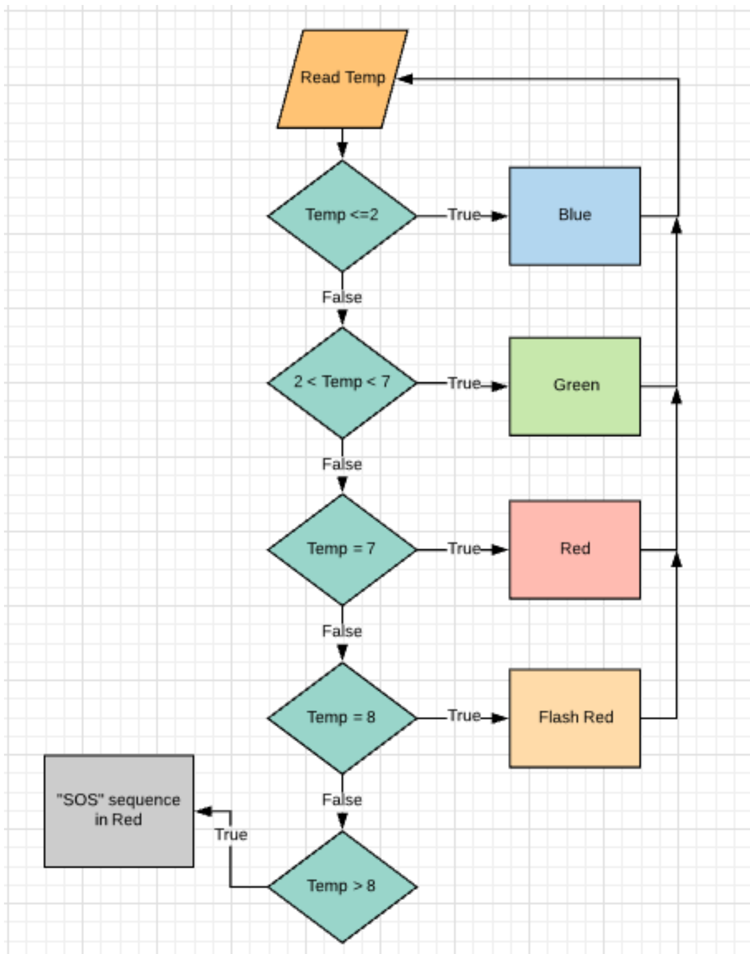
$\frac{106{,}000J}{3.538\ J/s} = 29960.43\ sec = 8.32$ hours

Scanned with CamScanner

Appendix K: Microcontroller Code and Flowchart

```
/*
Solar Freeze
Vaccine Cooler Temperature Indicator
Winter 2019
*/

if (tempC = 2){
void loop() {

  RunningLights(0,0,0xff, 50);
}

void loop() {
  RunningLights(0xff,0xff,0x00, 50);
}

void RunningLights(byte red, byte green, byte blue, int WaveDelay) {
  int Position=0;

  for(int j=0; j<NUM_LEDS*2; j++)
  {
      Position++;
      for(int i=0; i<NUM_LEDS; i++) {
        setPixel(i,((sin(i+Position) * 127 + 128)/255)*red,
                   ((sin(i+Position) * 127 + 128)/255)*green,
                   ((sin(i+Position) * 127 + 128)/255)*blue);
      }

      showStrip();
      delay(WaveDelay);
  }
}
}
else if (tempC > 2) || (tempC < 7){

  RunningLights(0xff,0xff,0xff, 50);
  void loop() {
  RunningLights(0xff,0xff,0x00, 50);
}

void RunningLights(byte red, byte green, byte blue, int WaveDelay) {
  int Position=0;

  for(int j=0; j<NUM_LEDS*2; j++)
  {
      Position++;
      for(int i=0; i<NUM_LEDS; i++) {
        setPixel(i,((sin(i+Position) * 127 + 128)/255)*red,
                   ((sin(i+Position) * 127 + 128)/255)*green,
                   ((sin(i+Position) * 127 + 128)/255)*blue);
      }

      showStrip();
      delay(WaveDelay);
  }
}
}

  else{
    RunningLights(0xff,0,0, 50);
      void loop() {
  RunningLights(0xff,0xff,0x00, 50);
}

void RunningLights(byte red, byte green, byte blue, int WaveDelay) {
  int Position=0;

  for(int j=0; j<NUM_LEDS*2; j++)
  {
      Position++;
      for(int i=0; i<NUM_LEDS; i++) {
```

```
        setPixel(i,((sin(i+Position) * 127 + 128)/255)*red,
                   ((sin(i+Position) * 127 + 128)/255)*green,
                   ((sin(i+Position) * 127 + 128)/255)*blue);
      }

      showStrip();
      delay(WaveDelay);
  }
}
  }
```



Appendix L: Failure Mode and Effects Analysis

Product: Peltier Powered Vaccine Cooler

Team: Solar Freeze

Design Failure Mode and Effects Analysis

Prepared by: Solar Freeze Team

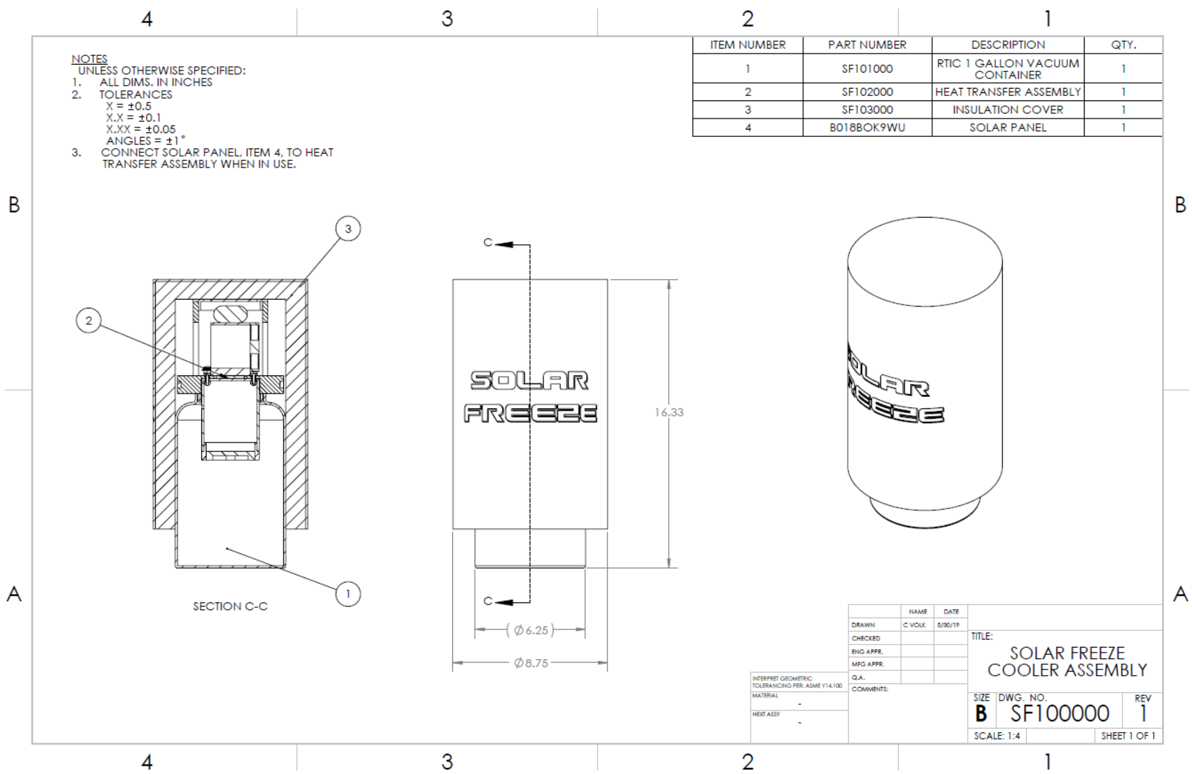
Date: 12/7/18 (orig)

												Action Results				
System / Function	Potential Failure Mode	Potential Effects of the Failure Mode	Severity	Potential Causes of the Failure Mode	Current Preventative Activities	Occurence	Current Detection Activities	Detection	RPN	Recommended Action(s)	Responsibility & Target Completion Date	Actions Taken	Severity	Occurence	Criticality	RPN
Cool Vaccines	Vaccines get too cold. Less than 2 degrees C	Vaccines freezes. Loses potency	10	1) Temp. feedback doesn't switch Peltier off 2) Over insulated 3) Miscalculation of Peltier output	1) Calibrate temp. feedback 2) Compare experimental data with calculations	2	Thermocouple inside vaccine chamber with digital readout	1	20	Calibrate temperature feedback mechanism appropiately	Cooper 1/31		10	2	1	20
	Vaccines get too hot More than 8 degrees C	Vaccines loses potency if it gets too warm.	10	1) Temp. feedback doesn't turn Peltier on 2) Under insulated 3) Improper seals allowing leaks 4) Water bath isn't effective 5) Peltier isn't powerful enough	1) Calibrate temp. feedback 2) Compare experimental data with calculations 3) Thermal analysis	8	Thermocouple inside vaccine chamber with digital readout	1	80	Calibrate temperature feedback mechanism appropiately	Cooper 1/31		10	8	1	80
Transport Vaccines	Vaccine containers break	Vaccines are ineffective if vials are broken	10	1) Container falls off of motorcycle 2) Vaccine container is dropped from too high of a height 3) Vials collide while transported 4) Motorcycle tips over or collides with another vehicle	1) Vaccines are held securely 2) Mesh nets in cylinder	3	Visual inspection	1	30	Have ample padding for vaccines. Calculate and test padding amount	Ben 3/20		10	3	1	30
	Vaccine capacity is too low	Not every child gets vaccinated	8	1) Chamber is too small 2) Weight restrictions forced cooler to be scaled down 3) Cost restrictions	1) Secure more funding	5	Visual inspection	1	40	Enlarge vaccine chamber while maintaining cooling effectiveness. (Testing/calculations)	Cody 2/20		8	5	1	40
Freeze Phase Change Material	PCM doesn't freeze	Vaccines are not kept at optimal temperature	10	1) Peltier is ineffective 2) Not enough insulation 3) Solar panel not effective enough to power Peltier	1) Test Peltier system effectiveness	6	Thermocouple inside PCM chamber with digital readout	1	60	Monitor temp. display frequently	Eilbron 4/20		10	6	1	60
Withstand Heat	Insulation is ineffective	Vaccines are not kept at optimal temperature	10	1) Gaps in insulation 2) Hot air leaks in 3) Insulation is not thick enough 4) Thermal conductivity is too high	1) Insulation calculations 2) Insulation testing 3) Don't have gaps 4) Eliminate paths of thermal conductivity	3	Testing of thermal conductivity of insulation	2	60	Add more insulation. Obtain a higher quality of insulation.	Ben 2/20		10	3	2	60
	Improper Seals	Vaccines are not kept at optimal temperature	10	1) Seal for vaccine chamber is ruptured 2) Peltier seal is ruptured	1) Have good seals between different components	1	Visual inspection	2	20	Obtain high quality seals	Cooper 4/31		10	1	2	20
	Peltier is ineffective	Vaccines are not kept at optimal temperature	10	1) Pelter cannot overcome heat that is leaking into system 2) Peltier connection is poor 3) Fan/Heat sink is poor causing to big of a temperature change across the Peltier rendering it ineffective	1) Limit the temperature change across the Peltier	4	Test Peltier and figure out efficiency	2	80	Do lots of testing with a Peltier	Team 3/20		10	4	2	80
General	PCM container leaks	PCM container not leak proof	8	1) Seal between PCM container and Peltier connection fail 2)	Design PCM chamber to be completely sealed	2	Visual inspection of vaccine chamber to see if PCM is leaking into it	3	48				8	2	3	48

Appendix M: Drawing Package

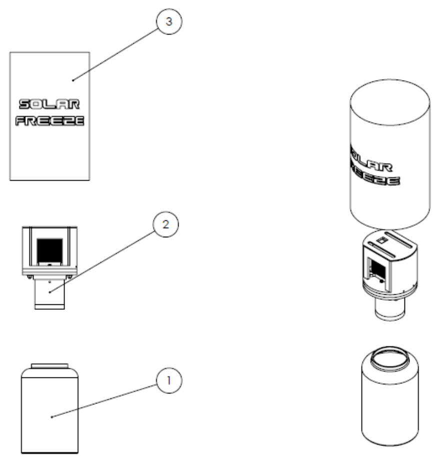
INDENTED BILL OF MATERIALS

Assembly Level	Part Number	Description				Vendor	Quantity	Cost	Total Cost
		Lvl0	Lvl1	Lvl2	Lvl3				
0	SF100000	Final Assembly				-----	----	----	----
1	SF101000		RTIC 1 gallon vacuum container			RTIC Coolers (Amazon)	1	38	38
1	SF102000		Heat Transfer Assembly			-----	----	----	----
2	SF102010			RTIC 1 gallon lid threads		RTIC Coolers (Amazon)	1	[38]	-
2	SF102012			3D Printed Lid		SOLAR FREEZE	1	10	10
2	SF102015			3D Printed Cap		SOLAR FREEZE	1	3	3
2	SF102020			Aluminum Chamber Assembly		-----	----	----	----
3	SF102021				Aluminum Plate	Online Metals	1	11.25	11.25
3	SF102022				3.0" Aluminum Pipe	Online Metals	1	7.41	7.41
3	PQC-101				3.0" Threaded ABS Plumbing Cap	Home Depot	1	3.13	3.13
3	SF102023				Phase Change Material	Vericor Medical	1	60.81	60.81
3	SF102024				Aluminum shaving craps	Cal Poly	1	0	0
3	178502				Plumbers Tape	Home Depot	1	1.38	1.38
2	TEC1-12715			TEC Peltier		Amazon	1	17.1	17.1
2	UCACO-A64D2-GBA01			Heat Sink/Fan with mounting hardware		SLO Acheivement House	1	0	0
2	92942A737			Nylon Pan Head Slotted Screws, 8-32 Thread, 5/8" Long		McMaster Carr	2 (pack of 100)	6.51	6.51
2	90295A400			Nylon Plastic Washer for Number 8 Screw Size, 0.173" ID, 0.375" OD		McMaster Carr	4 (pack of 100)	7.11	7.11
2	94812A400			Nylon Hex Nut, 8-32 Thread Size		McMaster Carr	2 (pack of 100)	6.5	6.5
2	91772A548			18-8 Stainless Steel Pan Head Screw, 1/4"-20, 1-3/4" Long		McMaster Carr	4 (pack of 25)	7.62	7.62
2	90107A029			Stainless Steel Washer for 1/4" Screw Size, 0.281" ID, 0.625" OD		McMaster Carr	8 (pack of 100)	8.25	8.25
2	91845A029			18-8 Stainless Steel Hex Nut, 1/4"-20 Thread Size		McMaster Carr	4 (pack of 100)	4.31	4.31
2	SF102040			Temperature Contoller		----	----	----	----
3	WS2812B				RGB LED Light Strip	Amazon	1	6.79	6.79
3	EL-CB-004				Arduino Nano	Amazon	1	5.92	5.92
3	SF102042				Arduino Nano Housing	SOLAR FREEZE	1	2	2
3	DS18B20				Sensor	Amazon	1	9	9
3	KG10GK-A				Portable Charger 10000mAh	Amazon	1	12.99	12.99
2	98003			Thermal Paste		Home Depot	1	6.63	6.63
1	SF103000		Insulation Cover			----	----	----	----
2	SF103010			12" Acrylic Cylinder		Amazon	1	15	15
2	SF103020			8" Foam Cylinder		Home Depot	1	11	11
1	B018BOK9WU		Solar Panel			HQST (Amazon)	1	95	95
								Total	356.71


NOTES
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN INCHES
2. TOLERANCES
X = ±0.5
X.X = ±0.1
X.XX = ±0.05
ANGLES = ±1°
3. CONNECT SOLAR PANEL, ITEM 4, TO HEAT TRANSFER ASSEMBLY WHEN IN USE.
ITEM NUMBER | PART NUMBER | DESCRIPTION | QTY.
1 | SF101000 | RTIC 1 GALLON VACUUM CONTAINER | 1
2 | SF102000 | HEAT TRANSFER ASSEMBLY | 1
3 | SF103000 | INSULATION COVER | 1
4 | B018BOK9WU | SOLAR PANEL | 1
SECTION C-C
SOLAR FREEZE
16.33
Ø6.25
Ø8.75
DRAWN C VOLK 5/30/19
TITLE:
SOLAR FREEZE COOLER ASSEMBLY
SIZE B
DWG. NO. SF100000
REV 1
SCALE: 1:4
SHEET 1 OF 1

NOTES
1. CONNECT SOLAR PANEL, ITEM 3, TO HEAT TRANSFER ASSEMBLY WHEN IN USE.
2. PLACE INSULATION COVER, ITEM 3, UNDER VACUUM FLASK WHILE CHARGING.

ITEM NUMBER	PART NUMBER	DESCRIPTION	QTY.
1	SF101000	VACCINE CHAMBER ASSEMBLY	1
2	SF102000	HEAT TRANSFER ASSEMBLY	1
3	SF103000	INSULATION COVER	1
4	B018BOK9WU	SOLAR PANEL	1



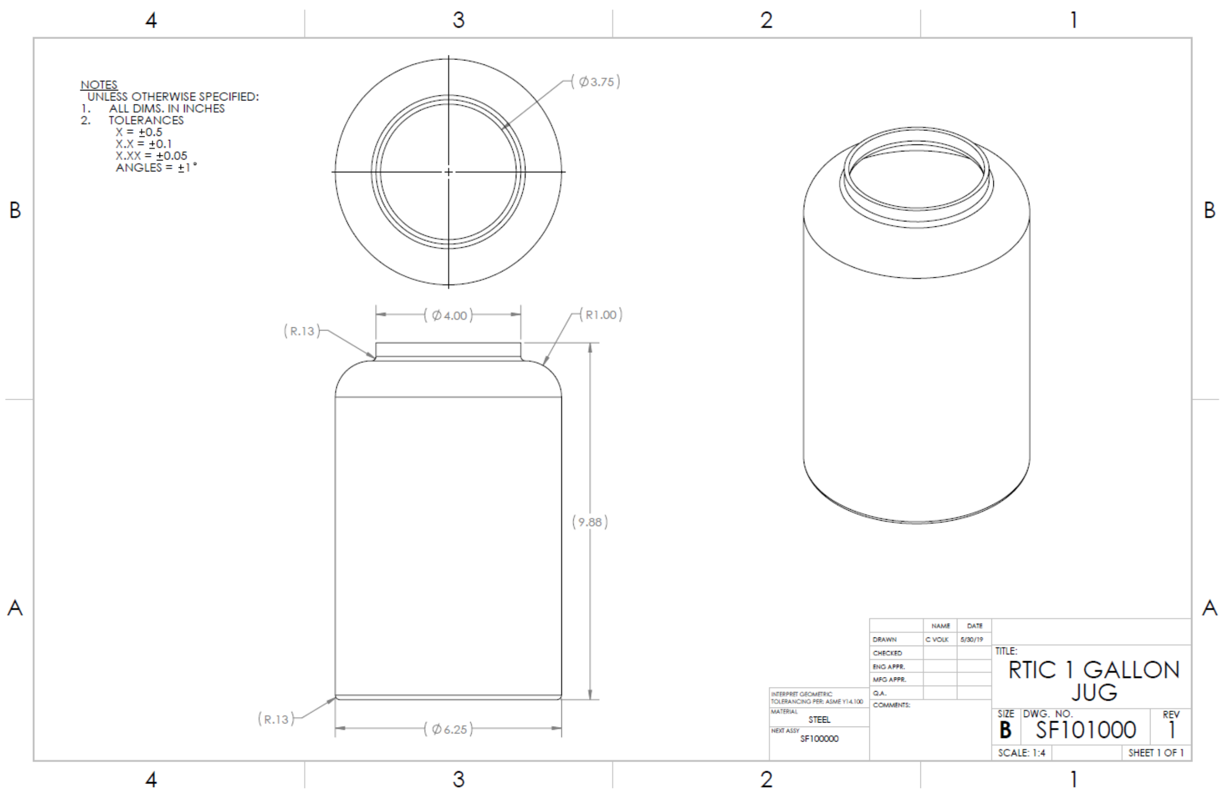
	NAME	DATE
DRAWN	C VOLK	5/30/19
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

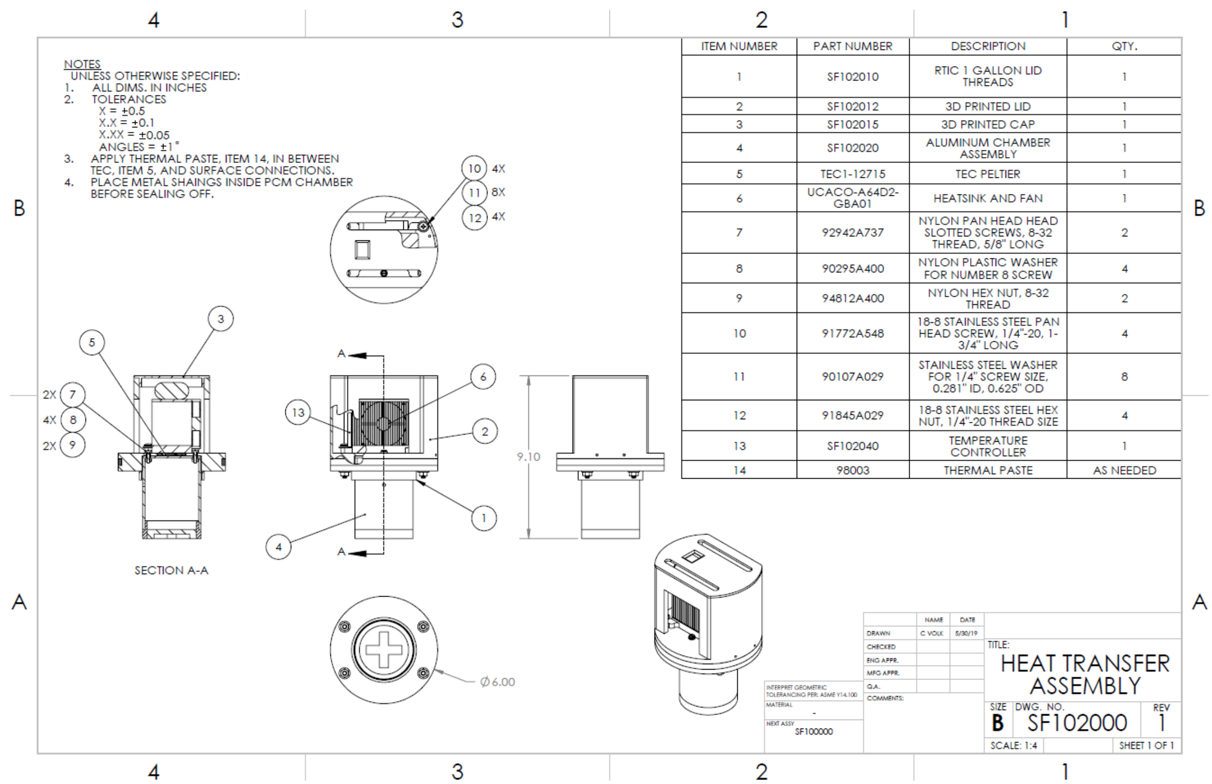
INTERPRET GEOMETRIC TOLERANCING PER: ASME Y14.100
MATERIAL -
NEXT ASSY -

TITLE: SOLAR FREEZE VACCINE COOLER (EXPLODED)

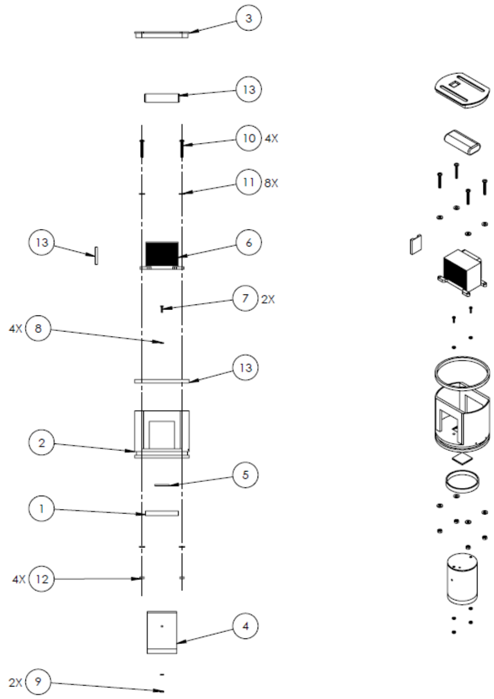
SIZE B DWG. NO. SF100000E REV 1

SCALE: 1:16 SHEET 1 OF 1


NOTES
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN INCHES
2. TOLERANCES
X = ±0.5
X.X = ±0.1
X.XX = ±0.05
ANGLES = ±1°
(Ø3.75)
(Ø4.00)
(R1.00)
(R.13)
(9.88)
(R.13)
(Ø6.25)
NAME
DATE
DRAWN
C VOLK
5/30/19
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
MATERIAL
STEEL
NEXT ASSY
SF100000
TITLE:
RTIC 1 GALLON JUG
SIZE
B
DWG. NO.
SF101000
REV
1
SCALE: 1:4
SHEET 1 OF 1



ITEM NUMBER	PART NUMBER	DESCRIPTION	QTY.
1	SF102010	RTIC 1 GALLON LID THREADS	1
2	SF102012	3D PRINTED LID	1
3	SF102015	3D PRINTED CAP	1
4	SF102020	ALUMINUM CHAMBER ASSEMBLY	1
5	TEC1-12715	TEC PELTIER	1
6	UCACO-A64D2-GBA01	HEATSINK AND FAN	1
7	92942A737	NYLON PAN HEAD HEAD SLOTTED SCREWS, 8-32 THREAD, 5/8" LONG	2
8	90295A400	NYLON PLASTIC WASHER FOR NUMBER 8 SCREW	4
9	94812A400	NYLON HEX NUT, 8-32 THREAD	2
10	91772A548	18-8 STAINLESS STEEL PAN HEAD SCREW, 1/4"-20, 1-3/4" LONG	4
11	90107A029	STAINLESS STEEL WASHER FOR 1/4" SCREW SIZE, 0.281" ID, 0.625" OD	8
12	91845A029	18-8 STAINLESS STEEL HEX NUT, 1/4"-20 THREAD SIZE	4
13	SF102040	TEMPERATURE CONTROLLER	1
14	98003	THERMAL PASTE	AS NEEDED



ITEM NUMBER	PART NUMBER	DESCRIPTION	QTY.
1	SF102010	RTIC 1 GALLON LID THREADS	1
2	SF102012	3D PRINTED LID	1
3	SF102015	3D PRINTED CAP	1
4	SF102020	ALUMINUM CHAMBER ASSEMBLY	1
5	TEC1-12715	TEC PELTIER	1
6	UCACO-A64D2-GBA01	HEATSINK AND FAN	1
7	92942A737	NYLON PAN HEAD HEAD SLOTTED SCREWS, 8-32 THREAD, 5/8" LONG	2
8	90295A400	NYLON PLASTIC WASHER FOR NUMBER 8 SCREW	4
9	94812A400	NYLON HEX NUT, 8-32 THREAD	2
10	91772A548	18-8 STAINLESS STEEL PAN HEAD SCREW, 1/4"-20, 1-3/4" LONG	4
11	90107A029	STAINLESS STEEL WASHER FOR 1/4" SCREW SIZE, 0.281" ID, 0.625" OD	8
12	91845A029	18-8 STAINLESS STEEL HEX NUT, 1/4"-20 THREAD SIZE	4
13	SF102040	TEMPERATURE CONTROLLER	1
14	98003	THERMAL PASTE	AS NEEDED

	NAME	DATE
DRAWN	C VOLK	5/30/19
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

INTERPRET GEOMETRIC TOLERANCING PER: ASME Y14.100

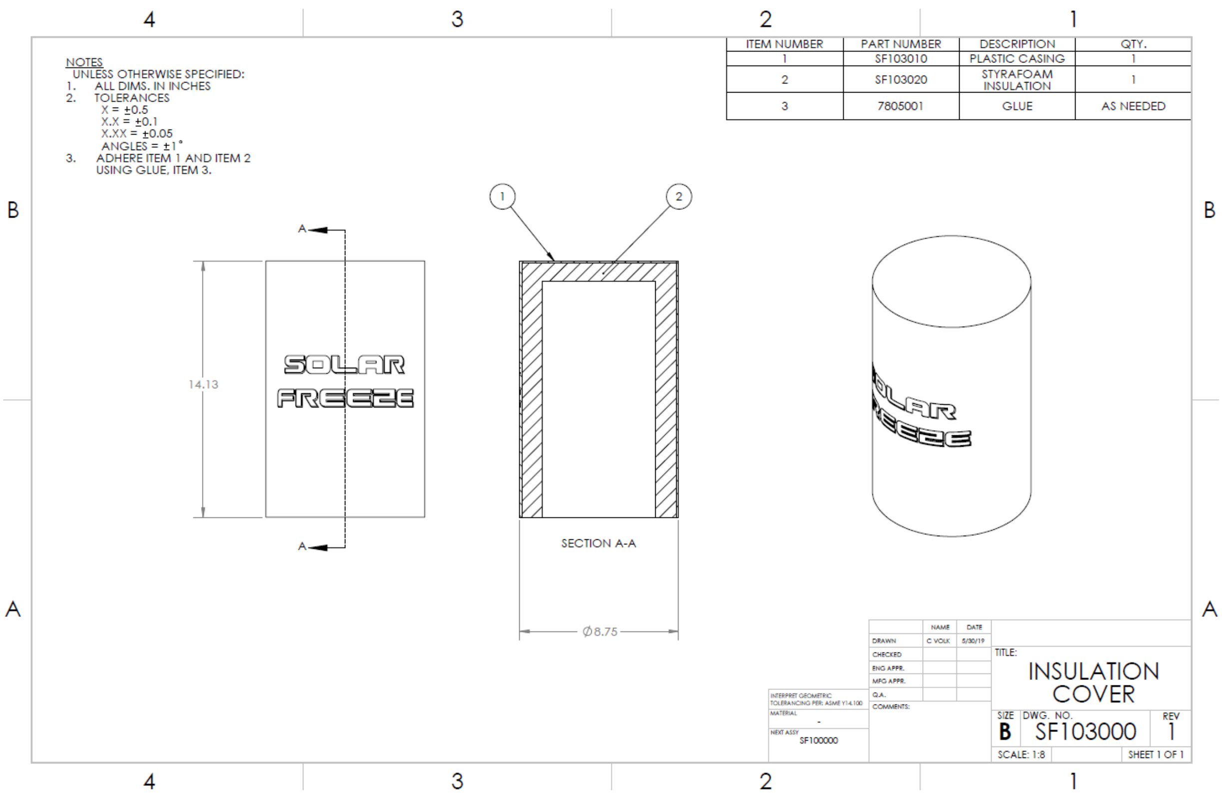
MATERIAL: -

NEXT ASSY: SF100000

TITLE: HEAT TRANSFER ASSEMBLY (EXPLODED)

SIZE: B | DWG. NO.: SF102000E | REV: 1

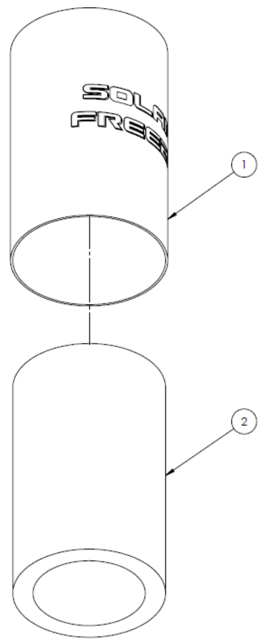
SCALE: 1:8 | SHEET 1 OF 1



ITEM NUMBER | PART NUMBER | DESCRIPTION | QTY.
1 | SF103010 | PLASTIC CASING | 1
2 | SF103020 | STYRAFOAM INSULATION | 1
3 | 7805001 | GLUE | AS NEEDED
NOTES
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN INCHES
2. TOLERANCES
X = ±0.5
X.X = ±0.1
X.XX = ±0.05
ANGLES = ±1°
3. ADHERE ITEM 1 AND ITEM 2 USING GLUE, ITEM 3.
SOLAR FREEZE
14.13
SECTION A-A
Ø8.75
DRAWN C VOLK 5/30/19
TITLE: INSULATION COVER
SIZE B
DWG. NO. SF103000
REV 1
SCALE: 1:8
SHEET 1 OF 1
NEXT ASSY SF100000

NOTES
1. ADHERE ITEM 1 AND ITEM 2 USING GLUE, ITEM 3.

ITEM NUMBER	PART NUMBER	DESCRIPTION	QTY.
1	SF103010	PLASTIC CASING	1
2	SF103020	STYRAFOAM INSULATION	1
3	7805001	GLUE	AS NEEDED



	NAME	DATE
DRAWN	C VOLK	2/7/19
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL -

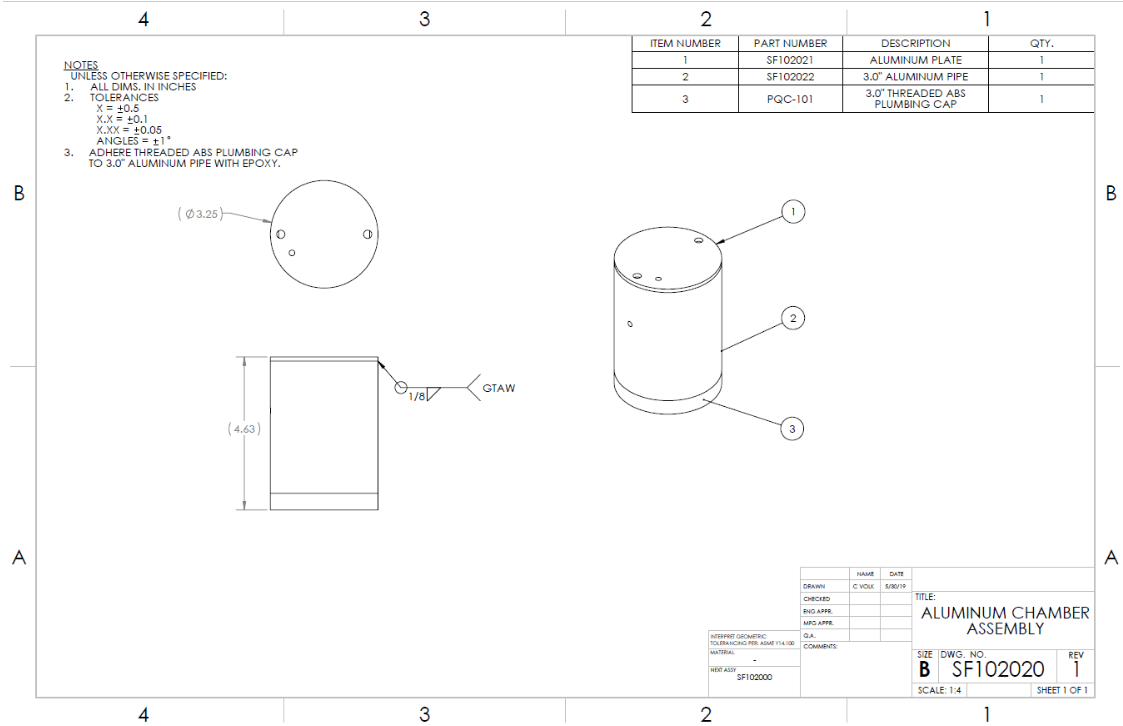
NEXT ASSY SF100000

COMMENTS:

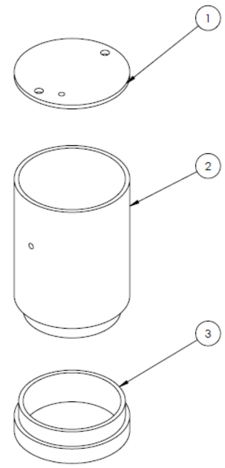
TITLE: INSULATION COVER (EXPLODED)

SIZE B DWG. NO. SF103000E REV 1

SCALE: 1:8 SHEET 1 OF 1


NOTES
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN INCHES
2. TOLERANCES
X = ±0.5
X.X = ±0.1
X.XX = ±0.05
ANGLES = ±1°
3. ADHERE THREADED ABS PLUMBING CAP TO 3.0" ALUMINUM PIPE WITH EPOXY.
ITEM NUMBER | PART NUMBER | DESCRIPTION | QTY.
1 | SF102021 | ALUMINUM PLATE | 1
2 | SF102022 | 3.0" ALUMINUM PIPE | 1
3 | PQC-101 | 3.0" THREADED ABS PLUMBING CAP | 1
(Ø3.25)
(4.63)
1/8
GTAW
1
2
3
NAME
DATE
DRAWN
C VOLK
5/30/19
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
INTERPRET GEOMETRIC TOLERANCING PER: ASME Y14.100
MATERIAL
-
NEXT ASSY
SF102000
TITLE:
ALUMINUM CHAMBER ASSEMBLY
SIZE
B
DWG. NO.
SF102020
REV
1
SCALE: 1:4
SHEET 1 OF 1

ITEM NUMBER	PART NUMBER	DESCRIPTION	QTY.
1	SF102021	ALUMINUM PLATE	1
2	SF102022	3.0" ALUMINUM PIPE	1
3	PQC-101	3.0" THREADED ABS PLUMBING CAP	1



	NAME	DATE
DRAWN	C VOLK	5/30/19
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

INTERPRET GEOMETRIC TOLERANCING PER: ASME Y14.100

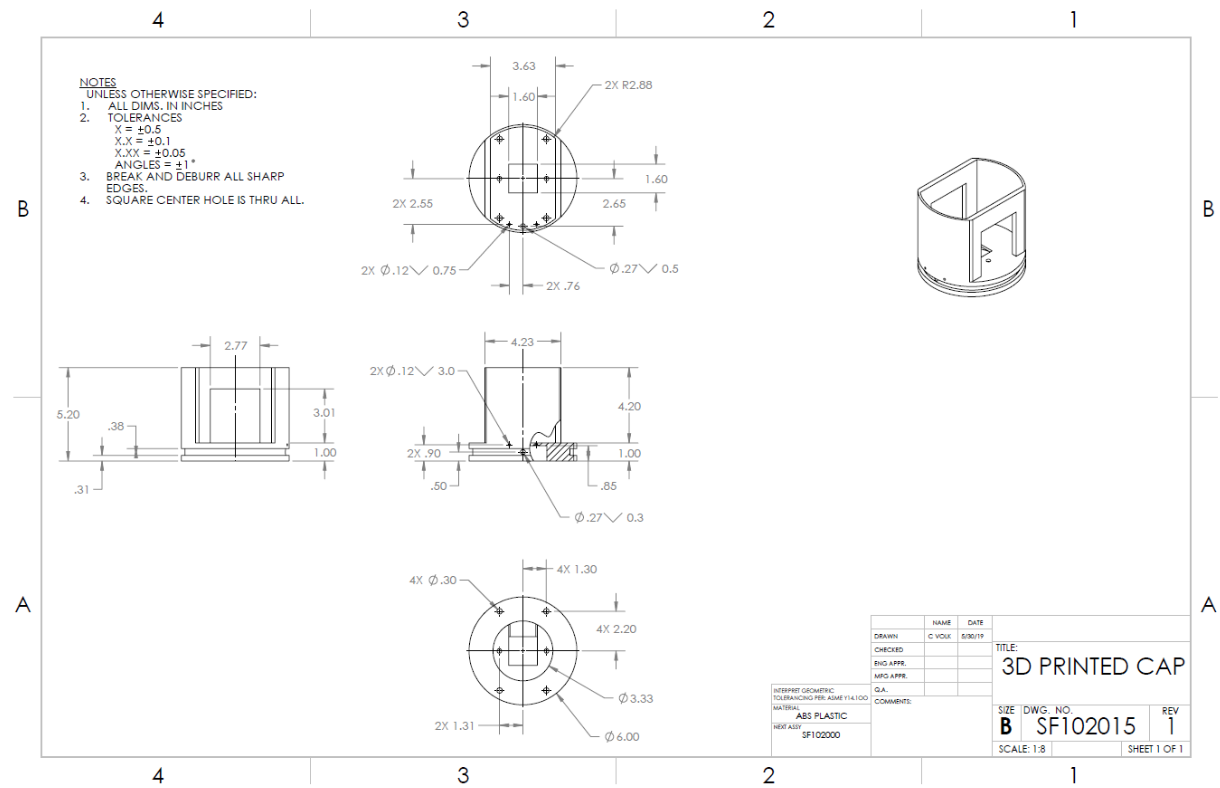
MATERIAL -

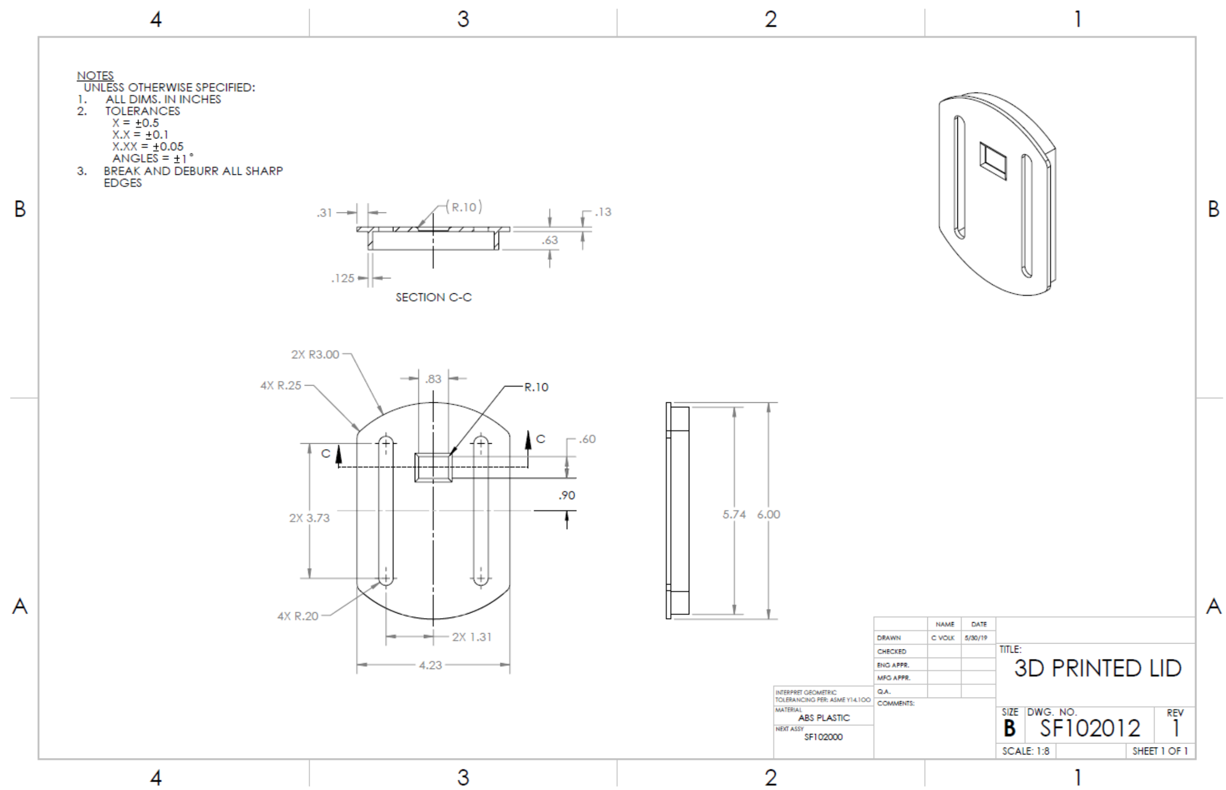
NEXT ASSY SF102000

TITLE: ALUMINUM CHAMBER ASSEMBLY (EXPLODED)

SIZE B | DWG. NO. SF102020E | REV 1

SCALE: 1:4 | SHEET 1 OF 1


NOTES
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN INCHES
2. TOLERANCES
X = ±0.5
X.X = ±0.1
X.XX = ±0.05
ANGLES = ±1°
3. BREAK AND DEBURR ALL SHARP EDGES.
4. SQUARE CENTER HOLE IS THRU ALL.
3.63
1.60
2X R2.88
1.60
2X 2.55
2.65
2X Ø.12 ✓ 0.75
Ø.27 ✓ 0.5
2X .76
2.77
5.20
.38
3.01
1.00
.31
4.23
2X Ø.12 ✓ 3.0
4.20
2X .90
1.00
.50
.85
Ø.27 ✓ 0.3
4X Ø.30
4X 1.30
4X 2.20
Ø3.33
2X 1.31
Ø6.00
NAME
DATE
DRAWN
C VOLK
5/30/19
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
INTERPRET GEOMETRIC TOLERANCING PER: ASME Y14.100
MATERIAL
ABS PLASTIC
NEXT ASSY
SF102000
TITLE:
3D PRINTED CAP
SIZE
B
DWG. NO.
SF102015
REV
1
SCALE: 1:8
SHEET 1 OF 1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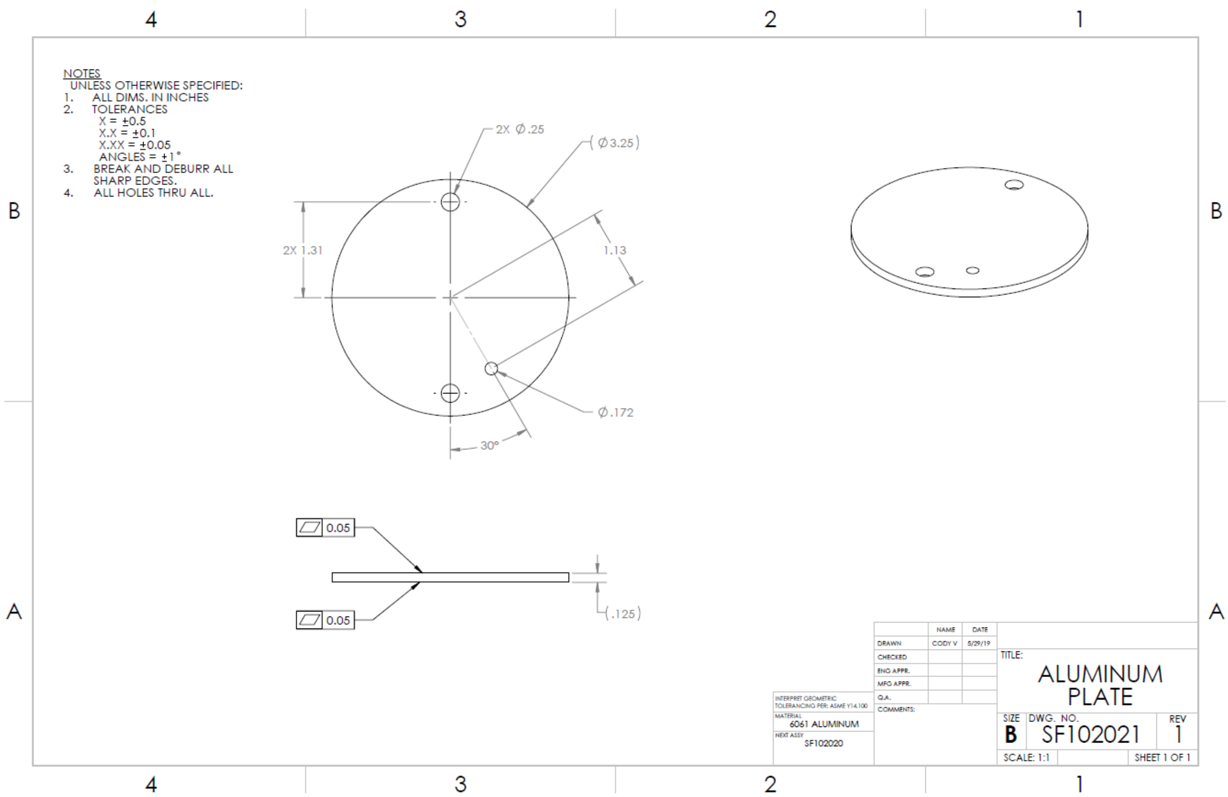
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN INCHES
2. TOLERANCES
X = ±0.5
X.X = ±0.1
X.XX = ±0.05
ANGLES = ±1°
3. BREAK AND DEBURR ALL SHARP EDGES
SECTION C-C
3D PRINTED LID
DRAWN C VOLK 5/30/19
MATERIAL ABS PLASTIC
NEXT ASSY SF102000
SIZE B
DWG. NO. SF102012
REV 1
SCALE: 1:8
SHEET 1 OF 1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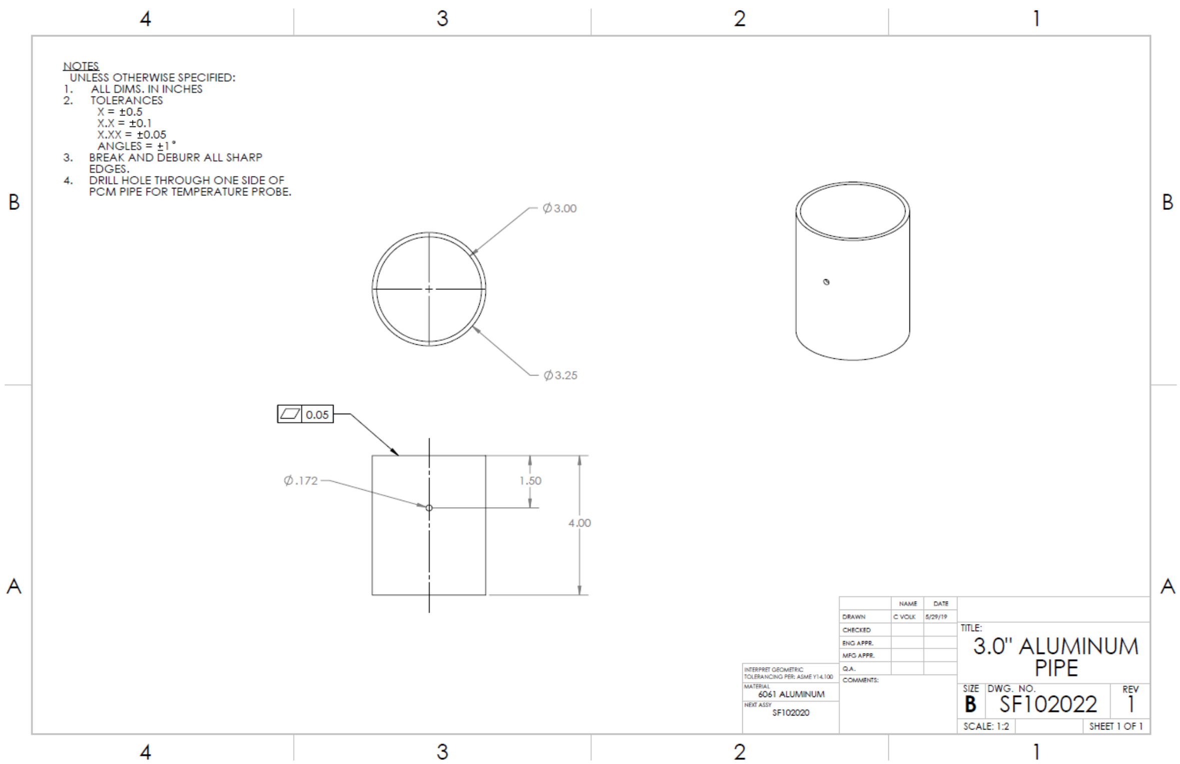
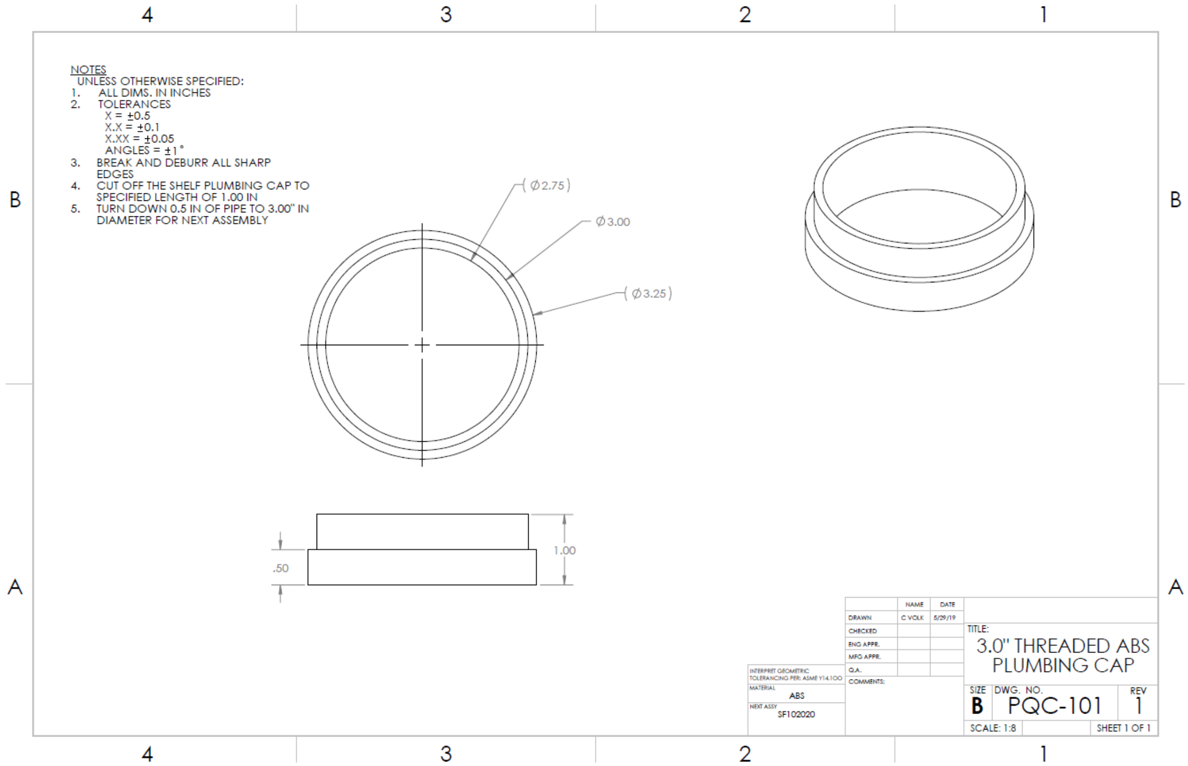
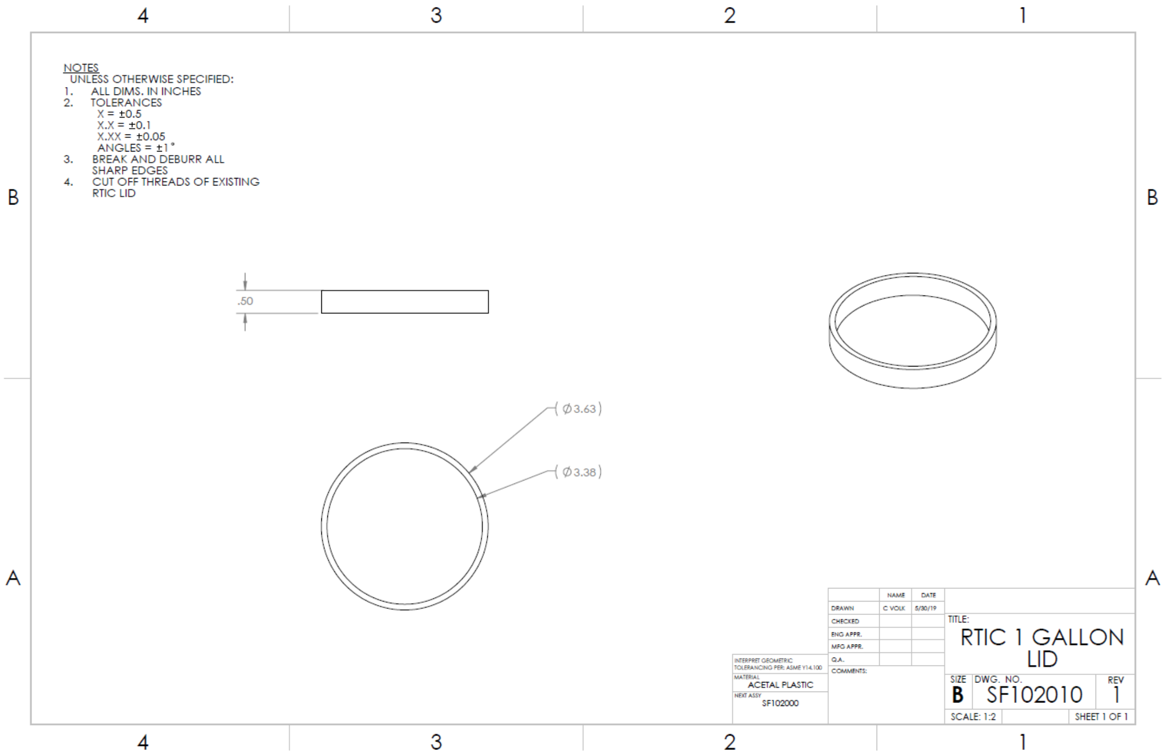
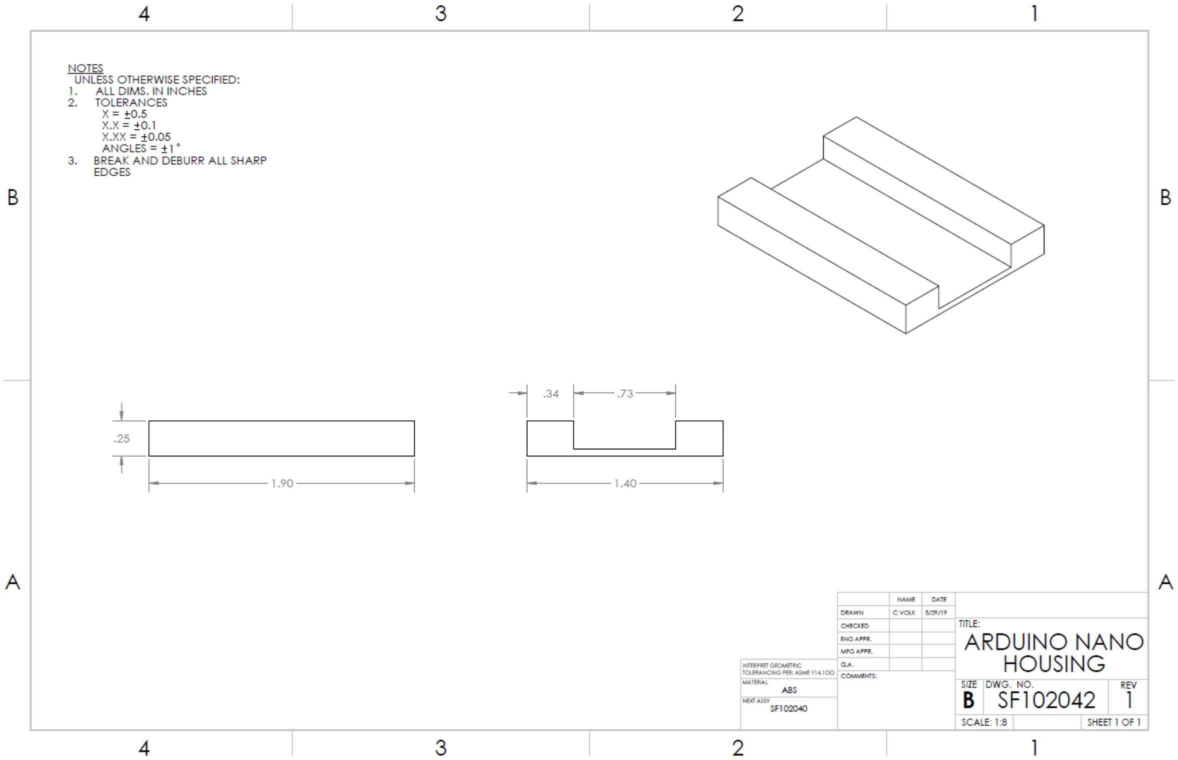
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN INCHES
2. TOLERANCES
X = ±0.5
X.X = ±0.1
X.XX = ±0.05
ANGLES = ±1°
3. BREAK AND DEBURR ALL SHARP EDGES.
4. ALL HOLES THRU ALL.
2X Ø.25
(Ø3.25)
2X 1.31
1.13
Ø.172
30°
0.05
0.05
(.125)
NAME
DATE
DRAWN
CODY V
5/29/19
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
INTERPRET GEOMETRIC TOLERANCING PER: ASME Y14.100
MATERIAL
6061 ALUMINUM
NEXT ASSY
SF102020
TITLE:
ALUMINUM PLATE
SIZE
B
DWG. NO.
SF102021
REV
1
SCALE: 1:1
SHEET 1 OF 1
4
3
2
1
B
A

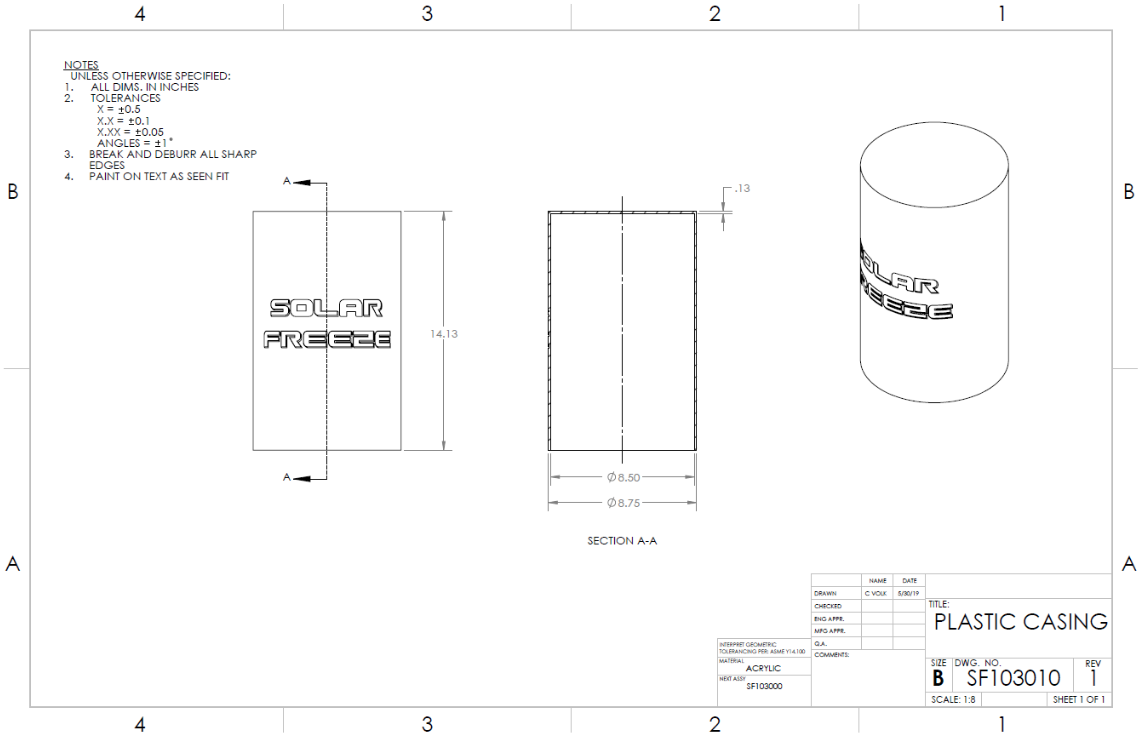

NOTES
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN INCHES
2. TOLERANCES
X = ±0.5
X.X = ±0.1
X.XX = ±0.05
ANGLES = ±1°
3. BREAK AND DEBURR ALL SHARP EDGES.
4. DRILL HOLE THROUGH ONE SIDE OF PCM PIPE FOR TEMPERATURE PROBE.
Ø3.00
Ø3.25
0.05
Ø.172
1.50
4.00
NAME
DATE
DRAWN
C VOLK
5/29/19
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
INTERPRET GEOMETRIC TOLERANCING PER: ASME Y14.100
MATERIAL
6061 ALUMINUM
NEXT ASSY
SF102020
TITLE:
3.0" ALUMINUM PIPE
SIZE
B
DWG. NO.
SF102022
REV
1
SCALE: 1:2
SHEET 1 OF 1
4
3
2
1
B
A

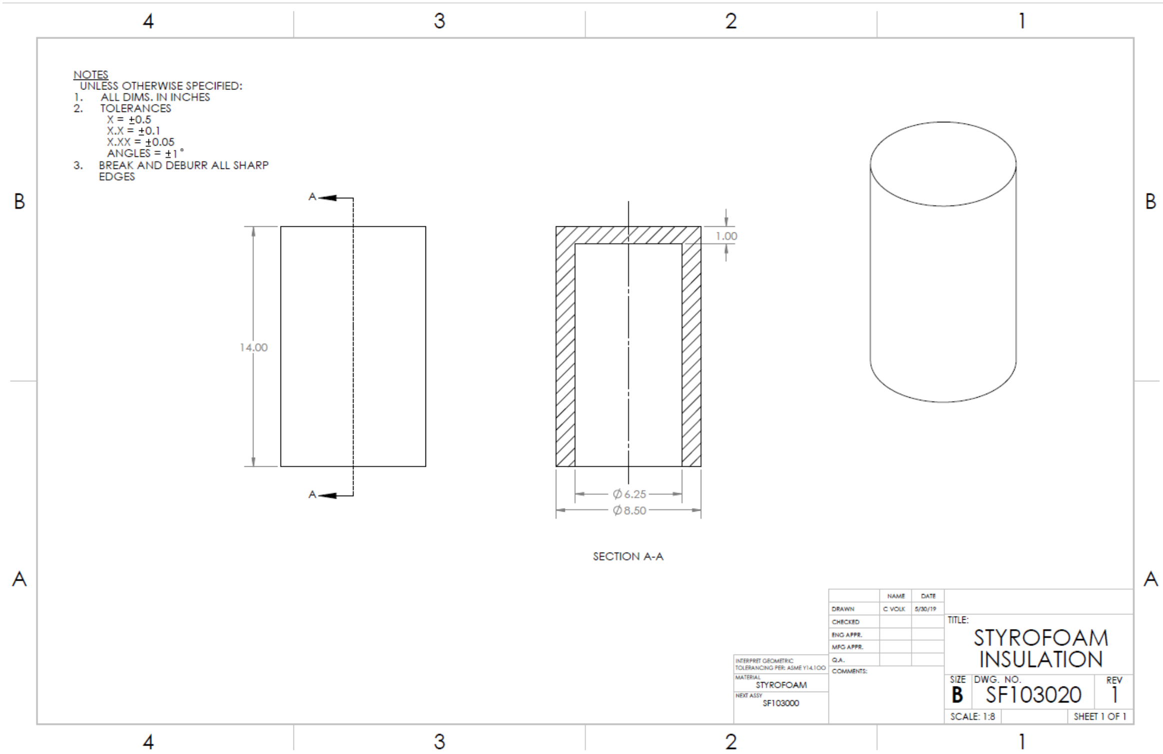


NOTES
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN INCHES
2. TOLERANCES
X = ±0.5
X.X = ±0.1
X.XX = ±0.05
ANGLES = ±1°
3. BREAK AND DEBURR ALL SHARP EDGES
4. CUT OFF THE SHELF PLUMBING CAP TO SPECIFIED LENGTH OF 1.00 IN
5. TURN DOWN 0.5 IN OF PIPE TO 3.00" IN DIAMETER FOR NEXT ASSEMBLY
(Ø2.75)
Ø3.00
(Ø3.25)
1.00
.50
NAME
DATE
DRAWN
C VOLK
5/29/19
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
INTERPRET GEOMETRIC TOLERANCING PER: ASME Y14.100
MATERIAL
ABS
NEXT ASSY
SF102020
TITLE:
3.0" THREADED ABS PLUMBING CAP
SIZE
B
DWG. NO.
PQC-101
REV
1
SCALE: 1:8
SHEET 1 OF 1


NOTES
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN INCHES
2. TOLERANCES
X = ±0.5
X.X = ±0.1
X.XX = ±0.05
ANGLES = ±1°
3. BREAK AND DEBURR ALL SHARP EDGES
4. CUT OFF THREADS OF EXISTING RTIC LID
.50
(Ø3.63)
(Ø3.38)
NAME
DATE
DRAWN
C VOLK
5/30/19
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
INTERPRET GEOMETRIC TOLERANCING PER: ASME Y14.100
MATERIAL
ACETAL PLASTIC
NEXT ASSY
SF102000
TITLE:
RTIC 1 GALLON LID
SIZE
B
DWG. NO.
SF102010
REV
1
SCALE: 1:2
SHEET 1 OF 1


NOTES
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN INCHES
2. TOLERANCES
X = ±0.5
X.X = ±0.1
X.XX = ±0.05
ANGLES = ±1°
3. BREAK AND DEBURR ALL SHARP EDGES
.25
1.90
.34
.73
1.40
NAME
DATE
DRAWN
C VOLK
5/29/19
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
INTERPRET GEOMETRIC TOLERANCING PER: ASME Y14.100
MATERIAL
ABS
NEXT ASSY
SF102040
TITLE:
ARDUINO NANO HOUSING
SIZE
B
DWG. NO.
SF102042
REV
1
SCALE: 1:8
SHEET 1 OF 1


NOTES
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN INCHES
2. TOLERANCES
X = ±0.5
X.X = ±0.1
X.XX = ±0.05
ANGLES = ±1°
3. BREAK AND DEBURR ALL SHARP EDGES
4. PAINT ON TEXT AS SEEN FIT
SOLAR
FREEZE
A
A
14.13
.13
Ø8.50
Ø8.75
SECTION A-A
NAME
DATE
DRAWN
C VOLK
5/30/19
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
INTERPRET GEOMETRIC TOLERANCING PER: ASME Y14.100
MATERIAL
ACRYLIC
NEXT ASSY
SF103000
TITLE:
PLASTIC CASING
SIZE
B
DWG. NO.
SF103010
REV
1
SCALE: 1:8
SHEET 1 OF 1


NOTES
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN INCHES
2. TOLERANCES
X = ±0.5
X.X = ±0.1
X.XX = ±0.05
ANGLES = ±1°
3. BREAK AND DEBURR ALL SHARP EDGES
A
A
14.00
1.00
Ø 6.25
Ø 8.50
SECTION A-A
NAME
DATE
DRAWN
C VOLK
5/30/19
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
INTERPRET GEOMETRIC TOLERANCING PER: ASME Y14.100
MATERIAL
STYROFOAM
NEXT ASSY
SF103000
TITLE:
STYROFOAM INSULATION
SIZE
B
DWG. NO.
SF103020
REV
1
SCALE: 1:8
SHEET 1 OF 1

Appendix N: Hand Calculations

FAN: ARTIC Alpine 64 Pro Rev 2 CPU Cooler ←

20$

92mm size

36.7 CFM

$= 0.0173\ m^3/s$

$\rho = 1.225\ kg/m^3$

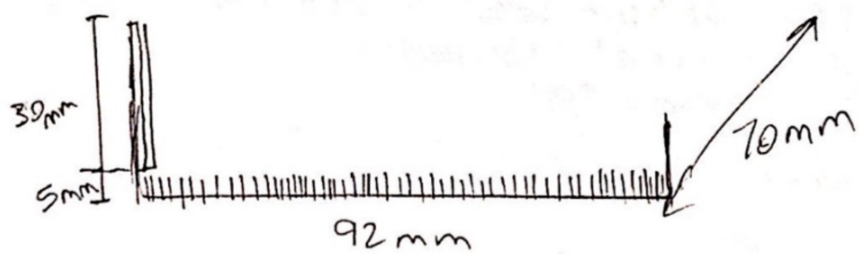
$\dot{m} = \left(1.225\ \frac{kg}{m^3}\right)\left(0.0173\ m^3/s\right) = 0.0212\ kg/s$ air

ANSYS: Heat flow: 130 W

60 fins

t=.5 mm

gap=1 mm



41

Novel Concepts calculator; Forced·Convection Heat Sink

→ gave $h = 758 \frac{W}{m^2 K}$ Film coeff.

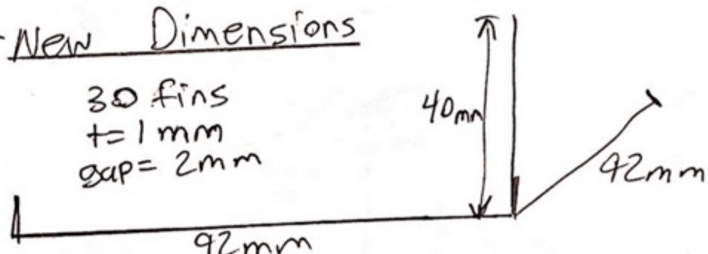
→ Engineersedge.com heat sink convection with fins calculator

- 30°C base
- 25°C Envirn.
- Same dimensions as Pg 41
- $K = 205 \frac{W}{mK}$ (Aluminum)

→ gives a $Q = 137$ W ✓ good

<u>New Dimensions</u>

30 fins
t = 1 mm
gap = 2 mm



Env. temp: 25°C ☆ "wet rag" ☆ This has huge impact on Q

Base Temp: 30°C

$Q = 163$ W ✓ good!

Equ: $Q = NKAn\Delta T\left(\frac{X_1}{X_2}\right)$

$X_1 = \sinh(nL) + \left(\frac{h}{nK}\right)\cosh(nL)$

$X_2 = \cosh(nL) + \left(\frac{h}{nK}\right)\sinh(nL)$

Appendix O: Source Code for Temperature Indication System

spc

```
#include <FastLED.h>
#include <OneWire.h>
#include <DallasTemperature.h>

// How many leds in your strip?
#define NUM_LEDS 29

//data pin for the leds
#define DATA_PIN 7

//not used
#define CLOCK_PIN 13

//data ping for the temperature sensor
#define ONE_WIRE_BUS 5


//global variables for temperature sensor
OneWire oneWire(ONE_WIRE_BUS);
float Celcius=0;
float Fahrenheit=0;
DallasTemperature sensors(&oneWire);

// Define the array of leds
CRGB leds[NUM_LEDS];

void setup() {
  //init output to terminal
  Serial.begin(9600);
```

spc

```
  //init temp
  sensors.begin();

  Serial.println("resetting");

  //init leds
  LEDS.addLeds<WS2812B,DATA_PIN,GRB>(leds,NUM_LEDS);
  LEDS.setBrightness(50);
}

void fadeall() { for(int i = 0; i < NUM_LEDS; i++) { leds[i].nscale8(240); } }

void loop() {


      static uint8_t hue = 0;
      int i = 0;
      int num_rev = 0;

     while(1){

         //set led coor from temp
         if (Celcius < 26.0){
             leds[i] = CRGB::Blue;
         }else if (Celcius >= 26.0 && Celcius < 27.0){
             leds[i] = CRGB::Green;
         }else{
             leds[i] = CRGB::Red;
```

spc

```
        }else{
            leds[i] = CRGB::Red;
        }


    // Show the leds
    FastLED.show();
    // now that we've shown the leds, reset the i'th led to black
    // leds[i] = CRGB::Black;
    fadeall();

    // Wait a little bit before we loop around and do it again
    delay(25);
     i++;

     if (i >= NUM_LEDS){
        i = 0;
        num_rev++;
     }

     if (num_rev > 10){
       num_rev = 0;
       Celcius=sensors.getTempCByIndex(0);
       sensors.requestTemperatures();
     }

     }

}
```

Appendix P: Heat Seepage Test Hand Calculation

5-29-19 Wed

Heat Seepage Test

1,000 mL of water @ $\approx$ 4.7°C

$T_{atm} = 23.6°C$

Started at 3:10pm 5/29

stopped at 8:00am 5/30

4.5°C @ 300 sec

8.9°C @ 30,000 sec

$c_{water} = 4.186 \frac{J}{g°C}$

$q = mc\Delta T$

$q = (1000\,g)\left(4.186 \frac{J}{g°C}\right)(8.9 - 4.5°C)$

$q = 18{,}418.4\ J$

Heat seepage: $Q = \frac{q}{t} = \frac{18{,}418.4\ J}{(30{,}000 - 300)s}$

$Q = 0.620\ W$

Scanned with CamScanner

Appendix Q: Operators Manual

This operator's manual includes instructions for product use and important safety information. Read this section entirely including all safety warnings and cautions before using the product.

<u>WARNING:</u> Do not leave vaccine chamber open for long periods of time in order to preserve internal temperature of chamber.

Instructions for Inserting Vaccines

Follow these instructions to safely insert vaccine vials into the cooler:

1. Ensure that all the wires in the system are completely disconnected from the solar panel.
2. Unscrew cap and remove both the cap and phase change material container from the vaccine chamber.
   CAUTION: Be gentle with any exposed wires. If the device is not connected to a power supply, touching the wires is fine. Be sure to not to let the wires get caught on anything or damaged.
3. Carefully insert vaccine vials into the vaccine chamber.
4. Replace cap onto vaccine chamber and screw closed firmly.

Instructions for Charging* Cooler

Follow these instructions in order to safely charge the cooler to the acceptable transport temperature:

*Charge or charging the cooler means to use the solar panel to power the Peltier which cools the phase change material until it is frozen and can act as an ice pack.

1. Make sure the heatsink, fan, cap, and PCM container is placed on the vaccine chamber (vacuum flask) and tightened securely. The insulation cap can be slid onto the bottom of the vaccine chamber See Figure 37 below.
2. Connect exposed, labeled wires to solar panel. Red to red, black to black.
3. Set up device in a place with direct sunlight. Charging will now begin. The fan on the heatsink should be running continuously. Do not stick any objects into blades of fan.
4. Let the device operate until the LED indicator lights turn green, indicating an adequate internal chamber temperature. This will take roughly 2.5-3 hours to reach the optimal temperature of about 4°C .
5. Unplug wires and place insulation cover over the top of the device to prevent heat seepage into the vaccine chamber. Insulation cap also doubles to protect device during transportation. See Figure 37 below for visual representation.

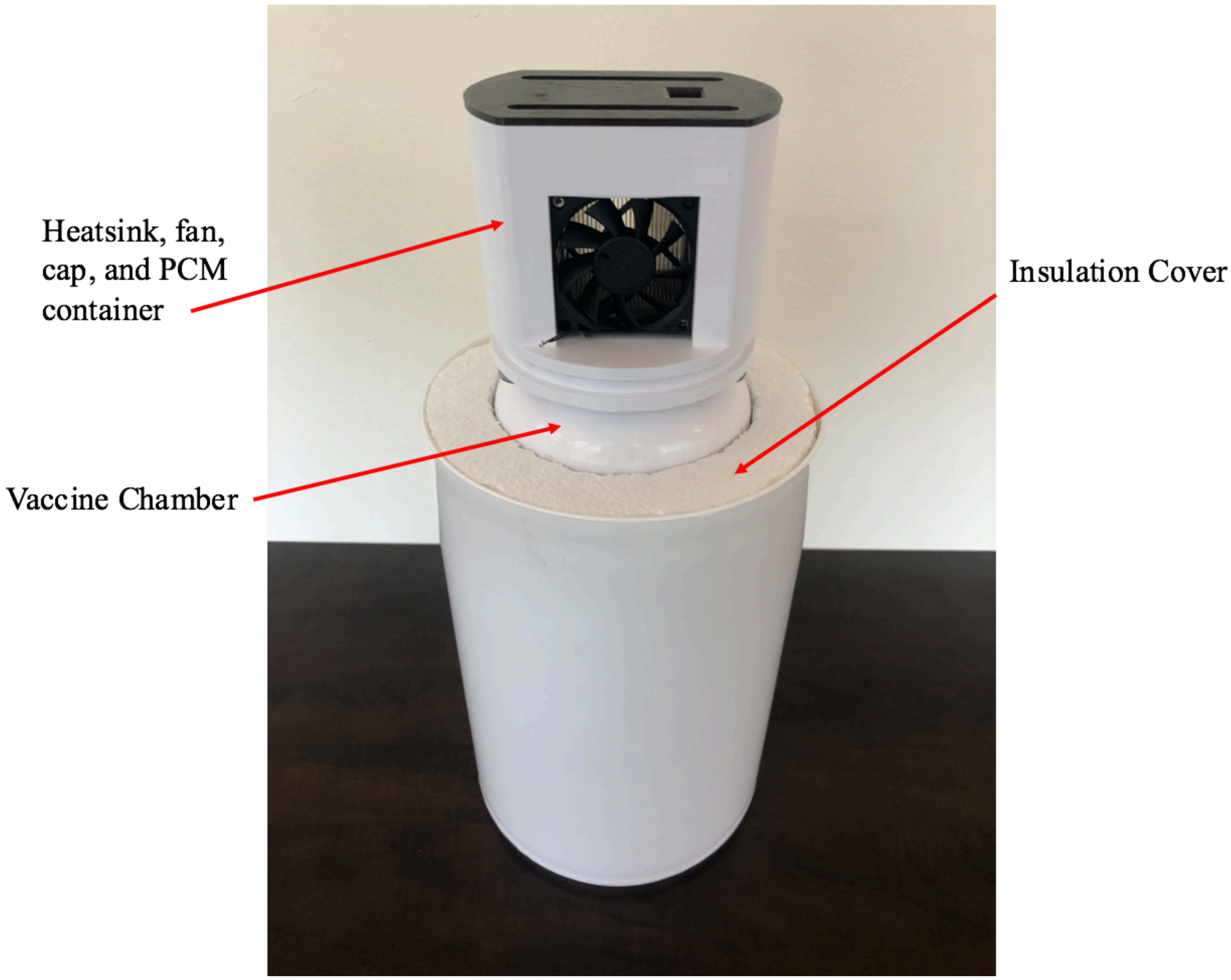


Figure 37. System ready to charge as described in Step 1.

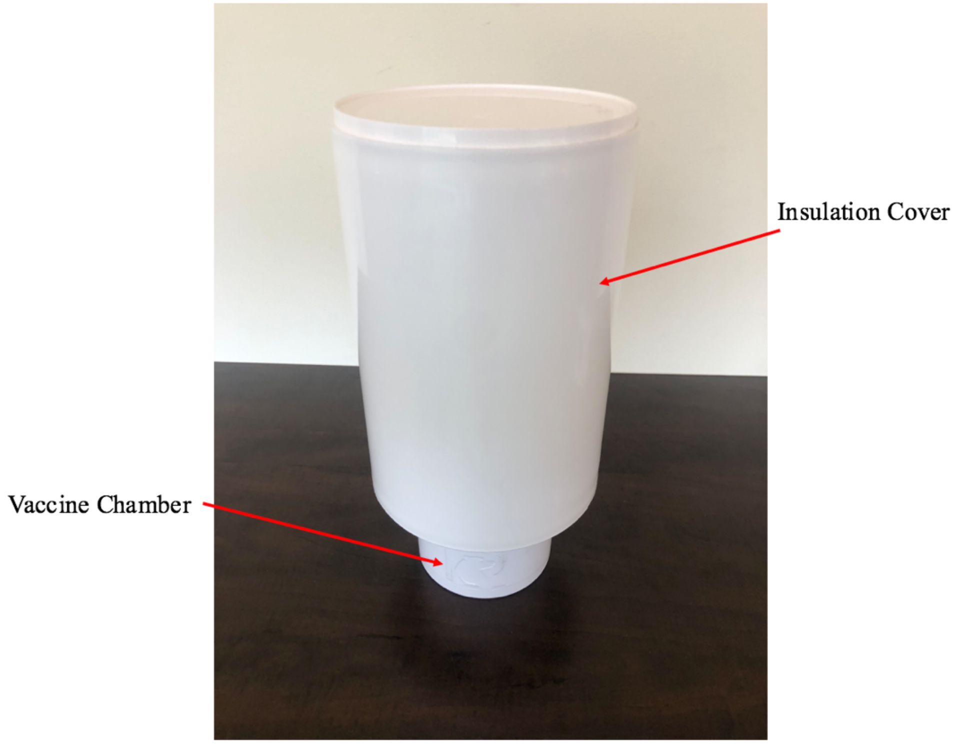


Figure 38. Vaccine cooler system with insulation cap on top as described in Step 5 above.

Instructions for Monitoring LED Warning Lights

Follow these instructions to properly monitor the LED warning lights located on the cap to ensure that vaccines remain at the appropriate temperature.

1. Wait to disconnect the vaccine cooler from the power source until it is fully "charged" and the vaccine chamber is at the optimal temperature of 4°C. This will be indicated when the LED lights are blue.
2. Once disconnected, the vaccine chamber will slowly increase temperature. The LED lights will light up green indicating that the internal temperature is safe for the vaccines. The safe temperature range for vaccines is 2-8°C.
3. If the LED lights change to red, the temperature inside the vaccine chamber has reach the upper acceptable limit for the vaccines to not lose potency (8°C). When the LEDs turn red, the device should be connected to a power source as soon as possible.
4. If the LED lights begin to flash red, the internal temperature of the vaccine chamber has exceeded the acceptable limit and the vaccines have likely been corrupted.

Table 13. Table of LED warning lights indications.

Lights Color	Vaccine Chamber Temperature	Meaning
Blue	4 °C	System fully charged.
Green	2-8 °C	System in the optimal range.
Red	8 °C	System on edge of optimal range.
Flashing Red	Above 8 °C	Vaccines compromised.

NOTE: The LED indicator lights are powered by a portable battery which will need to be recharged roughly every month. The battery can be charged by removing it from the system via the top lid and plugging it into a standard micro-USB charging cable. The battery charge level is indicated by a ring of lights on the top of the battery and can be viewed by looking through the lid on the top of the device.

Transportation Instructions/Warnings

Follow these instructions and warnings to safely transport vaccines:

1. If vaccines are present, only transport the device when the cooler is fully "charged".
2. Never charge the cooler during transportation.
3. During transportation, the insulation cap must stay on at all times unless vaccines are being removed.
4. Do not tip vaccine cooler upside down as this may disturb the vaccines and the phase change material container.
5. During transport, ensure that the device is securely fastened and so it will not be jostled or disturbed.

Trouble-shooting

Table 14. Trouble-shooting.

Issue	Solution
LED Indicator lights are not working.	Check battery charge level.
	Check wire connection from battery to lights.
	Check wire connection from micro-controller to lights
Heatsink fan is not working.	Check wire connection to power supply.
	Check if any debris is lodged in fan blades.
Vaccine chamber is not getting cold enough.	Check wire connections from solar panel to Peltier.
	Peltier could be burnt out/broken. Needs to be replaced.

Maintenance

Regular maintenance on the vaccine cooler includes cleaning of the fan and heatsink with a rag as needed.

Repair and Replacement of Parts

If a part were to break, it would be unlikely that the part could be repaired by hand. A complete list of parts along with where those parts can be found is in the Bill of Materials in Appendix M.

Appendix R: Risk Assessment

designsafe Report

Application:	Solar Freeze Vaccine Cooler	Analyst Name(s):	Cody Volk, Eilbron Younan, Cooper Gibson, Ben Larson
Description:		Company:	Solar Freeze
Product Identifier:	SF100000	Facility Location:	San Luis Obispo
Assessment Type:	Detailed		
Limits:			
Sources:			
Risk Scoring System:	ANSI B11.0 (TR3) Two Factor		

Guide sentence: When doing [task], the [user] could be injured by the [hazard] due to the [failure mode].

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
1-1-1	All Users Common Tasks	mechanical : Crushing Dropping product or component during manufacturing.	Moderate Likely	Medium	Put on rollers if too heavy. Team lift if needed. /Not Applicable	Moderate Unlikely	Low	
1-1-2	All Users Common Tasks	mechanical : cutting / severing Cut by fan blades or cut during manufacturing by jigsaw, drop saw, hand saw, dremel, or sharp edges.	Serious Unlikely	Medium	Read warning labels on machines and follow safety procedures. Two hands on handles of larger machines. /Not Applicable	Serious Unlikely	Medium	
1-1-3	All Users Common Tasks	mechanical : drawing-in / trapping / entanglement Hair or clothing caught in lathe, drill press, or grinder.	Serious Remote	Low	Tie up long hair and secure loose clothing. /Not Applicable	Serious Remote	Low	
1-1-4	All Users Common Tasks	mechanical : pinch point Fingers pinched in between workpiece and machine chuck. Fingers pinched in between cap and RTIC jug when assembling product.	Moderate Unlikely	Low	Keep fingers clear of enclosing surfaces. /Not Applicable	Moderate Unlikely	Low	
1-1-5	All Users Common Tasks	mechanical : impact Not securely clamping workpieces in machinery.	Serious Unlikely	Medium	Test rotation of workpiece before tooling. Double check torque before turning on machine. /Not Applicable	Serious Remote	Low	

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
1-1-6	All Users Common Tasks	electrical / electronic : energized equipment / live parts Cutting wires while using machines.	Moderate Unlikely	Low	Secure wires and inspect machines before use /Not Applicable	Moderate Remote	Negligible	
1-1-7	All Users Common Tasks	electrical / electronic : water / wet locations Wet workspace while using welding machine and other equipment.	Moderate Remote	Negligible	Inspect workspace before using machines. Put up signs if workspace is wet. /Not Applicable	Moderate Remote	Negligible	
1-1-8	All Users Common Tasks	slips / trips / falls : slip Wet workspace areas.	Moderate Remote	Negligible	Inspect workspace before using machines. Put up signs if workspace is wet. /Not Applicable	Moderate Remote	Negligible	
1-1-9	All Users Common Tasks	slips / trips / falls : trip Messy and unorganized workspace areas.	Moderate Unlikely	Low	Inspect workspace before using machines. Don't work in messy areas. /Not Applicable	Moderate Unlikely	Low	
1-1-10	All Users Common Tasks	slips / trips / falls : falling material / object Dropping material and components.	Moderate Unlikely	Low	Put on rollers if too heavy. Team lift if needed. /Not Applicable	Moderate Unlikely	Low	
1-1-11	All Users Common Tasks	ergonomics / human factors : lifting / bending / twisting Lifting heavy objects in machine shop.	Moderate Unlikely	Low	Put on rollers if too heavy. Team lift if needed. /Not Applicable	Moderate Unlikely	Low	
1-1-12	All Users Common Tasks	fire and explosions : sparks Sparks generated from welding torches.	Minor Likely	Low	Wear safety glasses and welding mask. Ensure light covers are up to protect other in the shop. /Not Applicable	Minor Unlikely	Negligible	

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
1-1-13	All Users Common Tasks	fire and explosions : hot surfaces Hot material from manufacturing processes such as welding and cutting. Hot side of the peltier device if not properly connected.	Serious Unlikely	Medium	Let hot material sit before handling by hand. Cool overly hot workpieces in water. /Not Applicable	Serious Unlikely	Medium	
1-1-14	All Users Common Tasks	heat / temperature : burns / scalds Burns from welding process or hot material.	Serious Unlikely	Medium	Let hot material sit before handling by hand. Cool overly hot workpieces in water. /Not Applicable	Serious Unlikely	Medium	
1-1-15	All Users Common Tasks	noise / vibration : noise / sound levels > 80 dBA High sound levels while cutting material in shop.	Minor Unlikely	Negligible	Wear hearing protection during loud processes. /Not Applicable	Minor Unlikely	Negligible	
1-1-16	All Users Common Tasks	chemical : chemical emissions Chemicals emitted during welding.	Moderate Remote	Negligible	Stop welding if too much smoke is emitted. Check tank of gas make sure there are no leaks. /Not Applicable	Moderate Remote	Negligible	