PPE Comfort Solution for the Ebola Crisis
Final Report

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INTRODUCTION

Our design project required us to attend a 3-day Ebola Design Charette hosted by the Penny W. Stamps School of Art & Design. From this charette, we gained valuable background information regarding the Ebola Viral Disease (EVD), its treatment, and all the problems associated with its containment. We defined the scope of our project from this charette.

The Ebola crisis in West Africa, primarily in Guinea, Liberia, and Sierra Leone, continues to claim lives with more than 8,200 deaths in the region since the outbreak was officially declared on March of 2014 [1]. Patients continue to become infected because containment of the disease is proving to be difficult and currently there is no cure. The disease is transmitted through bodily fluids such as vomit, blood, diarrhea, saliva, sweat, and semen. It is contracted through physical contact, most easily by eye, mouth or nose, however even a non-visible break in one's skin is enough to transmit the disease [2].

There are many cultural factors inhibiting the efforts to contain the EVD in West Africa. The international borders in the region are not heavily protected and allow anyone to unknowingly carry the virus with them to neighboring countries [3]. In many villages, it is customary that funeral activities involve touching of a potentially infected body, continuing the transmission of EVD. In addition, there is a very large lack of trust in government in the region, which is inhibiting aid from reaching some West Africans [3]. These are only a few of the many cultural barriers health workers and officials are working to overcome.

Due to the relatively high fatality rate, health workers treating Ebola victims are advised to wear full-body personal protective equipment (PPE), leaving no skin showing. These suits are impermeable to prevent liquid and airborne contaminants from entering the suit and infecting the healthcare worker (HCW). In West African climates, where temperatures can reach 115 °F and 90% relative humidity [4], operating in these suits can quickly become uncomfortable and potentially dangerous to the HCW.

During our time at the charette, it was noted by Holmes [5] that over-heating and being uncomfortable in PPE suits is a great concern and is a significant factor in determining how long HCWs can effectively work while suited. Holmes [5] stated that if there were some type of cooling device to keep workers more cool and comfortable, the useable time of the suits could be extended dramatically. Another one of Holmes' [5] concerns was the frequent doffing process. She claimed that a large percentage of the instances of medical workers contracting Ebola most likely occurred during the doffing stage of suit usage. If one were able to prolong the amount of time HCWs could comfortably use their suit, the HCWs would have to doff less frequently and therefore reduce their risk for exposure to Ebola.

In as quickly as 20 minutes, a suited HCW begins to experience discomfort [6]. According to Armand Sprecher, a medical advisor to Doctors Without Borders, health workers are unable to wear the PPE for more than 30 or 40 minutes in tropical heat [7]. This limited time in the suit makes caring for patients inefficient as it takes roughly 20 minutes for a trained worker to put on (don) and 20 minutes to take off (doff) the PPE [6]. "Sean Casey, head of the Ebola response team in Liberia for International Medical Corps, said that workers in the African heat sweated profusely in their suits, losing about a quart of water an hour" [8].

Not only are the uncomfortable conditions a problem, but also the doffing process itself is rigorous and puts HCWs at a high risk for contamination, especially if all precautions are not taken. Since December 2013, more than 200 HCWs have died [9]. Keeping aid workers healthy and safe is very important considering that human resources are limited in West Africa. Research has been cited that unsafe acts increase significantly at temperatures above 95 °F [10]. This is in the range of environmental conditions experienced by HCWs wearing full-body PPE in West Africa. If these workers are under heat stress, mental alertness and concentration will be impaired and safety procedures may be overlooked [11], which increases the chance of contracting Ebola.

PROBLEM

West African climates are causing extreme discomfort in PPE that health workers use when treating Ebola patients. Not only does this lead to reduced HCW productivity, but it puts them at risk by increasing the frequency of doffing. The goal is to develop a user-portable system that will extend the comfortable PPE suit use-time. Increasing suit comfort will reduce the frequency of doffing, increase mental alertness and decision making, reduce exposure to contaminants, and reduce suit disposal. Overall, health workers can work more efficiently and have a greater impact on handling the Ebola crisis.

BACKGROUND

To validate our future design solution and demonstrate its increased effectiveness, we developed a baseline data set under our own controlled conditions. Additionally, we evaluated existing design solutions to understand their shortcomings in solving this problem.

Problem Benchmarking

To create a controlled data set to benchmark our final design, we performed a preliminary experiment using PPE in a West African temperature. This environment was replicated using a sauna with a measured average temperature of 110ºF and the PPE was a 3M Protective Coverall 4510 disposable suit [12]. In Figure 1 shown below, one of our team members has donned the same PPE used for EVD containment [5], wearing a fluid impermeable suit, a hood, disposable gloves, and boots.

Figure 1: Correct PPE used in EVD containment consisting of a fluid impermeable suit, a hood, disposable gloves, and boots.

Each of the 4 team members entered the sauna wearing the proper PPE and a chest mounted thermometer and humidity sensor. The participant then stood in the sauna with minimal physical activity. Then we proceeded to take data every 2 minutes, recording a personal comfort on a 10-point scale and internal suit temperature and humidity. The comfort scale was a qualitative indicator of the user's personal comfort, ranging from 10 (indicating perfect comfort) to 0 (indicating approaching heat exhaustion). This qualitative measurement was used to determine approximately the time the user could comfortable withstand the conditions in the PPE.

The figure below shows the internal suit temperature over time for our 4 team members over time during their trials wearing the PPE in 110ºF. As shown by the figure, the internal suit temperature increased at approximately the same rate for all 4 team members. However, each team member had a different comfort threshold limiting the amount of time they were able to spend wearing the PPE. This time ranged from 34-50 minutes and in one case a team member did not reach a level of discomfort. This experiment does not take into account the additional heat generated while the HCW is involved in physical activity, which may lead to lower tolerable time in the suit.

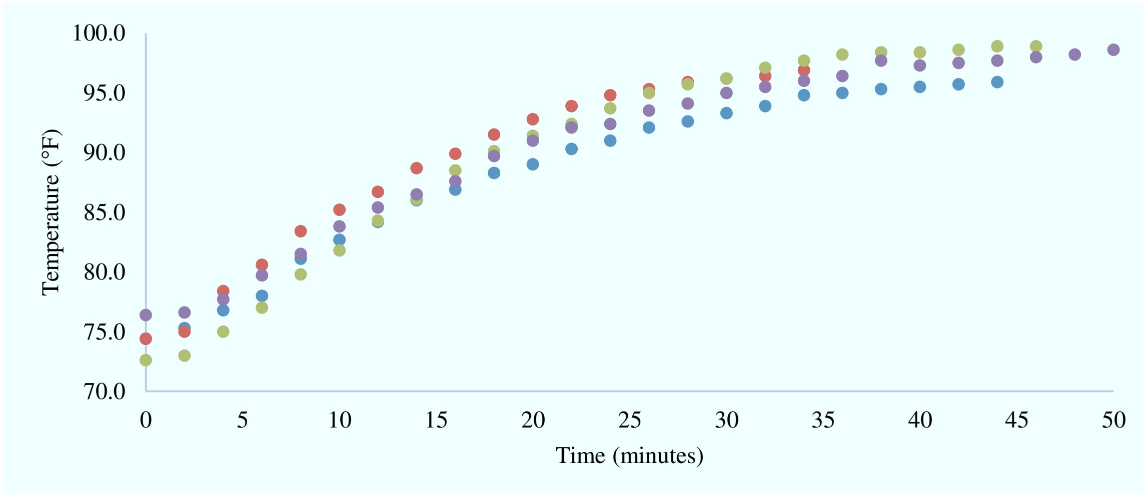


Figure 2: Internal suit temperatures for the four team members wearing PPE in 110ºF to identify comfort threshold time range.

From this experiment, we have concluded that 40 minutes is a reasonable amount of time for comfortable operation within the suit. This conclusion aligns with the current acceptable amount of HCW working time mentioned by our previous sources.

Product Benchmarking

Single-Circulation Personal Cooling System with Evaporator in Cooling Suit [13]: This invention utilizes a refrigerator based cooling system with an evaporator integrated into a cooling suit and an external compressor and condenser. Heat dissipated by the user is absorbed directly from the evaporator and the heat is then dissipated outside of the cooling system in a condenser. The invention claims that having the evaporator in the suit directly cooling the user saves weight and complexity versus having an evaporator-liquid interface where the secondary liquid would then directly cool the person. From the patent drawing below [13], the suit (B) is sketched as well as the internal evaporator system (A). Additionally, the external condenser (2), compressor (1) and power source (5) are shown in the next patent drawing below [13].

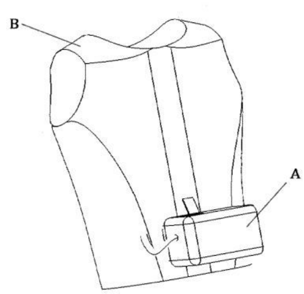


Figure 3: Sketch of the patent drawing [13] showing the location of the internal evaporator system (A) on the suit (B).

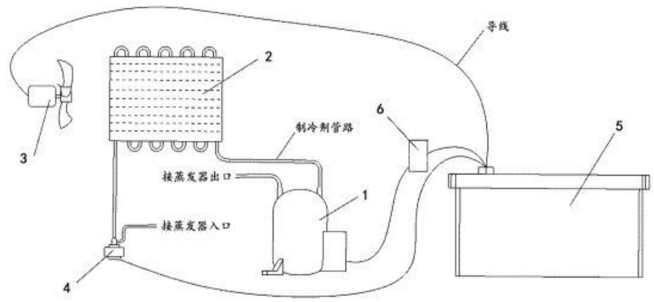


Figure 4: Sketch of the patent drawing [13] showing the compressor (1), the external condenser (2), and the power source (5).

For our application this suit would most likely be too complex and large. It requires an expensive external refrigeration system and flexible refrigerant tubing to connect the user to the condenser. Our goal is to design something more portable that could be integrated directly into the suit to reduce donning complexity as well as transportation and usage complexity.

Man Portable Micro-Climate [14]: This invention encompasses a cooling suit in which several types of cooling, dehumidifying and packaging methods are proposed. A closed loop portable cooling system is proposed using air circulation, a desiccant module, an air pump module and a heat pump module. This invention utilizes a vest worn by the user, which circulates air that is cooled and dried by a color-changing desiccant and a thermoelectric heat pump, pumped with a rotary-vane pump and a battery power supply. As shown below in the patent drawing [14], the patent details an air delivery system which has flexible parallel intake and exhaust hoses to circulate air around the person's back or chest.

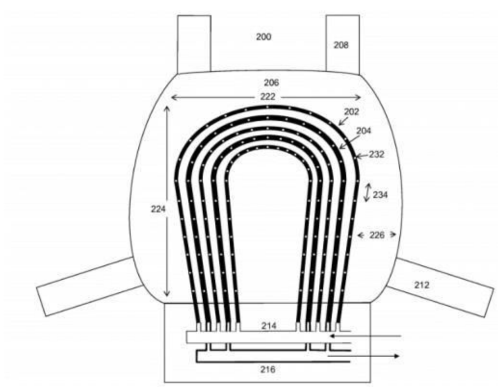


Figure 5: Sketch of the patent drawing [14] showing flexible parallel intake and exhaust hoses used for air circulation.

The figure below details a small, side mounted heat-pump and desiccant pump module which can remove heat on the order of "at least 25 thermal watts" [14]. The invention specifies that the heat removed by the heat-pump (308) is then dissipated externally by an un-specified heat-exchanger. This invention is a step in the correct direction for the design requirements of our device. However, the dissipation of heat would have to be orders of magnitude more than the mentioned 25 thermal watts**.** This is evidenced from the generated metabolic heat transfer of a resting human (70-110 W) and a human walking (280-350 W) [15]. Additionally, no external heat-exchanger is mentioned which would be a very important component of the design to dissipate the high thermal wattage we estimate necessary to cool a user in high-temperatures prevalent in West Africa. Finally, to dissipate this amount of heat, a battery power-supply would most likely not be sufficient when keeping in line with our weight design requirements.

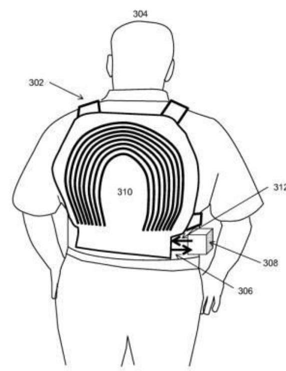


Figure 6: Sketch of the patent drawing [14] showing location of mounted heat-pump and desiccant pump module on suit.

Body temperature control system [16]: This invention details a liquid-interface cooling system in which the user wears a vest with cool liquid circulation to remove heat. Externally there is a box which contains a compressor-refrigerant cooling system and heat exchanger to cool the liquid circulating through the user's vest. As shown below from the patent drawings [16], the user wears a liquid cooled vest that interfaces with a heat exchanger to remove heat from the body.

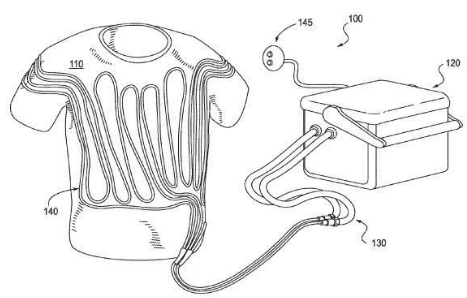


Figure 7: Sketch of the patent drawing [16] demonstrating the liquid cooled vest and heat exchanger interface.

This design uses a liquid cooling interface that cools the user, which is unable to remove moisture from the air like an air-based cooling system. Our device would ideally be able to remove moisture from the air as well as heat, to aid in the body's natural evaporative-sweat based cooling.

Personal Body Ventilation System [17]: This system incorporates a battery-powered blower combined with a disposable vest to control the comfort of the user. The circulated air may be heated or cooled based on the user's comfort requirements. This patent claims that this product increases the user's comfort by circulating the air within the suit, allowing the body's cooling by sweat evaporation to work. From the patent drawing below, the suit is sketched and shown how it would be used.

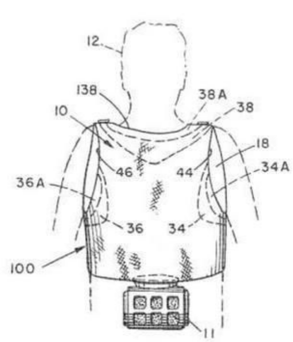


Figure 8: Sketch of the patent drawing [17] showing the battery-powered blower attached to the disposable vest.

Additionally, the next patent drawing below shows a more detailed sketch of the internal fan components that would drive the air circulation within the suit.

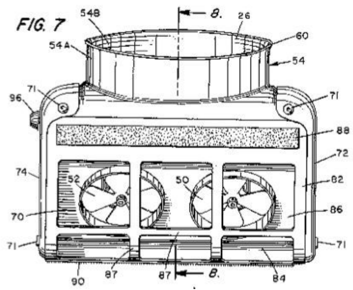


Figure 9: Sketch of the patent drawing [17] depicting a detailed view of the battery-powered blower components.

However, once a high humidity level is reached in the suit, this product would stop working because the recirculating air would be unable to absorb any more water and the user's comfort would decrease. There is also no active cooling system built into this device, which ours would ideally have to maintain the highest levels of comfort.

Cooling Sweatband [18]: This patent aims to cool a user in a significantly different manner than any of the previously mentioned suits. Rather than cooling the core of the body with a wearable vest or suit, this invention relies on pulse point cooling. Pulse point cooling uses the body's natural cooling methods and amplifies them by cooling the points of the body where the capillaries and veins are closest to the surface of the skin [18]. By cooling the blood at these pulse points, this allows for a more efficient and concentrated cooling effort. The patent claims a sweatband that wraps around the forehead and wrists that doubles as a pouch for storing ice packs. The product is also claimed to be made of chamois leather, a highly absorbent material that will wick away sweat at the same time as cooling the body. As shown in the figure below, the invention is strapped onto a wrist, which is one of the body's pulse points.

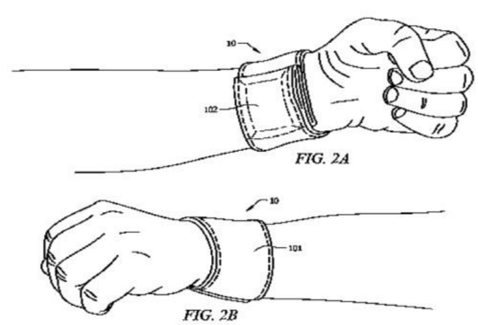


Figure 10: Sketch of the patent drawing [18] showing the attachment of the cooling sweatbands on the wrists (pulse points).

This invention has the benefit of being small and tucked away underneath the PPE, as well as having a low manufacturing cost. However, this product relies on the use of ice packs which would need to be refrozen after each use. This product also does not remove moisture from the contained air. The other drawbacks to this are that there would need to be a refrigeration system on site at the hospital and there would need to be a large number of ice packs in circulation at all times.

USER REQUIREMENTS AND SPECIFICATIONS

Attending the Ebola Design Charette provided a greater understanding of the conditions HCWs deal with in treating this disease. These working conditions were simulated during the preliminary testing phase. A list of user requirements was created (Table 1) in order to properly address their needs. It was determined the most important user requirements were extending comfortable personal protection equipment (PPE) suit use-time, compatibility with current personal protection protocol, and being able to function is hot climates such as ones in Africa.

Each of the determined user requirements was translated and compiled into a list of engineering specifications. The comfort of the suit and the inability to wear it for long periods of time is one of the prominent issues faced by HCWs wearing PPE [5]. Wearing a PPE suit for longer than 30-40 minutes under these conditions becomes unbearable for the worker [6]. This was confirmed during the preliminary testing (Figure 2, page 4). Being able to increase the working time of the HCWs in the PPE by at least 50% will lead to greater productivity and a reduced risk for exposure to EVD. Safety protocol is a serious matter in dealing with EVD. The detailed procedure that must be followed during donning and doffing is vital to protect the worker from infection, where each process can take as long as 20 minutes [5]. To minimize additional donning and doffing time, a limit of 5 minutes is placed on donning and doffing our design solution. The design solution must be able to meet the requirements above in the African environment where temperatures of 110°F are common [4].

To ensure that the designed product will not add to the current discomfort experienced by the HCW, a weight limit of 10 pounds is imposed, an acceptable typical backpack weight. The current state-of-the-art technology for these disposable PPE suits (3M Protective Coverall 4510) is offered by the manufacturer 3M [12]. Having a product that is compatible with the current technology will ease the transition to use in the field. Lastly, the proposed product must be compatible to accommodate various body sizes and types. Currently 3M offers size ranges of S-4XL for current disposable PPE suits [12]. Our design solution should work with these suit sizes, ensuring compatibility with HCWs of varying body sizes and types.

Table 1: Summary of determined user requirements and engineering specifications for project.

User Requirement	Relative Priority	Source	Specification	Rationale
Extend comfortable PPE suit use-time	High	4,8,10	Comfortable suit use-time > 50%	Increase worker productivity, decrease risk of exposure
Current personal protection protocol compatibility	High	5,6	Increase donning/doffing < 5 minutes	Ensure usage of design solution
Hot climate functionality	High	3,4	Meets all requirements in 110°F	Functional in West African climate
Portable on user's body	Moderate	6,8	< 20 lbs.	Limits strain on body
Disposable full-body PPE suits compatibility	Moderate	12	Compatibility with 3M Protective Coverall 4510	Works with current PPE suits
Various body size/type compatibility	Low	12	Compatibility with 3M sizes (S-4XL)	Does not limit on-site staff usage

FUTURE WORK

Based on our benchmarking and product research, we have identified technologies to investigate further as an application to our design solution.

Air Cooling

In order to have an efficient air cooling system, the heat must be transferred efficiently throughout the body. Air cooling can be characterized by a simplified convection heat transfer equation [19]:

$$Q = h * A * \Delta T \qquad \text{Eq. 1}$$

where Q is the heat transfer rate [J/s], h is heat transfer coefficient [W/m^2*K], A is cross-sectional area perpendicular to heat flow [m^2], and ΔT is change in temperature between body surface and the air. Relying on empirical data for an air speed range of 10-15 m/s, the heat transfer coefficient varies from 30-35 W/m^2*K [20]. Water however, has a higher heat transfer coefficient range from 50-1000 W/m^2*K [20]. Thus we can conclude that air is not as effective as circulating water in cooling the human body. This approach also tends to be a more bulky suit in order to have proper air circulation space. However, an advantage for air-cooling is the ability to remove water saturated air from within the suit.

Circulating Liquid-Cooling Systems

This technology has proven to be currently the most effective method for providing microclimate cooling for the skin and ultimately the body [15]. The methodology behind this technology consists of using protective clothing that has imbedded in it an integral network of microtubes (circulation channels) where the fluid can flow through. A disadvantage of this suit is the inability to remove moisture from the air and directly remove moisture from the skin. Ambient air humidity leads to condensation of water vapor on the heat exchange tubes leading to inefficiency for the heat removal system as a whole [15]. Moisture on the user's skin adds to the current discomfort that comes with just wearing the suit.

Evaporative Cooling

Evaporative cooling becomes prominent as the temperature gradient between the skin and the environment is reduced [15]. The human body is able to transfer approximately about 2400 kJ of heat energy to the environment for each liter of sweat [15]. The biggest drawback to not being able to fully utilize such natural tendencies of the body for cooling purposes is due to being enclosed inside the suit. Wearing the PPE, the evaporative cooling process is slowed drastically since sweat is trapped inside the garments and can't be removed. This leads to significant reductions in the capacity of the evaporation to remove heat energy [15]. However, there are several type of cooling methods that facilitate evaporative cooling. For example, there are desiccant systems, dehumidifying systems, and air ventilation systems. Any system, such as these, that is able to remove moisture from the air aids in the body's natural evaporative cooling process using sweat.

Phase Change Cooling

Advancements in this technology have allowed for replacing traditional ice packs that used to be stored in PPE pouches with a new chemical mixture (hexadecane and tetradecane) that offers a better cooling effect to the body [21]. The problem with the ice packs was that the effective cooling decreased with time until it all melted. The pack then became a thermal insulator that brought even greater discomfort leading to overheating instead of cooling the user. With the chemical mixture, the comfort of the user is enhanced because the melting temperature can be adjusted to 42ºF - 64ºF [21]. The disadvantage is that the latent heat of fusion for both hexadecane and tetradecane is half the latent heat of fusion for water [21]. In order to obtain equivalent heat absorption capacity, this results in needing twice the mass of these chemicals when compared to the mass of water [19]. This in turn adds weight to the overall system increasing user discomfort. Additionally, obtaining PCM and cooling PCM may prove to be difficult in West Africa.

Peltier Cooling

Thermoelectric coolers (TECs), also known as Peltier coolers, are solid-state heat pumps that utilize the Peltier effect to move heat [22]. This Peltier effect is described as the cooling that occurs at a junction of dissimilar electrical conductors and semiconductors [20]. When a current is passed through a junction made up of different conductors/semiconductors, heat can be removed at the junction. Thus why it is advantageous to use a Peltier cooler to transfer heat from one end to another. Passing the current produces a heat differential of around 40°C, or as much as 70°C in high-end devices, allowing to displace heat from one place to another [22]. The amount of heat absorbed or released at the thermocouple junction is determined by Eq. 2 below [22]:

$$W = P * I * t \qquad \text{Eq. 2}$$

Where W is the amount of heat [J], P is the Peltier Coefficient (the amount of heat evolved or absorbed at the junction of a thermocouple), I is the passing current [A], and t is the time [s]. Peltier coefficient depends upon temperature and the two materials of which the thermocouple is made [20].
The effectiveness of a thermocouple is given a "figure of merit" designated as ZT. It is calculated as follows [22]:

$$ZT = \frac{S^2 * T}{r * k} \qquad \text{Eq. 3}$$

where S is the Seebeck coefficient [V/K], T is the temperature [K], r is the electrical resistance [W], and k is the thermal conductivity [W/m*K]. S, r and k are all material properties and are going to vary with choice of materials.

A Peliter cooling system could be taken advantage of due to its compact size and physical simplicity. This large temperature differential could be used to easily transfer large amounts of heat from inside the suit to outside the suit with minimal moving components.

DESIGN REVIEW 2 GANTT CHART

Table 2: Planned workload to meet Design Review 2 requirements.

	January					February											
Task	27	28	29	30	31	1	2	3	4	5	6	7	8	9	10	11	12
Design Review 1 Report																	
Based on DR1, Revise Project Requirements																	
Eljon Elezi - Develop Five Concepts																	
Zach Griftka - Develop Five Concepts																	
Shreyas Parat - Develop Five Concepts																	
Robert Self - Develop Five Concepts																	
Concept Selection																	
Perform Initial Numerical Analysis																	
Mockup Design																	
Design Review 2 Report																	

CONCEPT DEVELOPMENT

We generated multiple design concepts as potential solutions that met the user requirements and the engineering specifications outlined earlier in the design process. The motivation behind these design concepts came from benchmarking current products and recognizing their advantages and shortcomings in attempt to achieve the ultimate goal: provide sufficient cooling to the human body in PPE suits. Each team member proposed 5 unique design concepts for a total of 20 ideas (Appendix A). We named each concept using the first letter of the respective team member's name and the corresponding concept number (e.g. R1 for Rob's first design concept). All concepts were reviewed and similarities allowed us to group some concepts together. This narrowed our selection process down to 14 unique concepts (Table 3, pg. 16). The concept categories varied across several cooling technologies including evaporative cooling, phase change cooling, and thermoelectric cooling. The two main methods of heat removal from the body discussed were pulse point cooling and core body cooling.

Pulse Point Cooling

This cooling technology utilizes the human body's natural cooling system of blood circulation to move heat from the inside of the body to the surface of the skin. The pulse points are located throughout the human body where the blood circulates closest to the surface of the skin. Targeting these points directly allows for smaller surface areas of heat transfer, compared to a cooling vest. Three separate concept designs (R3, E1, and S1) utilized this approach (Appendix A).

E1 – internal-suit pulse point air-based cooling: Eljon's approach to this design attempts to target as many pulse points throughout the body as possible. It uses a heat pump that is attached to the user's waist that circulates air to and from the pulse point locations on the body. Bands that allow the passage of air are attached to the pulse points by hoses that lead back to the heat pump. Along the hose lines, as well as under the band attachments, there is a porous honeycomb feature that provides separation and avoids direct contact with the skin.

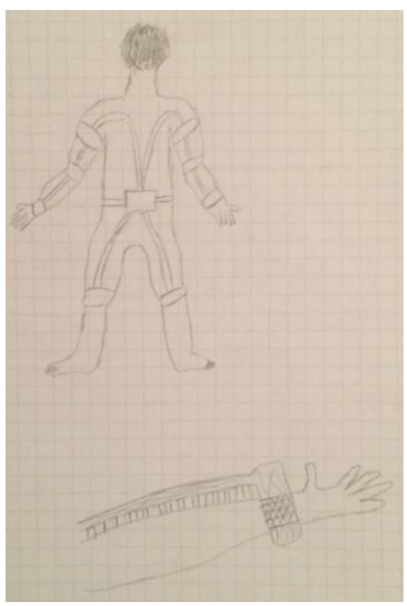


Figure 11: Schematic of E1, internal-suit pulse point air-based cooling.

R3 – internal-suit pulse point liquid-based thermoelectric cooling: Rob's idea for this cooling technology uses a thermoelectric fluid pump that circulates a cooled fluid to the wrist and leg pulse points. Fluid is carried to and from the pump by a series of hoses. Attachment to the pulse point locations is by bands that wrap around providing fluid circulation across the exterior surface area.

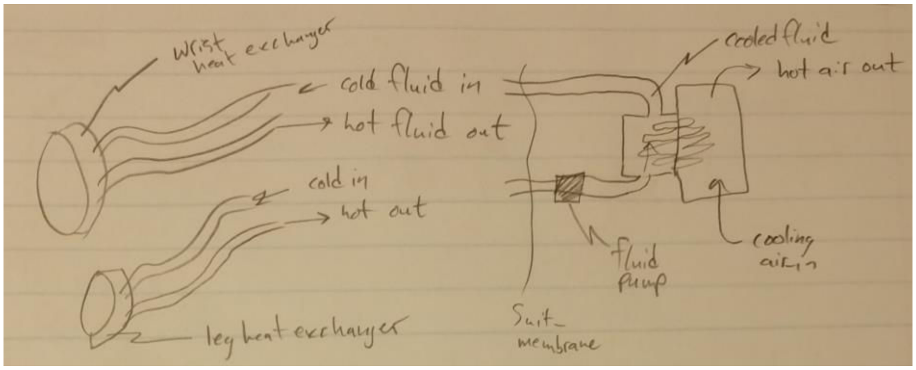


Figure 12: Schematic of R3, internal-suit pulse point liquid-based thermoelectric cooling.

S1 – external-suit pulse point thermoelectric conductive cooling: Shreyas' concept is different from the others in that it is worn outside of the PPE suit. The user wears bands of thermoelectric coolers around pulse points on their arms and legs. The cool side is pressed against the PPE suit and by means of conduction draws heat from the pulse points of the body. The hot side is exposed to the external environment and heat is dissipated through conduction to the air.

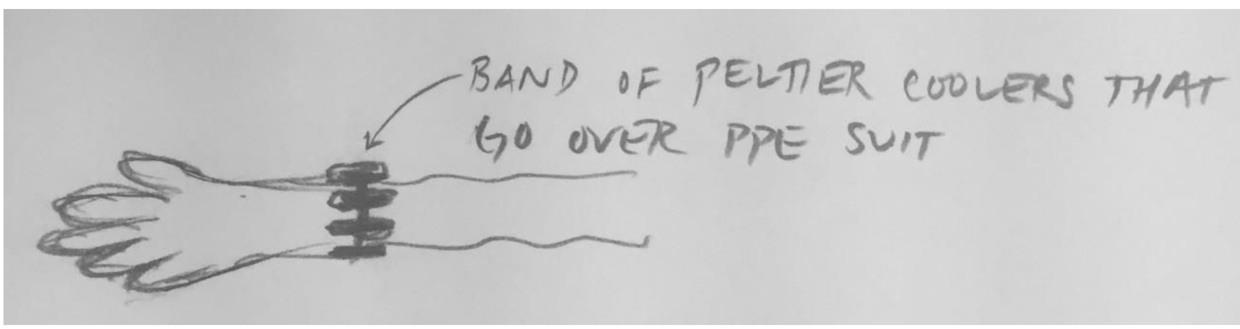


Figure 13: Schematic of S1, external pulse point thermoelectric conductive cooling.

Core Body Cooling

This technology was the most popular among the group members with each member incorporating it in at least one of their five designs. These concepts focus on cooling the user's core body using air-based, liquid-based, and phase change cooling methods. Four separate concept designs (R1, R4, E2, and S2) incorporated this technology (Appendix A).

R1 – internal-suit air-based thermoelectric cooling: For this idea, Rob uses an air-based cooling vest with a thermoelectric heat pump. The cooling vest and heat pump are integrated in a one-piece design, which is worn inside the suit. The vest contains channels that supply cool air to the body and remove hot, moist air to be cooled and recirculated by the heat pump. The hot side of the heat exchanger is mounted inside the suit and is cooled by air ducts and a fan blowing air from outside the suit.

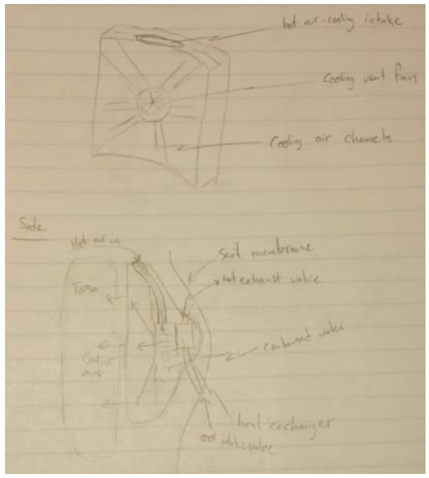


Figure 14: Schematic of R1, internal-suit air-based thermoelectric cooling.

R4 – internal-suit liquid-based thermoelectric cooling: This design utilizes a cooling vest with an integrated thermoelectric cooler and heat sinks worn by the user inside the PPE suit. The vest circulates fluid cooled by a thermoelectric cooler through copper tubing in contact with the user. The hot side of the thermoelectric cooler is cooled by external-suit air circulated through air ducts by a fan over the hot side heat sink.

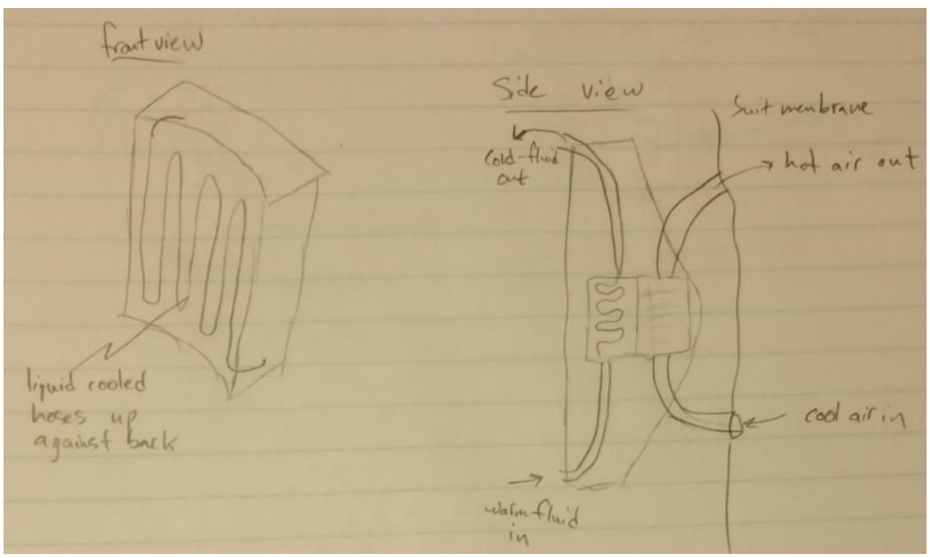


Figure 15: Schematic of R4, internal-suit liquid-based thermoelectric cooling.

E2 – integrated-suit conductive thermoelectric cooling: Eljon's idea utilizes many thermoelectric coolers attached to a belt to be worn around the user's waist. This concept is integrated into the suit material having components both inside and outside the suit. The cool side of each cooler (inside the suit) contacts the user's body, conducting heat away from the user. The hot side of each cooler is external to the suit and is enclosed in a cover to prevent contamination. This cover contains storage spaces for ice packs that act as heat sinks for the thermoelectric coolers. The cover can also be detached for disinfecting.

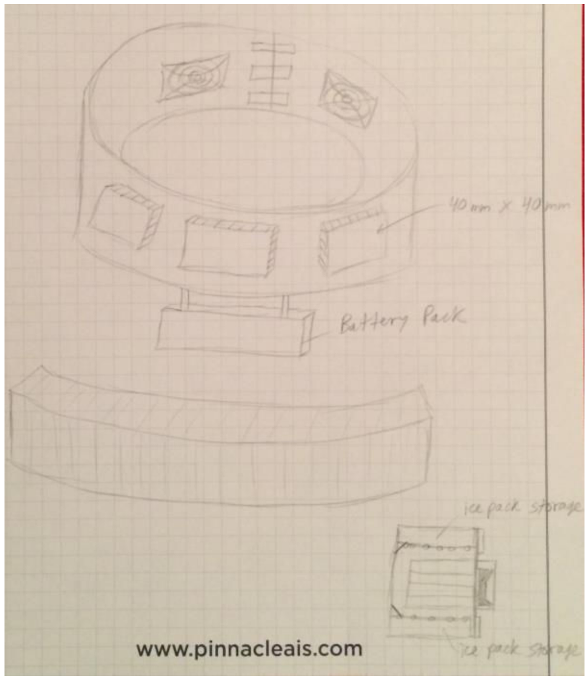


Figure 16: Schematic of E2, integrated-suit conductive thermoelectric cooling.

S2 – external-suit conduction-based thermoelectric cooling:
This concept works using thermoelectric coolers pressed against the back of the user, but from the outside of the suit. This allows for a simple one-piece backpack with simple cooling for the hot side of the thermoelectric coolers. The hot side can be cooled by a fan blowing air over it, or using replaceable ice packs. This concept would be contained within an easy to disinfect plastic backpack.

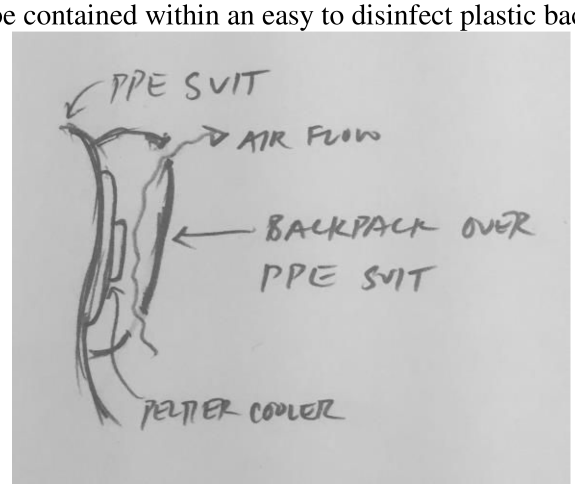


Figure 17: Schematic of S2, external-suit conduction-based thermoelectric cooling.

CONCEPT SELECTION

After developing 20 different concepts between the members of our design team, we broke down our user requirements/engineering specifications into weighted criteria to rank our initial concepts. We then grouped similar concept ideas and evaluated a total of 14 unique concepts according to these weighted criteria. Using these weighted scores, we quantitatively narrowed our concepts to the top three ranking concepts. After deliberation on the merits of the top three concepts, we decided on our final design solution.

Pugh Chart

To quantitatively determine the best solution from our concepts, we used a Pugh chart with weighted metrics to score all concepts. We rated each metric with a weight from 1-5 with a weight of 5 indicating 'most important.'

Metrics: We used the following metrics and weighting to assess the feasibility and potential for our designs:

- **Heat Transfer Capacity** – We determined this to be the most important metric to meeting our design requirement of "Extend comfortable PPE suit use-time by >50%." We agreed heat removal from the body is the most important characteristic to increase time of comfort in the suit. Therefore, we weighted this metric as a 5.
- **Dehumidification** – We speculated that dehumidification of the suit could lead to a more comfortable suit micro-climate for a longer period of time. However, because of our uncertainty with the relationship between suit humidity and comfort of the user, we weighted this metric a 3, slightly less important than "Heat Transfer Capacity."
- **Existing Technology** – After researching currently patented technology we wanted to make sure our design solution differentiates itself from existing technologies aimed at cooling users in enclosed suits. This metric indicates similarity of the concept to existing technologies, with a higher score indicating a completely unique design. We weighted this metric at a 3 as not to infringe on existing ideas.
- **Portability (weight)** – Our user requirements indicate a low weight as a priority for our solution to allow for easy and strain-free use in the hot environments of West Africa. Due to the importance of usability of this device in hot environments we rated this metric as a 2. This indicates importance, however it is not as important as heat transfer or other highly weighted metrics. We agreed the device should be lightweight, however if it can't adequately cool a user, it fails as a solution to the problem.
- **Complexity + Manufacturability** – As is a consideration with all products, manufacturability and complexity have significant implications on cost and ease of use. We determined this metric to be moderately important, however not a key design requirement. We agreed on a weight of 2 for this metric.
- **Power Consumption** – As electricity availability in West Africa can sometimes be limited, we determined this metric to be relevant to our design solution. However, we agreed that while this metric is a consideration, most designs which have high heat transfer capacities will have larger power requirements. Additionally, electricity is a universally available power source as many devices can be used to generate it (e.g. solar panels, fuel-powered generators, power plants, etc.). Therefore we agreed to weight this metric as a 1, of least importance to our design decision.
- **Cost** – As with all products cost is a significant player in the availability of a product and feasibility as a design solution. We determined this to be relevant in our design selection, however we agreed the $400 course budget would act as a good limitation in the cost of our final design solution. Therefore we agreed on a weight of 1 for this metric.

Pugh chart development: After deciding on relevant metrics from our User Requirements and assigning appropriate weights to all of the metrics, we went through and scored each design concept as shown below in Table 3 (pg. 16).

Table 3: R4 was chosen as our final design solution as shown in our concept Pugh chart.

	IDEAS	Heat Transfer Capacity	Dehumidification	Exisiting Tech.	Portability (weight)	Complexity + Manufacturability	Power Consumption	Cost	TOTAL
	-2, -1, 0, 1, 2 scoring system	5	3	3	2	2	1	1	
R1	Internal-suit air-based thermoelectric cooling	1	1	1	-1	-1	-2	-2	3
R2	External-suit air-based thermoelectric cooling	1	1	1	-1	-2	-2	-2	1
R3	External-suit pulse point liquid-based thermoelectric cooling	0	-2	2	-1	-2	-2	-1	-9
R4	**Internal-suit liquid-based thermoelectric cooling**	**2**	**-2**	**2**	**-1**	**-1**	**-2**	**-2**	**2**
R5	External-suit liquid-based thermoelectric cooling	2	-2	-2	-1	-2	-2	-2	-12
E3	Sweat collection vest	-2	-1	0	1	2	2	2	-3
E5	Internal-suit head and neck phase-change cooling	0	-2	-2	0	2	2	0	-6
Z1	Internal-suit forearm band phase-change cooling	0	-2	-2	-1	2	2	0	-8
Z2	Dyson-like air fan for the neck	-2	-1	2	-1	-1	0	-1	-12
Z3	Internal-suit liquid-based recycled water cooling	-1	-2	-2	-2	0	-1	0	-22
Z5	Internal-suit air-based recycled air and dessicant vest	-2	2	-1	0	0	0	-1	-8
S1	External-suit pulse point liquid-based thermoelectric cooling	0	-2	-2	2	1	-2	-2	-10
S2	External-suit conduction-based thermoelectric cooling	0	-2	2	-1	-1	-2	-2	-8
S4	External-suit air-based phase-change cooling	1	-2	2	-2	0	0	0	1

Top design assessment: After assigning scores of -2, -1, 0, 1 or 2 to all of our concept ideas ranking them against each other, we multiplied these scores by the weight of the metric being scored. These weighted scores were then summed to determine the overall score for each concept idea. We then looked at the top three design ideas according to our scoring metrics to determine our final design idea.

- **(1st) R1 internal-suit air-based thermoelectric cooling** – This concept utilizes a thermoelectric cooler which can generate high amounts of heat transfer. However due to the air-based cooling system (and air's low specific heat) this concept was given a +1 for "Heat Transfer Capacity." Due to this concept's air-based cooling system, it would have to potential to condense out small amounts of water and dehumidify the air, thus we rated it +1 for "Dehumidification." This concept was very unique, however slightly related to a patent we found, therefore we rated it a +1 for "Existing Technology." This concept would be somewhat heavy due to a large heatsink and electronic components, therefore we rated it a -1 for "Portability (weight)." This concept utilizes a one-piece design which is simpler than the two-piece concepts we had, however the heatsinks and vest design would be somewhat complex. Therefore we rated it a -1 for "Complexity + Manufacturability." Due to the thermoelectric cooler, this device would use a lot of electricity, we rated it a -2 for "Power Consumption." The cost of this device would be one of the most expensive of all of our devices. We rated it a -2 for "Cost."
- **(2nd) R4 internal-suit liquid-based thermoelectric cooling** – This concept utilizes a thermoelectric cooler which can generate high amounts of heat transfer. Due to this system's liquid-based cooling system, it can also transfer larger amounts of heat from the body than an air-based cooling system. Therefore, this concept was given a +2 for "Heat Transfer Capacity." Due to this concept's lack of air-based cooling system, it would have no ability to condense out water from the air in the suit, thus we scored it a -2 for "Dehumidification." This concept was completely unique from any patent we found and existing products that are sold. We assigned it a +2 for "Existing Technology." This concept would be somewhat heavy due to a large heatsink and electronic components, therefore we rated it a -1 for "Portability (weight)." This concept incorporates a one-piece design which is simpler and easier to use, however the heatsinks and

vest design would be somewhat complex. We rated this concept a -1 for "Complexity + Manufacturability." Due to the thermoelectric cooler, this device would use a lot of electricity, we rated it a -2 for "Power Consumption." The cost of this device would be one of the most expensive of all of our devices. We rated it a -2 for "Cost."

- **(3rd) S4 external-suit air-based phase change cooling** – This concept uses the energy absorbed from ice melting to cool, which can generate high amounts of heat transfer. However due to the system being air-based and air's low specific heat we rated this concept +1 for "Heat Transfer Capacity." Due to this concept's liquid heat exchanger and lack of design for condensing moisture from the air, we agreed on a rating of -2 for "Dehumidification." This concept is very unique from existing patents and technology, therefore we rated it a +2 for "Existing Technology." This device would be very heavy as ice and water would be carried on the users back. This almost makes the idea un-usable for our application and thus we rated it a -2 for "Portability (weight)." This device is somewhat simple compared to our thermoelectric cooler designs however, somewhat more complex than the simple Phase Change based devices. Therefore we rated it a 0 for "Complexity + Manufacturability." The power consumption of this device would be somewhat low as there is only a fan consuming power, thus we rated it a 0 for "Power Consumption." The cost of this device would be somewhere in the middle of our concept ideas and thus we rated it 0 for "Cost."

Final concept selection: Based on the scoring methods discussed above and group deliberation over the top three designs determined by our Pugh Chart, we decided on "R4 internal-suit liquid-based thermoelectric cooling" as our final design for several reasons.

- **Heat Transfer Capacity** – Due to the liquid interface between the user's skin and the thermoelectric cooler we determined this design would have the highest potential for heat transfer from the user's body. By insulating this liquid-skin heat exchange from the externally hot temperatures we can maximize the amount of heat that comes from the user versus the surroundings. This is not as easy with an air-cooled vest system as an air-cooled vest would have to be larger to accommodate air channels and would be difficult to insulate from the hot external atmosphere temperatures. Additionally, the air-based system can't carry as much heat from the user's body as air has a lower specific heat capacity.
- **Existing Technology** – This device is very unique and has not been attempted before. This is exciting because it would allow us to approach this problem from a new angle that is not currently used or available to purchase.
- **Complexity of Single Piece Design** – By utilizing a one-piece design that is completely contained in the suit, the device is easier to put on, easier to manufacture and because it is inside the suit, has minimal sanitation requirements.
- **Cost, Weight and Power Consumption Considerations** – Although the cost of this concept is higher and it has higher power consumption, we determined that the potential heat transfer capacity of this device far outweighs these other considerations. Our main priority is to build a solution that fully meets our cooling requirements. After we achieve this, we can reflect back on how to reduce the cost, power consumption and weight in further stages of development.

In light of all these points, we decided this solution would give us the highest probability of meeting our most important design requirement: extending the time PPE suits can be comfortably used in West African climate.

CHOSEN DESIGN MOCKUP

Our chosen design was mocked up using a drawstring bag, sheets of acrylic plastic, foam-core board, rope, and hot glue to hold it all together. The exercise of assembling the mockup was useful in the sense that it gave us a spatial idea of what the concept actually looks like, how much space it takes up, and how the user might interact with it. This model was built to scale to give us an accurate representation of how the design would fit under our hazmat suit.

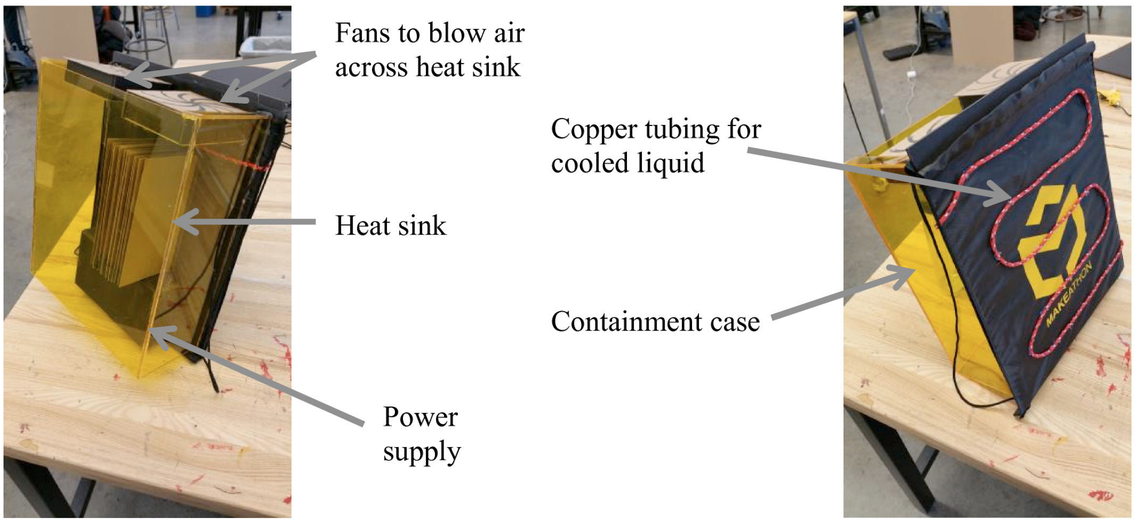


Figure 18: Labeled mockup of chosen design.

The fans, heat sink, and power supply were modeled using reference dimensions and cardboard, foam board, and hot glue. The copper tubing was modeled using rope. The layout of the tubing is not correct; it is merely a placeholder to show that we would intend it to snake along the user. The following image shows the cooling device being worn as a backpack.

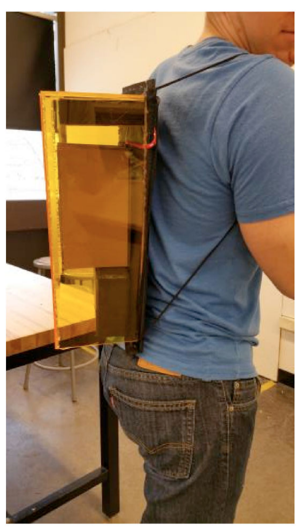


Figure 19: Mockup being worn on a user.

KEY DESIGN DRIVERS AND CHALLENGES

Our primary design specification is to increase the time HCWs can comfortably work while wearing the appropriate PPE suits by 50%. In order to meet this specification, heavy emphasis is being placed on maximizing the heat transfer away from the HCW. Specifically, we are estimating that our personal cooling system will need to remove more than 100 W of heat from the body [15].

Thermoelectric cooling offers large advantages for compactness and large temperature differentials, but is extremely inefficient. Large quantities of electrical energy are needed to power the thermoelectric coolers, which also significantly increases the amount of heat that needs to be dissipated. From preliminary analysis, our largest challenge moving forward will be removing extremely large amounts of heat from the hot-side of the thermoelectric cooler. This is made even more difficult by the high external air temperatures we are designing for.

In order to meet our primary objective, we will have to design a custom heat sink solution. A custom manufactured heat sink would be extremely expensive, so we are limited to what's available on the used industrial product market. We are quickly realizing that dissipating heat from the thermoelectric cooler requires a very large heat sink, making our device heavier. Going forward, we will need to minimize weight in all other components to offset the large weight of the heat sink. We may have difficulty meeting our weight requirements due to heavier components than anticipated.

In addition to weight limitations, we also need to be aware of high temperatures that the heat sink will be at during operation. We do not want to damage any electrical equipment, melt materials, or cause harm to the user. In the future, we will need to be very aware of the electrical power demands to implement correct wire gauging and fuses. Our design will also need to isolate the heat sink from any user interaction and ensure that the air manifold, which encases the heat sink, will perform as expected at high operating temperatures.

DESIGN REVIEW ONE CHANGES

Our original goal of 10 lbs as a maximum weight for our solution seems unfeasible because of the large size heat sink required. We have adjusted this weight to 20 lbs in the design specifications (Table 1, pg. 8) to account for heavier components than anticipated. However, after some research we believe this weight is acceptable because the average backpack weight of a 6^{th} grade student was 18.4 lbs in a study done by the New York Times [23].

DESIGN REVIEW 3 GANNT CHART

Table 4: Planned workload to meet Design Review 3 requirements.

	Feburary														
Task	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Design Review 2 Report															
Update Design Report 2 Based on Feedback															
Update Mockup Based on Feedback															
Complete Modeling Analysis for all Components															
Finalize Specs on Parts (Heatsink, pump, etc)															
Create Initial CAD Design for all parts															
Create Manufacturing Plans for all parts															
Design Review 3 Report															

CONCEPT DESCRIPTION

The main components of the chosen concept are a thermoelectric chip, a cold side liquid heat exchanger, a water pump, a hot side heat sink, two cooling fans, and a power supply. The entire concept is mounted on a surface, which is in turn mounted onto the back of an insulated vest.

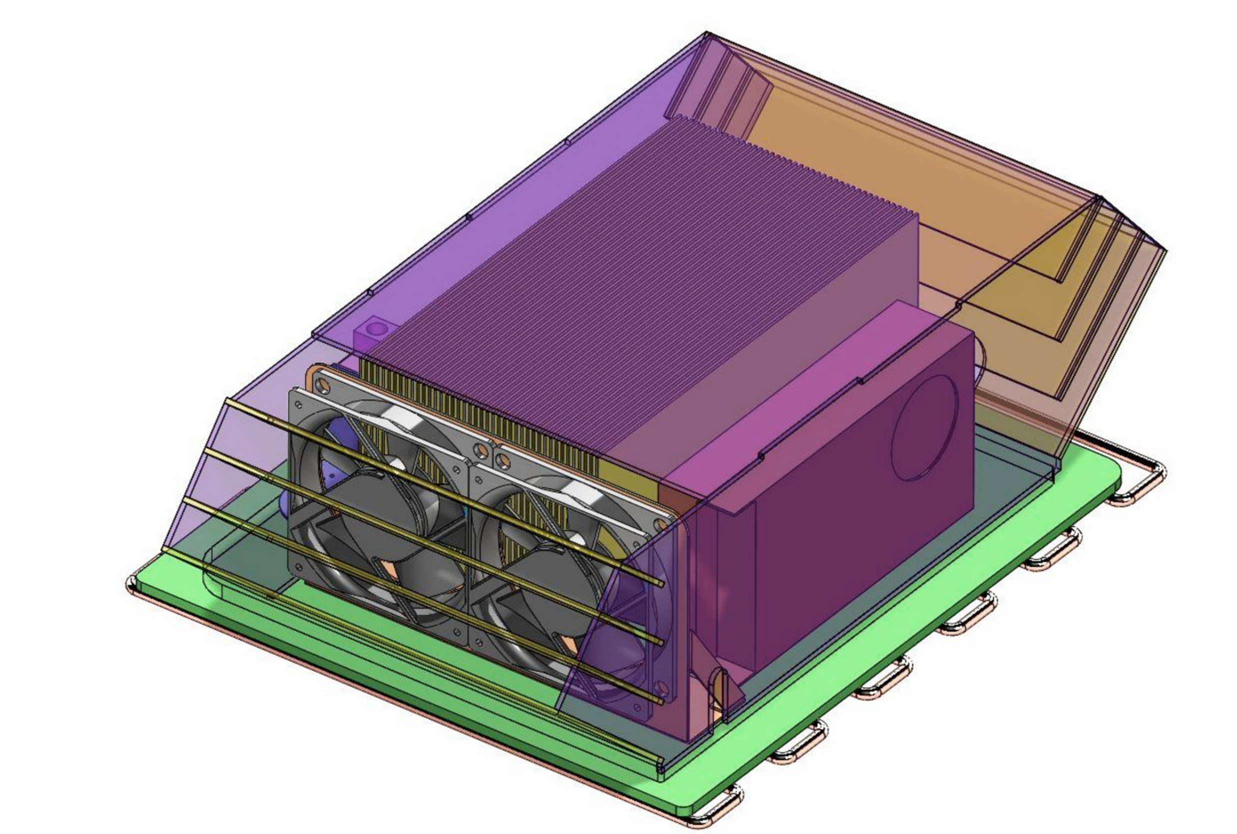


Figure 20: Isometric view of the thermoelectric cooling device.

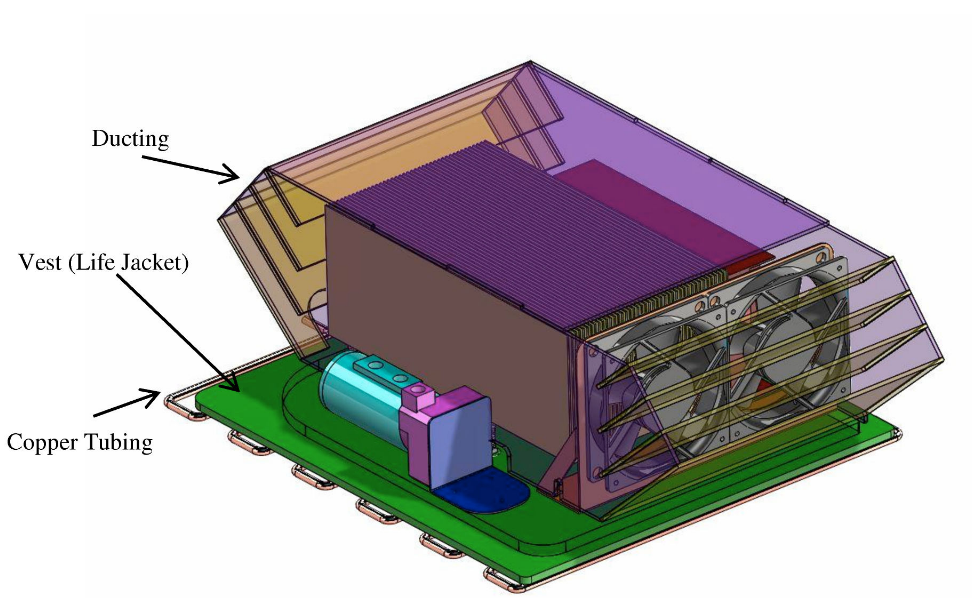


Figure 21: Second isometric view highlighting the other side of the thermoelectric device.

The first isometric image shows the majority of the components mounted onto a back plate that is secured onto the back of the user's vest. The vest is made of an insulating material so that any heat generated by the device does not transfer back to the user, which would reduce the device's effectiveness. The heat sink and power supply are mounted in this manner to allow air to flow over both components. It is necessary for the heat generated by the power supply to be dissipated; otherwise the unit could sustain damage and fail to operate. Seen in Figure 21 (pg. 21), the cool side coolant pump and the coolant reservoir are mounted in a separate part of the ducting. This keeps the coolant as distant from other heat sources as possible, preventing the device from having to do extra work to remove extra heat added to the liquid by other sources such as hot air or the hot heat sink.

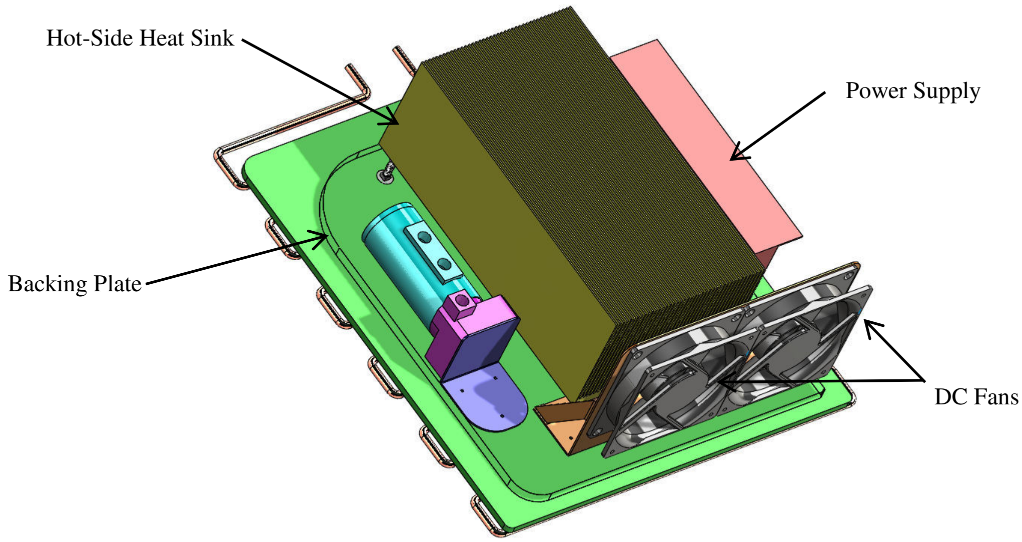


Figure 22: Isometric view without the ducting.

Figure 23, below, shows a top view of the device, as it would be worn on a user. The majority of the components are mounted longitudinally, thereby reducing the user's discomfort of wearing the pack.

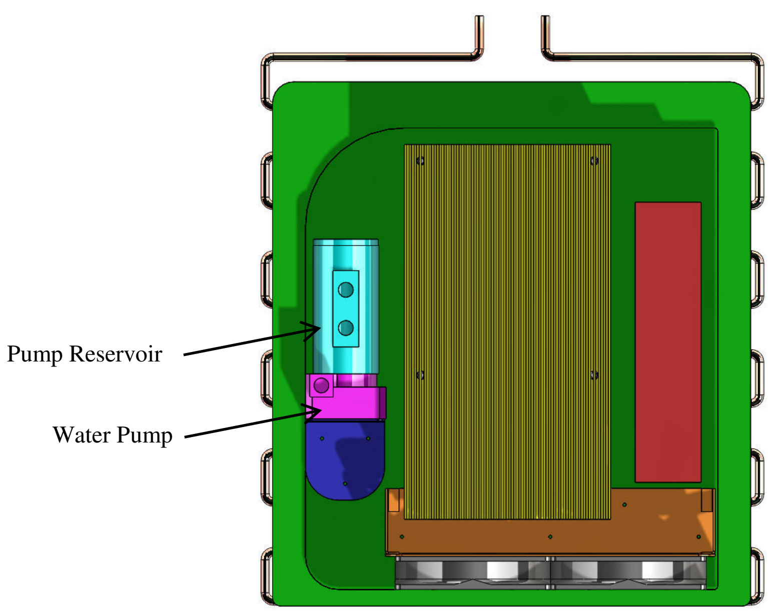


Figure 23: Top view without the ducting.

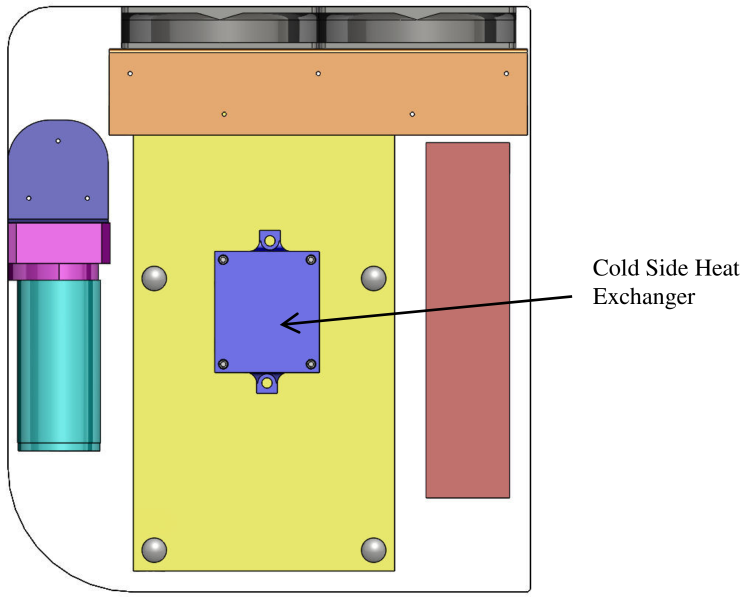


Figure 24: Bottom view without the ducting, vest (life jacket), and copper tubing.

In Figure 24, the back of the device is shown with the insulating vest removed from the image. Most significant is the cold side heat exchanger. The hidden thermoelectric chip is placed in between this component and the heat sink. The liquid used as the coolant is water. The heated water coming from the body is pumped through snaking channels inside of the cold side heat exchanger and the heat is transferred to the hot side of the chip, to be drawn away using the heat sink and the fans.

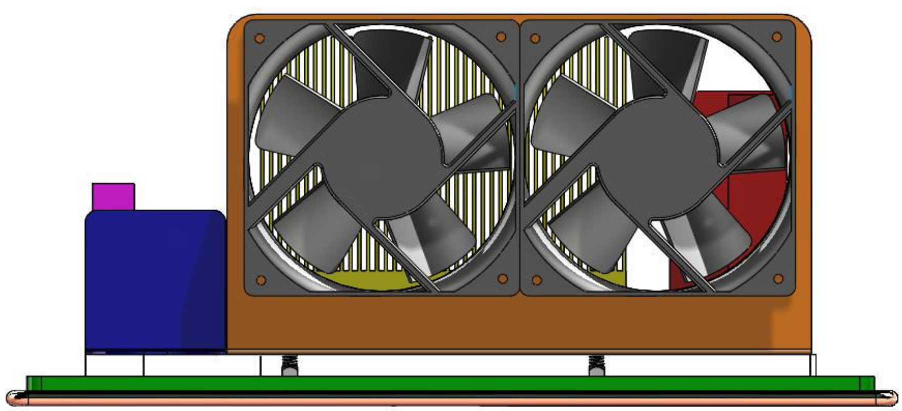


Figure 25: Front view without the ducting.

In Figures 25 and 26, the profile of the heat sink is clearly visible. This heat sink is large, but we chose this size in order to test the maximum heat transfer achievable with this device. The thermoelectric cooler is visibly stacked in between the cold side heat exchanger and the heat sink in Figure 26.

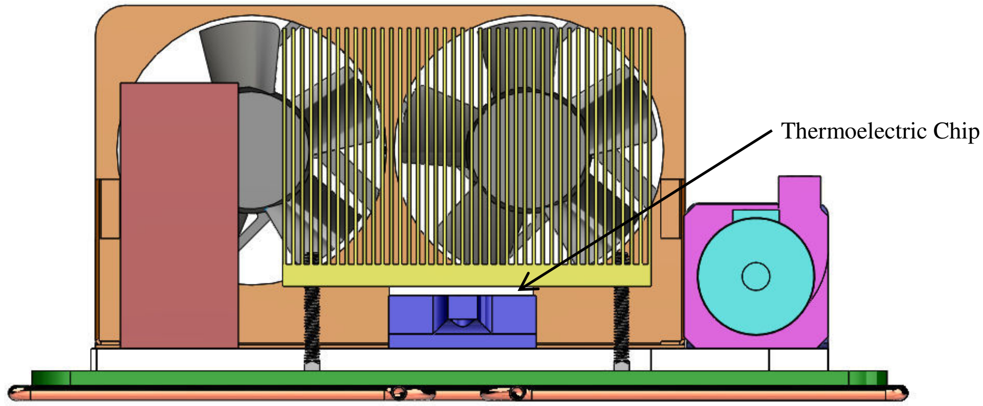


Figure 26: Back view without the ducting.

Figures 27-31 include exploded views of the entire assembly (Figure 27) and different subassemblies. Seen below, all of the hardware is mounted to the backing plate, which comes together with the ducting and the vest/tubing to complete the prototype.

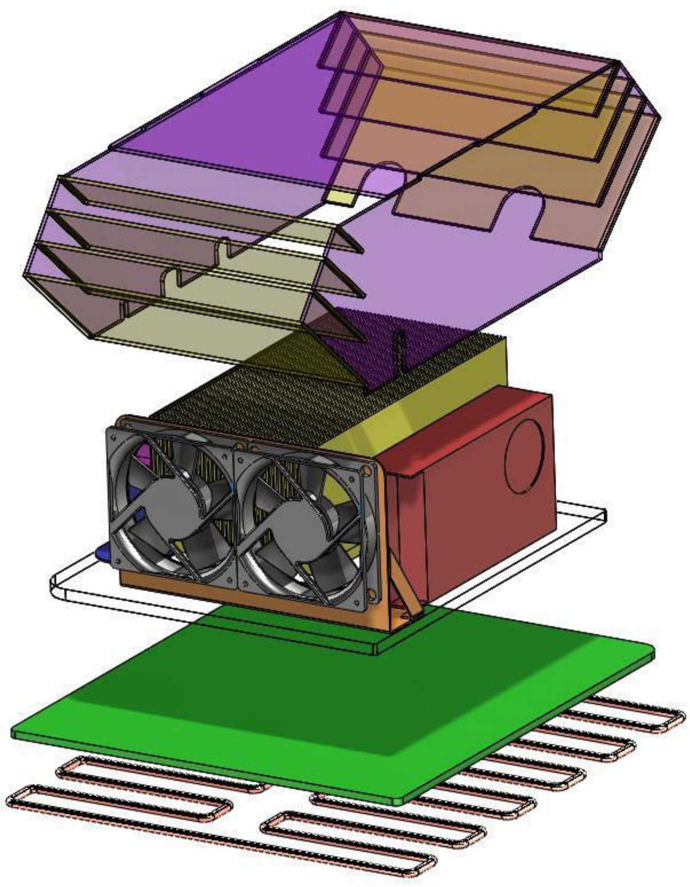


Figure 27: Exploded view of the major subsystems; ducting, hardware, and vest/tubing.

Figure 28 (pg. 25) shows the most complex subsystem, the hardware, in an exploded view to illustrate all of the major components that are mounted to the backing plate.

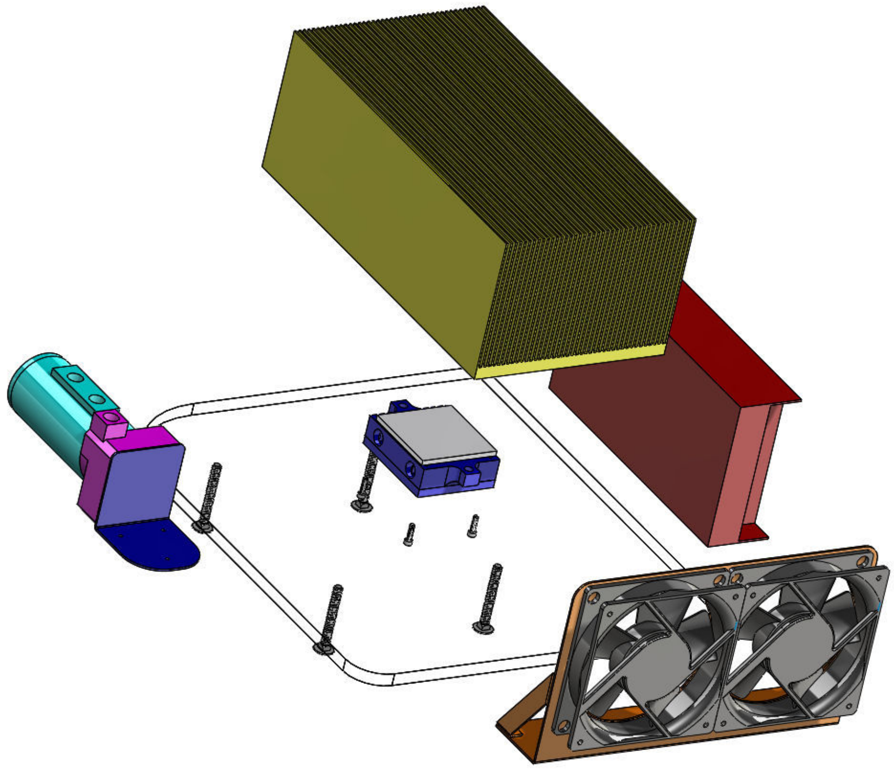


Figure 28: Exploded view of the hardware subsystem.

Figure 29 below shows the different components that make up the water pump assembly: pump reservoir and cap, the pump itself, and the mounting bracket.

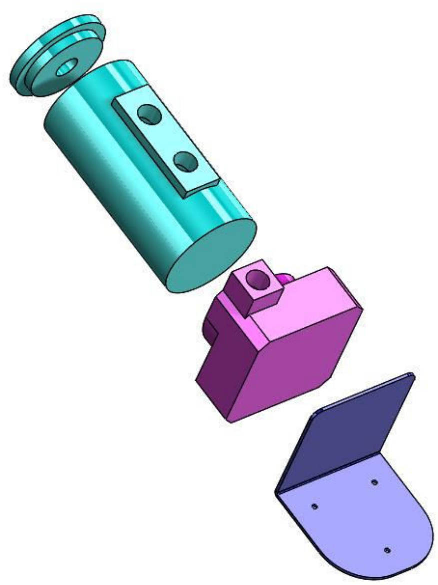


Figure 29: Exploded view of the water pump assembly.

The two DC fans are mounted to the fan bracket, which is structurally supported with two supporting arms that are riveted to the main bracket.

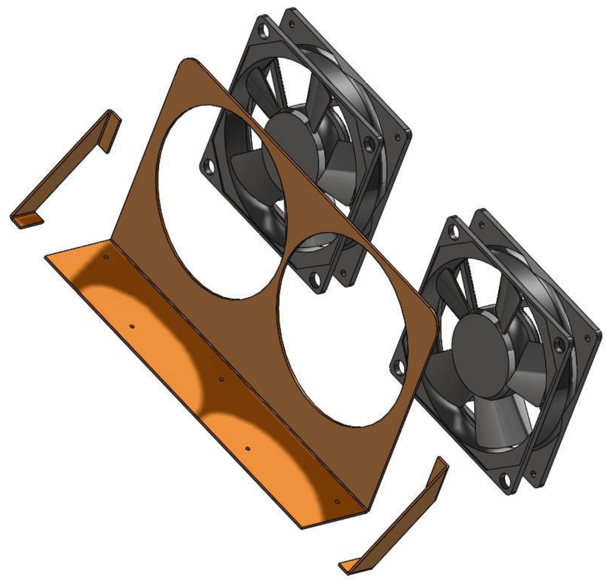


Figure 30: Exploded view of the DC fan assembly.

The cold side heat exchanger is sealed with an epoxy between the top plate and the channeled body. The thermoelectric chip is compressed between the two heat exchangers and thermal paste is used on the surfaces to reduce thermal contact resistance.

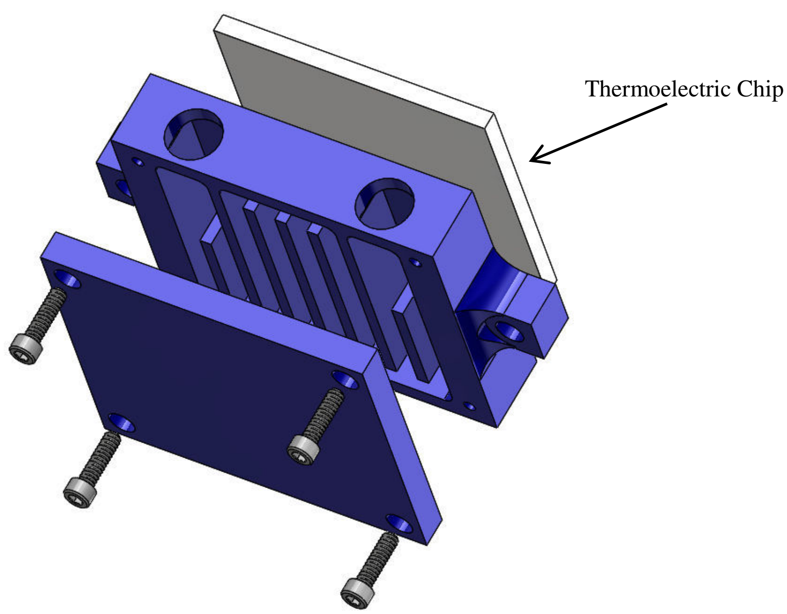


Figure 31: Exploded view of cold side heat exchanger assembly.

ENGINEERING ANALYSIS

The key drivers of our design are the heat transfer to and from the thermoelectric cooler, which is where we focused our preliminary analysis. Part of this analysis was creating the theoretical models for heat transfer with conduction and convection, as well as empirical testing to verify our key design drivers.

Key Design Drivers and Challenges

As stated before, our primary design driver is the successful heat transfer of our system, which will increase the amount of time comfortably spent in the PPE worn in extreme West African climates. Specifically, we need to design our system so that (1) sufficient heat can be removed from the hot side of the thermoelectric cooler with an attached heat sink, and (2) sufficient heat can be removed from the user's skin (> 100 W) to significantly increase time in the suit. Simple heat transfer principles, applied for our situation, have driven important design decisions we have faced. Specifically, our analysis has guided our selection in heat sinks (size), cooling fans (speed capability), water pump, tubing material, as well as the liquid medium used in our system (water). Our theoretical and empirical analysis details the estimated criteria that we need to meet in our design.

Theoretical Model (Hot-Side Heat Transfer Model)

In order to estimate the amount of heat our hot-side heat sink could transfer away from the thermoelectric cooler in our hot climate conditions, we developed a heat transfer model to estimate the heat transfer due to conduction from our hot side heat sink. We compared various geometry used by industrial heat sinks we found available online and compared their ability to transfer heat. We also compared different fan configurations and assessed their ability to move air across our heat sink. The MATLAB script used to perform these calculations is listed in Appendix B.

We assumed the heat sink was rectangular with width (a), length (w), height (L), fin number (N) and fin thickness (l). We used provided fan flow rates from the manufacturer in cubic feet per minute (FanFlow), assumed thermoelectric cooler hot side temperature based on the datasheet (BaseT), used ambient air temperature of our surroundings (Tinf), ducting enclosure for the fans with width (EnclosureW) and height (EnclosureH). From the enclosure size and fan flow we calculated the air speed across the heat sink (AirSpeed). We used constants at standard temperature for conductivity of air (k_f), air viscosity (v_f) and conductivity of aluminum (k_s).

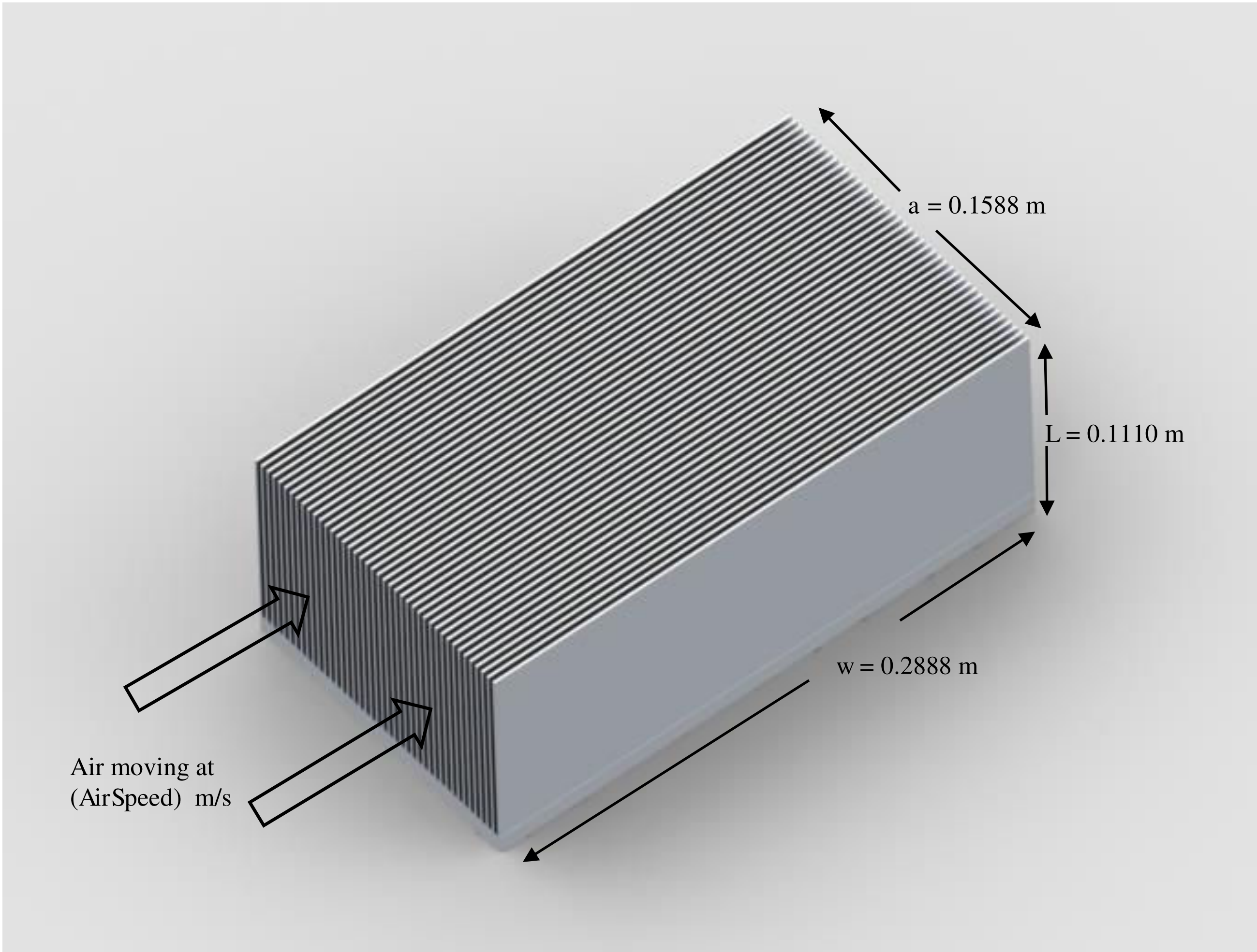


Figure 32: Geometric layout of our chosen heat sink and airflow parameters.

We first calculated the speed of the air flowing over the fins of the heat sink as show in Equation 4.

$$AirSpeed = \frac{FanFlowVolume\left(m^3/_s\right)}{EnclosureW*EnclosureH} \quad \text{(Eq. 4)}$$

We then calculated the Reynolds number for the flow as shown in Equation 5.

$$Re = \frac{AirSpeed*w}{v_f} \quad \text{(Eq. 5)}$$

Next we calculated the Nusselt number for the flow based on whether the flow was laminar ($Re < 5 \times 10^5$) or turbulent ($Re > 5 \times 10^5$) as show in Equations 6 and 7.

$$Nu\ (laminar) = 0.664 * Re^{1/2} * 0.69^{1/3} \quad \text{(Eq. 6)}$$

$$Nu\ (turbulent) = (0.0378 * Re^{4/5} - 871) * 0.69^{1/3} \quad \text{(Eq. 7)}$$

We then calculated for the geometric fin parameters of the heat sink as shown in Equations 8-12.

$$L_c = L + l/2 \quad \text{(Eq. 8)}$$

$$P_{ku} = 2w + 2l \quad \text{(Eq. 9)}$$

$$A_k = w * l \quad \text{(Eq. 10)}$$

$$A_{ku} = P_{ku} * L_c \quad \text{(Eq. 11)}$$

$$A_b = a * w - N * A_k \quad \text{(Eq. 12)}$$

We then calculated the fin parameter m (Eq. 13) which is used in calculating the fin efficiency η_f.

$$m = \frac{P_{ku}\frac{Nu*k_f}{w}}{A_k k_s} \quad \text{(Eq. 13)}$$

We then calculated the fin efficiency for the heat sink in Equation 14.

$$\eta_f = \frac{\tanh(mL_c)}{mL_c} \quad \text{(Eq. 14)}$$

Next we calculated the average surface-convection resistances for the bare surface of the heat sink ($R_{ku,b}$) and the fin ($R_{ku,f}$) in Equations 15 and 16.

$$R_{ku,b} = \frac{w}{k_f\ Nu\ A_b} \quad \text{(Eq. 15)}$$

$$R_{ku,f} = \frac{w}{k_f\ Nu\ A_{ku}\ \eta_f\ N} \quad \text{(Eq. 16)}$$

We then calculated for the overall thermal resistance of the heat sink in Equation 17 given the airflows and dimensions previously described.

$$R_\Sigma = \frac{1}{\frac{1}{R_{ku,b}} + \frac{1}{R_{ku,f}}} \quad \text{(Eq. 17)}$$

Finally we calculated the potential heat transfer from the heat sink in Equation 18 due to our calculated overall thermal resistance (R_Σ), external air temperature of 43 degrees Celsius (Tinf) and estimated heat sink temperature of 60 degrees Celsius (BaseT).

$$Q_{ku} = \frac{BaseT - Tinf}{R_\Sigma} \quad \text{(Eq. 18)}$$

We calculated this heat transfer to be 722 watts for the heat sink dimensions shown above in Figure 32. By running some simple calculations from the thermoelectric cooler data sheet we know that under our conditions the maximum heat the thermoelectric cooler could move would be 200 watts. To power the thermoelectric cooler to move 200 watts, we would need to supply 480 watts of electricity. Therefore under the maximum heat transfer circumstances, we would need the hot-side heat sink to dump 680 watts into the atmosphere. Given that our chosen heat sink could potentially dump 722 watts, we conclude that this heat sink should be adequate for our application.

Theoretical Model (Cold-Side Heat Transfer Model)

We considered convection and conduction modes of heat transfer to determine approximate heat dissipation values from the user's body to the cool water flowing through the copper tubing system. These heat values provided rough estimates of how much heat could be moved in order for us to evaluate the feasibility of our proposed final design. The cooling system behavior was analyzed using an internal flow-forced convection model as well as a conduction model. For simplicity, the copper tubing was treated as a hollow cylinder with a thin wall. The MATLAB script used to perform these calculations is listed in Appendix B.

Internal flow-forced convection model: A control volume analysis was performed on the copper tubing with water flowing from the inlet to the outlet. The diameter (D), length (L), and thickness (t) of the copper tubing as well as the water flow rate ($\dot{m}$) are shown in Fig. XX below. This figure also shows the direction of heat flow from the human torso to the copper tubing system with inlet temperature ($T_{m,i}$), outlet temperature ($T_{m,o}$), and mean tube surface temperature (T_m).

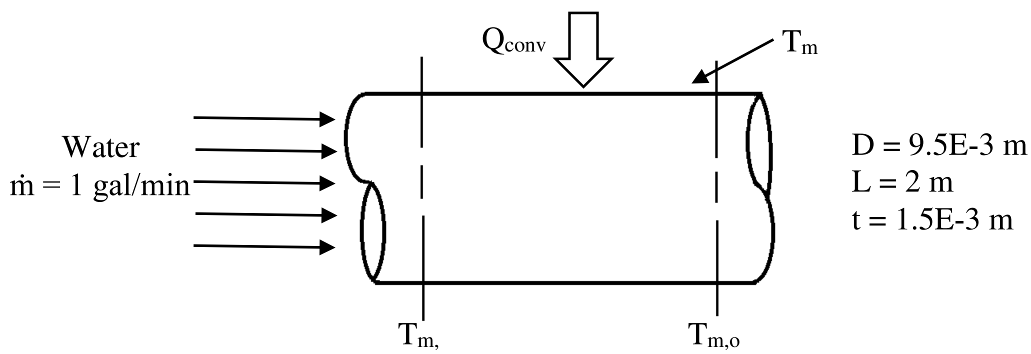


Figure 33: Cylinder schematic representing copper tubing modeling heat dissipation via convection heat transfer.

To determine the outlet temperature of the water leaving the copper tubing, the inlet cooled water temperature was assumed to be 20°C and the average human skin temperature was assumed to be 25°C. T_m was then found using the following equation:

$$T_m = \frac{T_s + T_{mi}}{2} \quad \text{(Eq. 19)}$$

This is the average water temperature in the copper tubing between the inlet and outlet, assuming the outlet reaches skin temperature. All water properties (density, viscosity, Prandtl number, specific heat, and thermal conductivity) were evaluated at this mean tube surface temperature for the rest of the calculations.

The mean fluid velocity (u_m) of the flow was determined in order to calculate the Reynolds number (Re) for this model and determine whether the flow was laminar or turbulent. The flow was considered laminar for Reynolds numbers less than 2300 and turbulent for Reynolds numbers greater than 2300.

$$u_m = \frac{\dot{m}}{\rho * A_c} \qquad Re = \frac{\rho * u_m * D}{\mu} \quad \text{(Eq. 20, 21)}$$

where $\dot{m}$ is the water flow rate converted to metric units [kg/s], ρ is the water density [kg/m^3], A_c is the cross-sectional area [m^2], and μ is the water viscosity [N*s/m^2].

Using the Nusselt number approximations for cylinders under the assumption that the surface is at uniform temperature, we were able to determine the convective heat transfer coefficient (h) for the laminar and turbulent cases. Equation 22 (**note-left equation) is for the laminar condition and Equation 20 (**note-right equation) is for the turbulent condition:

$$h = 3.66 * \frac{k}{D} \qquad h = 0.023 * Re^{0.8} * \mathrm{Pr}^{0.3} * \frac{k}{D} \quad \text{(Eq. 22, 23)}$$

where k is the water thermal conductivity [W/m*k], Re is the Reynolds number [] found above, and Pr is the Prandtl number [] for water evaluated at temperature T_m above.

The outlet temperature can then be determined by the equation below using the uniform surface temperature case:

$$T_{m,o} = T_m - \left(T_m - T_{m,i}\right) * \exp\left(-\frac{\pi * D * L}{\dot{m} * c_p}\right) * h \qquad \text{(Eq. 24)}$$

where c_p is the specific heat for water [J/kg*K] and h is the convective heat transfer coefficient found above [W/m^2*K].

Finally the heat dissipation was evaluated using the relationship described by the equation below:

$$Q_{conv} = \dot{m} * c_p * (T_{m,o} - T_{m,i}) \qquad \text{(Eq. 25)}$$

From this model we estimate that the water at our given flow rate is able to transfer 358 W of heat. There are numerous factors that affect the overall cooling so this heat value will vary once the entire system is assembled together. This was just used as a feasibility check to see if reasonable heat values were possible with our current proposed design.

Conduction model: A control volume analysis was performed on the thickness of the copper tube to model the conduction effects as thermal resistances. Copper tube dimensions including the diameter (D), length (L), and thickness (t) are shown in Figure 9 below. This figure also shows the direction of heat flow from the human torso through the thickness of the copper tubing material to the cooled water flowing inside of the tubing system. The figure also shows the temperatures at the inner surface ($T_{m,i}$) and at the outer surface (T_m).

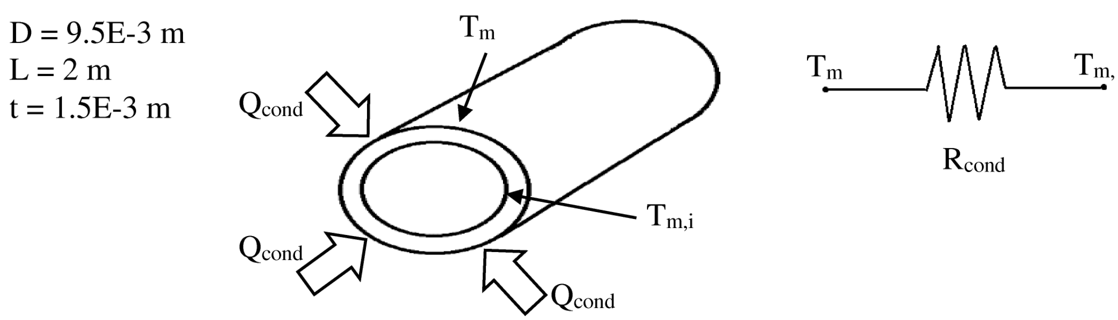


Figure 34: Cylinder schematic of copper tubing modeling heat dissipation via conduction heat transfer with thermal circuit.

Treating the copper tubing as a hollow cylinder with a small thickness, we were able to use the thermal circuit in Figure 34 above to evaluate the thermal resistance (R_{cond}) across the copper tube thickness:

$$R_{cond} = \frac{t}{0.08 * \pi * D * L * k_{cu}} \qquad \text{(Eq. 26)}$$

where k_{cu} is the thermal conductivity of copper [W/m*k] and all other dimensions are given above. We estimated that 30° out of 360° of the copper tubing are in contact with the user's body, therefore only 8% of the tubing's surface area is transferring the heat; hence the 0.08 factor in the denominator. Based on our estimated skin and water temperatures, the heat dissipated via conduction (Q_{cond}) can easily be calculated with the given relationship:

$$Q_{cond} = \frac{T_{mi} - T_m}{R_{cond}} \qquad \text{(Eq. 27)}$$

Using this conduction model we estimated the maximum heat transfer under ideal conditions from the copper to the skin to be 3.15 kW. This is fairly large because copper is an excellent heat conductor with a high thermal conductivity coefficient.

Based on our two conduction and convection calculations, the limiting factor of 358 W from the water flow is still well above our desired heat transfer of greater than 100 W. This reassures the feasibility of our design.

Empirical Testing

An experiment was performed by each of the four team-members to replicate working conditions that HCWs experienced while wearing PPE in West African climates. The purpose of this experiment was to better define the comfortable time of wear for the suit and verify this with the research findings. Wearing the suit in this replicated environment allowed for first-hand understanding of the problem, allowing us to propose designs that address the most relevant issues.

Equipment used: The equipment that was worn for this experiment was the same PPE that HCW wear in the field. This consisted of a 3M Protective Coverall 4510 disposable suit, a fluid impermeable hood, a disposable respirator, sterile disposable latex gloves, and boots. Figure 35 below shows one of the team members wearing the necessary equipment right before their experimental trial.

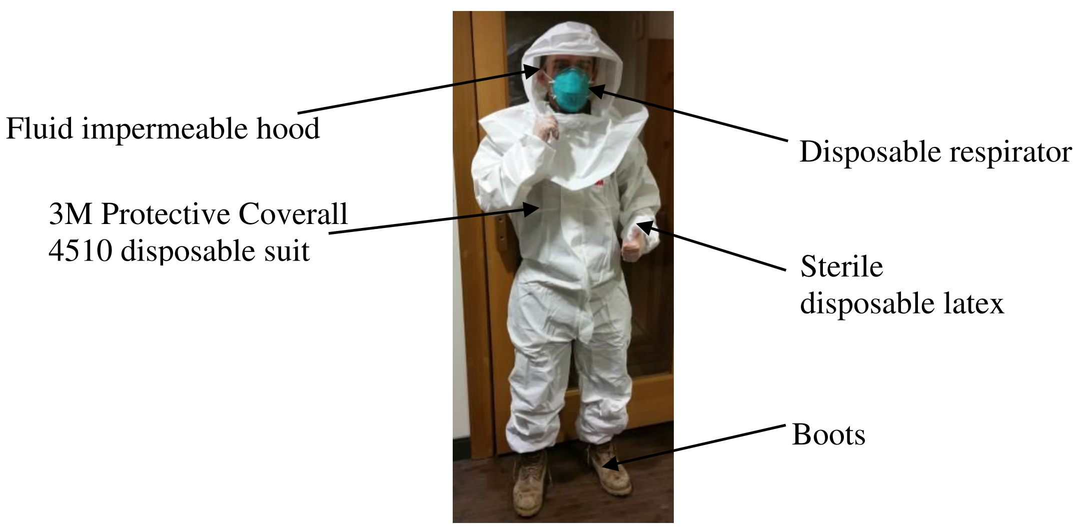


Figure 35: Team member in front of the sauna wearing the proper PPE before the start of an experimental trial.

The sauna room was set at an averaged measured temperature of 110°F and used to provide the replicated environment of the West African climate. Measurements of body temperature and interior suit humidity were taken using a chest mounted, remote thermometer and humidity sensor. The temperature and humidity of the sauna room were monitored using a WS-1173A Wireless Advanced Weather Station apparatus. Figure 36 shows each of these apparatuses separately.

Figure 36: Chest mounted, remote thermometer & humidity sensor (left) and WS-1173A Wireless Advanced Weather Station apparatus (right) used for measurement purposes throughout the duration of the experiment.

Experimental set-up: The sauna was set to an averaged measured temperature of 110°F for the whole duration of the experiment. The entrance door to the sauna room remained closed for majority of the time to ensure no temperature fluctuations that would alter the data. The experiment was conducted four separate times, once for each team member. Each member securely attached the chest mounted thermometer and humidity sensor apparatus using tape. They then proceeded to put on all the necessary PPE as shown in Figure 11 above. Each of the four team members then entered the sauna room and stood around with minimal physical activity. A personal comfort scale was defined by the group that ranged from 0 (indicating heat exhaustion) to 10 (indicating perfect comfort). Internal suit temperature, internal suit humidity, and personal comfort measurements were taken every 2 minutes. The experiment continued for each team member until each participant felt uncomfortable and was ready to come out of the sauna room. All PPE was then removed and the next team member repeated the experiment.

Results: Internal suit temperature, internal suit humidity, and personal comfort data that were recorded during the experimentation were plotted for each team member for their time of duration in the sauna room (Fig. 37-41, pg. 34-36). The general trends for these three categories of measurement were similar among all four team members with slight deviations from one another.

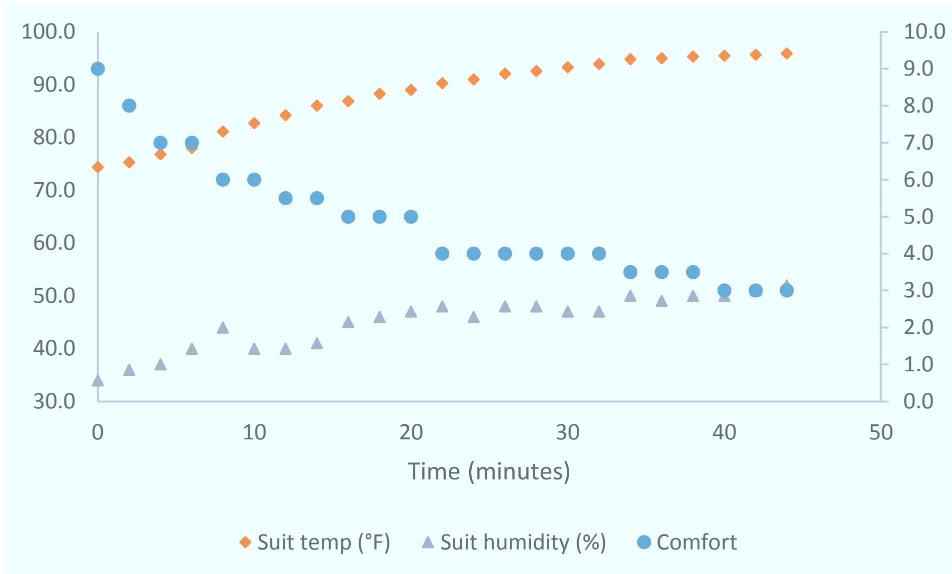


Figure 37: Measurements of internal suit temperature, internal suit humidity, and personal comfort for duration of Eljon's trial.

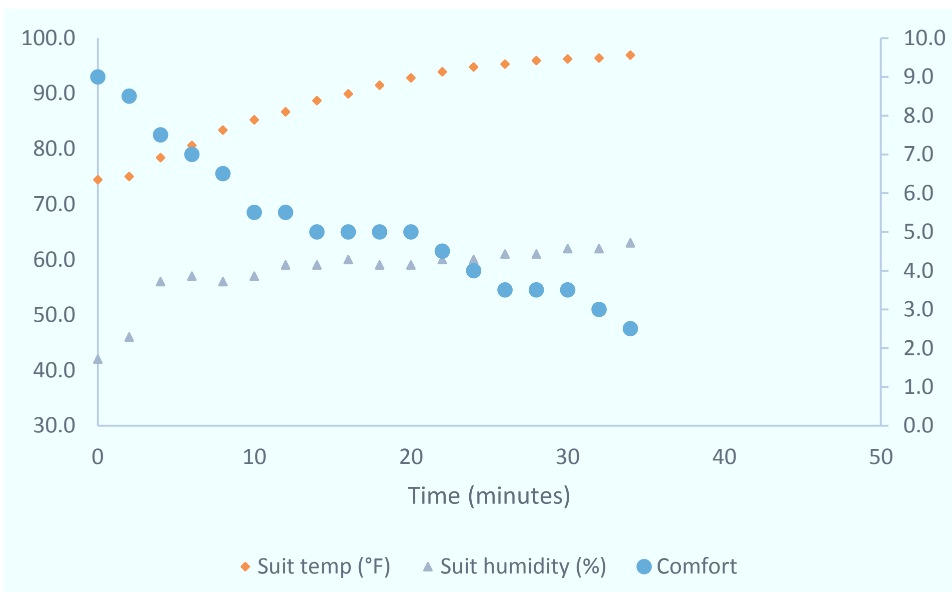


Figure 38: Measurements of internal suit temperature, internal suit humidity, and personal comfort for duration of Rob's trial.

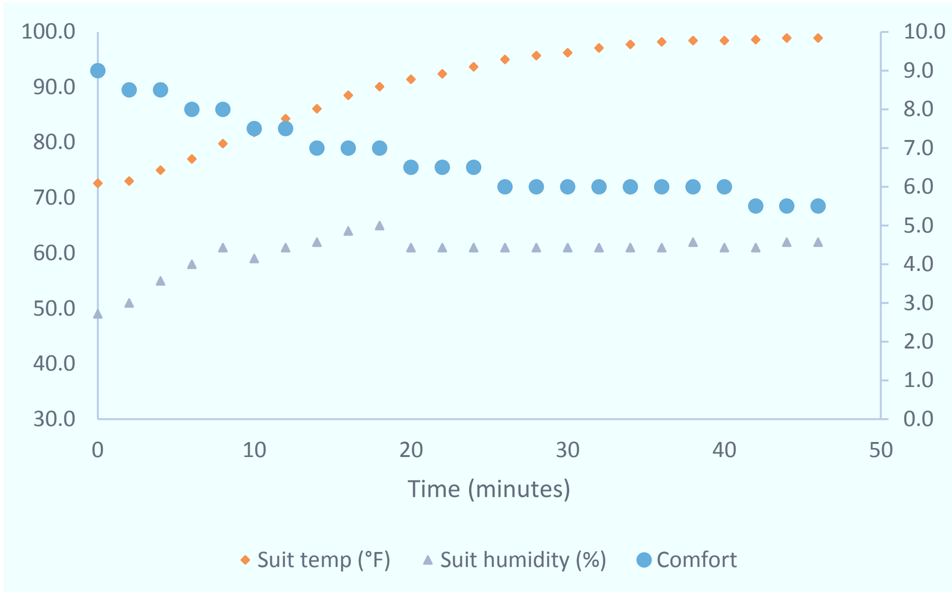


Figure 39: Measurements of internal suit temperature, internal suit humidity, and personal comfort for duration of Shreyas' trial.

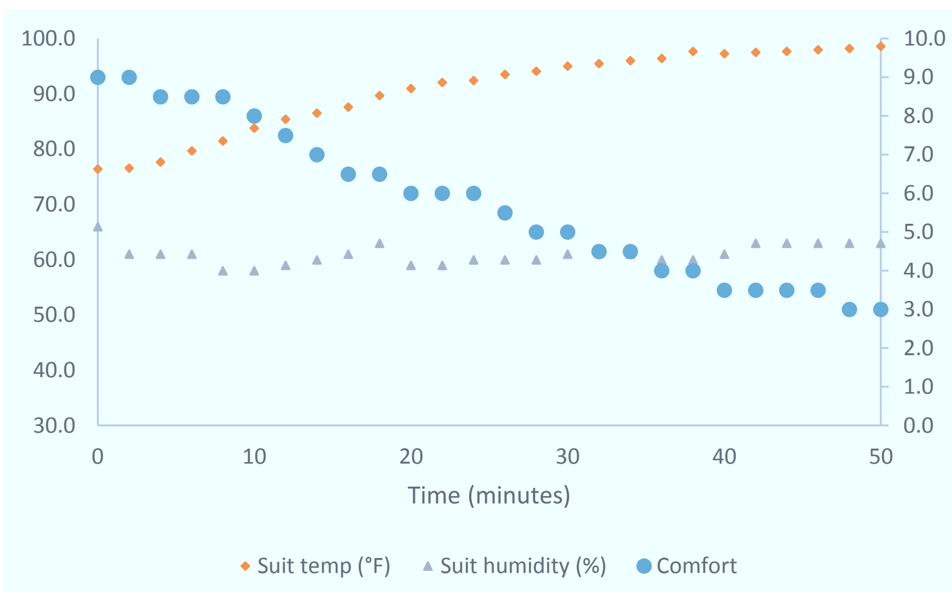


Figure 40: Measurements of internal suit temperature, internal suit humidity, and personal comfort for duration of Zach's trial.

Figure 41 (pg. 36) shows the internal suit temperature over time for each team member wearing the PPE in the 110°F sauna room. As shown by the figure, the internal suit temperature increased at approximately the same rate for all four team members. However, each team member had a different comfort threshold limiting the amount of time they were able to spend wearing the PPE. This time ranged from 34-50 minutes and in one case a team member did not reach a level of discomfort (Shreyas). Eljon was able to last 47 minutes, Rob was able to last 34 minutes, and Zach was able to last 50 minutes. This experiment does not take into account the additional heat generated while the HCW is involved in physical activity, which may lead to lower tolerable time in the suit.

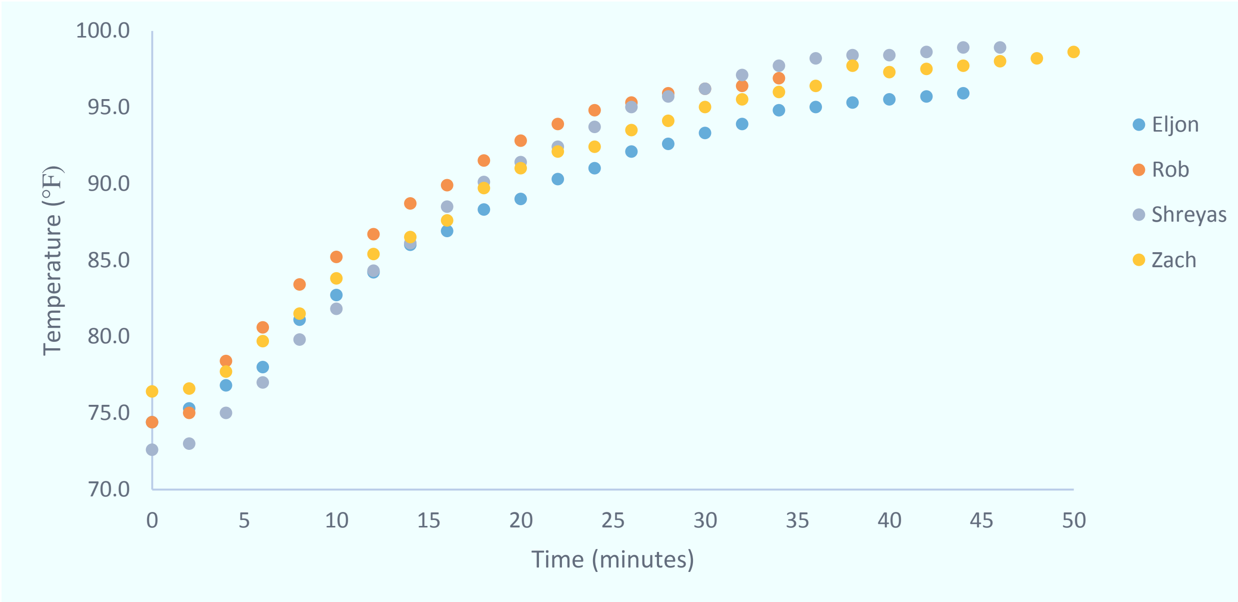


Figure 41: Measurements of internal suit temperature for each of the four team members showing threshold comfort time range.

With the conclusion that 40 minutes is the reasonable time to be wearing the suit for these specified conditions, the final proposed design will strive to increase this time to at least 60 minutes (1 hour).

Analysis Summary

The analysis we performed was at a very simplified level, mostly due to the complex behavior of the thermoelectric cooler. We understand that our models are simplified and lack comprehensive detail, but because of unpredictable behavior, further adding details to our analysis would not add any value and only create more room for misuse. Our analysis is primarily being used as an estimate for sizing and specifying components for our device. Our results depict a rather ideal situation in some cases, but we understand that, and we have selected components that exceed our simulated situations. For a more reliable analysis of our system, we will need to begin experimentation of our prototype system. Experimental results will help us quantify our analysis more accurately because we will have initial conditions and steady-state behavior. In addition, through experimentation, we will be able to reason if our neglected heat transfer terms are justified (eg. heat generated from water pump, radiant heat from one heat sink to the other). Based on our results, we may also have the opportunity to reduce the size of the hot-side heat sink in order to minimize its effective weight.

In summary, we are not placing full confidence into our preliminary calculations; however, we do believe that we have selected the best components for our system to maximize success. Through experimental data, we will be able to tune the models and gain a better understanding of the thermoelectric cooler's behavior. We believe our cooling device will function properly, but we will not know how successful it is until after experimentation.

CURRENT CHALLENGES

As mentioned in the analysis, the largest uncertainty in our design process is the behavior and operating conditions of the thermoelectric cooler (TC). This is important because it directly impacts the performance and success of our system. To gain understanding and be able to predict the behavior of TC, we will have to experiment early, and often.

Another challenge we will face in the near future is the manufacturing of the manifold that will direct airflow in and out of the suit. We are considering vacuum-forming our ducting manifold and in order to do that we require access to a CNC router for the mold and a vacuum chamber for the manifold creation. Fortunately we have been in contact with a faculty member from the STAMPS School of Art & Design who has offered to help us access resources and create our manifold.

Mounting all of the hardware on the neoprene life jacket may also pose some challenges as well. The challenge lies in mounting relatively heavy equipment to the neoprene lining, which may not be very structurally sound. We have put some thought into how we can distribute the loading so that the jacket material will not fail, but this is an obstacle that will have to be tackled after our system is successfully tested.

FAILURE MODES AND EFFECT ANALYSIS (FMEA)

The FMEA shown below is a preliminary risk analysis that is used to identify potential sources of failure within sub-systems of our complete design. Each failure mode's impact was assessed to provide a quantitative measure of risk, which will guide our design and testing process to minimize system failure and potential dangers. The Risk Priority Number (RPN), for each failure mode, captures the severity of the failure, the probability of failure, and the detection rate of a potential failure. RPN numbers less than 30 are reasonable and values greater than 100 indicate failure certainty.

Table 5: Failure Modes and Effect Analysis (FMEA) of thermoelectric cooling device.

Item / Function	**Potential Failure Mode**	**Potential Effect(s) of Failure**	**Severity**	**Potential Cause(s) / Mechanism(s) of Failure**	**Occurrence**	**Current Design Controls**	**Detection**	**RPN**	**Recommended Action(s)**
Thermoelectric Cooler (TC)									
Provides temperature differential which drives cooling in the system	Exceed maximum current	Damage to thermoelectric cooler, fire possible	10	Misuse during testing	1	30 Amp fuse	1	10	None
	Exceed maximum voltage	Damage to thermoelectric cooler, fire possible	10	Misuse during testing	1	Max voltage level not within power supply's operating range	1	10	None
	Fails before lifetime	Device does not cool as intended	8	Extended use / misuse	2	Using very reliable TC with service life ≈ 200,000 hours	2	32	None

Water Pump									
Pumps water through the vest so that heat will be removed from the body	Exceed maximum voltage	Damage to pump, possibly failure	10	Misuse during testing	2	None	1	20	Monitor voltage supplied during testing with DMM
	Debris enters pump blades	Damage to pump and blades, possibly failure	10	FOD entering upon installation or from manufactured parts	2	Filter in reservoir	1	20	None
	Fails before lifetime	No water flow, no cooling of user, freezing of water in heat sink	8	Extended use / misuse	2	Using very reliable pump with service life ≈ 50,000 hours	2	32	None
DC Fans (x2)									
Move external air over a heat sink mounted to the hot side of the thermoelectric cooler	Exceed maximum voltage	Permanent damage to fan, heat damage to thermoelectric cooler	9	Misuse during testing	2	None	2	36	Monitor voltage supplied during testing with DMM
	Debris enters fan blades	Damage to fan and blades, possibly failure	9	FOD entering manifold from environment	2	None, although audible detection may be feasible	2	36	Consider using screen or filter on ends of manifold
	Fails before lifetime	Heat damage to thermoelectric cooler, possibly failure	9	Extended use / misuse	2	None	2	36	None
Life Jacket (Vest)									
Provide an interface between the user and equipment	Jacket rips (fails)	Equipment detaches from user, potential device failure	8	Excess equipment weight, poor attachment	2	Distribute neoprene attachment across large washers	1	16	None
	Material melts, thermal fatigue, burning	Potential harm to user, jacket failure, equipment detaching from jacket	9	Excess temperatures from thermoelectric cooler	2	Thermally isolating thermoelectric cooler and heat sink from user/other eq.	1	18	None

Air Manifold									
Direct external air into the suit, across the heat sink, and out of the suit	Excess heat	Melting of manifold, damage	9	Unusually high temperatures	2	Use appropriate material for temperatures < 80°C	1	18	None
	Seal failure	Hot air escapes into suit, causes added discomfort to user	5	Poor assembly, poor construction	3	None	1	15	Emphasize design for good seals, and procure it carefully
Power Supply									
Convert 110 VAC to variable DC, powering TC, pump, and fans	Overheating	No power delivered to equipment	8	Poor cooling exposure	2	Place power supply within air manifold to be cooled by fans	1	16	None
Liquid Heat Sink									
Exchange heat from water circulating throughout vest to cool side of TC	Leaking	Water depleted from plumbing, loss of user cooling, water disposed in suit	9	Poor sealing of heat sink, poor pipe fittings	3	Seal with silicone gasket for better seal	1	27	Test unit under pressure for leaks before experimentation

The DC fans, which are vital in transferring heat away from the hot side of the thermoelectric cooler, are at the highest risk of failure in our design. Although we do not expect these fans to fail during operation, unless the maximum voltage is accidentally exceeded, the consequences can be drastic. If the fans were to fail, the thermoelectric cooler could reach unsafe temperatures, causing material damage, product failure, or even a chance of fire. We currently do not have any safety controls for this, due to time and budget limitations, but the fans themselves are quite audible (~62 dB per fan). We will need to closely monitor the fans, through hearing, to ensure that they do not die out (they are not expected to die out). In addition, we will use a digital multi-meter to monitor and ensure the maximum operating voltage for the fans is not exceeded. To protect against foreign objects and debris (FOD), we are going to consider using screens or filters at the intake and exhaust ends of the manifold. After implementing these precautions and observing successful experimental testing, we will have reassured confidence in the safety of the fan components. In the case that the DC fans fail anyways, we will immediately cut off power to the system with a switch.

MASS PRODUCTION CONSIDERATIONS

This device is designed with considerations to the Ebola crisis in West Africa, with the added versatility of use in normal hazardous material PPE suit operation. Because we widened the scope to meet all PPE usage situations, this increases the use-case scenarios and demand, thereby allowing us to manufacture and sell at a higher volume, decreasing cost of the device.

Process Involved

The processes involved can be broken down into three sections: manufacturing of custom parts, obtaining readily available parts, and assembly of the device. The parts that require custom manufacturing are the hot side heat sink, the cold side heat exchanger, a custom vest to nest and integrate copper tubing, and the backing to which all the parts are mounted. Parts that can be sourced from third-party suppliers are the coolant pump and reservoir, the cooling fans, the copper tubing, and the power supply. Finally, all the parts must be assembled in house and tested to meet safety regulations and standards.

Overall Production Cost

Currently, our design will cost us approximately $400 in materials and components. With mass production, we would be able to decrease the cost of the individual parts, but when labor costs are considered, the price would rise again. We estimate the overall mass manufactured cost to be around $400 per unit.

DISCUSSION

Design Critique

Through the process of designing and building a PPE cooling device a lot was learned about the capabilities of body-mounted cooling systems, thermoelectric cooling and the advantages and limitations that they present. The device was able to meet the performance specifications regarding physical size, donning time, interface with the suit and function at high temperature. However, it was unable to extend the comfort time of the user by 50% and it was heavier than the 20 pound maximum set by the project requirements. The device was heavier due to the design for best-case cooling capacity. A large heat-sink was used to dissipate heat as well as possible and a large, power-hungry thermoelectric chip was used to provide the highest cooling capacity. However, even with the oversized components, cooling was not adequate to extend the comfortable usage by 50%. Due to the constraints of the size and mass of a body-mounted cooling system, it does not seem likely that a body mounted cooling system would be capable of providing the required cooling in the hot West-African climate. The over-sized, heavy device was not able to provide the proper cooling capacity so a lighter device with capacity would also not likely be able to keep workers cool. Based on this knowledge, an endeavor to design a body-mounted device to cool workers in hot climates seems to be fruitless. A much better alternative however is to mount the heat-pump within an external device. This would be the direction taken if the project were to be done over from the start.

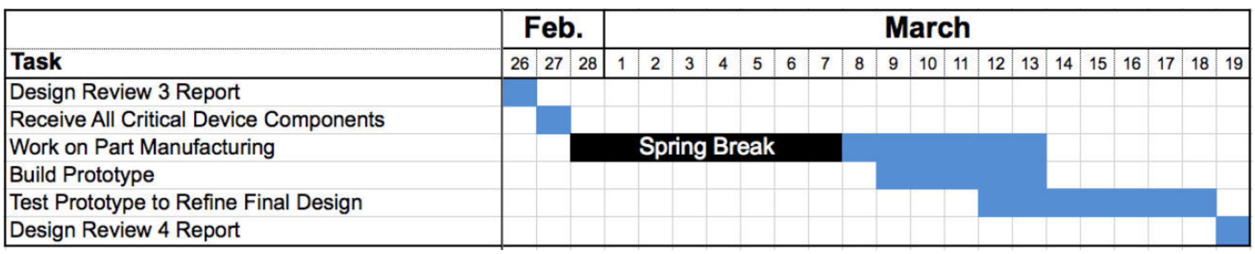
Future Work

A lot was learned through the exercise of building a body-mounted cooling system for hot climate PPE use. The main point being that for proper cooling capacity, the weight required for the device is too great to be carried comfortably on the user. The next steps of this project would be to approach the device from a different perspective and mount the heat-pump externally from the user's suit and take advantage of the heavier, but more efficient, compressor-refrigerant based cooling system. This would lead to lower fatigue on the health care worker's body, the ability for higher cooling capacity and a simpler interface with the protective suit which would also reduce contamination risk. This project has developed a lot of good information regarding the cooling of health care workers in West Africa treating Ebola patients. From this information, a next generation of this cooling device can be developed to better suit the needs of the health care workers in hot climates.

ACKNOWLEDGMENTS

Special acknowledgements are given to the many people who helped in the development of this body mounted cooling device. Thanks to Jan-Henrik Andersen and the Ebola Design Charette he hosted in coordination with the Stamps School of Art and Design at the University of Michigan. This design charrette served as the foundation for the design of the body mounted cooling device. Thanks to Marc Roe from 3M for providing personal protection suits to perform testing with. Thanks to the course staff at the University of Michigan who provided input to our design throughout the semester, notably: Professor Wei Lu and Professor Brent Gillespie. Finally, thank you to Amy Hortop for providing the opportunity for this unique design project and setting up the funding for the prototype.

DR4 GANTT CHART



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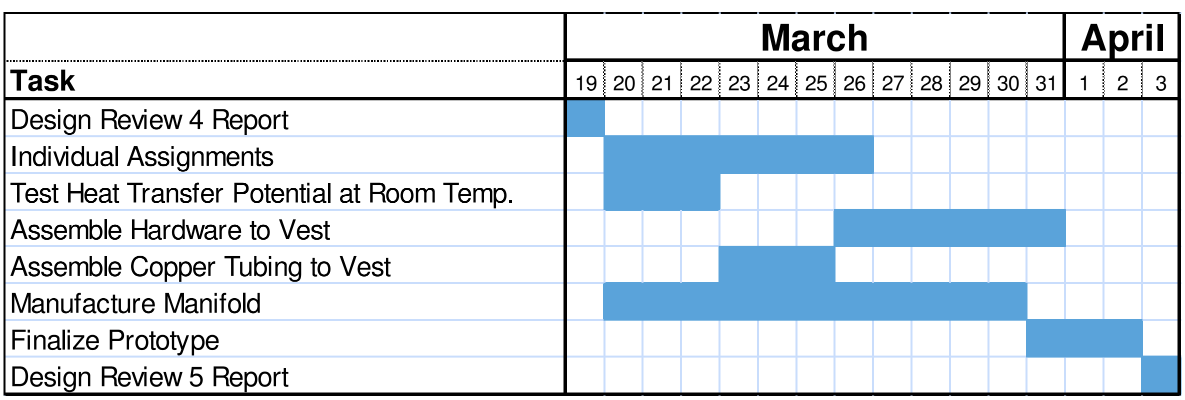

AUTHORS

Eljon Elezi is a senior at the University of Michigan and will be graduating in May 2015 with a B.S.E in Mechanical Engineering. He has conducted on-campus research, participated in a summer study abroad program in Berlin, Germany, and has interned at Air Products. After graduation, Eljon will begin his career working full time at General Motors as a Mechanical Design Engineer for the Global Electrification Powertrain Converter Design Team.

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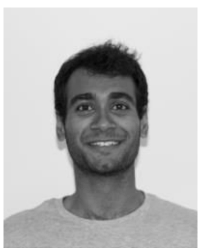

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REFERENCES

[1] Medecins Sans Frontieres (Doctors Without Borders), 2015, from http://www.doctorswithoutborders.org/our-work/medical-issues/ebola.

[2] Peters, C.J., 2012, *Harrison's Principles of Internal Medicine*, 18th ed., McGraw-Hill, New York, NY, Chap. 197.

[3] McGovern, M., 2015, Associate Professor of Anthropology at University of Michigan, U.K., private communication.

[4] Kitamura, M., 2014, "Inside an Ebola Suit at 115 Degrees, Where Skipping a Step Can Mean Death," Bloomberg, from http://www.bloomberg.com/news/2014-09-23/inside-an-ebola-protective-suit-that-feels-115-degrees.html.

[5] Holmes, J., Jan. 16th, 2015, University of Michigan Hospital Emergency Department Director of Operations, Ann Arbor, MI, University of Michigan Stamps School of Design Ebola Charrette.

[6] Wells, E.V., 2015, Director of Preventative Medicine Residency at University of Michigan, U.K., private communication.

[7] Silver, M., 2014, "This Suit Keeps Ebola Out – So How Can A Health Worker Catch It?" NPR, from http://www.npr.org/blogs/goatsandsoda/2014/07/24/334948345/this-suit-keeps-ebola-out-so-how-can-a-health-worker-catch-it.

[8] Zarembo, A., 2014, "Ebola suits keep wearers safe if all rules are followed, experts say," Los Angeles Times, from http://www.latimes.com/nation/la-na-ebola-suit-20141016-html-htmlstory.html.

[9] Greenemeier, L., 2014, "Ebola Spread Shows Flaws in Protective Gear and Procedures," Scientific American, from http://www.scientificamerican.com/article/ebola-spread-shows-flaws-in-protective-gear-and-procedures/.

[10] Hancock, P.A., Vasmatzidis, I., 2003, "Effects of heat stress on cognitive performance: the current state of knowledge," International Journal of Hyperthermia, **19**(3), pp. 355-372.

[11] Yang, Y., Stapleton, J., Diagne, B.T., Kenny, G.P., Lan, C.Q., 2012, "Man-portable personal cooling garment based on vacuum desiccant cooling," Applied Thermal Engineering, **47**, pp. 18-24.

[12] 2015, "PPE Safety Solutions: 3M Protective Coveralls 4510." From http://solutions.3m.com/wps/portal/3M/en_EU/PPE_SafetySolutions_EU/Safety/Product_Catalogue/~/3M-Protective-Coveralls-4510?N=7576203+3294411303+3294857473&rt=rud

[13] Weixing, Y. and Bo, Y. and Yufei, Y. and Xiugan, Y., 2013, "Single-Circulation Personal Cooling System with Evaporator in Cooling Suit." China, CN102920063.

[14] Priddy, R. and Rothschild J., 2014, "Man Portable Micro-Climate." World, WO2014031128.

[15] Cheung, S. S. and Flouris, A. D., 2006, "Design and Control Optimization of Microclimate Liquid Cooling Systems Underneath Protective Clothing," Annals of Biomedical Engineering, **34**(3), pp. 359-372

[16] Creech J. and Drees, J., 2012, "Body Temperature Control System." United States, US2012227432.

[17] Elsherif, Dina; Green, Lawrence, 1996, "Cooling Sweatband." United States, US5564124.

[18] Decet, Dennis 2013, "Cooling Sweatband." United States, US2013145518.

[19] Borgnakke, C. and Sonntag, R. E., 2013, Fundamentals of Thermodynamics, 8th ed., John Wiley & Sons, Inc., Hoboken, NJ

[20] Kaviany, M., 2011, Essentials of Heat Transfer Principles, Materials, and Applications, Cambridge University Press, New York, NY

[21] Sutterlin, W. R., 2011, "Phase Change Materials, A Brief Comparison of Ice Packs, Salts, Paraffins, and Vegetable-derived Phase Change Materials," The Journal of Pharmaceutical & Biopharmaceutical Contract Services

[22] Active Cool, "Understanding Thermoelectric Cooling," from http://www.activecool.com/technotes/thermoelectric.html

[23] Parker-Pope, T. 2009, "Weighting School Backpacks," The New York Times, from http://well.blogs.nytimes.com/2009/07/21/weighing-school-backpacks/

APPENDIX A

Eljon Elezi's Concept Designs

E1 – Internal-suit pulse point air-based cooling: Eljon's approach to his first design attempts to target as many pulse points throughout the body as possible. It uses a heat pump that is attached to the user's waist that circulates air to and from the pulse point locations on the body. Bands that allow the passage of air are attached to the pulse points by hoses that lead back to the heat pump. Along the hose lines, as well as under the band attachments, there is a porous honeycomb feature that provides separation and avoids direct contact with the skin.

Figure A.1: E1 – Internal-suit pulse point air-based cooling.

E2 – Integrated-suit conductive thermoelectric cooling: Eljon's idea utilizes many thermoelectric coolers attached to a belt to be worn around the user's waist. This concept is integrated into the suit material having components both inside and outside the suit. The cool side of each cooler (inside the suit) contacts the user's body, conducting heat away from the user. The hot side of each cooler is external to the suit and is enclosed in a cover to prevent contamination. This cover contains storage spaces for ice packs that act as heat sinks for the thermoelectric coolers. The cover can also be detached for disinfecting.

Figure A.2: E2 – Integrated-suit conductive thermoelectric cooling.

E3 – Internal-suit absorbent vest evaporative cooling: This concept exploits the human body's natural cooling capabilities through sweat to provide cooling. This vest is worn inside the suit and comes in direct contact with the user's skin. A spongey, absorbent material is able to soak up the sweat that is released by the user. The various constricting bands around the chest are battery powered and are able to tighten at a comfortable level in order to extract the collected body sweat in the absorbent material. This sweat is then able to be collected in a circular basin around the vest to be emptied after use.

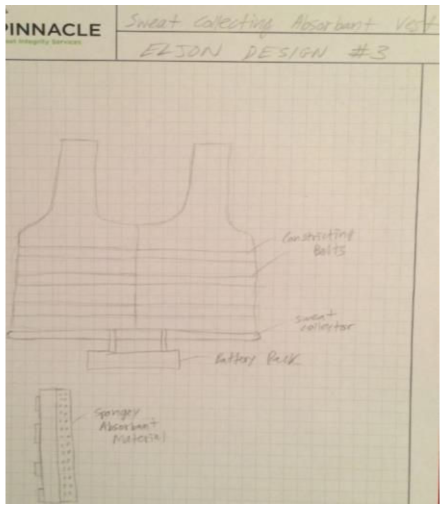


Figure A.3: E3 – Internal-suit absorbent vest evaporative cooling.

E-4 - Internal-suit air-based porous cooling: Through the use of an air circulation system, this concept allows the user to be cooled. This vest is wore on the inside of the suit by the user. The unique thing about this vest is that is has small pores throughout the inside of the vest where it is attached directly on the body. These pores are able to provide continuously supplied cooled air through a heat pump attachment. The dispersed air also allows for evaporative cooling since it will be able to dry off the excess sweat on the skin.

Figure A.4: E4 – Internal-suit air-based porous cooling.

E5 – Internal-suit phase change material cooling: This concept idea consists of a vest-like attachment to be worn inside the suit. It incorporates the use of phase change material to provide the cooling to the body. The unique feature of this concept is that it provides cooling to not only the body core, but also the neck and head. After use, the whole product would have to be stored in a very cold environment (i.e. refrigerator) to prepare it for another use cycle.

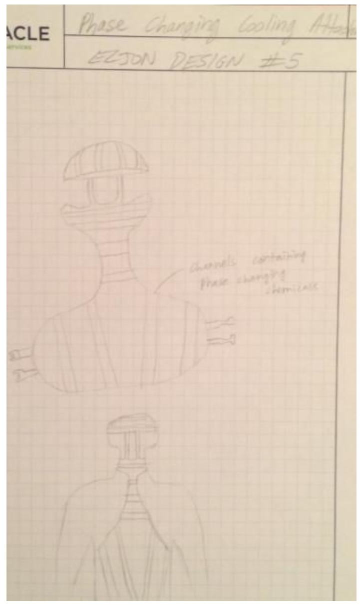


Figure A.5: E5 – Internal-suit phase change material cooling.

Rob Self's Concept Designs

R1 – Internal-suit air-based thermoelectric cooling: For this idea, Rob uses an air-based cooling vest with a thermoelectric heat pump. The cooling vest and heat pump are integrated in a one-piece design, which is worn inside the suit. The vest contains channels that supply cool air to the body and remove hot, moist air to be cooled and recirculated by the heat pump. The hot side of the heat exchanger is mounted inside the suit and is cooled by air ducts and a fan blowing air from outside the suit.

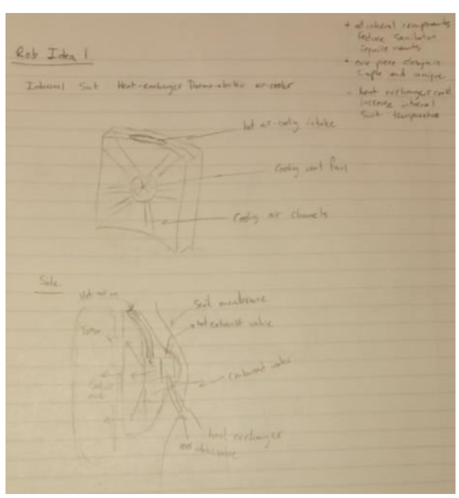


Figure A.6: R1 – Internal-suit air-based thermoelectric cooling.

R2 – External-suit air-based thermoelectric cooling: For this idea, Rob uses an air-based cooling vest with a thermoelectric heat pump. The cooling vest is worn by the user inside the suit with the heat pump and heat sink built into a backpack worn by the user outside of the suit. The vest worn by the user inside the suit contains channels that supply cool air to the body from the external backpack and alternating air channels remove hot, moist air to the heat exchanger backpack to be cooled and recirculated back into the suit. The hot side of the heat exchanger has a large heat sink mounted in the backpack worn outside the suit and is cooled by a fan blowing air over the heat sink.

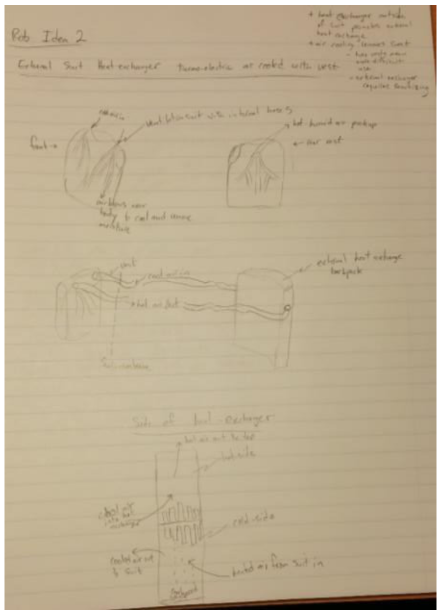


Figure A.7: R2 – External-suit air-based thermoelectric cooling.

R3 – External-suit pulse point liquid-based thermoelectric cooling: Rob's idea for this cooling technology uses a thermoelectric fluid pump that circulates a cooled fluid to the wrist and leg pulse points. Fluid is carried to and from the pump by a series of hoses. Attachment to the pulse point locations is by bands that wrap around providing fluid circulation across the exterior surface area.

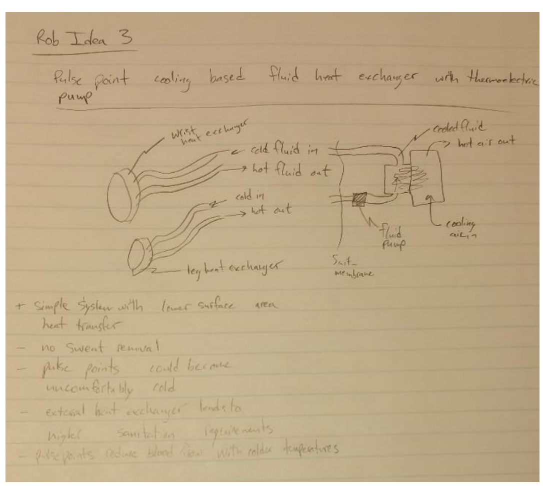


Figure A.8: R3 – External-suit pulse point liquid-based thermoelectric cooling.

R4 – Internal-suit liquid-based thermoelectric cooling: This design utilizes a cooling vest with an integrated thermoelectric cooler and heat sinks worn by the user inside the PPE suit. The vest circulates fluid cooled by a thermoelectric cooler through copper tubing in contact with the user. The hot side of the thermoelectric cooler is cooled by external-suit air circulated through air ducts by a fan over the hot side heat sink.

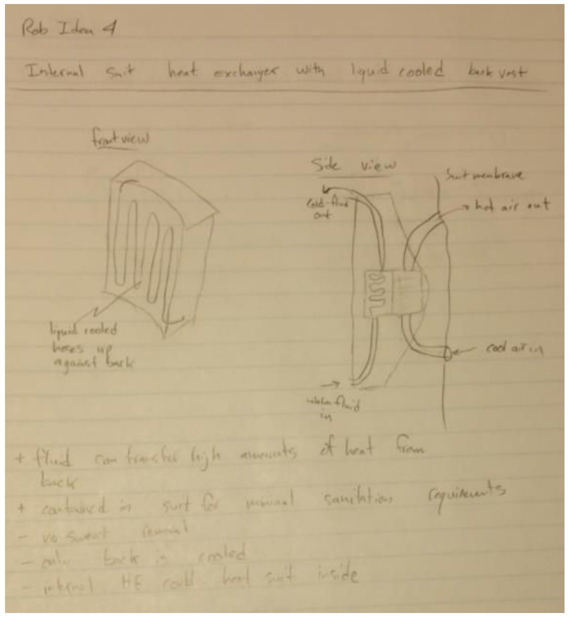


Figure A.9: R4 – Internal-suit liquid-based thermoelectric cooling.

R5 – External-suit liquid-based thermoelectric cooling: For this idea, Rob uses a liquid-based cooling vest with a thermoelectric heat pump. The cooling vest is worn by the user inside the suit with the heat pump and heat sink built into a backpack worn by the user outside of the suit. The vest worn by the user inside the suit contains integrated tubes carrying cooled liquid to the body from the external backpack. After the liquid is pumped through the cooling vest tubing, the warmed liquid is returned to the heat exchanger backpack to be cooled and recirculated back into the suit. The hot side of the heat exchanger has a large heat sink mounted in the backpack worn outside the suit and is cooled by a fan blowing air over the heat sink.

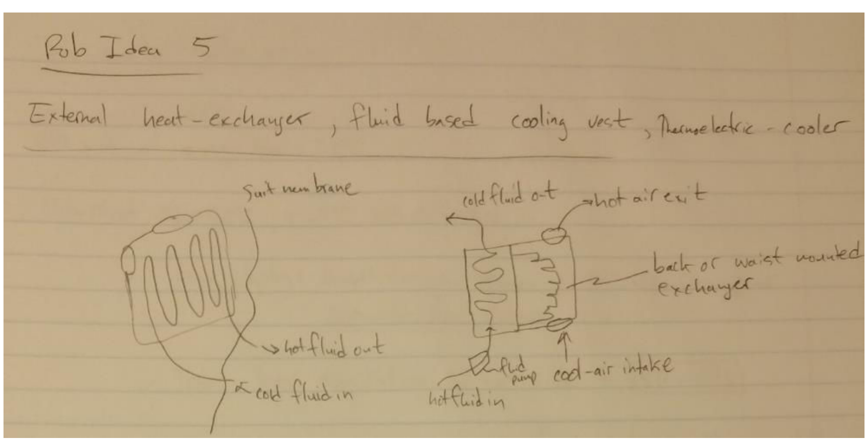


Figure A.10: R5 – External-suit liquid-based thermoelectric cooling.

Shreyas Parat's

S3 - Internal-suit air-based dehumidification: This dehumidification concept straps onto the user around their waist and consists of a fan and a desiccant or moisture absorbing filter. The fan would be running consistently and pushing air through the moisture removal filter. This would dehumidify the air and aid the body in cooling by sweat evaporation.

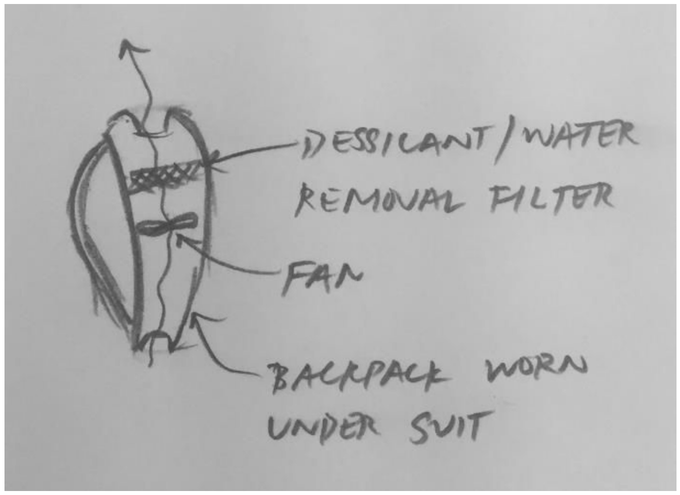


Figure A.13: S3 - Internal-suit air-based dehumidification.

S4 - Integrated-suit air/conduction-based cooling: This concept is integrated into the suit. It consists of a fan and snaking tubing on the backside of the suit, yet still within the suit. The concept works by sucking in external-suit air and blowing it through the tubes that are inside the suit. Because the outside air may be cooler than the inside of the suit, it would allow the humid, moist air to condense on the snaking tubes. In this manner it would dehumidify the internal suit environment.

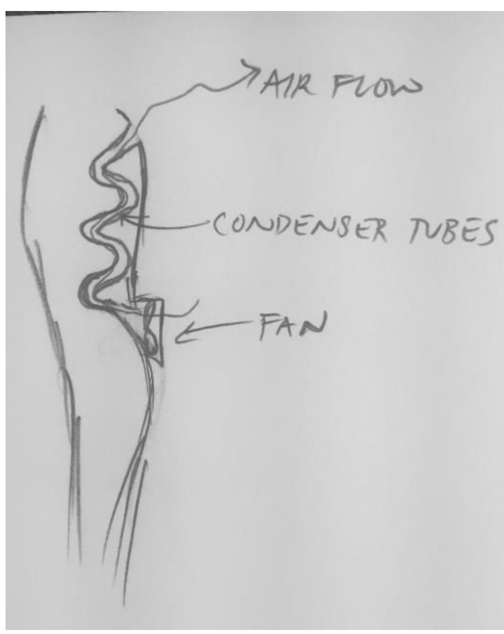


Figure A.14: S4 - Integrated-suit air/conduction-based cooling.

S5 - Internal-suit thermoelectric dehumidification: This concept is integrated into the suit. It consists of a fan and snaking tubing on the backside of the suit, yet still within the suit. The concept works by sucking in external-suit air and blowing it through the tubes that are inside the suit. Because the outside air may be cooler than the inside of the suit, it would allow the humid, moist air to condense on the snaking tubes. In this manner it would dehumidify the internal suit environment.

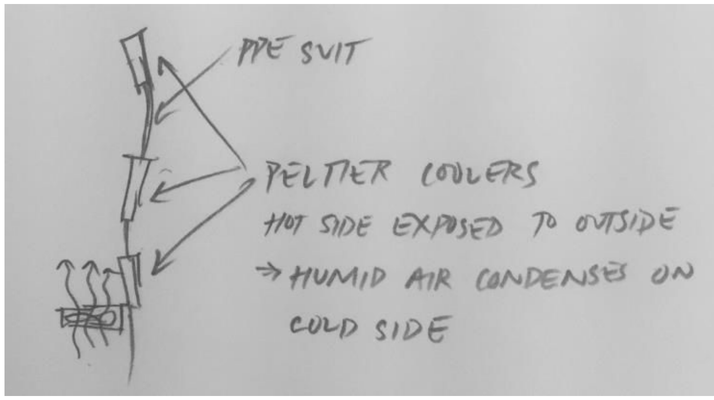


Figure A.15: S5 - Internal-suit thermoelectric dehumidification.

Zach Grifka's Concept Designs

Z1 - Internal-suit forearm phase change material cooling: This concept includes two sleeves that are worn inside the suit on one's forearms. The sleeves can be adjusted for many sized forearms with the velcro straps. Small packages of phase change material (eg. ice) are found around the sleeves to provide cooling upon skin contact, utilizing conduction to transfer heat from the skin to the packages. The phase change material would have to be solidified after use before being used again.

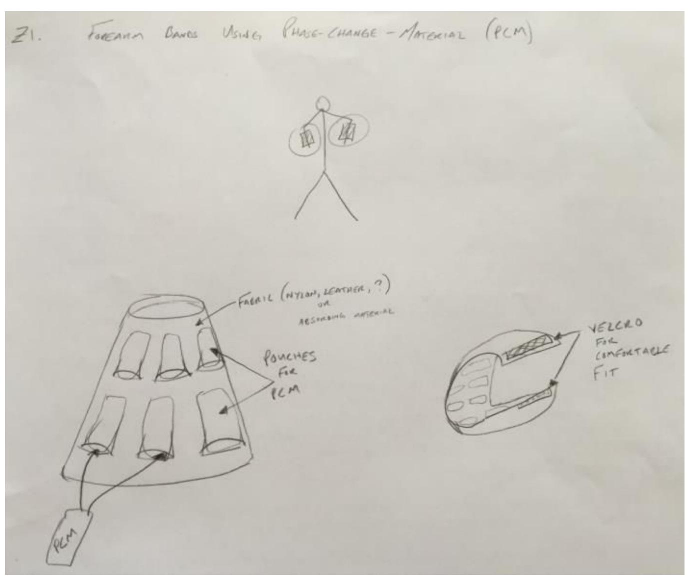


Figure A.16: Z1 - Internal-suit forearm phase change material cooling.

Z2 - Internal-suit air-based bladeless fan cooling: The bladeless feature is inspired from the Dyson Air Multiplier technology found in commercial stores. A little far-fetched, this concept imagines utilizing the same technology to blow air down the body within the suit starting from one's neck. The motor and power source would be outside of the suit worn around the waist using a belt. This concept would be recycling air contained in the suit, however the high velocity of the air would increase evaporative cooling.

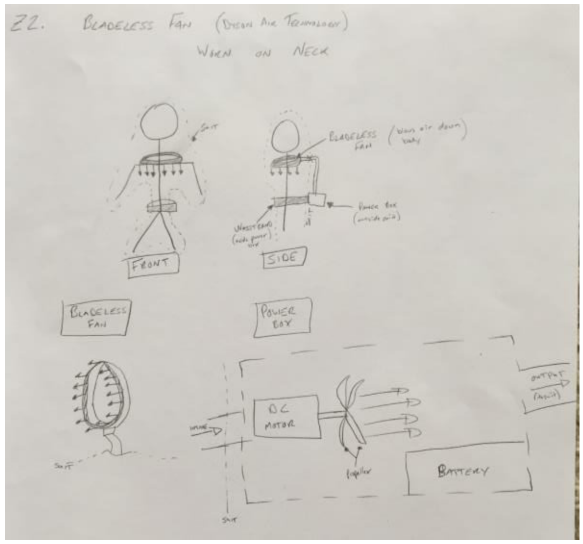


Figure A.17: Z2 - Internal-suit air-based bladeless fan cooling.

Z3 - Internal-suit liquid-based vest: Initially supplied with cooled water, this concept would recycle the same water through a wearable vest until its cooling potential would cease. The pump and power supply would be worn externally around the waist in the form of a belt. Water tubing would enter and exit the suit, while flowing through a network of tubing attached to the vest worn by the user. The liquid tubes would conduct heat away from the body with the help of surface convection.

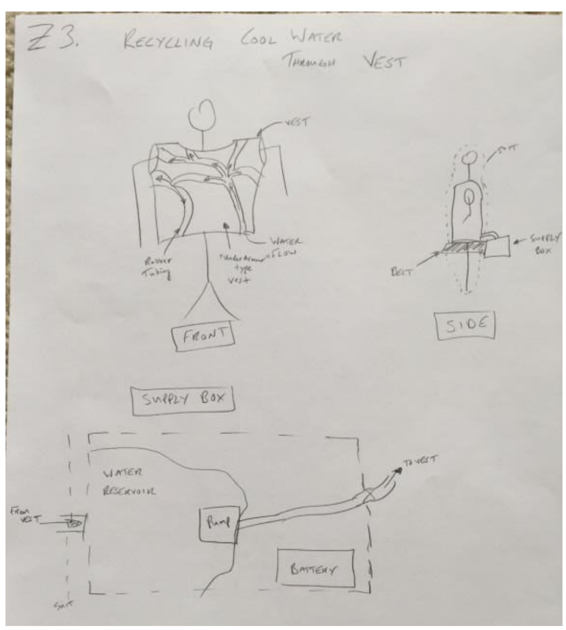


Figure A.18: Z3 - Internal-suit liquid-based vest.

Z4 - External-suit air-based thermoelectric cooling: Taking advantage of evaporative cooling, this concept also utilizes a thermoelectric device to cool the air that is re-circulating through the suit. Air continuously is sucked out of the suit, blown across a thermoelectric cooler, and then pushed through tubing into the suit by a fan. The air is then dispersed at the neck level providing additional comfort and cooling. The power supply and fan are worn outside the suit on a belt.

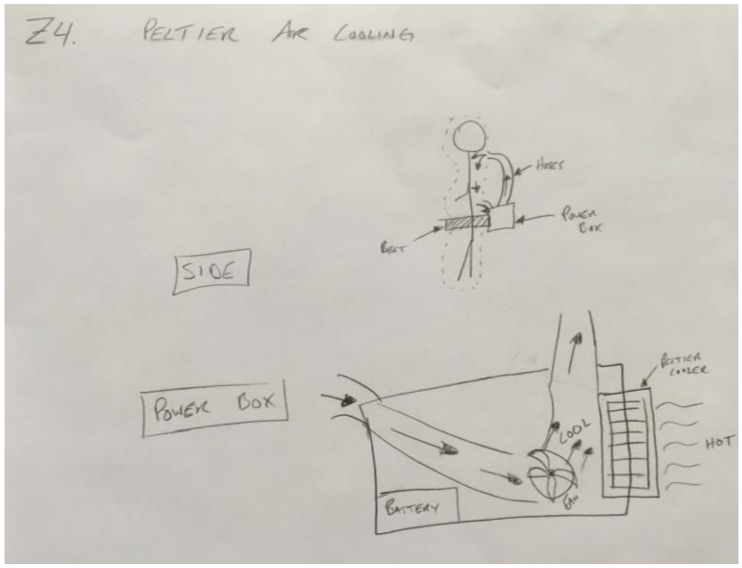


Figure A.19: Z4 - External-suit air-based thermoelectric cooling.

Z5 – External-suit air-based desiccant dehumidifier: This concept does not offer any cooling features, but instead focuses on dehumidifying the suit so that the body's natural cooling techniques can function efficiently. A fan is used to re-circulate air from the suit, but is also passing the air through a desiccant filter, which removes moisture from the air within the suit. Dehumidified air enters the suit near the neck and is dispersed towards the waist, where the air exits the suit and is recycled again. The desiccant and fan are housed outside the suit and worn on a belt.

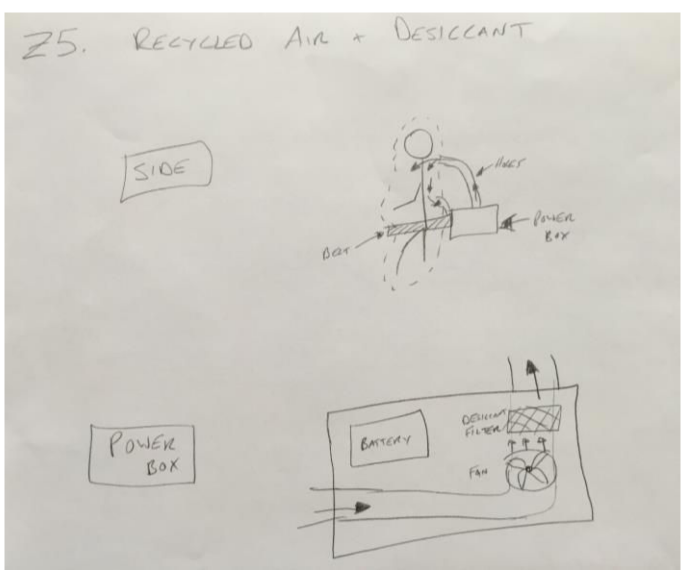


Figure A.20: Z5 - External-suit air-based desiccant dehumidifier.

APPENDIX B

MATLAB script used for hot side heat sink calculations

```
%Input heatsink dimensions to calculate heat dissipation
Nf = 42; %Number of fins
l = 0.002; %Fin width in (m)
L = 0.1110; %Height of heatsink (m)
a = 0.1588; %Width of heatsink (m)
w = 0.2888; %Length of heatsink (m)
EnclosureW = .24; %Width of sink enclosure (m)
EnclosureH = .12; %Height of enclosure (m)
Tinf = 43; %Air temperature (Celcius)
BaseT = 60; %Temperature of heat sink base (Celcius)
FanNum = 2; %Number of fans
FanFlow = 240; %Air volume transfer per fan (CFM)

kf = 0.0283; %Conductivity of air
vf = 17.73*1e-6; %Air viscosity
ks = 238; %Conductivity of aluminum

FanFlowM = FanFlow*(1/60)*(1/35.31)*FanNum; %Calculates fan flow in m^3/s
HeatSinkCrossArea = EnclosureW*EnclosureH; %Calculates area air flow when fan is taller than heatsink
AirSpeed = FanFlowM/HeatSinkCrossArea; %Calculates airflow speed over heatsink

%Reynolds number calculation
ReW = AirSpeed*w/vf; %Reynolds number assuming laminar flow

if ReW <= 5e5
   NuW = 0.664*(ReW)^(1/2)*(0.69)^(1/3); %Nusselt number assuming laminar flow
else
   NuW = (0.0378*(ReW)^(4/5)-871)*(0.69)^(1/3); %Nusselt number assuming turbulent flow
end

Lc = L+ l/2;
Pku = 2*w + 2*l;
Ak = w*l;
Aku = Pku*Lc;
Ab = a*w-Nf*Ak;

m = (Pku*(NuW*kf/w)/(Ak*ks))^(1/2);

nf = tanh(m*Lc)/(m*Lc); %Calculate efficiency

%Resistance calculations
RkuWb = w/(kf*NuW*Ab);
RkuWf = w/(kf*NuW*Aku*nf*Nf);

RSum = 1/(1/(RkuWb)+1/(RkuWf));

%Calculate heat transfer
Qku = (BaseT - Tinf)/RSum
```

MATLAB script used for cold side heat exchanger calculations

```
%Input parameters for the system
F_R = 1;                              %flow rate [gallons/min]
T_D = 0.375;                          %diameter of copper tube  [inches]
L = 2;                                %length of copper tube [m]
t = 0.001524;                         %thickness of copper tube [m]
k_cu = 401;                           %copper thermal conductivity [W/m*k]
T_mi = 20;                            %inlet water temperature (cooled) [deg C]
T_s = 25;                             %human skin temperature [deg C]
T_m = (T_s + T_mi)/2;                 %mean tube surface temperature [deg C]

%Properties of water at mean tube surface temperature (T_m) of 16.5 deg C or 290K
%Assuming skin contacts 30/360 = 8.33% of the copper tube surface
rho = 1000;      %density of water [kg/m^3]
mu = 0.00108;    %viscosity of water [N*s/m^2]
Pr = 7.56;       %Prandtl number for water []
c_p = 4184;      %specific heat of water [J/kg*K]
k = 0.598;       %thermal conductivity of water [W/m*k]

%Metric conversion calculations
m_dot = F_R*0.003785*1000/60;     %mass flow rate [kg/s]
D = T_D*0.0254;                   %tube diameter-metric [m]
A_c = pi*0.25*D^2;                %Cross Sectional Area [m^2]

%Calculation of mean fluid velocity [m/s]
u_m = m_dot/rho/A_c;

%Calculation of Reynolds Number[] with turbulence occuring @ Re=2300
Re = rho*u_m*D/mu;
%-------------------------------------------------------------------
%Convection Model: internal flow through cylinder

%Heat transfer coefficient calculation if laminar or turbulent
if Re < 2300
   h = 3.66*k/D;
else
   h = (k/D)*0.023*Re^0.8*Pr^0.3;
end

%Outlet water temperature [deg C] calculation
T_mo = T_m-(T_m-T_mi)*exp(-pi*D*L*h/m_dot/c_p);

%Convection heat transfer calculation
Q_conv = h*pi*D*L*(T_mi-T_mo)/log((T_m-T_mo)/(T_m-T_mi))

%Q_conv2 = m_dot*c_p*(T_mo-T_mi) *different formula verifies Q_conv wattage above

%-------------------------------------------------------------------
%Conduction Model: hollow cylinder with a thickness

%Thermal resistance calculation
%R_cond = log(0.5*D/(0.5*D-t))/(2*pi*L*k_cu);
R_cond = t/(0.08*pi*D*L*k_cu); % (8% included HERE)

%Conduction heat transfer calculation
Q_cond = (T_mi-T_m)/R_cond

%-------------------------------------------------------------------
%Total heat transfer dissipated
%Q_net = Q_conv+Q_cond
```

APPENDIX C

Validation Protocol

Our six main engineering specifications defined in DR1 are as follows:

- Increase the comfortable usage time of the suit by >50%
- Increase donning/doffing time by <5 minutes
- Device meets all requirements in 110°F
- Device is less than 20 lbs
- Compatible with 3M Coverall 4510
- Compatible with 3M sizes (S-4XL)

Of these, only the mass of the device can be measured by inspection alone. Through our validation procedure, we will need to measure the comfortable usage time the device provides while used with a protective suit, the donning/doffing times involved with the device usage, whether the device works in 110°F, the compatibility with 3M Coverall 4510 and compatibility with different Coverall sizes.

To perform these measurements we will need:

- Laser thermometer to monitor heat sink and user skin temperatures
- Wireless thermometers to monitor internal suit temperature and temperature of the surroundings
- Stopwatch to measure timing for suit donning and doffing as well as comfort times
- 3M Protective Coverall 4510
- Protective face hood
- Protective respirator
- Disposable gloves

Basic steps for validation of the device's functionality in 110°F include:

- Heat sauna to 110°F
- With cooling vest mounted on test stand, run device in the 110°F surrounding temperature for 30 minutes to ensure device functionality in high temperatures
- Monitor power supply temperatures, heat sink temperatures with laser thermometer to ensure operation at high temperatures is as expected

Basic steps for validation of the suit-device comfort usage time include:

- Put on 3M Coverall, temperature sensors and cooling device
- After fully hydrating, donn face hood, respirator and gloves to simulate health care workers treating Ebola patients
- With attention to safety plan and user's hydration and heat levels, enter the 110°F surrounding temperatures and monitor in 1-minute intervals the user's comfort levels, body temperature and external cooling device temperatures
- When user becomes uncomfortable exit from 110°F temperatures and remove protective gear
- Repeat for 3 other team members

Basic steps for donning/doffing time validation:

- With a timer, time the amount of time it takes the user to put on 3M Coverall, hood, respirator and gloves according to WHO procedure for Ebola treatment.
- Repeat timing activity while adding in cooling device donning

- Repeat for 3 other team members

Basic steps for assuring compatibility with 3M Coverall and sizes S-4XL:

- Properly prepare suit for interface with the cooling device
- Donn the suit and cooling device
- Through inspection, assure the suit is compatible with the cooling device
- Repeat procedure for varying suit sizes

Due to the limited number of people we have to test the cooling device and its usage (4 team members) we will be limited in the conclusions we can draw from our validation data. We will determine, based on the data, whether an average, median or other statistical metric is most suitable to describe the findings in our validation once we have collected the data. Most likely we will use an average of the required donning times and user comfort times in the hot climate testing. The other specifications are simply true or false specifications. The suit will either be compatible with our device or it won't, the device with be compatible with different sizes or it will not and the device will either function in the hot temperatures or it will not.

If further validation were to occur, we could go into more depth in the analysis of our data points for user comfort times and try to better quantify comfort of users and what that entails. However due to our limited resources, we will most likely have to rely on a simple average for our analysis.

APPENDIX D

This section contains all individual ethical and environmental impact statements from each team member.

Ethical Statements

Eljon Elezi: Safety and ethical concerns must be addressed at all times, but especially when designing for a product that has direct interactions with the user. As in the case with our Personal Protective Equipment body cooling device, the user specifications and engineering requirements had to be met while upholding the highest standards of safety. From our early empirical testing, working conditions that healthcare workers experienced were replicated for each team member in order to get an in depth understanding of their discomfort levels. We took this unique opportunity to evaluate the safety concerns associated with incorporating an electrical powered device inside these body suits. This also allowed us to determine how feasible it would ultimately be while preventing and reducing any risk associated to the user. In addition, the packaging of the many individual components was carefully thought out before assembly. Certain risk considerations such as electrical wiring being exposed, water leakage onto electrical components, and interference with the fans were taken to prevent component failure and ultimately protect the user who will be wearing this unit directly on their body. These preventive efforts for safety taken during the design of this product directly align with the first Fundamental Canon of the American Society of Mechanical Engineers (ASME) Code of Ethics.
Attending the Design Charrette early on this design process allowed us to gather an immense amount of knowledge about the Ebola Crisis. This helped layout the framework for the scope of our project and allowed us to see how we could contribute to the ultimate effort as mechanical engineering students. Interacting and listening to people from various backgrounds discuss their personal experiences with the disease and the environment in which is treated, was an eye-opening opportunity. This was extremely valuable later on in the design process when we had to consider maneuverability of the user and how our product would affect that. Another example was when we had to choose if this design was to be a tethered outlet powered unit as opposed to battery powered. Without the discussions we had with the health professionals present at the Charrette, and them telling us that being tethered to an outlet is a common scenario in the healthcare field, we would have been extremely limited to the power consumption with the battery powered unit. So in essence this Design Charrette was a valuable opportunity in which we increased our competence in the subject matter as opposed to blindly designing a product that we knew very little about, directly aligning with the second Fundamental Canon of the ASME Code of Ethics.
It goes without saying how rewarding this process has been not just as a technical experience, but being able to contribute to the relevant issues facing the world. Using our technical knowledge to help make this difference is one of the fundamental principles outlined in the ASME Code of Ethics.

Zach Grifka: Throughout the design process, safety of the user has been of highest priority, which is a pillar in ASCE engineering code of ethics. We needed to convince ourselves that we would feel safe using our product; (1) because it is ethical, and (2) because we needed to use the device to validate its effectiveness. So in effect, we were directly and indirectly using ethics in the design of our prototype.

Specifically, using water in the vicinity of electrical components requires special precaution and care. The entire water subsystem is closed, meaning that the greatest chance of fluid leaving the system and potentially damaging electrical hardware would be at the fluid connections. Therefore, we made sure to isolate our power distribution components from connections that direct water flow. Ideally, the electrical connections would be contained and isolated from the environment, to ensure more confidence in product safety, but we are confident in our current design for the prototype. The prototype has also been tested many times for leaks and reliability before considering human use.

In addition, we selected our electrical components so that they would not fail under our operating conditions. Each component's specification sheet was carefully reviewed so that we understood the limitations of our design and its parts. For redundancy, our design reviews were also chances for our technical peers to address any safety concerns they may have had.

We also designed our prototype so that the user would not be exposed to any moving parts, reducing the chance of injury. In our design, we limited the only moving parts to our DC fans, and the water pump. The water pump is entirely enclosed, and the DC fans are difficult to access with the air manifold that was designed to interface our device with the user's PPE suit.

In summary, we have made necessary design decisions to ensure that our prototype is safe to use. In future designs, more safety protocol could be implemented to increase redundancy in the form of control systems. In addition to safety, we plan on reporting all of our validation results with honesty, regardless of if they meet our engineering specifications. The value of our learnings from this project strongly depends on the truthfulness of our documentation, and it is in our best intentions to do so.

Shreyas Parat: Ethics were considered and applied to every aspect of the design process. Because the user is the number one priority of the product, all engineering specifications were designed around the user. From a greater viewpoint, this product is being designed to increase the safety and the comfort of the user. This product is deemed successful if the user is able to increase the amount of comfortable work time within their suit, thereby drastically reducing the probability of contracting Ebola.

In accordance with the first Fundamental Principle of the Code of Ethics of Engineering, we are "using [our] knowledge and skill for the enhancement of human welfare". By building this product, not only are we increasing the comfort of doctors and nurses putting themselves at risk, but we are making the risk less and helping them do better work.

Canon 1 of the Code of Ethics states that "engineers shall hold paramount the safety, health and welfare of the public in the performance of their professional duties". Similarly, this product is designed with the safety of the user in mind. For example, the fins underneath the fan serve two purposes: one, to smooth the incoming air flow, and two, to prevent the possibility of fingers or other appendages entering the fans and harming the user.

Canon 5 of the Code of Ethics states that "engineers shall respect the proprietary information and intellectual property rights of others, including charitable organizations and professional societies in the engineering field". This canon was followed throughout our design reviews, presentations, and papers. We learned a tremendous amount about the background behind the Ebola crisis from a variety of speakers and mentors at the Ebola Design Charette (Stamps Art & Design School), and wherever we used their knowledge or resources, they were appropriately cited and credited.

Rob Self: Throughout our team's involvement in the Ebola Design Charrette (Hosted by the University of Michigan STAMPS School of Art & Design), group brainstorming, concept selection, design development, device manufacturing and device validation, our sole goal has been to make the treatment of Ebola in West Africa easier. If the doctors who are out there risking their lives to stop the spread of this deadly disease can work a little more comfortably and a little safer due to our device, then we have succeeded. By designing a personal protection suit body cooler, we hope to reduce exposure of health care workers to infectious materials by extending comfortable work time and decrease costs of repeated suit disposal in the hot West African climate.

The ASME Code of Ethics states in the Fundamental Principles that Mechanical Engineers should "use their knowledge and skill for the enhancement of human welfare." By working to better this taxing Ebola outbreak in West Africa I believe our team is doing just that; working to enhance human welfare where it is needed most.

The Code of Ethics also states in Canon 1 that "Engineers shall hold paramount the safety, health and welfare of the public in the performance of their professional duties." By developing this device to improve the safety of health care workers and the treatment of people infected with Ebola, I believe we have also addressed this canon. Additionally we have been careful to make our device extremely safe to use and ultimately have a very positive impact on the Ebola crisis and potentially other infectious outbreaks.

Finally, the Code of Ethics states in Canon 8 that "engineers shall consider environmental impact and sustainable development in the performance of their professional duties." This is addressed thoroughly in my Statement on Environmental Impact. However, our team has been very conscious about reducing the excessive environmental waste of personal protection suits due to short comfort times in the West African climate. Our device has also been designed to be extremely long lasting. With only three moving components, parts are very unlikely to break down and the device should be in service for very long time periods.

By looking at how we can address the Code of Ethics as well as common-sense in our design and manufacturing, we have strived to create a device that can impact the world for the better. We looked to solve a problem that is currently impacting thousands of healthcare workers fighting Ebola and we believe we have made significant strides towards doing so.

Environmental Impact Statements

Eljon Elezi: Our current product, in its initial proof of concept stage, has an environmental footprint that can be reduced by implementing more efficient manufacturing processes and considering eco-friendly material selection. A Lifecycle Design Strategies (or LiDS) Wheel is a popular tool to analyze and evaluate the life cycle of a product to study its environmental impact before and after its mainstream (mass production) use. The LiDS Wheel addresses topics such as low-impact material selection, production techniques, distribution system, impact during use, and an end of life analysis. This methodology can be applied to our product.

The use of mainstream materials such as copper, aluminum, neoprene, etc. was an important consideration for our material selection process. By incorporating these common materials in our design, we are avoiding the need of new fabrication processes.

Mass production of this product will allow components that are customized and properly sized to further reduce the material waste. The aluminum heat sink used to dissipate heat away from the thermoelectric cooler is an example. This component can be scaled down to save on overall material usage. Having the control over the manufacturing behind each individual component will lead to processes that are more efficient and don't use up as many resources as we did in this initial design process.

The energy and resources used in distributing this product can be reduced by offering to manufacture and assemble this product in regions where it is going to be primarily used, primarily the Western African region. The manufacturing behind this product can be integrated into current industrial settings of a large city and distribute the manufactured components to nearby villages to complete the assembly. This will avoid transportation and shipping efforts that would further draw from environmental resources, ultimately reducing the product's footprint.

The drawback to the design of our product is the energy consumption that it requires during use. Since it requires being tethered to a power outlet and drawing from electrical energy, it is not a feasible approach in addressing long-term sustainability. A solution to this problem could be researching into solar powered batteries that are able to offer the power demands of the electrical outlet.

Majority of our current components consists of recyclable materials such as copper and aluminum that can be reused after the product has reached its lifetime use. Incorporating the use of such materials utilizes current efforts addressing recycling to promote sustainability. The components of the overall unit are stand-alone components. A defective component of the product can easily replaced and avoids the need to discard or replace the entire assembled unit.

Zach Grifka: Most of the materials used in our prototype are common metals or plastics, including copper, aluminum, polycarbonate, neoprene, and vinyl. The aluminum sheet parts that we manufactured were first cut on the waterjet, but were worked by hand afterwards. We purchased a used (recycled) aluminum heat sink, saving us from investing more work and energy into manufacturing, however I am sure that the process was relatively energy intensive when it was first manufactured. Manufacturing the cool side heat exchanger was very time and energy intensive as it was hand-milled from a piece of square aluminum stock. We also invested in a used life jacket, essentially recycling the materials composing the jacket. Most of the materials used in our design are also recyclable, including aluminum and copper.

When the prototype is operating, it is rather energy intensive because of the inefficient behavior of the thermoelectric chip. This is why the device has to be powered with a standard 120 VAC outlet and is not battery powered. Future work on this prototype could include a power management system that automatically reduces power consumption during cooler environmental conditions, making it more sustainable.

Although operation is relatively inefficient, the lifetime of our prototype is in the hundreds of thousands of hours. This will reduce the frequency of scrapping disabled components. Plus, the only components that are expected to fail over time are off-the-shelf components, meaning that the rest of the design can be reused as new components can be purchased and installed as required. The manufacturing intensive components are designed to last past many life-cycles of the off-the-shelf components, making this design one that can last.

If the time comes that the entire design fails, the copper and aluminum components can be recycled, however the off-the-shelf components will have to be disposed of. Our design's long lifetime, modularity, and use of recycled components are its sustainable benefits; however its sustainability can be further increased by minimizing material and electrical energy used.

Shreyas Parat: The Ebola viral disease requires health-care workers to wear full body suits and cover all parts of their body. These suits are made out of a teflon-like material and are disposable. The workers must dispose of their suits after each use because once they are covered in contaminants, it is incredibly difficult to clean each suit. It is much safer to simply dispose of the suit. All the contaminated suits must be burned in order to guarantee elimination of ebola contaminants. Our product extends the usable time of each suit, thereby reducing the number of suits that must be disposed. In this manner, the product has a great net positive environmental impact.

This device is designed with a lifetime of roughly 5 years of continuous operation. It was also designed with more use cases than just for the treatment of Ebola in West Africa. Because this device is designed to work in any condition that requires full body PPE, it can still be used to assist workers once the Ebola crisis has been halted.

Although the thermoelectric chip used to cool the user is an inefficient process, it allows for the elimination of several moving parts, reducing the need to replace broken parts or maintain the device. That in turn increases the life of the product and reduces the chances that it would need to be replaced. Similarly, the two main components with moving parts, the fans and the water pump, are off the shelf components that are ubiquitous and simple to replace. They are designed to withstand hundreds of thousands of hours of continuous usage, making the lifetime of this product very high.

One major environmental impact of this device is its need for a constant electric power source. Because these hospitals are generally located in rural areas without electricity, they operate using generators as power sources. The addition of a few of our devices would either require the addition of another generator or more frequent refueling of the generator. The extra fuel used would release extra pollutants into the air.

Lastly, the large aluminum heat sink and copper tubing are very easy metals to recycle at the end of the product's lifetime. In fact, our device is built using a recycled heat sink.

Rob Self: The main materials used in our personal body cooling device are aluminum, polycarbonate, neoprene, copper, thermoelectric cooler and power supply. We have put much time and consideration into the life-span of our device design and the implications that has on its environmental impact.

The most significant component of our device is the aluminum heatsink which is used to dump high-temperature heat into the atmosphere from the thermoelectric cooler. Aluminum is very energy intensive to make however it is easily recycled and reused at its end of life. In fact, the heat sink we are using on our device is a used industrial heatsink that we purchased online. When the previous device it was on reached its end of life, we repurposed it to use in our cooling device. This could easily be done with the heatsink on our device after it has reached the end of its life.

Polycarbonate is used in the backing and ducting of our personal body cooler due to its high strength while being very light weight and resistance to fracture. Additionally, polycarbonate is very easy to recycle and results in high recycling yields. At the device's end of life the polycarbonate used can be easily cut up and melted down to be used again with minimal energy input.

Neoprene is a synthetic rubber and was used in the construction of the mounting vest in our device. Neoprene works well due to its insulative properties that protect the user from exterior heat as well as its strength and pliability. At the end of its life, neoprene is commonly recycled into sheets of rubber, fabrics, exercise equipment and any other product with recycled rubber.

Copper is an extremely valuable metal that is used extensively in our world. The heat exchange piping in our vest is made from copper due to coppers extremely high thermal conductivity and its ability to be shaped relatively easily. Copper requires quite a bit of energy to make as there is a lot of heat involved in its creation and extrusion, however, once made it can be easily recycled and re-casted or forged to make new copper parts.

The thermoelectric cooler is comprised of ceramic plates and semiconductors. The process of manufacturing semiconductors is somewhat energy intensive however due to the small size of the thermoelectric cooler it is not a significant factor in the overall device. Additionally, the rated life of the thermoelectric cooler is 200,000 hours of use. This means that the device will last for years of continuous usage which means that the impact of the energy required to manufacture the components is divided out over an extremely long time period and ultimately reduces the total environmental impact of the device as compared to something that lasts only 1,000 hours of use for example.

The switching power supply is composed of an electronic circuit board with capacitors, transistors, resistors and other standard electronic components. The board and electrical components do require a fair amount of energy to manufacture however, the lifetime of this power supply should come near to matching the thermoelectric cooler at around 200,000 hours. Recycling of the power supply is a little more difficult but is possible. The board can be stripped of its metal and the components can be recycled individually at the power supply's end of life.

Overall, the only consumable our cooling device has is electricity. The components chosen to operate the vest are all computer cooling grade and are designed to all last tens of thousands of hours of usage. The first components to fail would be the water pump or fans which could be inexpensively replaced and don't require the entire vest to be scrapped. The device consumes around 400 to 500 watts of electricity during usage, which is somewhat significant. However, due to electricity's adaptability to renewable sources, this device could be easily powered by solar panel systems especially in the hot climates it is designed to be used in. With up to a 200,000 hour usage life-span, minimal moving components and replaceable parts, our personal cooling vest is designed with the environment in mind. Even at the end of its life cycle, all of the components are easily recycled after providing many hours of service cooling healthcare workers.

APPENDIX E

Bill of Materials

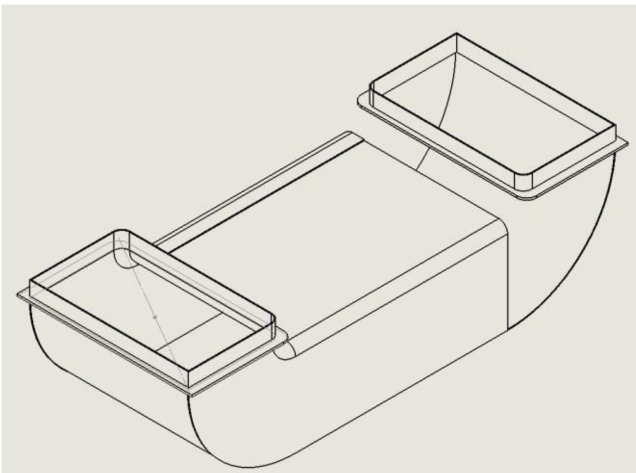
Item	**Make / Model #**	**Supplier**	**Qty**	**Price**
Thermoelectric Cooler (Peltier Module), 62x62x4.8 mm	TEC1-12730HTS	Electron.com	1	$64.70
Power Supply, 36 Amp 41 Amp Peak 9-15.5 VDC	S-400-12	MegaWatt	1	$65.00
Hot Heat Sink (Aluminum), 11.375x6.25x4.375 inches	N/A	Private (ebay)	1	$46.84
Adult Male Medium Ski Vest 38-40	301	Ocean Pacific	1	$39.95
Cold Liquid Heat Sink ½ in barb ¼ in NPT fitting	N/A	Swiftech	1	$6.40
Polysynthetic Ceramic Thermal Grease, 14 grams	AA-14G	Arctic Alumina	1	$7.75
Yamalube Yamabond Semi Drying Liquid Gasket, 7 oz.	ACC-BOND4-MC-00	Yamaha	1	$11.15
Hot Heat Sink Fan, 120 mm	AFB1212GHE-CF00	Delta	2	$48.98
Cold Heat Sink Pump	MCP50X	Swiftech	1	$84.34
Heat Pump Reservoir	MCP50X - RES	Swiftech	1	$29.95
Copper Soft Refrigeration Coil Pipe, 3/8" OD x 20 feet	D-06020PS	Home Depot	1	$30
Clear Vinyl Tubing, 5/8" ID by ½", 20 feet	SVKI20	Watts	1	$7.26
½" Black Chrome Barb with G1/4" Threads	Ex-tub-1025	XSPC	2	$6.99
Fittings, M4 Screws, Tube Cutter	Various	Home Depot	N/A	$40.56
Acrylic Cement, Low-VOC, 5 oz. clear tube	16 10315	SCIGRIP	1	$7.99
Polycarbonate Scrap Material, 3/8" thickness	Custom	Machine Shop	1	$0
Acrylic Scrap Material, 1/8" thickness	Custom	Makeathon Event	3	$0
6061-T6 Aluminum Scrap Material, ¼" thickness	Custom	Machine Shop	1	$0
6061-T6 Aluminum Scrap Material, 3/4" thickness	Custom	Machine Shop	1	$0
6061-T6 Aluminum Sheet Metal Scrap Material, 1/16" thickness	Custom	Machine Shop	1	$0
		Total		$497.86

APPENDIX F

This section contains all Engineering Change Notices (ECN) made from design changes that occurred after DR4.

Air Manifold

WAS:



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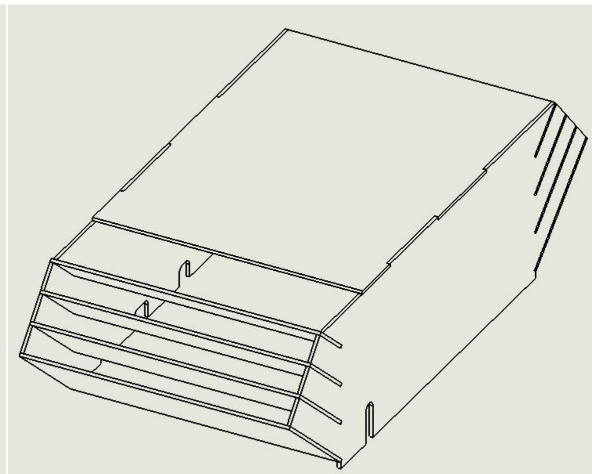
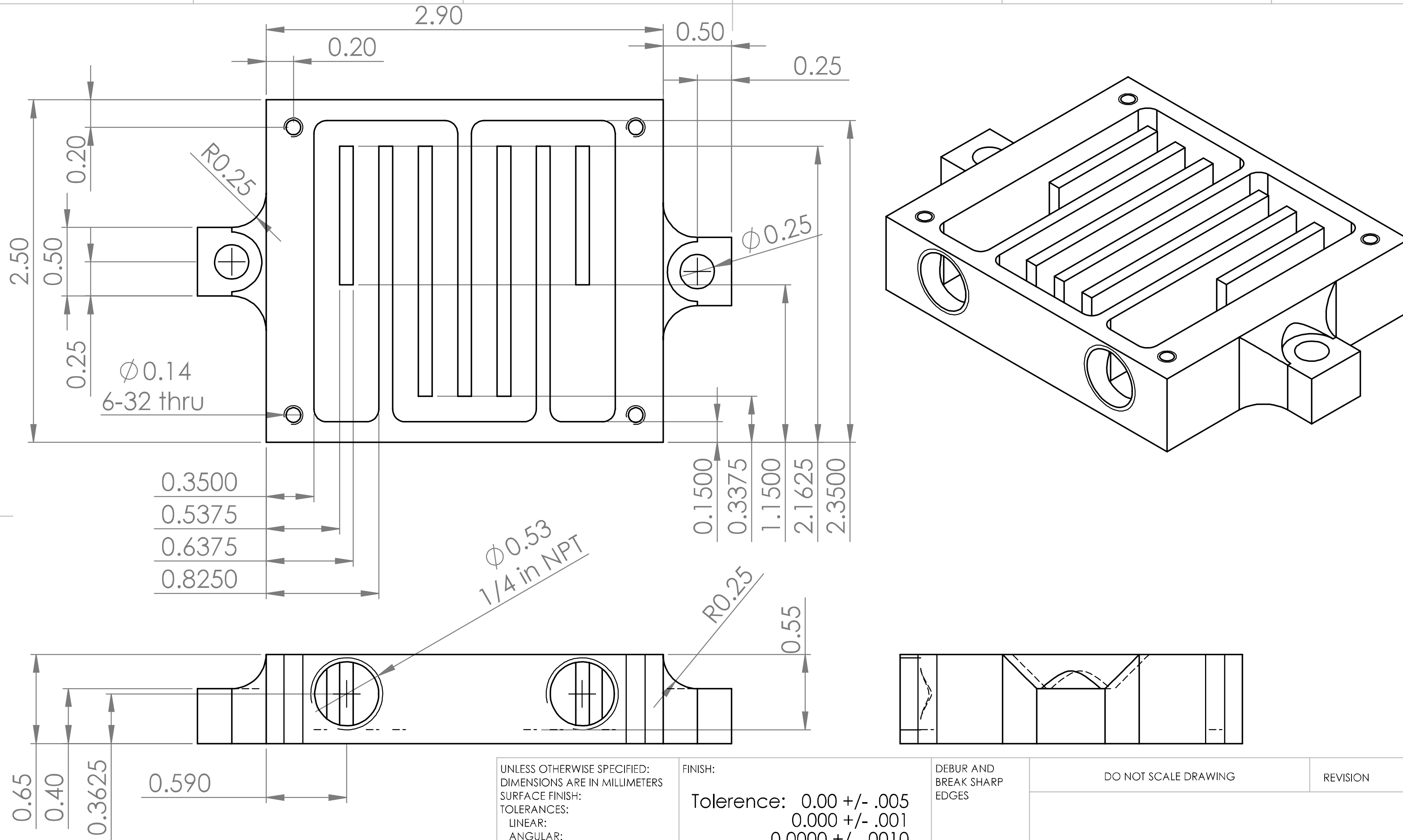


The entire design of the air manifold was changed before manufacturing, due to time and resource constraints. The new design features simple subcomponents that can be laser cut from 1/8” acrylic, saving time and complexity. The design change does not affect the performance of the air manifold, as both designs will successfully direct air flow from the outside of the suit, across the heat sink, and then out of the prototype. Shreyas was responsible for creating both designs, but the entire team supported the design change to benefit the project.

APPENDIX G

Formal engineering drawings for all manufactured parts contained in our prototype can be found in this appendix.



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CHK'D						
APPV'D						
MFG						
Q.A				MATERIAL: Aluminum	DWG NO. No. 3 - Team 23	A4
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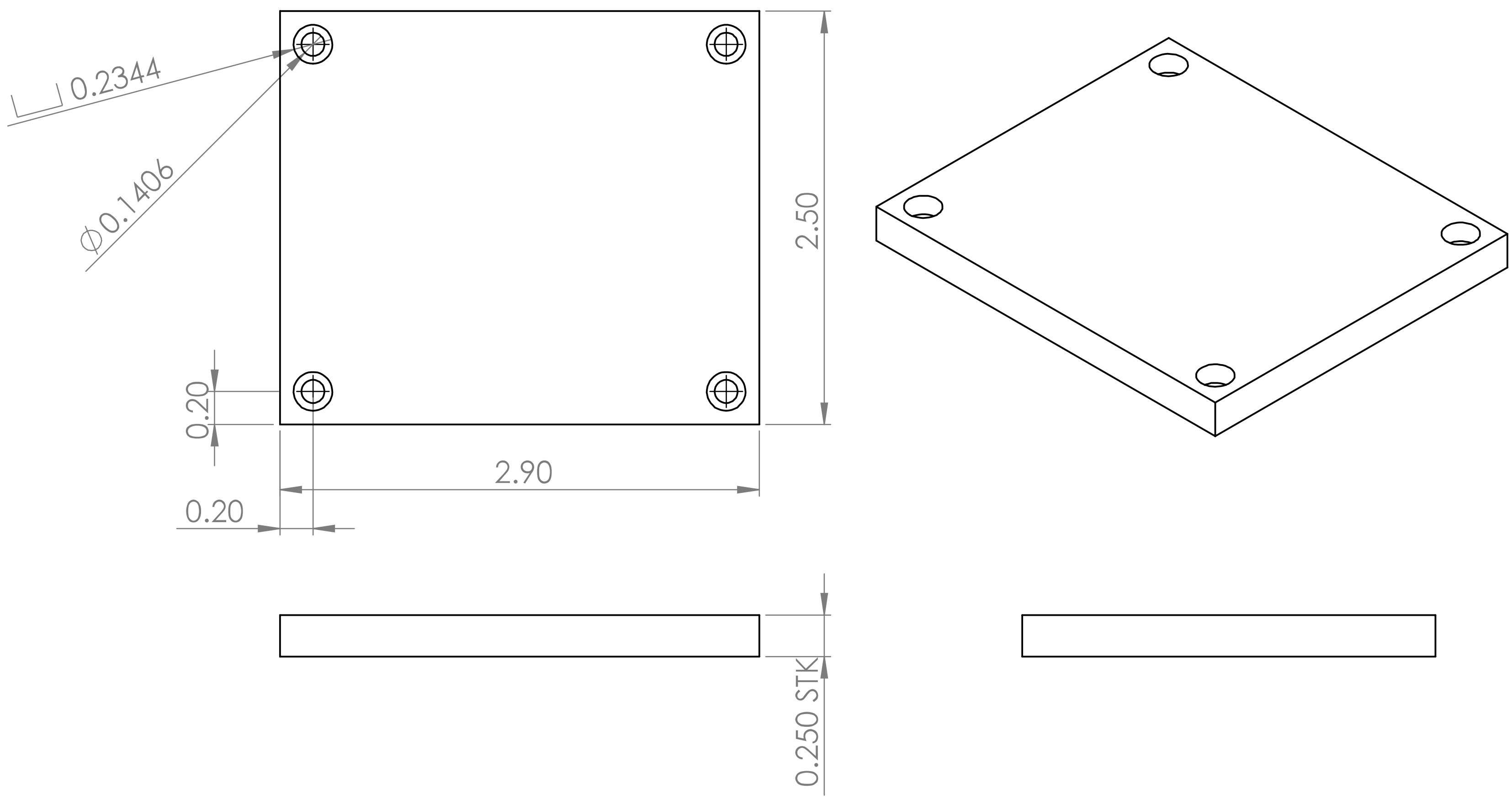

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0.000 +/- .001
0.0000 +/- .0010

DEBUR AND BREAK SHARP EDGES

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CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:
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No. 2 - Team 23

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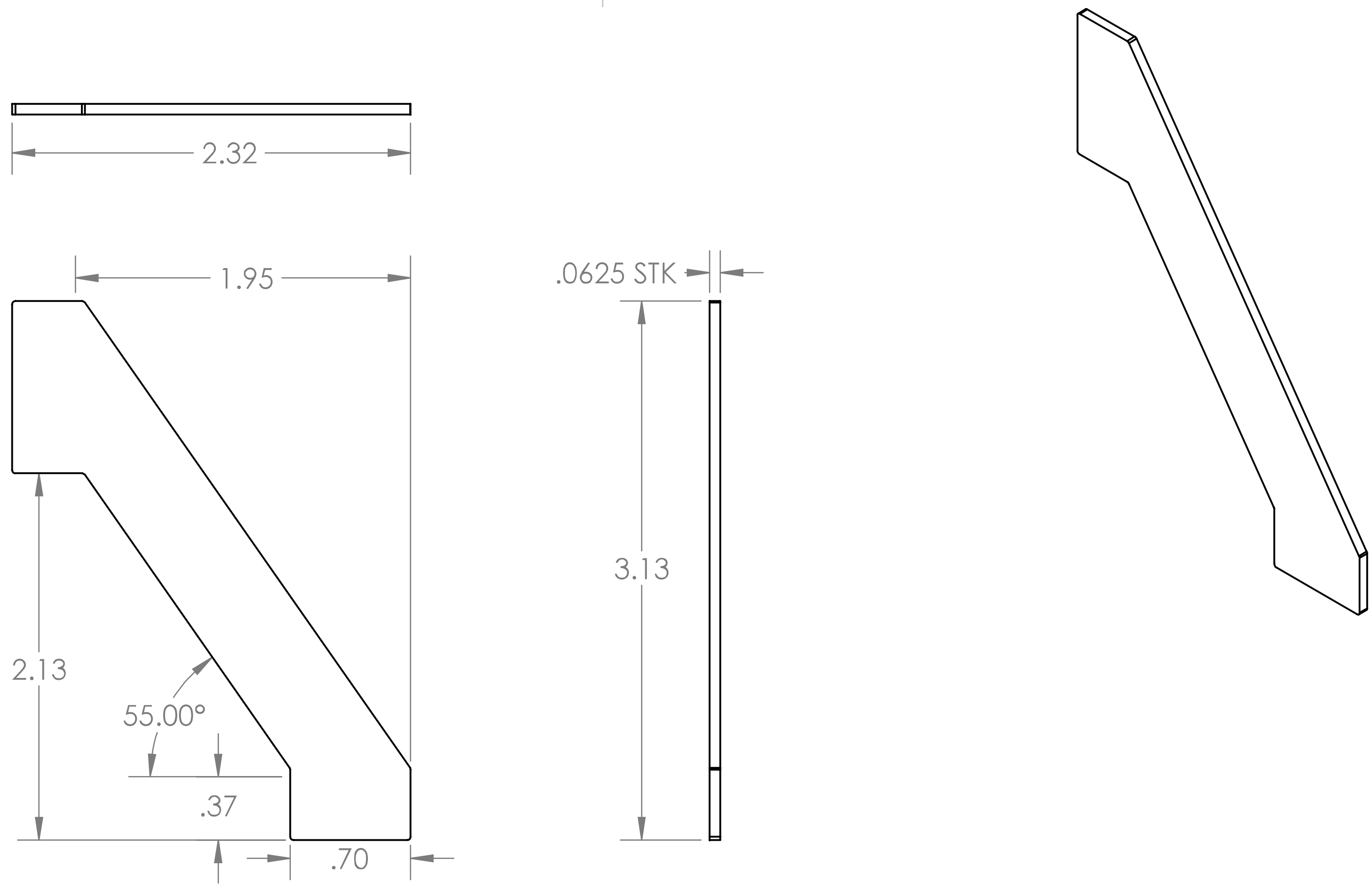
SHEET 1 OF 1



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CHK'D				
APPV'D				
MFG				
Q.A				

TITLE:

Fan Bracket Support (x2)

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A4

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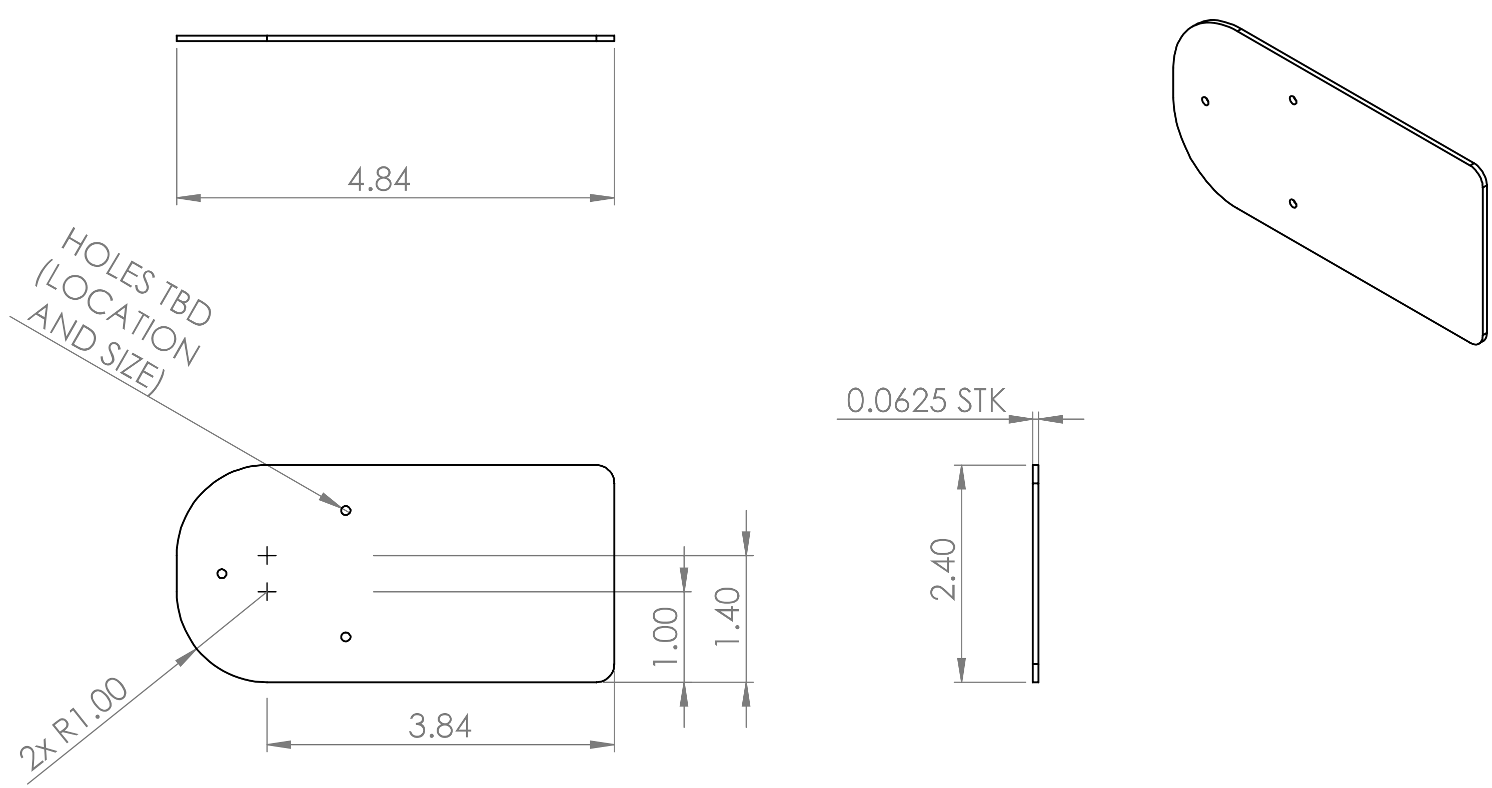
SHEET 1 OF 1



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CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

Water Pump Bracket

MATERIAL:

Sheet Aluminum

DWG NO.

No. 5 - Team 23

A4

WEIGHT:

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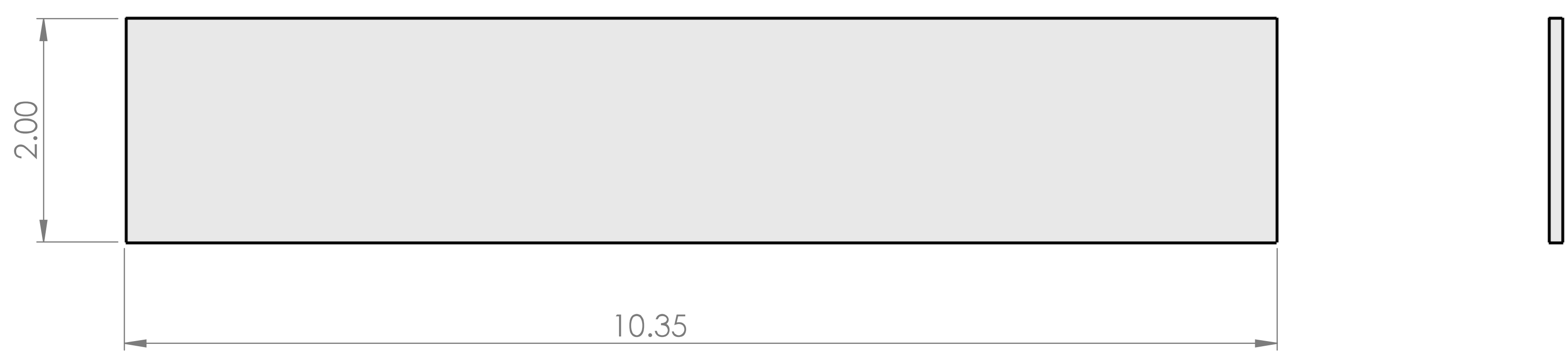
SHEET 1 OF 1



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APPV'D						
MFG						
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APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:

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A4

WEIGHT:

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DEBUR AND BREAK SHARP EDGES

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REVISION

Note: 2X

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DRAWN			
CHK'D			
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TITLE:

MATERIAL:

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A4

WEIGHT:

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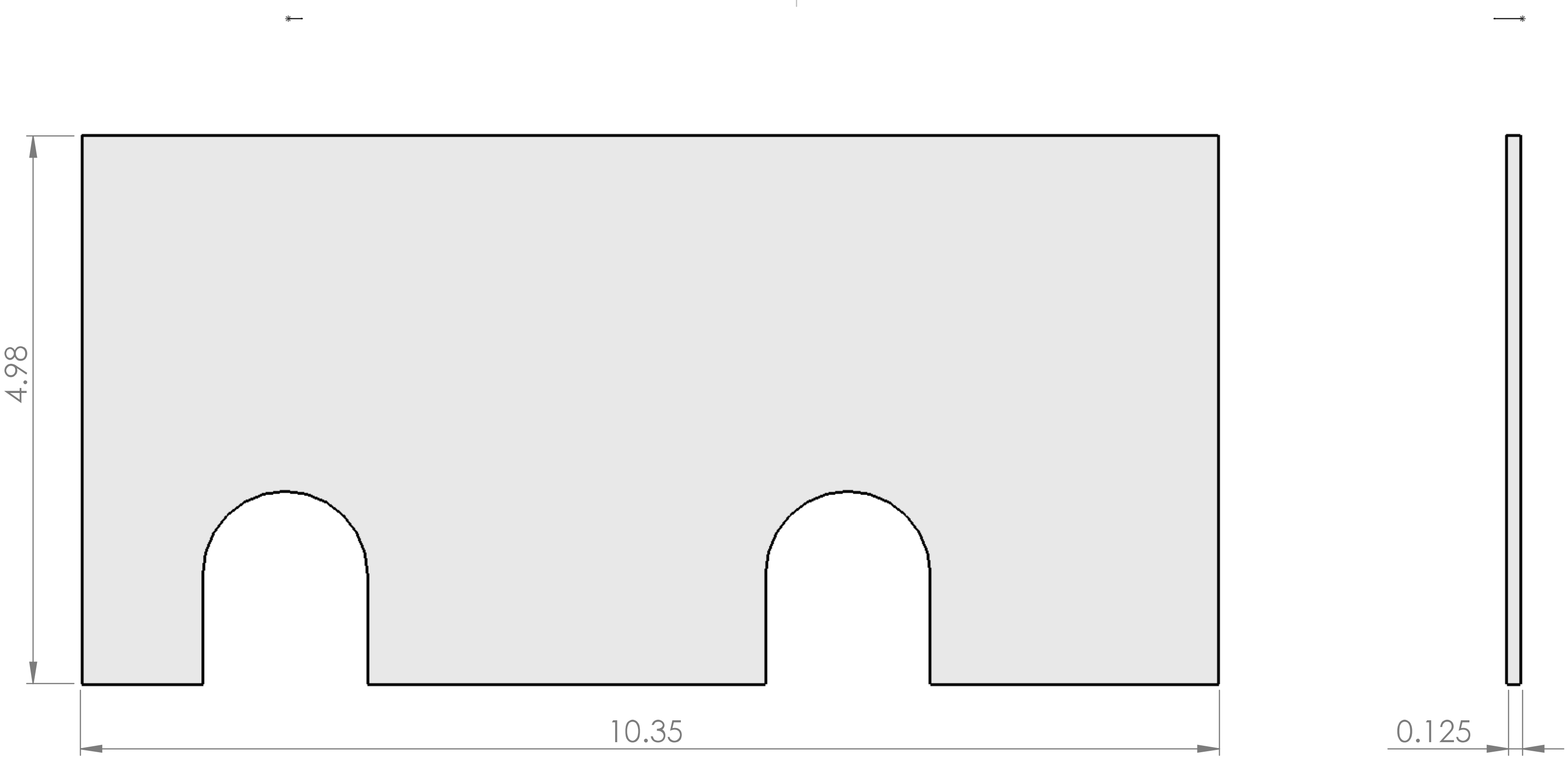

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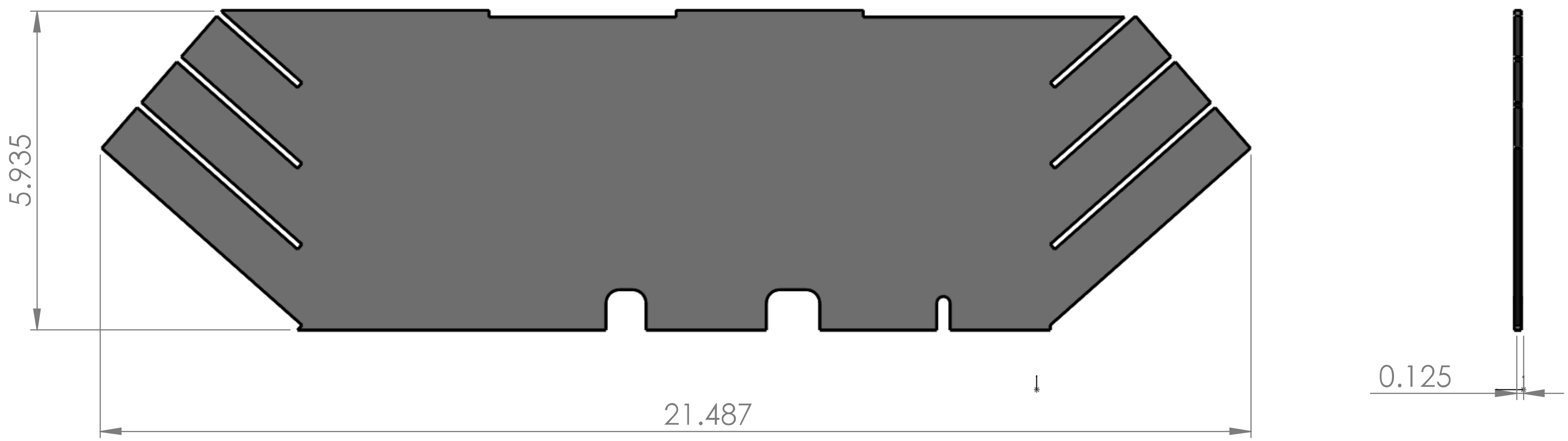

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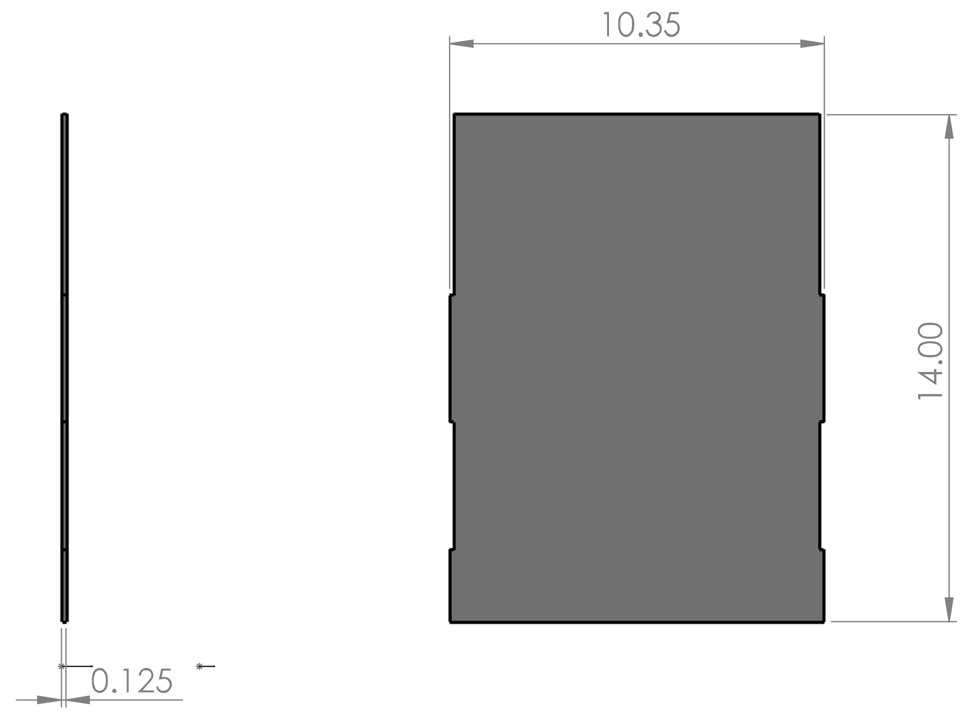

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APPV'D					
MFG					
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