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THERMAPPAREL – MULTIPLE SCLEROSIS BODY COOLING SYSTEM
Project Number: P16013

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ABSTRACT

Some illnesses, such as Multiple Sclerosis, have symptoms that are exacerbated by excessively warm environments. This cooling system aims to assist such patients with regulating their body temperature by applying a cooling load sourced from the latent heat capacity of wax Phase Change Materials (PCMs). This substance melts at a temperature slightly above room temperature, allowing it to be refrozen without the use of a freezer or refrigerator. Body heat will be conducted into the PCM and stored in the form of latent heat. This system will be worn as a belt around the midsection and be relatively inconspicuous on the wearer. This paper will discuss the initial requirements for the system set forth by the customer, the project budget, the design process and engineering models, the testing set-up and results as well as recommendations for future work to be done on the project.

NOMENCLATURE

Phase Change Material (PCM): a wide category of materials capable of storing and releasing large amounts of energy during the melting/freezing process. A common example of a PCM is ice/water.

INTRODUCTION

Multiple Sclerosis (MS) is a degenerative disease in which the immune system attacks the central nervous system and is estimated to affect 2.3 million people worldwide [1]. The immune system specifically attacks the myelin sheaths surrounding the nerve fibers as well as the nerve fibers themselves. This causes the nerve impulses travelling to and from the brain and spinal cord to be interrupted which can cause a multitude of symptoms including fatigue, numbness, weakness and gait problems among many others [2]. MS patients can be adversely affected by heat; they fatigue more quickly and their symptoms become more pronounced in warmer environments.

There are currently a variety of body vests and accessories on the market with the goal of providing cooling relief to MS patients, but none of them are ideal. Most of these products are bulky, short-lived and unfashionable making them unpopular with MS patients. Research done in the summer of 2015 identified phase change materials as a potential solution for use in a body cooling system aimed at MS patients.

The goals for this project are to analyze and optimize the phase change material in the body cooling application and to determine the feasibility for use. A testing apparatus will be designed to test different garments to determine the ideal cooling parameters. The end result will be a functional prototype that has been tested and found to provide the most efficient method of cooling. In the future, this system also has other potential applications including for the military, athletes, and construction workers, among others.

PROBLEM DEFINITION

After consulting with stakeholders including MS patients, caregivers, MS Society professionals, and clinicians, a list of customer requirements and engineering requirements were created and are shown in Table 2 and Table 3, respectively. These requirements include both those for the final body cooling system as well as the testing apparatus needed to determine the cooling efficiencies of various materials. Based on these requirements, preliminary prototype designs and testing plans have been created. An important part of the testing is determining the effectiveness of various phase change materials as well as the insulative and wicking materials that will be used to create the garments.

The most effective phase change materials were found by using the First Law of Thermodynamics and with technical information provided by the manufacturer, PureTemp.

$$\Delta Q = mc\Delta T \ (1)$$

Where ΔQ is the heat that flows into a system, m is the mass, c is the specific heat, and ΔT is the change in temperature. Through these calculations, the net cooling starting from both freezer temperature (-18°C) and room temperature (20°C) were found, as seen in Table 2. Based on these results and the discontinuation of PureTemp 24, PureTemp 23, 25, and 27 were chosen for further testing.

BUDGET & MARKET ANALYSIS

The initial budget for the project was $3,000 and an additional $1,250 and $1,000 were obtained as a result of taking second place in the RIT Tiger Tank Competition and the RIT Effective Access Technology Competition, respectively.

There is a large market potential for a body cooling device among MS patients. Currently, about 200 Americans are diagnosed every week with MS, over one American every hour, which helps predict market growth rates. After gaining customer awareness in the MS market, the team can expand its focus into other markets that could benefit from this product. The key barrier to entry in the medical device industry is the FDA approval process. However, ThermApparel can navigate more easily through this process due to the fact that the phase change material being used is FDA compliant.

Moving forward, the team has approximately $820.86 left from the initial $3,000 budget. This will move forward with the project and will be used to support human testing compensation. Additional costs are also expected but not yet known including legal fees, FDA related expenses, manufacturing costs, and raw material costs if the device is moved into production by future teams.

DESIGN PROCESS

Most of the specifications for designing the cooling device came directly from the voice of our customers. The requirements of the customers were obtained through communication with Adam Podolec, Research Engineer and liaison to Al Sigl Community of Agencies, clinicians and patients at the upstate NY chapter of the MS Society, and various caretakers from the Al Sigl Community of Agencies. The team then translated these customer requirements into engineering requirements for both the cooling device and test rig, as shown below in Table 1 and Table 2, respectively. These requirements were then ranked according to relative importance with a score out of 9. The requirements that stood out to be most important for the device were the ones relating to its cooling ability, total weight, and how noticeable it is. For the test rig, the most important requirements related to its accuracy and ability to record meaningful data.

To meet these requirements, the team came up with various alternative concepts. These included a belt, a collar/dickey design, a design that covers the back, and designs for more conspicuous areas like the ankles or wrists. To gather more information about which location of the body to pursue, subject matter experts were consulted. The belt was found to be the most feasible concept given the goals, requirements, and limitations of the project.

Two insulative and three wicking materials were researched and tested to determine the ideal materials for the final prototype. 3M Thinsulate J250 was the best insulative material according to the greatest temperature difference across the material with one side exposed to a heat source. This material was not available from the manufacturer at the time of order and had greater than a 16 week lead time, so 3M Thinsulate 150 was ordered instead. Any team conducting future iterations of this design may want to look into the potential availability of J250 as it was proven to be about 20% more effective at insulation than 150, although 150 is thinner and therefore makes the device less cumbersome. Polyester Flatback Mesh from Rockywoods Fabrics was determined to be the ideal material for the rest of the device since it would lie between the human user and the PCM and would best allow heat transfer to keep the user cool.

Customer Requirements			
Category	**Requirement #**	**Importance**	**Description**
System	CR1	9	Light weight
System	CR2	9	Unnoticeable or fashionable
System	CR3	3	Comfortable
System	CR4	1	Allergy conscious
System	CR5	3	Quick recharge
System	CR6	3	Easy to use (system)
System	CR7	9	Efficiently cools body
System	CR8	9	Long duration of cooling
System	CR9	9	Safe
Test Rig	CR10	9	Test for ideal phase-change material properties
Test Rig	CR11	9	Test for optimal insulator material thickness
Test Rig	CR12	9	Determine duration of cooling
Test Rig	CR13	9	Determined duration of recharge
Test Rig	CR14	9	Test for weight of system
Test Rig	CR15	9	Determine rate of cooling
Test Rig	CR17	9	Easy to use (rig)

Table 1: Customer requirements

Engineering Requirements									
Category	**Requirement #**	**Importance**	**Source**	**Description**	**Unit of measure**	**Target Value**	**Verification Method**	**Actual Value**	**Requirement Met?**
System Design	ER1	9	CR1	Total Weight of Body Cooling System	lbs	< 3lbs	Weigh using scale	1 lb 1.55 oz	Yes
	ER2	9	CR2	% of observers who notice system	percentage	< 10%	Survey Observers	TBD	TBD
	ER3	3	CR3	Time worn and deemed comfortable (score <=3 out of 10 on pain scale)	Subjective ranking	<=3	Survey users	TBD	TBD
	ER4	1	CR4	% Composition of Latex	percentage	0%	Observation	0%	Yes
	ER5	3	CR5	Time to refreeze after use	hrs	< 2 hrs	Time the process	8 minutes in freezer, 90 minutes at room temperature	Yes
	ER6	3	CR6	Time to put on/take off system	mins	< 2 mins	Time the process	22.5 seconds	Yes
	ER7	9	CR7	Rate of body cooling (sedentary)	Deg C/min	0.1 Deg C/min	Use Thermometer & Stopwatch	N/A	N/A
	ER8	9	CR8	Duration of Cooling	Hours	> 2 hours	Time the process	2 hours	Yes
	ER9	9	CR9	FDA compliant	Binary	Successful	Pass or fail	Pass	Yes
	ER10	9	CR3	Flexibility	Angle (degrees)	<20 Deg difference	Goniometer test	TBD	TBD
Test Rig	ER11	9	CR10	Net Energy Storage capability	Joules	340J	Temp. Sensor	110,000 J	Yes
	ER12	9	CR15	Accuracy of Temperature measurement	Deg C	"+/-" .5 Deg C of actual	Digital therm. specs	0.5 Deg C	Yes
	ER13	9	CR14	Accuracy of Weight measurement	lbs	"+/-".1lbs of actual	Digital scale specs	0.003 lbs	Yes
	ER14	9	CR11,12,13,15	Accuracy of Time value measurement	s	"+/-".1s of actual	Sensor specifications	0.01 s	Yes
	ER15	9	CR10 - CR15	Sensor response time	s	< 1s	Sensor specifications	0.01 s	Yes
	ER16	3	CR17	Setup Time of rig	mins	< 5 mins	Time the process	1 min. 27 sec.	Yes
	ER17	3	CR17	Space taken up by test rig	sq ft	< 25 sq ft	Measure dimensions	10 sq ft	Yes

Table 2: Engineering requirements and final performance of the cooling belt. Requirements with an actual value of TBD were not able to be tested without IRB approval for human testing and will therefore be tested once IRB approval is obtained in future stages of the project. The rate of body cooling could also not be determined without IRB approval for human testing, but since the human body is very good at regulating the core temperature, the group decided that it would not be feasible for future groups to measure this.

PRELIMINARY DESIGN

Figure 1: Preliminary prototype of the ThermaBelt.

The garment is designed to encompass the phase change material inside a pocket of wearable materials as shown` in Figure 1. The insulative material between the phase change material and the outside environment is designed to insulate the phase change material in order to not lose any of the cooling efficiency of the device. The material between the phase change material and the user is designed to wick moisture away from the user's skin and keep them cool and dry while wearing the garment.

The garment is also designed to be easy to put on and take off for the user since MS patients already suffer from reduced mobility. The final prototypes have adjustable Velcro to strap the garment onto the patient and also allow for easy removal. The user will be able to put on the garment when they are entering a warmer environment, such as going outside during the summer. They will then wear the garment to keep them cool throughout the time spent in the warmer environment and will remove it for recharging once they have returned to a more comfortable environment.

The phase change material being studied for use in this device has melting temperatures ranging from 23-27° C allowing it to recharge at room temperature (approximately 21°) in about 90 minutes. Once the user removes the garment and places it into a room temperature environment, the phase change material will begin to recharge as it freezes. The user will also have the option of recharging the device in a freezer or in ice water to accelerate the freezing process as this only takes about 8 minutes... Once the device is refrozen, it is ready for another use.

ENGINEERING MODEL

In order to test the preliminary design provided by the Industrial Design team, a test setup was created to evaluate the performance of various materials and determine their efficacy as a part of the larger cooling system. The three primary areas of focus included the choice of PCM, insulation, and structural fabric that would make up the bulk of the system.

Given a choice of PCMs, several factors were taken into consideration. Total energy storage as well as rate of transfer were the most important features. The substance needed to have high enough liquid and solid specific heats and heat of fusion to store large amounts of thermal energy from the wearer. The melting temperature was a key determinant of the rate of cooling, as thermal energy travels faster over large temperature differentials. As the PCM warms and slowly melts within the system, the temperature plateaus at the melting temperature until all of the PCM is fully melted. Because of this, the melting temperature needed to be optimized to grant a high energy flux, but low enough to maximize the duration of effective cooling. PureTemp24 was theoretically chosen as the most ideal substance, but was unavailable for purchase. PureTemp23 was chosen in its stead, having similar energy storage capabilities and a slightly lower melting temperature that would cause a slightly faster rate of energy transfer. To verify this prediction, PureTemp23 was purchased and tested against strong competitors including PureTemp25, PureTemp27, and Nexotherm, a proprietary PCM with unknown properties. The properties of PureTemp 23, 25 and 27 can be seen highlighted in Table 3 below.

PCM Material	Freezing Temp (°C)	Cp_s(Kj/KgK)	Cp_L(Kj/KgK)	H_{fus}(Kj/Kg)	Net Cooling (Kj/Kg) (Ti=-18°C)	Net Cooling (Kj/Kg) (Ti=20°C)
Water	0	2.11	4.187	334.8	531	75
PureTemp 12	12	1.76	2.25	181	292	40
Puretemp 15	15	2.25	2.56	182	315	46
Puretemp 18	18	1.47	1.74	192	279	31
Puretemp 20	20	2.07	2.15	171	288	288
Puretemp 23	23	1.84	1.99	227	332	326
Puretemp 24	24	2.85	3.04	184	345	334
Puretemp 25	25	1.99	2.29	187	302	291
Puretemp 27	27	2.46	2.63	202	341	324
Puretemp 28	28	2.34	2.54	190	322	304
Puretemp 29	29	1.77	1.94	202	302	286
Puretemp 33	33	2.34	2.53	179	310	280
Puretemp 35	35	2.44	2.72	181	318	281

Table 3: PureTemp PCM Material Properties for PureTemp 12 through 35.

Testing consisted of placing 100 g of a PCM into an insulated container with temperature probes spaced throughout the solid (Figure 2). Over the course of several hours, the PCM would be slowly melted and the temperature profile would be recorded.

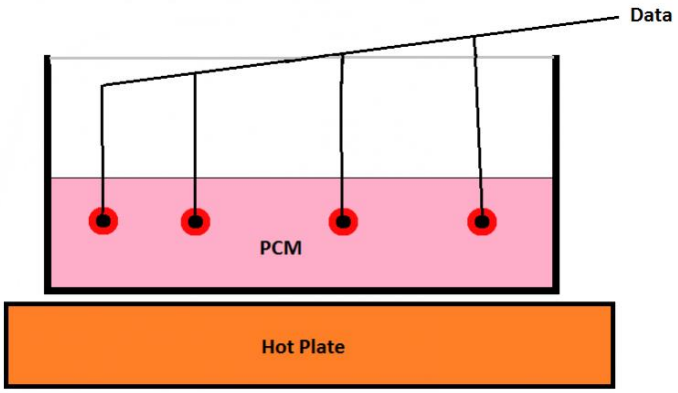


Figure 2: PCM Properties Test Set-up

This profile, when compared to the profile of the other PCMs was used to compare actual melting temperatures and specific heats, obtained by the temperature plateau and the slope of the gradients respectively. As shown below in Figure 3, PureTemp 23 remained in the melting phase considerably longer than PureTemp25 and PureTemp27, and melted at a lower temperature than Nexotherm. While Nexotherm was a strong competitor to PureTemp23 with respect to duration of cooling, other factors such as cost, accessibility, and political complications made it prohibitive and PureTemp23 was chosen as the preliminary PCM for the final prototype.

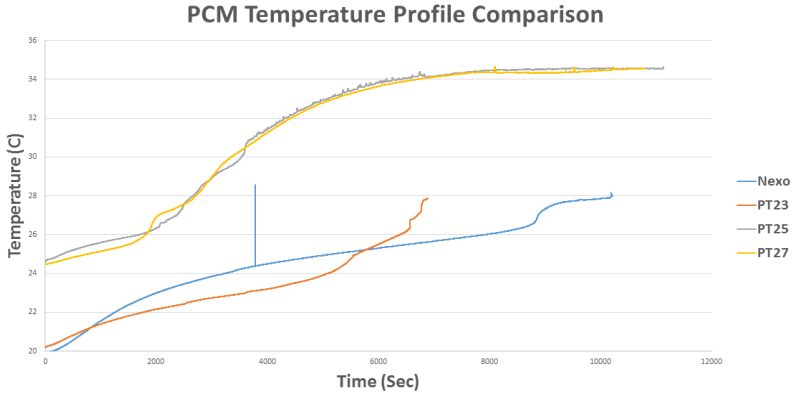


Figure 3: Plot of the PCM temperature profiles while undergoing the PCM properties test.

Insulation was chosen to prevent heat infiltration from the environment if the device was started from a colder environment, such as a freezer. To determine the most effective insulation, a simple temperature differential was recorded by placing a sample of each insulation on a hot plate and placing probes on either side (Figure 4, left). The greater the temperature difference, the more effective the insulation was deemed. An identical test was performed with the fabric (Figure 4, right), though in that case the smallest temperature differential was preferred to minimize any effect on the heat flow from the wearer to the PCM.

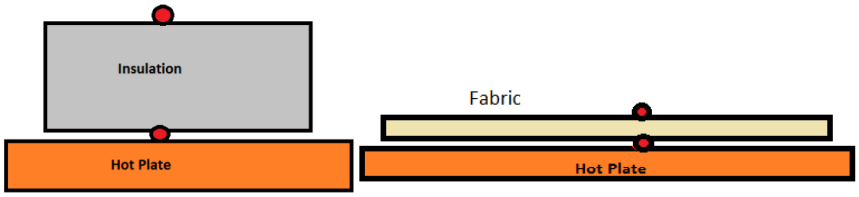
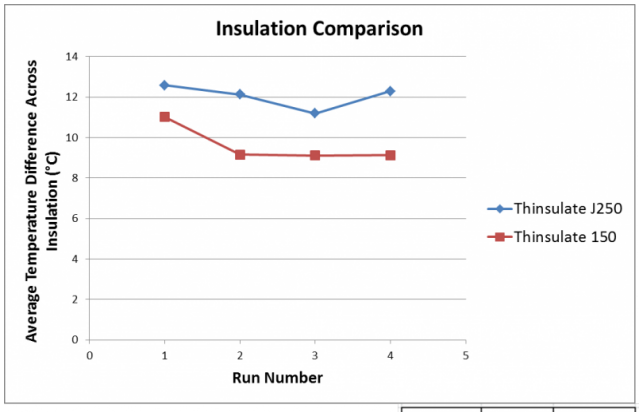


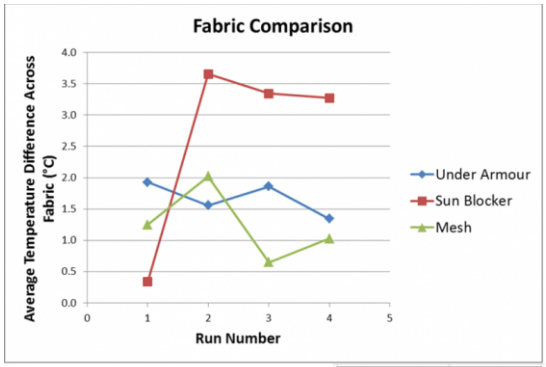
Figure 4: Insulation (left) and fabric (right) test set-ups consisting of the hotplate, temperature sensors, and either insulation or fabric.

As seen below in Figure 5, Thinsulate J250 was measurably superior to Thinsulate 150; unfortunately the J250 insulation was discontinued by the manufacturer. Thinsulate 150 was chosen instead and happens to be slightly thinner. Future efforts should be made to obtain J250 if possible; it would minimize the infiltration of heat from the environment when the PCM is started from a cooler temperature.

The fabric with the least insulative properties was the mesh, followed closely by the sun blocker material. Ultimately, the mesh fabric was selected for use when taking into effect temperature difference as well as subjective comfort and aesthetic factors.



Average temperature difference across insulation for all runs:	J250	150	% Effective
	12.05	9.60	80%



Average temperature difference across fabric for all runs:	Averages
Under Armour	1.671
Sun Blocker	2.653
Mesh	1.235

Figure 5: Temperature difference across the various insulations (left) and fabrics (right).

EXPERIMENTAL SET-UP AND PROCEDURE

In order to test the body cooling device for efficacy two different methods of testing can be employed; both tests are set up in the same manner. The first method is to test the cooling belt on a tissue plate consisting of layers of materials mimicking skin, subcutaneous fat, and skeletal muscle intended to model the human abdomen. The second set of tests can be run on human subjects and the results between the two methods compared. Human tests were not run during this semester due to pending Institutional Review Board (IRB) approval, but the protocol that follows can be implemented in the next phase of the project. For the tissue plate test, a hot plate was heated to 37° C and the tissue plate was placed on top of it with the skin side facing up and allowed to reach equilibrium. When the tissue plate reached equilibrium, one half of the cooling belt with the PureTemp 23 PCM inside was placed on the hot plate. PASCO Temperature Array temperature sensors were placed between each layer with adhesive patches as follows: on top of the hot plate, on top of the tissue plate, inside the belt on the bottom of the PCM, inside the belt on the top of the PCM, and on top of the belt. The Temperature array was connected to a laptop via a PASCO USB link. Temperature data was recorded using PASCO Capstone software until the temperature of the PCM's plateaued signaling that it was completely melted. The testing set up was then disassembled and the data was saved for analysis.

In the case of the human testing, a protocol has been set up for future temperature and flexibility tests. The test subject will first be asked a series of questions regarding the appearance of the cooling belt. This survey can be seen on the team's EDGE website. Next, the test administrator will explain to the subject about the belt and how to put it on and the subject will be asked to put on the device and the time taken will be recorded. The subject will then be asked to take off the belt and the time will again be recorded. The test administrator will also ask for subjective feedback based on putting on and taking off the belt. The subject will next be asked to put on the goniometer sensor vertically with the vertex at their hip using a Velcro belt around their waist and another around their leg. The goniometer sensor will be connected to the laptop using the USB link and angular data will be recorded as the subject is directed to do the following movements: lean forward as far as possible bending at the waist, lean backward as far as possible bending at the waist, and repeat both bends again. The subject will then be directed to put the cooling belt back on over the Velcro band and repeat the bending tests again. This test will be repeated with the goniometer vertex at the small of the subject's back while asking the subject to bend to both the left and the right this time. Next, the goniometer and Velcro belts will be removed and the PASCO Temperature Array temperature sensors will be placed on the belt as follows: underneath the belt (closest to the test subject), inside the belt on the bottom of the

PCM, inside the belt on top of the PCM, and on top of the belt (closest to the ambient environment). The subject will be instructed to put on the cooling belt containing the temperature sensors and to sit in a comfortable position that they can maintain for approximately 2.5 hours. Temperature data will then be collected using the PASCO Capstone software until the temperature of the PCM's plateaus. After the temperature data collection is complete, the subject will be asked about the comfort and flexibility of the device and if they have any additional input on the device. Using this data, the duration of cooling, the time to put on and take off the system, and the average difference in flexibility with the device versus without the device can be found. The comfort level of the system and aesthetic input from the test subject will also be analyzed to improve future iterations.

DATA ANALYSIS

Preliminary data obtained from tissue plate testing as well as other tests is promising and can be seen in Figure 6 below. Multiple temperature profile graphs were recorded using the Pasco software, showing an effective usage time of around 7000 seconds with the most effective transfer occurring in the first 4500 seconds before the PCM fully melted. Other results were consistent with this analysis, with each developing solid and plainly visible curves. At times, due to sliding of the tissue on the hot plate, the data would spike or dip as the probes changed positions. This could be minimized in the future by the creation of a belt-sample with the same dimensions as the surface of the hot plate rather than using a full sized belt which does not fit as easily on the hot plate. These results provide a worst-case scenario for the usage of the belt; most users prefer to wear it on the outside of clothing which add to the insulation separating the PCM and the heat generation of the human body. In addition, the tissue plate model assumes a wet boundary and minimal body fat which increases the rate of heat transfer and provides a shorter-than-actual effective time. During actual human testing, an effective duration of 9000-10000 seconds is anticipated, though the penalty of this gain is a slower thermal energy transfer and a lower cooling effect.

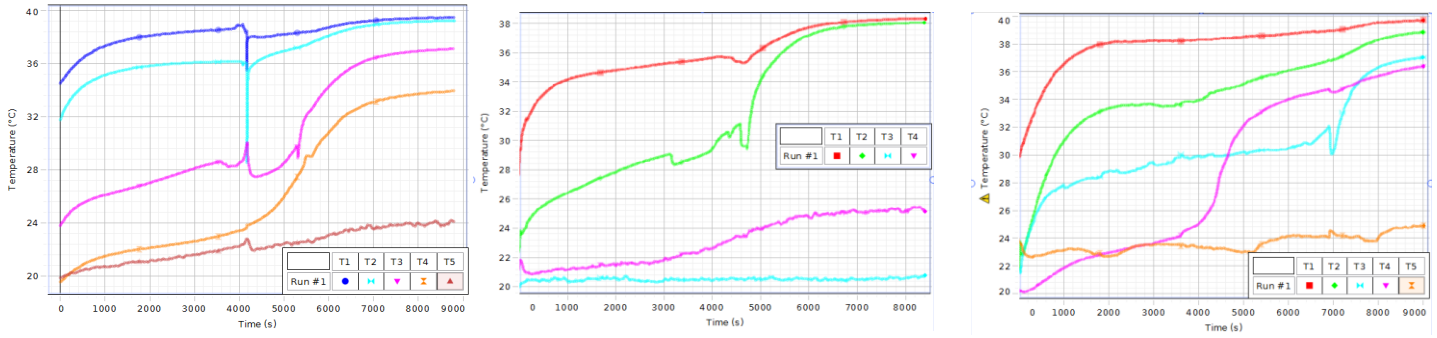


Figure 6: Preliminary data from three tissue plate tests.

CONCLUSION

Most of the original design goals for this project were achieved and the team is confident that the ones that were not measurably achieved will be during the next phase of the project that includes human testing. The engineering requirements along with their target and final values and if the requirement was met or not can be seen in Table 1. All requirements that have TBD listed as their final value are To Be Determined once IRB approval is gained for human testing. These requirements cannot be measured and met without testing the device on humans which was not able to be conducted this semester. As the project moves forward into future phases, the test setup and protocol is in place to conduct these tests and gain insight into these requirements. After consideration of the ability to measure the rate of body cooling, engineering requirement 7 was deemed to be not applicable as the human core temperature only changes in miniscule amounts in response to the phase change material. This is due to the extremely efficient control systems of the human body maintaining homeostasis.

Overall, the most important requirements for both the system and the testing apparatus were met. The weight of the device, the time to put it on and take it off and the duration of cooling all exceeded initial expectations. The device also contains no latex and is FDA compliant if future groups decide to submit this device for FDA approval. All of the testing apparatus requirements were met, as can be seen in Table 2, and therefore the testing apparatus is well-equipped to support the development of future iterations of a body cooling system including various types of devices.

RECOMMENDATIONS FOR FUTURE WORK

The first recommendation the team has for future work is to pursue getting enough test results at room temperature to be considered statistically significant. More than 30 tests would be ideal, as the team did not have sufficient time to complete this many during this first iteration. After these results are collected, it would be beneficial to then consider varying different environmental conditions like humidity and temperature. Instead of testing at room temperature, tests could be conducted at a variety of different temperatures, most likely higher than room temperature to simulate hotter environments. The humidity might also have an effect on the cooling efficiency, so testing at a few different humidity levels could prove beneficial as well. However, the team recognizes that varying these conditions would likely require some type of environmental control chamber or room. Testing at higher temperatures and different humidity levels would give a better understanding of how the device would act in these different environments which exist around the world.

The team also recommends that throughout this process the future team continually keeps their eyes open for potentially better fabrics or insulation. New fabrics and insulation come out very frequently and if a better combination exists then it might be beneficial to explore. However, it would have to be kept in mind that the current test results were completed with the existing fabric/insulation combination, so comparing results might be challenging. It is also worth noting that the team recommended PureTemp 24 as the best PCM to use, but was unable to obtain it as it was discontinued. If this PCM becomes available again and the specifications are the same, it could be beneficial to pursue.

Additionally, the future team could explore different garment types other than the belt. They could follow the same design process as was followed for the belt. Other potential garment types could include a collar/dickey or one that covers the back, but these are certainly not the only potential devices.

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EXTERNAL REFERENCES

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