

A NOVEL PERSONAL COOLING SYSTEM FOR USE BY SOLDIERS IN HOT CLIMATES

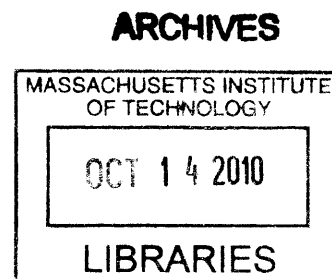
By

Margaret H. Gentile

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A NOVEL PERSONAL COOLING SYSTEM FOR USE BY SOLDIERS IN HOT CLIMATES.

By

Margaret Gentile

Submitted to the Department of Mechanical Engineering on
May 10, 2006 in Partial Fulfillment of the Requirements
for the Degree of Bachelor of Science in Mechanical Engineering.

Abstract

This report focuses on the design, testing and fabrication of a lightweight personal, portable cooling system for use by soldiers beneath their Interceptor body armor. An alpha prototype was constructed and was used to generate promising, quantitative results. This first level data was combined with an analysis of the strengths and weaknesses of the design to lay down the framework for the beta prototype which will be constructed at a later date. The military and physiological requirements for such a device are briefly discussed, as are concerns over fit, wearer comfort, product durability and ease of use.

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Please be advised that a multimedia CD is included with this thesis which contains additional material.

1. Introduction

There currently exist several varieties of personal, portable cooling systems in the market today. Most of these use ice or chemical ‘cold’ packs to keep the wearer cool. This current system, obviously, has several problems. Ice melts the fastest when one needs its cooling effects the most, and the chemical packs tend not to last long and can leak if punctured. Both systems require that the wearer have ready access to a freezer or other cold source in order to ‘recharge’ the vest. These vests are also largely impractical for most kinds of work.

A personal, portable and effective cooling system is greatly desired by many individuals and institutions, most notably the United States military. Even in hot climates, the average soldier is wearing multiple layers of clothing, as well as relevant accessories like helmets, face masks and body armor. Even with advances in fabric technology (such as the tactical Under Armour(tm) currently issued to American soldiers) his BDU can still become unbearably hot, especially during periods of high activity. This leads to increases in incidences in fatigue, dehydration, heatstroke, and even in extreme cases--death.

Large-scale cooling systems like air conditioners are not easily portable, and can only cool a limited, enclosed space. They do nothing for the soldiers in the field--the ones who need it the most. Currently available ‘personal cooling’ technology is not terribly effective, as well as being too bulky to be effectively integrated with the soldiers’ standard kit. The desired system will be thin and lightweight, able to be worn beneath the soldiers’ body armor without interfering

with its fit or comfort level. A portable cooling system that can go anywhere the soldiers go would protect them from heat related health problems and enable them to better perform their duties. It is possible, utilizing simple technologies that have been around for decades, to create a battery-powered, personal cooling system which is lightweight, portable and effective.

There are a variety of constraints that this system must be able to handle. There are physiological limitations and fallibilities of the human body which must be addressed in the cooling vest design.

2. Design Requirements and Concerns

2A. Physiological Concerns

-The cooling system must be able to continuously remove at least 100 Watts of heat from the wearer's body, preferably 150 W. This heat can be removed from anywhere but there are places on the body which are more effective, specifically the chest, stomach, back, neck and head.

-The level of cooling the system delivers must be adjustable for different wearers. Cooling is not one-size fits all. Cooling a user too much is as potentially harmful as not cooling them enough. The veins beneath the person's skin can constrict if cooled too much or too quickly, and this results in decreased circulation and ineffective cooling.

-The system must be able to be separately configured for men and women due to anatomical reasons. A woman's breasts are very sensitive and contain fatty tissue which prevents effective cooling of this area, so any cooling elements must be placed *around* the breasts. Placing cooling elements on the breasts is ineffective and also uncomfortable for the woman.

2B. Environmental/Other Concerns

-The system must be able to *passively* exhaust the heat to the environment. Active exhaustion complicates the system and adds unnecessary weight, parts, and maintenance costs.

-The entire cooling system must weigh less than 4 lbs, preferably less than 3 lbs.¹ This weight excludes batteries. The soldiers are carrying enough equipment in their standard retinue, and any extra weight beyond what's absolutely necessary will only be a bother to them. (The same applies if the vest is to be used by any other people requiring portable cooling--firemen, policemen, steel workers, runners, etc...)

-The system must be durable as possible, and able to withstand the inevitable abuse it will take in the field. This means keeping exposed components to a minimum, making sure fragile parts of the vest are adequately protected, and complying with any relevant military standards for the manufacture of such a device.

¹ This weight is based on military requirements given to us by the Institute for Soldier Nanotechnologies (ISN) at MIT.

-The system must be a system of gradual degradation (i.e. a system where catastrophic failure is near impossible). Damaged cooling vests should maintain as much functionality as possible.

-The system must be easy to maintain and repair. It should be able to be disassembled for cleaning, and made of modular, 'plug-in' components. Training required to maintain and use the vest should be minimal. This means no special tools, and that the basic operation and maintenance instructions for the vest should be able to take up less than five printed pages of text.

-The system components (excluding batteries) should be non-toxic and otherwise safe to handle while intact or broken. If a cooling system is damaged while it is being worn, the risk to the user should be minimal. This includes risk from electric shock, leaking fluids, sharp edges, etc...

3. Basic System Overview

This cooling system utilizes simple, time-tested technologies in a novel way to effectively cool the wearer. The entire system is worn like a pullover vest, with the bulk of the important components contained on the chest portion of the vest.

The main element responsible for heat removal from the body is an array of thermoelectric modules which are placed in a configuration on the front of the vest such that they come into contact with major veins and arteries which are close to the surface of the skin. This configuration is different for men and women, but beyond thermoelectric placement, the rest of the system components are identical (in manufacture) for all users.

Running a current through the thermoelectric array causes a temperature difference across the surfaces of the device, resulting in a 'hot side' and a 'cold side.' Heat is drawn from the 'cold side' and exhausted to the 'hot side' as long as the current is flowing through the thermoelectrics.²

As the heat collects on the hot side of the thermoelectrics, it must be carried somewhere so it can be effectively exhausted to the environment. Heat pipes are very efficient heat transfer devices which have been around for over a century. A heat pipe is essentially a metal tube which contains a wicking material and a small amount of water (or coolant). Placing one end of a heat pipe (called the evaporator) in contact with the hot side of the thermoelectrics causes a pressure difference inside the tube, and the fluid rapidly migrates down the length of the tube in an attempt to equalize the pressure. This heated fluid then comes into contact with the colder end of the tube (the condenser) and transfers the heat removed from the hot side of the thermoelectrics. Once the heat is removed and the fluid condenses, it returns to the evaporator via capillary action

² On a side note, the orientation of the hot side and cold sides of the thermoelectric unit is solely determined by which direction the current is run through the device. Running the current in the opposite direction reverses the hot and cold sides. Because of this, the vest can also be used as a heater in cold climates. (more on this later)

through the wick. This is a cyclical and continuous process which enables the heat pipe to constantly move heat from one location to another.

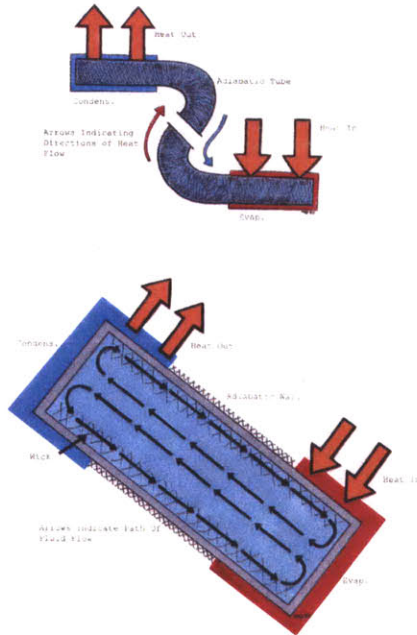


Figure (1): A diagram showing how a typical heat pipe operates.

This rapid heat transfer enables the movement of heat away from the hot side of the thermoelectrics with minimal unwanted losses back to the body.

Once the heat is carried away, it must then be exhausted to the environment. Simply leaving the condenser ends of the heat pipes sticking out is inadequate. The thermoelectrics are clearing heat away from the body at a rate far quicker than natural convection between metal and hot air, so it must be possible to store as well as exhaust heat. This is done by attaching the heat

pipes via a thermally conductive coupling to a small aluminum box which is partially filled with water and evacuated to a vacuum. This box uses a fluid with a high heat capacity to store and transfer heat. The water in the box evaporates due to the heat from the heat pipes and condenses on the comparatively cold walls of the box, transferring heat to the walls where it can be lost to the environment via convection into the air. This box is essentially a heat pipe, but the large volume of fluid enables the heat to be stored as well as transferred.

The heat pipes are attached to this box with a detachable coupling so the box can be removed for repair or replacement. Making the system modular better enables the soldier to repair his vest in the field and helps keep replacement costs lower. The soldier only needs to replace the damaged components, rather than the entire system.

4. Detailed Theory: First Level Prototype

4A. Thermoelectric System

The thermoelectric (TE) array must *collectively* remove at least 100 watts, ideally 150 Watts, from the human body. This assumes an environmental (ambient) temperature of 104 °F (40 °C) and the standard human body temperature of 98.6 °F. The very rough efficiency estimations for this heat exhaustion system are $COP_{\text{fridge}} = .3$ for the TE cooling the body and

$COP_{heat}=4$ for the heat pipes cycling heat away from the body.³ These are found with the equations:

$$COP_{heat} = \frac{1}{1 - \left(\frac{Tl}{Th}\right)} \quad (1)$$

and

$$COP_{fridge} = \frac{1}{\left(\frac{Th}{Tl}\right)^{-1}} \frac{\sqrt{ZT+1} - Th/Tl}{\sqrt{ZT+1} + 1} \quad (2)$$

Where ZT is a material property and is approximately 1 for most materials, including those used in our TE. A value of 1 was used in this calculation for simplicity.

For the TE, the COP is essentially a ratio of heat moved by the TE to electrical power used by the TE. More power is required to transfer more heat across the TE surface. As a rough example, say a TE removing 20 W from a person's body requires 20 W of electrical power to do this. This TE will then have to exhaust 40 W from its hot side.

³ Assuming a hot side TE temperature of 140 °F. (60 °C) This is on the high side, with the actual hot side temperature closer to 120 °F, but the 'worst case scenario' numbers must be used to ensure the best calculation results.

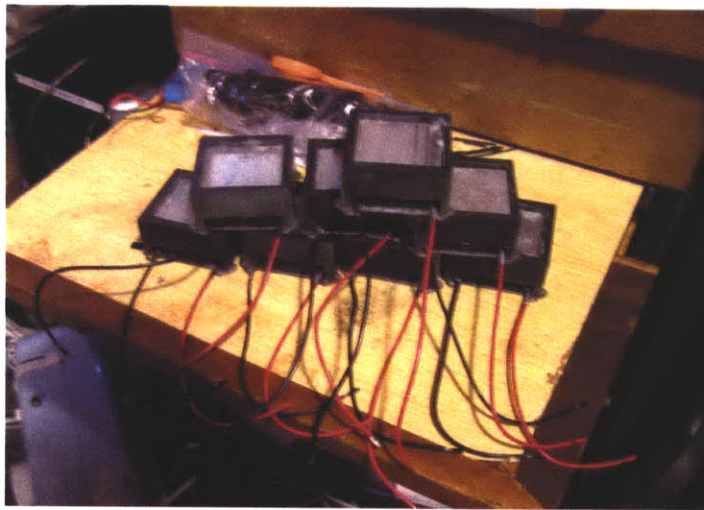
For the heat pipes, the COP is to an extent a measure of the heat losses along the heat pipe length. For the heat pipes to work, a temperature gradient must be maintained where the temperature at the evaporator is higher than the temperature at the condenser and the temperature at the condenser is higher than the ambient temperature. The larger this gradient between evaporator and condenser (and subsequently condenser and environment) generally the better the heat pipe performs, assuming it is operating within its heat transport capacity. Since no heat pipe is perfect there will be some heat losses along its length, and this must be compensated for by adjusting the temperature of the hot side of the TE. (Shakouri) Thus these two COP are linked, and heat pipe efficiency will to an extent determine the behavior of the TE. (More on heat pipe losses in 'Heat Pipes.')

There are a variety of different, commercially available thermoelectrics which meet our criteria. However, we must also take into consideration the maximization of battery life, so the thermoelectrics chosen must draw the minimum of current and voltage. The specific numbers are not important. (i.e., the voltage does not have to draw in a recognized battery value, because the current/voltage regulator will handle that)

For the prototype, we used the CP1.4-127-045L. Eight of these thermoelectrics, arranged in two groups of four in series electrically, will cool at 117 Watts for 2.2 A and 19.4 V and 150 Watts for 2.5 A and 22 V, and they can also be run at higher and lower currents, though higher is not recommended because it reduces TE efficiency and battery life. These voltages and currents

in DC are not harmful to the wearer, so if the wires are accidentally broken, there is no danger of shock.

Thermoelectrics must be insulated along the edges in order to prevent heat leakage from the hot side to the cold side. Sealing the edges of the TE with insulating epoxy or some other material (In the prototype, strips of food-grade silicone was used.) helps, but it is not enough to stop the hot and cold sides from eventually reaching thermal equilibrium. The entire TE must be encased in a fitted sleeve of some insulative material to minimize heat leakage. For the prototype, solid nylon was used because of its high machinability and low thermal conductivity of .25 W/W/m-K.⁴ It was machined on a waterjet into a one piece sleeve into which the TE was inserted. The overall length of the TE in the nylon sleeve is 2” on a side and 3/4” high.



⁴ This is the K of nylon at room temperature (20 °C) but it doesn't change much at higher temps. (Thermal Conductivity Science)

Figure (2): The TE units. The top surface is unfinished in this picture. The units were surfaced in a mill to their final dimensions.

The nylon sleeve also holds the block into which the heat pipes are anchored. To ensure maximum thermal contact with the hot side of the TE, the round heat pipes could not simply be pushed against the hot side. For durability and efficiency, they need to be embedded in a block of material with a high thermal conductivity. 1100 Aluminum was used in the prototype because it is cost effective, lightweight, and has a K value of 222 W/m-K. The blocks were waterjet-cut and slipped into the nylon sleeve with the TE. Thermal grease was applied between the block and the TE to improve heat exchange between the two bodies.

Thermoelectrics are notoriously fragile--they are little more than small pads of various semiconductors sandwiched between two wafer-thin ceramic plates. They can break if dropped or struck. For this reason it is unwise to have the thermoelectrics exposed in any way. The cold side must also be covered, but covered in such a way that does not keep the wearer from feeling the maximum amount of cooling possible. For this, 1/16th inch thick AISI 1000 series steel pads were attached to the nylon sleeve to cover the cold side. Steel has a K value of 50 W/m-K and it is also much stronger than aluminum. Thermal grease was applied between the TE and steel pads to maximize heat exchange between the bodies, and small holes were drilled in the steel pads so that the TE units could be sewn onto the vest body.

4B. Heat Pipes

The heat pipes are perhaps the most difficult part of this design. It is difficult to design a heat pipe system without the ability to directly experiment with multiple prototypes, and this requires specialized equipment. A main necessity of this vest is that the heat pipes be flexible and adiabatic along their length, except for, of course, the evaporator and condenser ends, which must be solid and thermally conductive. Flexible heat pipes do exist--they are frequently seen in various aerospace applications. Design of the heat pipes is essentially a list of requirements that a company would use to build what one wanted.

Since the thermoelectric array will ideally collectively remove at least 150 watts of heat, the heat pipe array should be able to handle at least 200 watts collectively. It is nearly impossible to overload a TE, but it is very easy to overload the heat transport capacity of a heat pipe and if this overload occurs, heat will not be able to be effectively carried away from the hot side of the TE, where it will accumulate and force the TE to draw more current than necessary to maintain the desired temperature difference. For an array of 8 TE, this means that each heat pipe should be able to remove 25 Watts of heat or more, which is a reasonable value for more robust heat pipes. The entire *array* of TE need to remove 150 Watts, which means that each TE removes roughly 1/8 of that value, or 18.75 W. The heat pipes are arranged in a configuration of 1 pipe per TE, so the heat pipes must be able to comfortably transfer the same amount of heat as each TE, with a buffer in case of TE malfunction.

These heat pipes must also be able to work against gravity. Most heat pipes with standard wicks cannot handle this, the hot side MUST be at the 'bottom' and the cold side MUST be at

the 'top,' to follow with the convention that hot fluids rise and cold fluids sink. However, there is one variety of wicking material, sintered powder, which will work in any direction without a severe sacrifice of heat pipe efficiency. Sintered powder heat pipes are packed with a very fine metal powder, usually copper or a copper alloy, instead of a standard wick.

The flexible adiabatic midsection is typically made of a combination of treated rubber and a very fine flexible metal mesh tubing. (Similar to a tube of woven nylon cord only made with metal fibers.)

Due to the nature of the vest, the heat pipes are not all the same length. Larger people require longer heat pipes so that the heat pipes can connect to the heat sink box (discussed later) worn on the belt, and the individual heat pipes on any given vest are different lengths in order to minimize slack which adds bulk and can get in the user's way. Different lengths can also effect heat pipe efficiency (shorter heat pipes work better than longer ones) which is why the 50 watt collective safety factor (mentioned above) is important. If the heat pipes are designed to handle far higher levels of heat transfer than what they will actually see when the vest system is used, then small variances in efficiency due to varying heat pipe lengths will not impact overall vest performance in any significant way.

Due to ordering difficulties and limited funds, we were unable to acquire truly flexible heat pipes for the prototype. The flexible heat pipes are a custom-order product, and often require a minimum order of thousands of pieces or extended manufacturing/shipping time. So we instead

had to use standard copper heat pipes in construction of the vest prototype. These heat pipes were bendable but NOT flexible, and this presented some difficulties.

They came in two standard lengths, 7 inch and 13 inch. For some of the TE unit/heat sink box connections, the heat pipes had to be coupled together to form a longer unit. This was done using small blocks of pure copper cut on a waterjet and drilled with two holes.

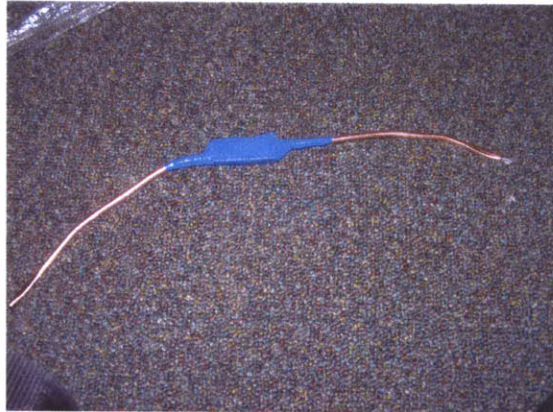


Figure (3): An image of one of the heat pipes we actually used. Note the copper coupling holding the two heat pipes together. (underneath the blue tape)

These long heat pipes, even though they are ‘adiabatic⁵’ with the exception of the evaporator and condenser ends, do have some heat losses along their length. This is found, in a very simplified context, by multiplying the heat flux by the thermal resistance and summing the

⁵ Heat losses along the heat pipe lengths were kept to a minimum through the use of insulation. The bare heat pipes themselves were not adiabatic, being just long copper tubes filled with sintered powder wick.

results for the evaporator, condenser, and the axial length of the tube (which we assume is ideally adiabatic and is thus zero) The full equation looks like:

$$\Delta T = (q_{evap} \times R_{evap}) + (q_{axial} \times R_{axial}) + (q_{cond} \times R_{cond}) \quad (3)$$

For 20 inch long heat pipes, the losses are about 3.4 degrees to the environment. This means that if, for example, the evaporator were at 50 °C, the condenser would be at 46.6 °C.

(Garner)

4C. Heat Sink Box

Since the rate of dissipation of heat to the environment is strictly limited by the rate that heat can be lost by convection to the surrounding air, we must be able to store heat at the same time it is being dissipated. It is impossible to completely match the 150 Watt rate of heat exhaustion from the body with a 150 watt rate of dissipation to the environment without some cumbersome and heavy device.

The heat sink box is a thermal capacitor, storing as well as dissipating heat. This allows the absorption of 150 W from the TE units while less than 150 W are being removed by convection with the surrounding air. There are ideal conditions for a box like this to operate (discussed in ‘production’) but manufacturing capabilities were severely limited for this part of vest production. I was limited to a waterjet machine and a non-CNC mill.

The box was cut from plates of 3/8 inch thick 1100 aluminum plate. Each individual plate was 'scooped out' to a thickness of approximately 1/8 inch using an endmill with the exception of a 3/8 inch border around the edge of the plate. This reduced the overall weight of the box. These plates were screwed together and all seams and screws on the box were epoxied to prevent water leakage. The 'lid' of the box was left unepoxied, and is held in place with three screws. A scavenged CPU fan on top of the box forces air onto the box surface from the environment, and a scavenged aluminum heat sink on the underside of the lid facilitates heat transfer from the water in the box to the box walls. The resulting box was roughly 4.5 inches on a side.

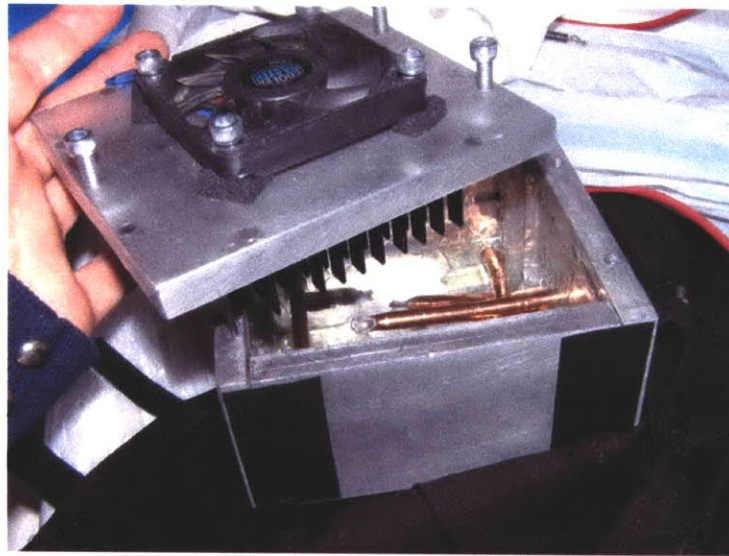


Figure (4): A view of the box on the first prototype, showing construction. The heat sink was damaged when it shifted from its original position and had to be hammered back into place.

Ideally, this box would be evacuated to vacuum (discussed in ‘production’) but that could not be done here due to a lack of money and appropriate equipment. The box was simply filled most of the way with clean, recently boiled water (degassed water), and the lid sealed closed. Since the box would be completely sealed to the environment, there would be no need to replace or replenish the water.

4D. Voltage and Current Control

There are several reasons why this system requires a voltage/current regulator.

-When hooked to a battery, TE will draw as much current from that battery as they can. This results in short battery life, battery overheating, and substantially decreased TE efficiency which results in TE overheating and thermal equalization. To prevent this, a regulator must be placed in the circuit to control how much current the TE can draw and at what level of voltage.

-Current and voltage regulators allow for adjustability in the circuit. This means that the user can ‘dial in’ the desired temperature that they want to feel on the cold side of the TE and the regulator can adjust the current and voltage accordingly.

-Even with the heat sink box absorbing the excess heat, it is still necessary to eventually shut down the vest to allow the stored heat to dissipate to the environment. Additionally, ‘pulsing’ (automatic on-off switching of the circuit) prolongs battery life by providing the

cooling as evenly spaced units of operational time (e.g. 1 minute of cooling, one minute of heating, or something similar) This has to be done by means of a regulator, the user certainly can't be expected to be constantly switching the vest on and off manually.

The prototype was originally meant to have a simple current regulator which would vary the current in a waveform similar in shape to the one below.

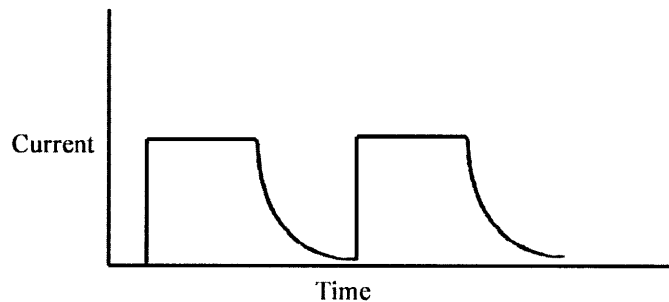


Figure (5): A sketch of the basic waveform desired in this situation.

The exponential decay 'ramp down' to zero current is so that the user does not feel discomfort as the vest is shut down. Simply cutting the current to the TE to turn them off results in an immediate equalization of temperature between the hot and cold sides. This means that the wearer feels a sudden rush of heat that takes a few minutes to dissipate. Shutting off the current flow gradually allows the heat pipes to continue removing heat from the hot side while the temperature difference between the hot and cold sides is gradually equalized.

This voltage/current regulator would dissipate power at a rate of 42.68 W if it were operated using 2.2 A and 19.4 V, or 55 W for 2.5 A and 22 V, the numbers mentioned in ‘Thermoelectric System.’

Unfortunately, problems with acquiring the proper components resulted in the current/voltage regulator not being able to be implemented. (More on this in ‘problems’ and discussion of a voltage/current regulator for a production model in ‘Production Model’) So the only circuitry components of the prototype were a pair of two-way switches that allowed the user to set the vest to ‘cool’ or ‘heat’ by reversing the direction of current flow through the TE.

4E. The Vest Base: Assembly of the Prototype

The vest base was made entirely from high-grade 100% cotton fabric. It was put together in the ‘pullover’ configuration, where the user slips the vest over his or her head. Once on, a pair of Velcro straps allow the wearer to tighten the vest to a snug fit, which is essential to good performance.

The vest consists of two layers of fabric, the underlayer, which was what was actually worn against the user’s body, and the overlayer which covered the vest workings and made the vest more aesthetically pleasing.

Several square holes were cut into the underlayer, each slightly smaller than the size of the steel contact pads on the TE units. One TE unit was sewn in place above each hole, creating 8 points of contact between the wearer's chest and the vest system. Since I was building the vest and often had no one to test it on but myself, the TE were arranged in the 'female' configuration.

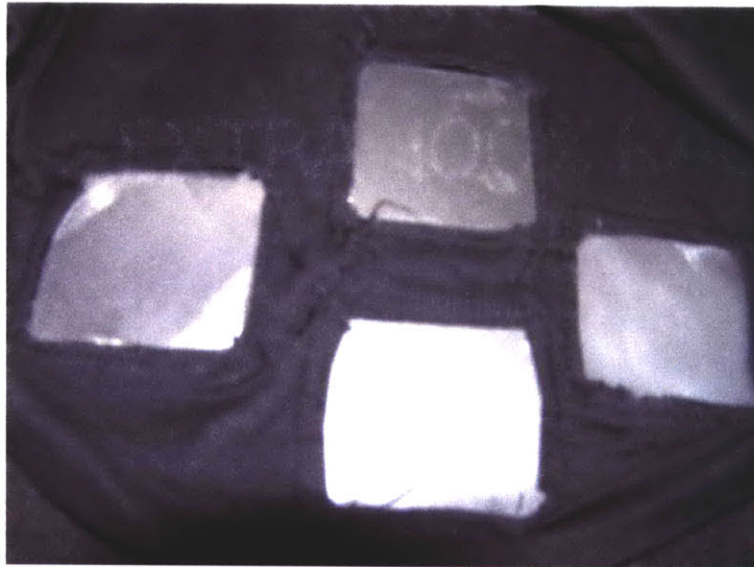


Figure (6): The underside of the prototype vest, showing the holes in the fabric layer to allow the steel contact pads to show through.

Around the TE units, 3 layers of neoprene insulation (each layer 1/4 inch thick) were built up to prevent the TE units from shifting around and to provide additional insulation against heat leakage from the hot side back to the user. A final layer of neoprene covered the TE to make the vest more aesthetically pleasing. Neoprene, a material used in a variety of insulative clothing such as wetsuits for divers is lightweight, soft, and a good insulator. The neoprene was only placed across the chest, all other areas on the vest were left as a single layer of cotton to allow for breathability.

Before placement on the vest, the TE units were drilled to allow the insertion of one heat pipe each. A generous and even layer of thermal grease was applied to one end of the heat pipes and they were placed, each one secured permanently in place with epoxy.

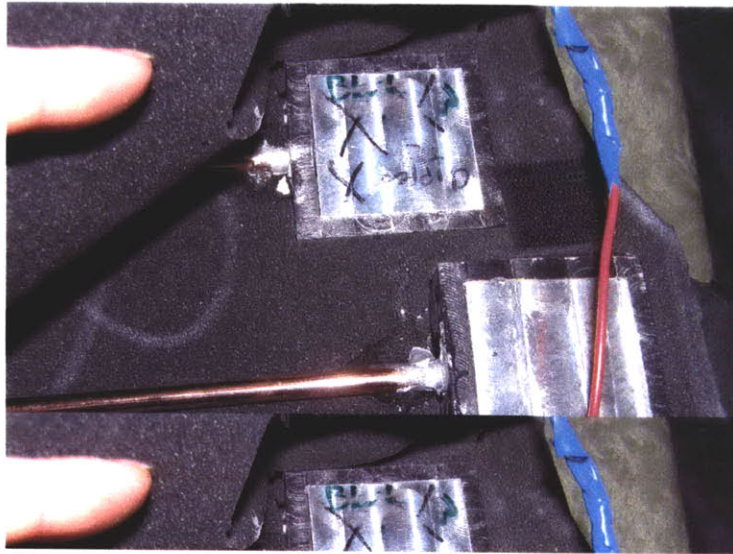


Figure (7): Image showing the heat pipe inserted into the TE unit.

Each heat pipe was individually bent by hand to fit into holes drilled in the heat pipe box. The heat pipes were fitted into the box and secured with epoxy. The condenser ends of the heat pipes required no thermal grease, since they are in contact with a fluid rather than a solid.

The heat sink box was encased in its own carefully fitted sleeve made from a cotton blend fabric which has a small amount of stretch to it. The sleeve has an adjustable loop on the back for a belt and was held closed with Velcro tabs. The sleeve is mostly for aesthetic purposes, to give

the vest a unified look, and to allow attachment of a belt to hold the box in place. (If the box were to move around, it might accidentally crimp the heat pipes) Covering the box in this way actually reduces its ability to convect heat to the environment. The cover was a simple, cheap solution to the problem of attaching the box to a belt. It was far easier to sew a cover from scrap cotton than it was to machine a belt loop from aluminum.

The batteries used a peculiar type of mil-spec connector which I was unable to find, so a makeshift connector was made using banana connectors clipped from the ends of cables and electrical tape.

The vast majority of this work was done by eye and with chalk to mark locations of holes, seams, etc., because I was working alone and did not have the benefit of a mannequin. I had to put on the vest, mark the locations of vest elements with chalk, and remove the vest again to place them. It is a crude method, but the vest turned out fine nonetheless.



Figure (8): The vest underlayer. Note the extra-long Velcro straps which have curled back slightly.

In the above image, I am wearing an undershirt beneath the vest. Direct contact between skin and vest is not problematic, but layers of clothing do lessen the cooling effect that the wearer sees. (Any type of clothing, regardless of its thermal properties, will act like an insulator in this situation.) An Under Armour (tm) or snug-fitting cotton undershirt will not severely impact vest performance, but a thick field jacket will.

The Velcro straps longer than ordinary on the prototype so that the vest could accommodate wearers of varying sizes. For the production model, the vest would come in several different sizes. (XS, S, M, L, XL), as well as a male version with a different TE configuration.

5. Results: The Day of Testing

Logistical and financial considerations taken into account, the vest performed remarkably well. Lack of sophisticated testing equipment meant that most of the tests with regards to cooling are based on wearer perceptions rather than gathered numerical data, but we were able to provide an effective proof-of-concept through this prototype.

Using a thermocouple to measure cold side temperature, it can be shown that immediately after the vest is switched on, the cold side drops one °F roughly every 5 seconds until it reaches a steady state of 60 °F. (The video cuts out once the temperature reaches 65 °F) This was running

the vest directly from a 14V/1 Ah military-grade battery. Similarly, the hot side temperature would increase by roughly five °F every five seconds. This level of cooling was perceptible through clothing, both natural (cotton) and synthetic (Under Armour). A video of the thermocouple test is available in the attached multimedia CD included with this document.

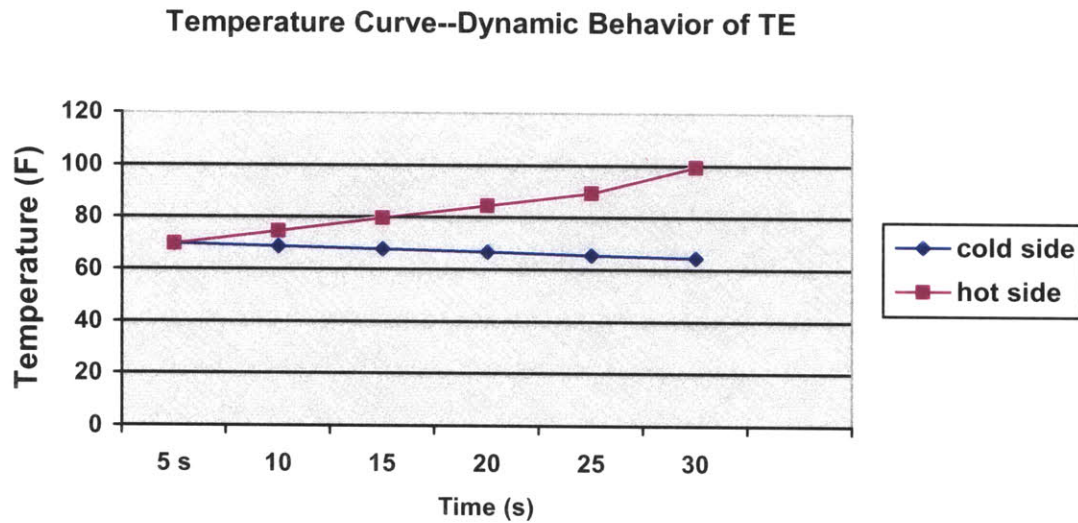


Chart (1): A graph showing the approximate dynamic behavior of the thermoelectrics after the vest is first switched on.

When worn (over one layer of hot-weather Under Armour) the vest was very comfortable. There were no sharp points or points of irritation. Moderate physical activity such as jogging and jumping jacks were performed without a problem, and the entire vest system did not affect range of motion in any significant way.

For a continuous period of operation (Approximately 40 minutes) the vest provided continuous cooling, with the curious note that some TE seemed to function better than others in

spite of the fact that all TE were receiving the same level of current. The box would become warm to the touch but never reached the same temperature as the hot side of the TE, which was between 45-50 °C, depending on the operating conditions.

6. Problems

6A. TE Warming

After approximately 20 minutes of operation, two of the TE seemed to lose their ability to cool. The cold side would warm up (It would never become perceptibly warm, but rather settle to a temp of approximately 80 °F and stay there.) and the hot side would become very hot to the touch. It was eventually determined that the heat pipes connecting these two TE units to the heat sink box were not making an effective connection with the units. This was due to a manufacturing defect when the holes in the TE units were drilled--the holes were accidentally drilled slightly too large, caused by wobble in the drill press used, and thus the thermal connection between block and heat pipe was not made properly, even with the application of thermal grease.

6B. Broken TE

One of the TE failed to work, and the vest had to be rewired during testing to deal with this problem. (As a result, the vest only had 7 functioning TE, though all 8 were in place.) The

TE that failed to function had been damaged in an earlier accident in which the box it was in was dropped, resulting in one TE being chipped and another broken completely. I only had 9 TE to work with, eight plus one spare, but the chipped one was tested and found to still be functioning, so it was used in vest construction. It was chipped where one of the wire leads entered the TE. Sometime during the assembly of the vest, however, the wire lead, already loose, broke apart, destroying the TE. The wire broke in such a way so it could not just be soldered back in place. Unfortunately, unprotected TE are quite fragile, and as can be seen below, even just a small amount of damage can completely destroy a TE.

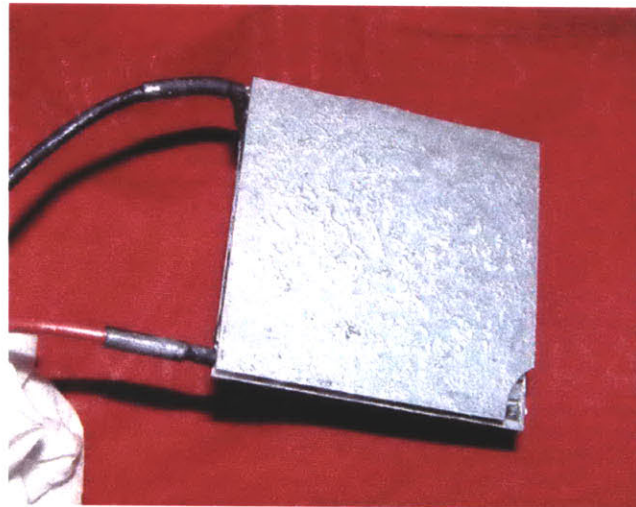


Figure (9): One TE which was broken during production. The damage is very small but that single chip rendered the entire TE useless. The grey material on the TE is thermal grease.

6C. Dead Current Regulator

The vest was initially meant to have a current regulator. Prior to final testing and display at the Soldier Design Competition, Kranthi blew out the chips we would be using in the regulator. It was not his fault--the chips we had were not meant to be used in the conditions we were attempting to use them in, and couldn't handle the levels of current we required, but they were all we could get with limited funds and limited time.

6D. Large Heat Sink Box

The Heat sink box was much larger and heavier than it needed to be. This was the primary reason why the vest weighed roughly 5 lbs instead of 3. The placement of the box and its size meant that when it was worn by a smaller person, like myself, I would bump the box with my leg while I was walking. It did not effect my range of movement, but after a while the feeling of something warm with hard corners bumping against you can be annoying

6E. Heat Pipe Bending

The heat pipes used in construction of the prototype were not the kind we wanted for the design. Instead of truly flexible heat pipes, these were simple bendable copper ones. The pipes were actually quite fragile and prone to crimping. They were meant for computer cooling applications, not for use in a wearable garment. One heat pipe had to be replaced during vest construction because I accidentally crimped it, in spite of taking care not to allow this to happen

while bending the heat pipes into shape. This made the vest unnecessarily fragile, and the heat pipes protruding from the bottom edge of the vest were unsightly.

7. Detailed Theory: Second Level Prototype

7A. Thermoelectric Array

The TE units for the first prototype were fragile--limited funds and manufacturing capabilities meant that the individual components were epoxied together, and they would pop apart if mishandled or dropped. I actually had to re-glue several of the TE units when the box I was carrying them in came apart and spilled its contents across a brick sidewalk. If the TE units cannot withstand a four foot fall, then they would certainly not be able to withstand life in the field and use by real soldiers, but this problem is an easy one to fix.

With injection-molding capabilities, it is possible to manufacture an insulated TE unit which comes as one piece, and requires no complicated assembly after the individual components are made. The contact pad (the side that the wearer would feel against their skin) and the block in which the heat pipes would be embedded would be cemented to the TE with a thermal adhesive. This unit would then be placed inside an injection mold, and the machine would pump the insulating plastic around the part, only leaving the contact pad exposed. The result would be a single, 'plug and play' unit which could be inserted into an elastic pouch on the vest. For a TE of comparable size to the ones used in the prototype, this unit would also be much

lighter, and it would be easy for a soldier to carry one or two spares with him into the field just in case he needs to repair the vest.

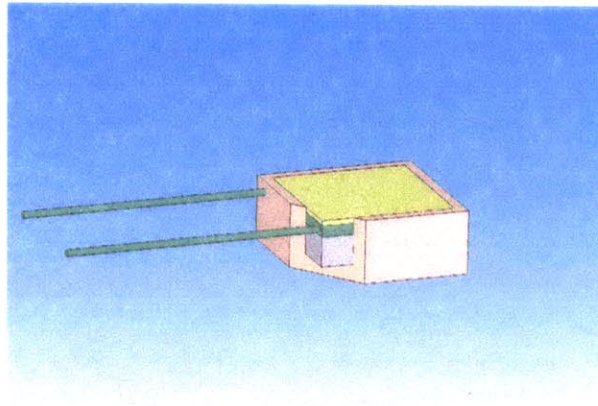


Figure (10): A cut-away solid model showing the production version of the TE unit. See 'Appendix' for a dimensioned model.

The TE unit would also have a small snap-in catch on the plastic, so that the heat pipe could be plugged in and removed. The hole would be star-shaped (see above) to improve thermal connection between the heat pipes and the block. There will also be a small loop of heavy wire on the top of the TE unit. This restraint loop will allow the TE unit to be snugly secured to the vest. (discussed later)

This TE unit uses the same type of thermoelectrics used in the production of the prototype. These TE met or exceeded all the desired specifications for this project, in addition to being reasonably priced when sold in bulk. The end result is a TE unit that is similar in size to the prototype units, roughly 2 inches square, but is thinner, and weighs far less. There are several different types of plastic that can be used in this situation. I personally recommend HDPE (high-

density polyethylene, which has a thermal conductivity comparable to that of nylon. It is inexpensive, easy to work with, and can be reclaimed from broken components for recycling, which reduces overall waste. On a similar note, the heat sink block, which is made of Aluminum, can also be reclaimed for recycling. The only part of the unit which cannot be effectively reclaimed is the thermoelectric itself.

7B. Heat Pipes

To maximize effective heat transfer between the TE and the and the heat pipe, one has to maximize the surface area of the evaporator. This can be done by making a star-shaped evaporator end (discussed earlier) The ‘fins’ of the star greatly increase the surface area while maintaining the desired tubular heat pipe structure, and with sintered powder heat pipe technology, the heat pipe can be made to virtually any shape we want.

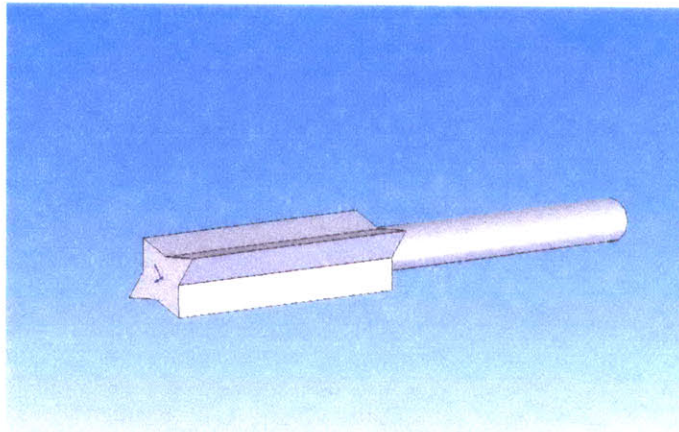


Figure (11): The star-shaped evaporator.

This star evaporator will slide into a slot on the heat pipe block on the TE array, where the plastic clips formed as a part of the injection-molding process will hold it in place.

The condenser end will have a square shape in cross-section and be made from 1100 aluminum, so that they can be stacked and bundled together in a grid-like array inside the aluminum plug which will attach to the heat sink box. They will be bonded inside the plug with a combination of thermally conductive adhesive and solder. This plug will have an overall star-shaped cross-section and fit into the slot on the side of the heat sink box. A threaded cap will screw down onto the box to hold the heat pipes in place. The condenser end will make up for less overall surface area by being longer.

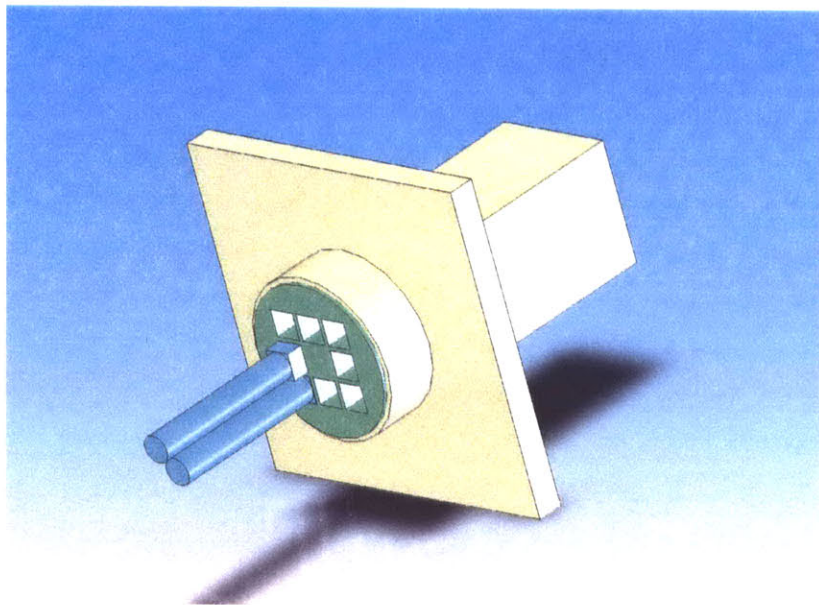


Figure (12): The adapter which will hold the condenser units. Here it is shown fitted into a sleeve. See 'Appendix' for dimensioned model.

The adiabatic tubes will also be bundled together inside a black, reinforced rubber sleeve for protection as well as to minimize the amount of cords hanging out from the vest.

With this system, the breakage of a single heat pipe would not effect the rest of the system. The other TE units, with their undamaged heat pipes, would still function normally. However, it would be difficult to replace one single heat pipe and leave the rest in place, particularly since the heat pipes are soldered into the thermal connector which attaches to the heat sink box, so it is simply easier for the soldier to replace all the heat pipes as a unit. The heat pipes would be given to the soldier as a single bundle, similar to a thick piece of electrical cable with several separate, thinner cables inside of it. They would replace the entire unit, and dispose of the old one. If the soldier was in a situation where the damaged heat pipe bundle could be stored and shipped home, the bundle could be sent 'back to the factory,' so to speak, for repair and refurbishing, which would reduce waste.

7C. Heat Sink Box

The heat sink box is essentially a heat pipe in square form. It operates on the same principles, consisting of a finned aluminum box filled partway with fluid and sealed to a vacuum. The outer walls of the box are the condenser, where the fluid transfers heat to the environment, and the inner tube chamber of the box is the evaporator, where the heat pipes transfer the heat from the TE to the water inside the box. The box relies on the high heat capacity of saturated

water to store excess heat while heat is being dissipated through the walls of the box. Using the equation:

$$Q = m(h_g - h_f) \quad (4)$$

We can see that it takes .063 g of water to absorb the 150 Watts of heat coming off the heat pipe array at ambient temperatures of above 45 °C.⁶ The latent heats h_f and h_g are found with a thermal fluid property book. (Brisson, et. al.) This seems like a very small number, but a single heat pipe often contains very little fluid and that this mode of heat transfer involves a phase change where the water goes from liquid to gas. The phase change allows the use of far smaller amounts of water to absorb far greater amounts of heat. This means that every second, .063 g of water is evaporated to steam, taking with it 150 J of heat. This is a reasonable number, but it should not be assumed here that it is an *accurate* one.

It is nearly impossible to work backwards to find the quantity of water without knowledge of actual pressures and dynamic temperatures inside the box, transient values which are found through direct prototyping and experimentation using equipment the author does not have. Since this is saturated water, the latent heats used in the above calculations occur at a pressure of $P = 9.595 \times 10^3 \text{ N/m}^2$, which is our expected ‘operating vapor pressure’ but this gives us no hint of how the box will behave dynamically once heat is pumped into it. Therefore, for purposes of this report, a safety factor of ten is included here, and the amount of water needed to absorb the heat is assumed to be .63 g instead.

If we assume we want at least 60 sec of cooling we multiply the .63g by 60 to obtain 37.2g of water. This volume of water easily fits into a 2 in by 2 in by 1 in 1100 aluminum box which is sealed and vented to vacuum. The interior of this box is covered with short (.25 in long) fins to increase surface area and it is .25 in thick.

This steam condenses on the finned walls inside the box, where the heat is deposited and the water returns to its liquid state. The movements of the user will help this process. (the water sloshing around inside the box will facilitate heat removal from the heat pipes and deposition on the heat sink walls of the box by creating turbulent currents in the water). This heat travels through to the other side of the box where it is exhausted to the environment by means of forced-air convection. The outside of the box is covered in rows of thick fins which are covered with a thin plate for protection (A box covered with exposed pointy fins would be uncomfortable to wear and would also snag easily on clothing, foliage, other people, etc...)

A hole in this plate contains a small fan, akin to those found inside computers, which forces air from the environment into the finned space. This fan should ideally run at 3.5 CFM. Forced air convection occurs generally at a higher rate than natural convection, and with the fins covered to protect them, blowing air through the fins is the only way to have effective heat removal. Forced air convection is assumed here with a convection constant of roughly $h=70$ W/m²K. The rate of heat loss from the surface of the box to the environment on a hot 40 °C day is found with the equation:

⁶ 45 °C is used here instead of 40 °C to allow for 'worst case scenario' padding.

$$Q = h_c A_s (T_s - T_{amb}) \quad (5)$$

Ideally the vest will need to be ‘shut down’ for one minute for every minute of cooling. It is not recommended that the vest be shut down for any longer amount of time than this, because while the human body can certainly take the hot temperatures (Soldiers currently walk around in hot places like Iraq or Afghanistan with no personal cooling systems.) This diminishes the effect of perceived cooling that the wearer experiences. Cooling is as much of a psychological experience as it is a physiological one, and if the person *feels* they are cool, then they will suffer less from the effects of heat.

However, if the vest is run continuously, then the water in the tank will eventually reach the same temperature as the hot side of the TE. When this happens, the heat pipes will no longer be able to transfer heat away from the TE because the evaporator and condenser ends will be the same temperature. The TE will have to draw more current in order to maintain the desired temperature on the cold side, and eventually the vest will overheat and the hot and cold sides of the TE will equalize.

If this were to happen, it would not irreparably damage the vest, but the user would be uncomfortable and the batteries would drain rather quickly.

These calculations are actually very inaccurate, because this box is quite similar to a heat pipe in how it operates. It is a dynamic system, changing every second it is in operation. Without a prototype built to specifications, is impossible to tell just how well the box will function in its intended environment. The basic principles behind the box are in fact very sound (the abundance of functioning heat pipes available on the market are proof) but it would require some fine tuning of the design

It is interesting to note here that it is possible to construct this box in the same way one would construct a sintered powder heat pipe. The interior of the box would be packed with powder and a small amount of fluid instead of a water in a tank situation. Calculations for this method, however, require data that must be acquired through direct prototype testing and is beyond the scope of this report.

7D. The Vest Base

While the vest in the prototype was simply a frame on which to test the various heat transfer components, the actual fabric vest base is an important part of the final design.

The vest will be the same pullover type as seen in the prototype, and still made from cotton. (A cotton blend is acceptable, but pure cotton is more breathable, and since the vest will be worn close against the body for extended periods of time, wearer comfort is paramount.) There will be a number of square holes spaced across the chest and upper abdomen of the vest

base, and across the chest there is a single layer of neoprene padding to act as a buffer between the heat pipes and the wearer (discussed later). These are the holes through which the contact pad of the TE unit will be exposed to the wearer. Above each of these holes will be a heavy duty elastic strap which is held in place with Velcro tabs. This strap will be slid through the wire restraint loop on the top of the TE unit. The elastic will keep the TE unit close to the body, and the wire loop will keep it from shifting around.

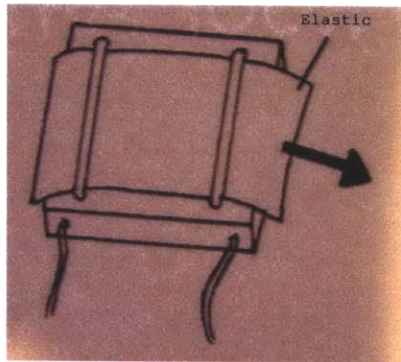


Figure (13): Drawing of a TE unit in place on the production model vest.

The heat pipes are inserted into the TE units once they are all strapped in place, and the TE units are plugged into the battery wires which are sewn into the vest itself. The neoprene will keep the heat pipes from being pressed against the wearer's chest. The heat pipes are adiabatic, so there is no danger of heat leakage, but the feeling of a narrow, hard, snake-like object digging into a sensitive area can cause discomfort, which is distracting.

There will be a neoprene chest pad which fits in place over the TE units for wearer comfort, as well as to provide a layer of padding between the TE units and the environment. This

upper pad will attach to the lower neoprene pad with Velcro tabs. A second layer of heavier cotton 'duck' fabric will cover all of the inner workings of the vest. This type of fabric is similar to what is used to make BDUs. This fabric will protect the vest from dust, debris, and bumps and scratches which arise from serious use. The complete and assembled vest would hide all of the inner workings except for the condenser heat pipe plug and battery plug which would protrude from the bottom edge of the vest.



Figure (14): Drawing of a soldier wearing the finished vest. (cutaway view)

When the wearer puts on this vest, they then dress as they normally would, taking care to make sure that the condenser and battery plugs protruded out from under their tunic or shirt. They would then slide the heat pipe box onto their belt using the attached belt loop, and connect the condenser plug, screwing it into place.

The battery plug is slightly different. The vest requires a current regulator, but it is unwise to have this circuitry buried beneath layers of clothing and equipment. The regulator should be

somewhere where the soldier can easily reach it, but this is somewhat difficult to accomplish. The modern soldier is covered head to foot in equipment, and there is little room for additional equipment mounted in a place where the soldier can actually reach it. The heat pipe box does not require human interaction, so it can be strapped to the belt where it faces the soldier's backside and it will not compete for space with more important items like spare ammunition or medical supplies.

The battery pouch and current regulator are a single integrated body. This is to reduce the amount of cables hanging off the soldier. Interceptor body armor is already designed to handle cords and cables for other equipment, so the addition of one more will not be a problem. The pouch will contain the circuit unit for the current regulator, and space for one battery. A loop on the back of the pouch will allow the user to attach the pouch to one of the many equipment loops on the front of the body armor. Even if the soldier is wearing full kit, these loops are seldom all filled with other equipment, and the placement of these loops is specifically designed so the soldier can have easy access to all of his gear. The battery is connected to the regulator and sealed inside the pouch, then the pouch is secured to the vest. The battery plug is connected to a second plug which protrudes from the pouch.

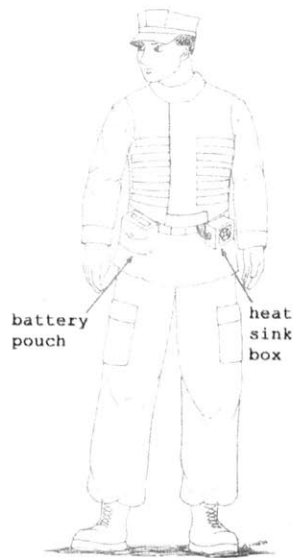


Figure (15): Drawing of a soldier showing how the exposed elements of the vest integrate with his existing equipment. Here the battery is shown clipped to his belt. It could also be clipped to the equipment loops on his body armor.

The pouch itself is made from cotton duck fabric, and can be made in a variety of different colors and patterns to match the soldier's BDUs

Optionally, the soldier can connect an adapter to the current regulator which allows him to hook himself up to a humvee (or similar vehicle) power supply. This saves batteries--the soldier can even recharge the vest battery while he is riding in the vehicle this way.

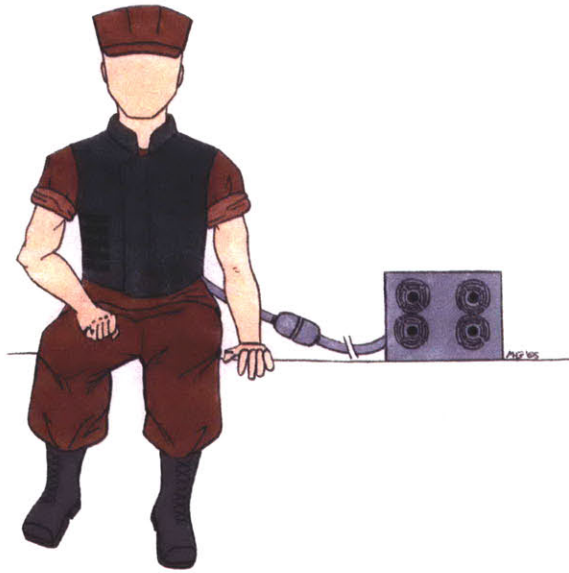


Figure (16): Soldier connected to an external power supply.

8. The Vest in Practice

The following is a basic scenario of a soldier acquiring, using, and repairing the vest.

The soldier would pick up his vest and its components from his supply officer. The vest would come with a simple page of instructions detailing assembly, disassembly, and maintenance of his new piece of equipment, though the soldier would have already received training on the use of the vest in a brief info session. He has picked up a size large men's configuration, but other sizes are available, and the Velcro straps mean that one size will fit a range of different body types.

He sits down and connects the pieces of his vest, first slipping each TE unit into place and connecting them to the color-coded wire leads which will run to the battery. He then connects the color-coded heat pipe cables to the TE units. The entire operation only takes a few minutes and is very user-intuitive. He then puts on the vest as-is, and puts on the rest of his kit as normal, being sure to let the battery cable and the heat pipe cable hang out from beneath his tunic.

He slips the heat sink box onto his belt, and screws the heat pipe cable into place. No other operations are necessary. Then he takes a new battery, puts it inside the battery pouch with integrated circuitry and connects it to the circuit board. He hangs this battery pouch from one of the equipment loops on his body armor, and connects the battery cable to the circuit.

The entire system is now in place. The soldier notices no immediate difference in weight to his equipment--the vest actually almost feels like it isn't there. He controls the vest using switches on the battery pouch. He flips a two-position switch to the 'cold' position (It's quite a warm day out--if he were in arctic conditions he would flip the switch to the 'hot' position, and run the battery current in the opposite direction.) and uses a knob to adjust the cooling level to the desired temperature--the temperature is displayed on a small LED display on the battery pouch--he sets it to 75 °F. He notices perceptible cooling almost immediately as the current flows through the TE. The cooling comes in waves, and the waves actually heighten perception of the lower temperatures as well as saving battery life.

The soldier leaves base and performs his duties for the day, switching the cooling system on and off as he needs it. He encounters a small skirmish, and his lowered core temperature allows him to think more clearly and act quicker because his body is not having to devote as much of its energy to keeping him cool. There is an explosion, but he escapes unharmed except for a couple of scrapes. He notices that there is a warm patch on his chest underneath where one of the TE units is positioned, but that the rest of them are working fine.

When the soldier returns to base and removes his equipment, he notices that the explosion damaged the heat pipe cable that attached the vest to the heat sink box. In spite of this damage, the vest system was set up in such a way to prevent catastrophic failure, so the rest of the TE continued to keep him cool. He goes to his supply officer and returns the damaged heat pipe cable, and receives a new one. There are plenty of spares for just such an emergency. If he were going out into the field for a long period of time, he would have brought spares with him. Replacing the damaged heat pipe cable with a new one only takes a few minutes. The damaged one will be sent home for refurbishment.

The soldier is again sent out later as a guard for a convoy taking supplies to a different base. He puts on his gear as normal and takes his place in one of the many humvees which are a part of the convoy. Each humvee comes equipped with a special adapter which allows him to connect his vest to the standard humvee power supply. There is no need for a bulky and ineffective air conditioning system inside the vehicle, because each soldier is wearing his own vest which he may choose to run off the vehicle. He connects the breakaway plug to the current

regulator circuitry, and uses his vest just as he would if it were running off battery power. The power supply also charges the battery for his vest as he is sitting in the vehicle.

When the soldiers need to get out of the vehicle, they simply disconnect themselves from the power supply. There is no need to worry if they are in a hurry, because the adapter plug disengages when only a very light force is applied to it, so the soldier can climb out of the vehicle without even thinking about disconnecting.

9. Conclusions

There is still much work to be done. Much of the 'beta work' for the next generation prototype has just begun, and some of it will require extensive prototyping and testing in facilities to which the author does not have access at this time. The circuit design--which due to the scope of this report and the author's background--was merely outlined, will be finalized and tested with mil-spec components. But the first generation prototype has promising, repeatable and quantitative results which indicate that the project is on the right track.

The thermal principles behind the vest system have been in use for decades. This vest is a simple idea that translates into a surprisingly complex system. Every component of the vest must be integrated perfectly both in design and execution for the vest to work properly. Size tolerances must be respected, because air gaps in the thermal couplings will result in poor connections and

poor heat circulation. If these tolerances are respected, the beta prototype of this vest will function well.

10. Sources

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All photographs, drawings, and charts in this report were made by the author, Margaret H. Gentile.

Appendix: Dimensioned Drawings

The following are dimensioned drawings of the for-production TE unit and the for-production condenser adapter.

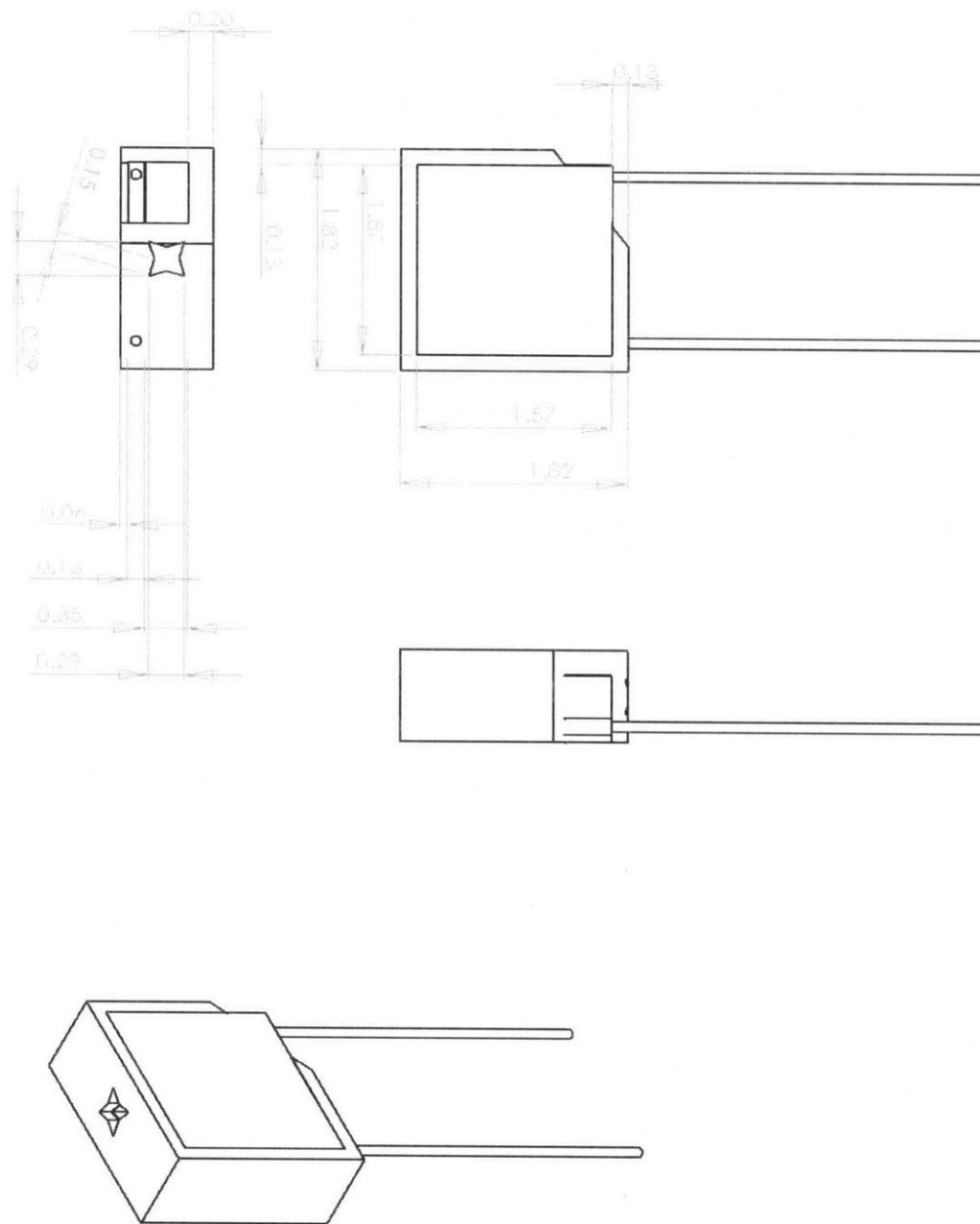


Figure (17): The for-production TE unit.

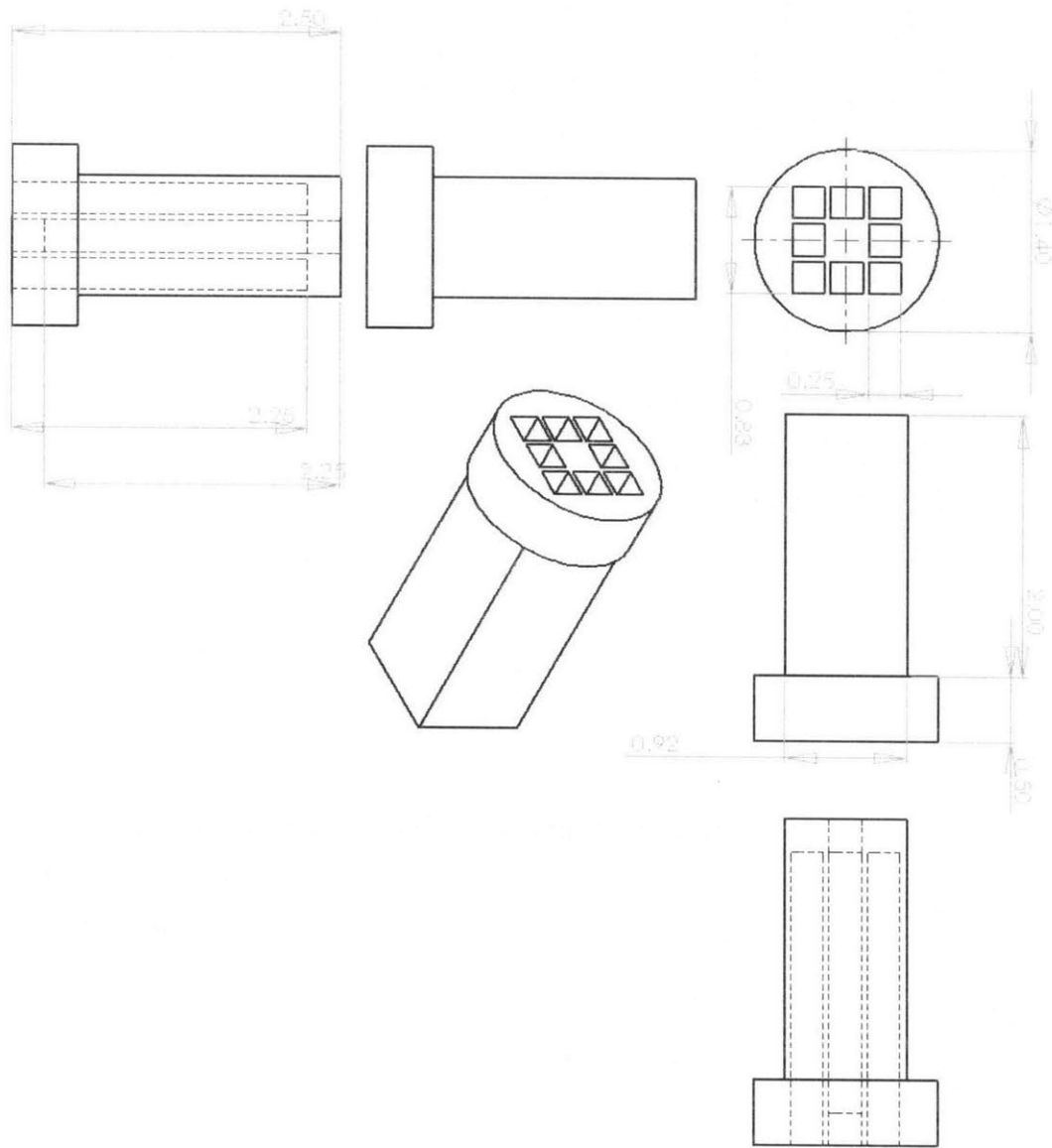


Figure (18): The for-production condenser adapter.

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