

Polymer Material Selection and Testing of Resistive Wire Arrangement for a
Transparent Infant Warming Blanket

by

Madeline Salazar

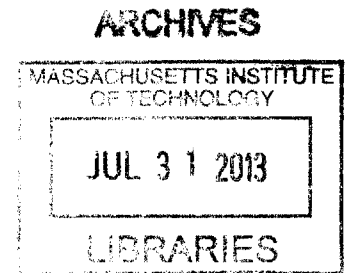
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ABSTRACT

The ThermoCloud was designed as a portable, scalable, transparent electrical blanket to warm and insulate infants, while permitting hassle-free medical transportation and maximum visualization of a patient's thorax and extremities, without removing the blanket. The blanket consists of a resistive network of wires, located between two sheets of a clear polymer and is designed to reach 37°C and provide 50W heat generation with a 12V power supply and a 3Ω effective resistance of the wire network. The alpha prototype of ThermoCloud is composed of thin nichrome wires arranged in parallel and sandwiched between two 0.76 mm thick sheets of PVC. The revised prototype developed in this thesis improves the performance by using a 0.10 mm thin sheet of polyethylene, which is softer, drapes and has better thermal conductivity, which will allow for an even distribution of heat. In addition, a new wire and network arrangement is explored that uses five parallel pairs of flat copper wires in series achieves the same resistance. Scale prototypes were fabricated and bench tested. While a temperature of 34°C was achieved and evenly distributed, hot spots formed at the copper bus bars and some likely failure modes were identified that should be addressed in future work.

Thesis Supervisor: Alexander H. Slocum
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Table of Contents

Abstract	2
Acknowledgements	3
Table of Contents	4
List of Figures	5
List of Tables	6
1. Introduction	7
1.1 Medical Transportation of Pediatric Patients	7
1.2 ThermoCloud	7
1.2.1 Benchmarking ThermoCloud	8
2. Blanket Material Selection	9
2.1 Melting Temperature and Glass Transition Temperature	9
2.2 Materials Comparison	9
3. Resistive Network of Wires for ThermoCloud	11
3.1 Resistor Networks	11
3.2 Resistive Network of ThermoCloud alpha prototype	12
3.3 Selection of Wire	14
3.3.1 FrostFighter Inspiration	14
3.3.2 Design of ThermoCloud using FrostFighter copper wires	15
4. Fabrication and Testing	15
4.1 Samples Fabricated	15
4.2 Experimental Setup and Procedure	17
5. Results, Discussion and Future Steps	18
5.1 Conclusion	19
6. Bibliography	21

List of Figures

Figure 1-1:	ThermoCloud on infant manikin	7
Figure 2-1:	Glass Transition Temperature and States of a Polymer	9
Figure 3-1:	Resistors in Series	12
Figure 3-2:	Resistors in Parallel	12
Figure 3-3:	Circuit Design and Blanket Top-View	13
Figure 3-4:	Tooling to position the layers, bus bars and nichrome wires	14
Figure 3-5:	FrostFighter Clearview kit by Planned Products LLC	14
Figure 3-6:	FrostFighter Defroster kit Wire Arrangement	15
Figure 4-1:	Sample of Beta Prototype of ThermoCloud	16
Figure 4-2:	Paper Template with Printed Grid Lines	16
Figure 4-3:	Experimental Setup for Sample of ThermoCloud	17
Figure 4-4:	Sample Thermo-imaging Photograph of ThermoCloud	18
Figure 5-1:	Thermo-imaging photographs at Different Times	18
Figure 5-2:	Temperature Achieved: Copper Wires vs. Bus Bars	19

List of Tables

TABLE 1-1: ThermoCloud Product Contract	8
TABLE 1-2: Benchmarking ThermoCloud with other Warming Medical Devices	8
TABLE 2-1: Materials Comparison	9
TABLE 2-2: Comparison of PVC and LDPE	

1. Introduction

Infants and young children lose heat faster than adults and are, therefore, among the most susceptible to hypothermia. Some of the factors that contribute to this are a thin dermis, underdeveloped hypothalamic function and hormonal secretion, a small percentage of fat due to limited fat stores and a large head-to-body ratio that contributes to a large heat loss through the head [1,2]. The risks are multiplied when an infant has undergone a medical procedure and energy is being expended to warm the body, rather than heal, especially when being transported around the hospital or outside. The consequences of hypothermia in an infant are both short-term and long-term, including increased probability of surgical site infections, impaired enzymatic function and changes in cerebral blood flow [3-9].

1.1. Medical Transportation of Pediatric Patients

During medical transportation pediatric patients are connected to devices that provide medication and intravenous fluids and often have tubes inserted into the stomach, bladder and other body cavities, in addition to the standard devices that monitor body temperature, blood pressure and heart rate. Dislodgment of the connection of any of these devices could be damaging and even fatal, which is why doctors must have direct, clear visualization of the infant's chest, abdomen and extremities. In addition, skin color is also a good indicator of the patient's condition.

1.2. ThermoCloud

There is a need for a product that caters to the needs of 3-12 month old infants, who no longer fit in an incubator, that maintains normothermia (normal core body temperature) while permitting the practitioner to maintain direct visualization of the patient's body during medical transportation. To fill this need, ThermoCloud, picture in Figure 1-1, was designed and prototyped by a group of students in Professor Alexander H. Slocum's fall 2012 2.75 Precision Machine Design course at MIT.



Fig. 1-1 ThermoCloud on infant manikin [10].

The ThermoCloud is designed to be a portable, scalable, transparent electrical blanket that prevents hypothermia using a resistive network of wires and 12V power source, including a vehicle running at 12V[10]. ThermoCloud aims to provide a uniform surface temperature of 37°C while preventing hot spots that pose a risk to burning the patient. The product contract with a list of functional requirements and specifications for ThermoCloud is shown in Table 1-1. While the alpha prototype of ThermoCloud addressed the major functional requirements in order to help prevent infant hypothermia, the PVC blanket material was not soft enough to drape easily and the fabrication method and process could be simplified by using a different wire and network arrangement.




Table 1-1. ThermoCloud Product Contract

Customer Need	Functional Requirements	Specifications
Maintain normothermia	Provide heating & insulation	Max temp. <43°C
Clear patient visibility	Transparent material	80% Transparent
Distribute heat	Thermally conductive material	>1.02 BTU*in/(hr*ft^2*°F)
Reusable	Sealed, sanitizable construction	>821 Hours of Active Use
Portable	Compact battery power supply	>45 mins of power
Safety – no burn risks	Avoid hot spots in wiring	Redundant network
Drape-ability	Mimics a blanket	Soft and flexible material

1.2.1. Benchmarking ThermoCloud

There are products currently available that make an attempt at providing a heat source that will maintain normothermia, however most target adult patients and do not meet the functional requirements of portability, scalability and reusability and none are transparent. Two common medical heating systems are the ChillBuster and Bair Hugger. The Chillbuster by ThermoGear is an electrical blanket that is powered using a portable power supply, however the blanket is not transparent, cannot be easily scaled and it is intended for adult patients [11]. The Bair hugger is a blanket that hugs the patient and is heated using forced-air warming but it too is not transparent nor portable or reusable [12]. Table 1-2 presents a benchmarking comparison between ThermoCloud and current products available.

Table 1-2 Benchmarking ThermoCloud with other Warming Medical Devices

	ThermoCloud	Chillbuster®	Bair Hugger
			
Temperature	37°C	40°C	38°C
Transparent	+	+	-
Portable	+	+	-
Reusable	+	+	-
Scalable	+	-	+
Cost	\$50	\$120	\$100

2. Blanket Material Selection

2.1. Melting Temperature and Glass Transition Temperature

In selecting the polymer material for the infant blanket, it is important to understand the properties of polymers that are related to the application of heat. The melting temperature and the glass transition temperature indicate the thermal limitations and relative flexibility of a material. The glass transition temperature is the temperature at which the material begins to transition from brittle and rigid to soft and rubber-like. Materials with glass transition temperatures below room temperature (22°C) are typically associated with elastomers while materials with glass transition temperatures above room temperature are associated with rigid polymers. **Figure 2-1**, compares the transitions and states for crystalline materials, curve 1, and amorphous materials, curve 2 [13].

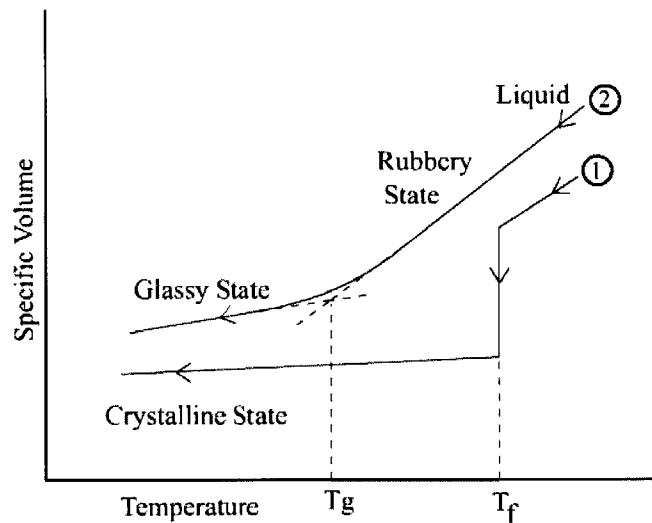


Figure 2-1. Glass Transition Temperature and States of a Polymer.

2.2. Materials Comparison

Table 2-1 Materials Comparison [14-19]

Material	Melting Point (°C)	Glass Transition (°C)
PVC (flexible)	160	82
Silicone, Pure	1,414	-125
Polycarbonate	155	145
PEBA	295 - 351	10
Polyamide 11	360-376	75.9 - 199
PET (polyethylene terephthalate), film	245	70
LDPE (Low-density Polyethylene)	105-115	-125

PU	70	189 - 222
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Using the Medical Materials Database [19], polymers that were transparent and thermally conductive were explored and considered for the construction of the infant blanket. Their properties are given in **Table 2-1**. First, the melting temperature must be above the temperature reached by any wire in the resistive network, nominally $38\pm 2^\circ\text{C}$ with a maximum of 43°C . Second, the glass transition temperature should be well below a room temperature of 22°C so that the material is sufficiently flexible to drape. Three materials were identified as having desirable characteristics: Silicone, Polyamide 11 and Low-density polyethylene (LDPE) and their properties are. Selecting the best from among these three materials required further consideration of the functional requirements listed in **Table 1-1**.

All three satisfy the first criterion of transparency. Silicone rubber is semi-transparent when made in thin sheets, Polyamide 11 comes in a dry transparent grade and LDPE is also transparent and thin. All three can be manufactured in thin enough sheets to satisfy the criteria of “drapeability.” Both Polyamide 11 and LDPE, both of which are “clean” polymers that can be wiped using every day disinfecting agents, satisfy the sterility criterion. On the other hand, silicone is a very viscous and would be very difficult to handle and maintain cleanliness.

Finally, the thermal conductivity and relative cost effective of Polyamide 11 and LDPE is considered. LDPE is not only more thermally conductive than Polyamide 11, but is also widely available, which makes it very cost effective. In particular an LDPE sheet of 12 ft^2 area and 4-mil thickness costs \$0.53, as sold by Husky Plastics. Two sheets of these dimensions compose ThermoCloud and therefore the costs of LDPE used to create a ThermoCloud infant blanket are \$1.06 in small quantities only, with reductions expected for large orders [20].

In comparison with the current PVC material used in the construction of ThermoCloud, polyethylene has various advantages: polyethylene provides a higher thermal conductivity, is comparatively cost efficient and its sheets come in varying thicknesses, including a 4-mil thickness that allows for the construction of a blanket that is very soft and drape-able [21-23]. Table 2-2 compares PVC and LDPE quantitatively, having already taken into account the fact that both are transparent and easy sanitized using antibacterial cleaning products already found in hospital settings.

Table 2-2 Comparison of PVC and LDPE

	PVC	LDPE
Thermal Conductivity (BTU*in/(hr*ft ² *°F)	1.02	2.29
Smallest Thickness (mm)	0.70	0.10
Cost per 12 ft ² (\$)	0.63	0.53
Weight (lb.)	0.035	.003

3. Resistive Network of Wires for ThermoCloud

3.1. Resistor Networks

Resistors placed in series share the same current I , with each experiencing a voltage drop shown in Figure 3-1. Summing the resistances, Equation 3.1, yields an effective resistance R_{eff} , with the voltage drop ΔV given by Ohm's Law, Equation 3.2.

$$R_{eff} = R_1 + R_2 + \dots + R_n. \tag{3.1}$$

$$\Delta V = IR_{eff} \tag{3.2}$$

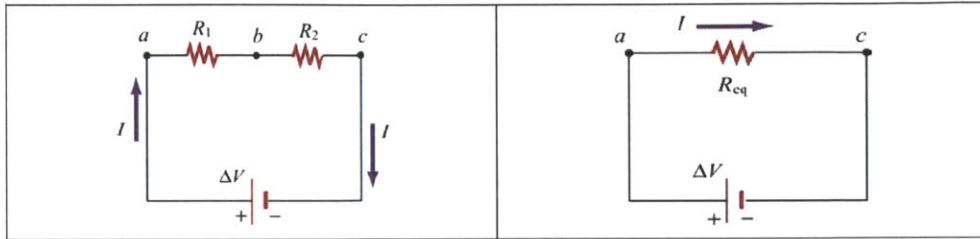


Figure 3-1. Resistors in Series

Resistors that are connected in parallel share a voltage and split the current as a function of the respective parallel resistances. As shown in Figure 3-2, the current from the voltage source is divided into two currents, I_1 and I_2 , which run across the resistors of resistance R_1 and R_2 .

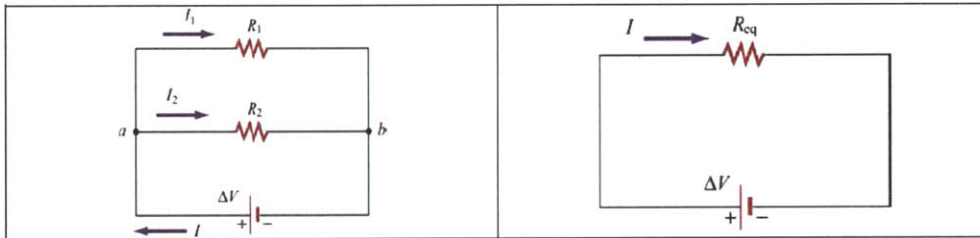


Figure 3-2 Resistors in Parallel

Once again, Ohm's law gives the potential across each resistor as equivalent to the voltage drop across the voltage source, $\Delta V = \Delta V_1 = \Delta V_2$, where $\Delta V_1 = I_1R_1$, $\Delta V_2 = I_2R_2$ and $\Delta V_3 = I_3R_3$. Knowing that the sum of I_1 and I_2 is equivalent to I and Ohm's law, Equation 3.2, the effective resistance of a parallel network is found and given in Equation 3.3. [24]

$$R_{eff} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2}} = \frac{R_1R_2}{R_1+R_2}, \tag{3.3}$$

3.2. Resistive Network of ThermoCloud alpha prototype

The development of the alpha prototype used thermodynamic models, which considered the convection, conduction and radiation involved in placing the blanket over an infant, both from the underside and off the surface into space (loss). The maximum blanket surface temperature was set at 37°C, which is below the maximum safe temperature for contact with an infant. Using the model and heat generation of 50 W was identified as necessary to maintain infant warming

under the blanket. Assuming a 12V power supply, which is readily available in battery packs and vehicles, using Equation 3.4 and Ohm's law the desired R_{eff} is found to be 3Ω .

$$P = I^2 R_{eff}, \quad (3.4)$$

where $V = IR_{eff}$, and the effective resistance is found to be

$$R_{eff} = \frac{V^2}{P}. \quad (3.5)$$

The alpha prototype of ThermoCloud consisted of a network of thin 0.08 mm diameter, round nichrome wires arranged in parallel, connected to bus bars on each end, and sandwiched between two thin (0.75 mm) sheets of polyvinyl chloride. As shown in Figure 3-3, 51 the wires are spaced 6.35 mm apart on a sheet with dimensions 900mm long by 600 mm wide mm. Spacing of the elements was set close enough to achieve a relatively uniform heat distribution but far enough apart that transparency was maintained. Two copper bus bars, perpendicular to the nichrome wires, complete the parallel circuit.

The nichrome wires were rated for a resistance of $2.5 \Omega/\text{cm}$ with each individual length having a resistance of 150Ω . A special case of Equation 3.3 exists when the resistors are share the same resistance value; in this case the R_{eff} is simply the resistance of one element R divided by the number of elements n . Thus the 51 wires have an R_{eff} of 2.94Ω which will approximately yield the desired 50 W. [10]

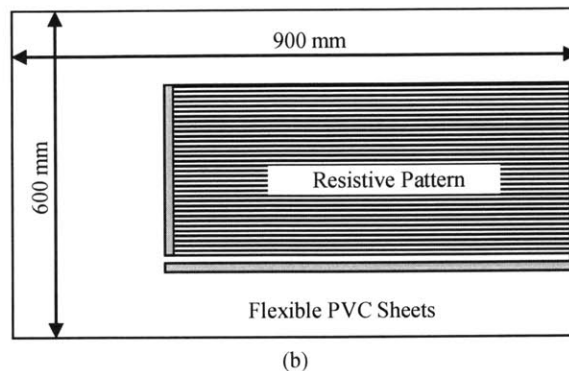
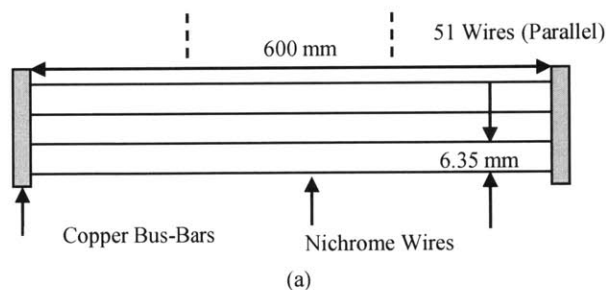


Fig. 3-3 Circuit design (a), and blanket top-view (b) [10]

3.3. Selection of Wire

In the alpha prototype of ThermoCloud, the nichrome wires and their arrangement proved to be an excellent choice for the construction of a proof-of-concept prototype. nichrome wires are lightweight, easily available, inexpensive and thin, which maximizes visibility through the blanket. In addition, they are rated for a resistance of 2.5 Ω /cm and the current arrangement of the wires in parallel results in an effective resistance of 2.94 Ω . However, fabricating the alpha prototype was a challenging task. A loom-like assistive template had to be built in order to hand-thread the nichrome wires along the loom to be 6.35 mm apart. The fabrication process is picture in Figure 3-4.

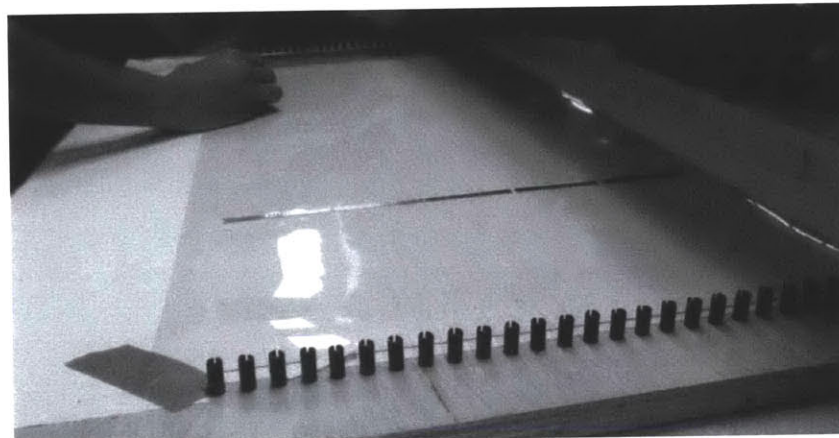


Fig. 3-4 Tooling to position the layers, bus bars, and nichrome wires [10].

In further developing the product, it is important to not only increase the accuracy of the effective resistance rating but also ease the fabrication process. This beta prototype of ThermoCloud tested an alternate arrangement of wires that placed resistive elements in both parallel and series, so as to achieve the desired resistance and power output.

3.3.1. Frost Fighter Inspiration

In deciding new arrangements of the resistive network of wires, inspiration was taken from a car window defroster.

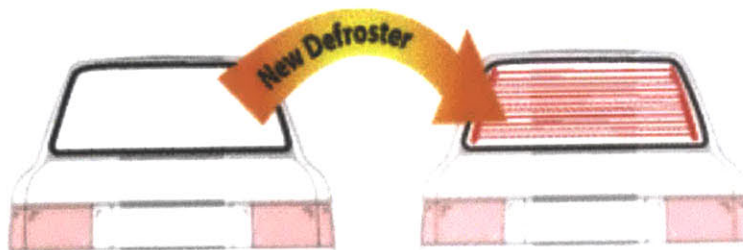


Figure 3-5 FrostFighter Clearview kit by Planned Products LLC

The FrostFighter Clearview kit, pictured in Figure 3-5, by Planned Products LLC is designed as a replacement product and provides adhesive strips of flat copper wires. The company was unable to provide exact specs, but flat copper wires were measured to be 1.40 mm wide, 0.07 mm thick and have a resistance of 0.00764 Ω /cm. As displayed in Figure 3-6, the FrostFighter Clearview Kit directions specify placing parallel pairs of wires in series, spaced 4 cm apart. The result is a resistive wire network that achieves an even heat distribution using either a 12V or 24V power supply depending on the model of defroster kit being used. [25]

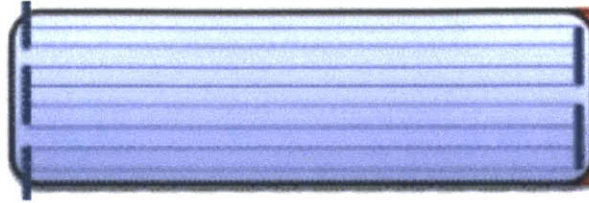


Figure 3-6. FrostFighter Defroster Kit Wire Arrangement

3.3.2. Design of ThermoCloud Samples using FrostFighter copper wires

From studying the FrostFighter defroster kit, a second design for the ThermoCloud was developed that arranged the adhesive copper wires on the LDPE sheet in a similar manner, while still achieving the desired 3 Ω equivalent resistance so as to have the same power distribution per area. The new blanket targets the projected area of the infant using an 800 mm by 300 mm resistive network. The copper 1.4 mm wide wires used in the FrostFighter Defroster kit were measured to have a resistance of 0.00764 Ω /cm and, thus, a wire of 800 mm long will have a resistance of 0.6112 Ω . Two of these resistors in parallel have an effective resistance of 0.3056 Ω . When ten of these parallel pairs are in series, there is an overall effective resistance of 3.056 Ω , a 1.86% error from the goal 3 Ω effective resistance. While the blanket is now of smaller areas, it target the projected area of the infant and it does not compromise its ability to warm the essential extremities of the infant. A spacing of 15 mm was expected to yield an appropriate heat distribution and validated during testing.

4. Fabrication and Testing

4.1. Samples Fabricated

Four 1/8 size scaled sample, 200 mm long and 150 mm wide, were created with the same resistive wire network arrangement discussed in section 3.3.2 and pictured in Figure 4-1, e.g. the wires are still spaced 15 mm apart but they are shorter and there are less pairs. The calculated effective resistance for the samples was 0.382 Ω while the average measured resistance is 0.449 Ω . The bus bars are assumed to have negligible resistance.

The four samples were composed of the same resistive network discussed in section 3.3.2, and the testing of these samples is discussed in section 4.2. In testing these samples, the objective was to discover the minimum thickness of polyethylene that would withstand the temperature of the wires without melting. The samples tested were composed of two identical sheets, each with

thicknesses 4 mil, 8 mil, 12 mil and one sample was a combination of a 4 mil sheet and a 12 mil sheet. The testing of the samples revealed that all were capable of withstanding the temperature of the wire, therefore making 4 mil the optimal thickness of the polyethylene sheet. A 4 mil sheet reduces the thickness of each sheet by 0.66 mm.

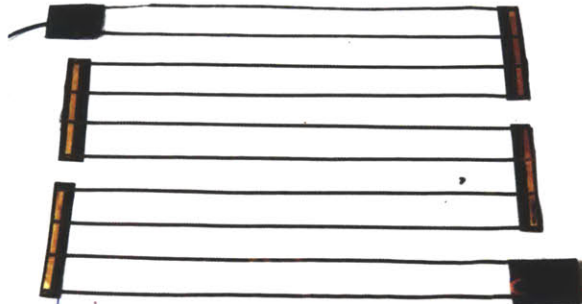


Figure 4-1. Sample of Beta Prototype of ThermoCloud

In comparison to the construction of the alpha prototype of ThermoCloud, pictured in Figure 3-4, the beta prototype of ThermoCloud does not require the construction of tooling board to wrap wires around and is fabricated in 6 simple steps. Instead a paper template with printed lines (seen through sample in Figure 4-2), spaced 15 mm apart, was used as a guide for the placement of the wires and because the copper wires are both flat and adhesive on one side they remained stationary once placed. The bus bars were made with multiple strips of the same copper wires.

Fabrication consisted of the following steps: (1) cut polyethylene sheets to size, (2) place over grid template, (3) with adhesive side down, place copper wires on polyethylene sheet using the template grid as a guide (4) place bus bars so as to create parallel pairs in series (5) connect 10 gauge wires to the furthestmost bus bars (6) add second layer of polyethylene, (7) using a pressing cloth and a heat sealer at 105°C, fuse the two polyethylene sheets.

A safety precaution that should be considered in the production of ThermoCloud is incorporating continual resistance measurement to ensure that the entire blanket remains at the effective resistance of 3.056Ω. In the case that a short is created on one wire, the change in effective resistance will be detected and the power supply will be shut off to prevent the wire parallel to the short from carrying the total current, overheating and burning the patient. The dual track of wires, however does prevent sparking in the case that one strand is broken.

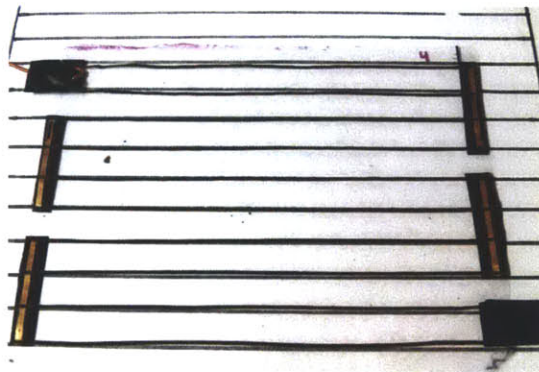


Figure 4-2. Paper Template with Printed Grid Lines

4.2. Experimental Set-Up and Procedure

The samples of the beta prototype of ThermoCloud underwent testing to verify that the resistive network would reach the desired temperature of 37°C and have an acceptable heat distribution. The free-hanging samples were held only at two corners and a voltage of 1.5V was applied using a Tenma DC Regulated Power Supply. A Flir T300 thermo-imaging camera was used to take photographs of the sample in 1-minute intervals. The experimental set up is demonstrated in Figure 4-3.

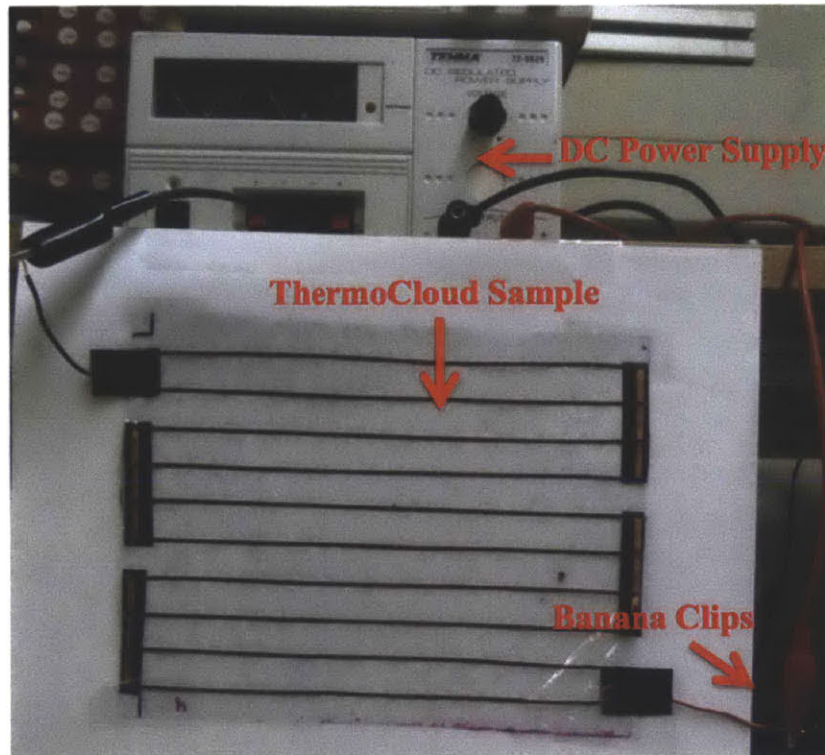


Figure 4-3 Experimental Setup for Sample of ThermoCloud

The 1/8 scaled (by area) samples of ThermoCloud should therefore deliver 1/8 of the full blanket's 50 W. Therefore, with a resistance of 0.382 ohms the supply voltage needed to be decreased. In this case the blanket was run at 1.5 V, 1/8th of the total expected voltage, 12V, to be run on the full sized blanket.

The resistance in the sample scales linearly with size, indicating that so should the voltage that is applied to it. The sample are 1/8 of the size of the full model of ThermoCloud, therefore the voltage applied should be 1/8 of the voltage applied to the full model. This setup on the scaled sample is representative of the performance of the full sized ThermoCloud.

The simple procedure performed to find the temperature the samples reached was the following:

1. Hang the sample using two corners so that the central body is free hanging

2. Use banana connectors to connect the Tenma DC Power Supply to the 10 gauge wires at opposite ends of the resistive wire network
3. After checking that the voltage dial on the power supply is turned to the lowest setting, turn on the Tenma DC Power Supply
4. Turn the voltage dial clockwise until 1.5 V is reached
5. In one-minute intervals, take pictures of the sample using the Flir T300 thermo-imaging camera. A sample photograph is seen in Figure 4-4.

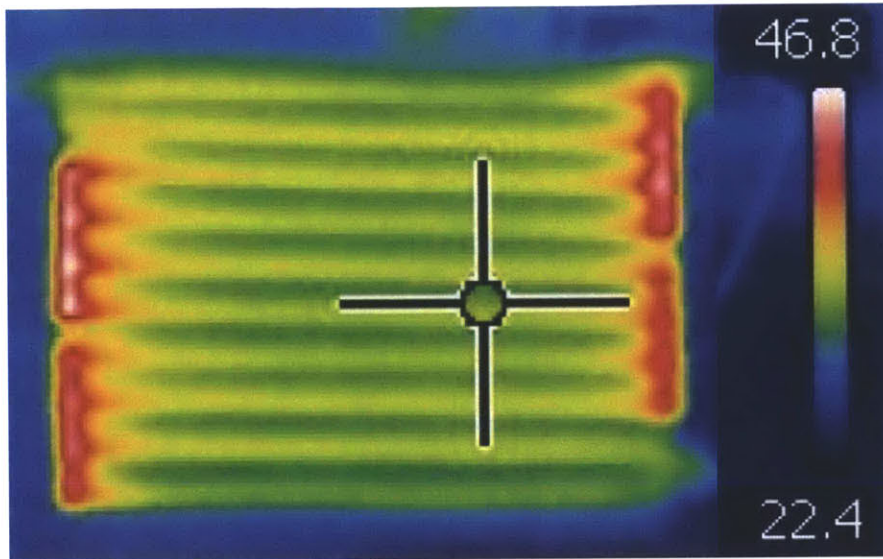


Figure 4-4 Sample Thermo-Imaging Photograph of ThermoCloud

5. Results, Discussion and Future Steps

The samples were tested for ten minutes, with images captured in one-minute intervals. There was a consistent, even distribution of temperature in the resistive network composed of copper wires achieving average temperatures of 34.22°C at the wires and 30.8 between the wires. The copper bus bars were consistently an average of 12.53°C warmer than the copper wires. Figure 5-1 displays a series of photographs, taken at different times that consistently show an even temperature in the copper wires and hot spots created on the bus bars.

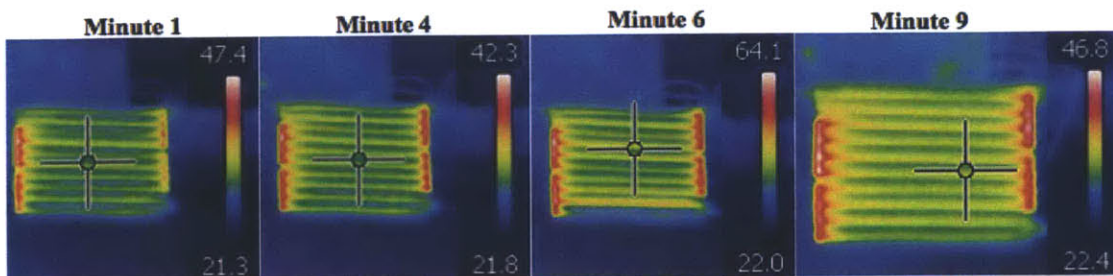


Figure 5-1 Thermo-Imaging Photographs at different Times

These hot spots are of concern because they have the potential to burn patients. The different temperatures achieved by the bus bars and the copper wire is displayed in Figure 5-2. To prevent these hotspots from forming the bars will need to be increased in width. Currently, the same 1.40 mm wide, flat copper wires used for the resistive network made up the bus bars. Using copper tape that is thicker and has a stronger connection to the resistive wire network will improve conductivity from the bus bars to the thin copper wire network.

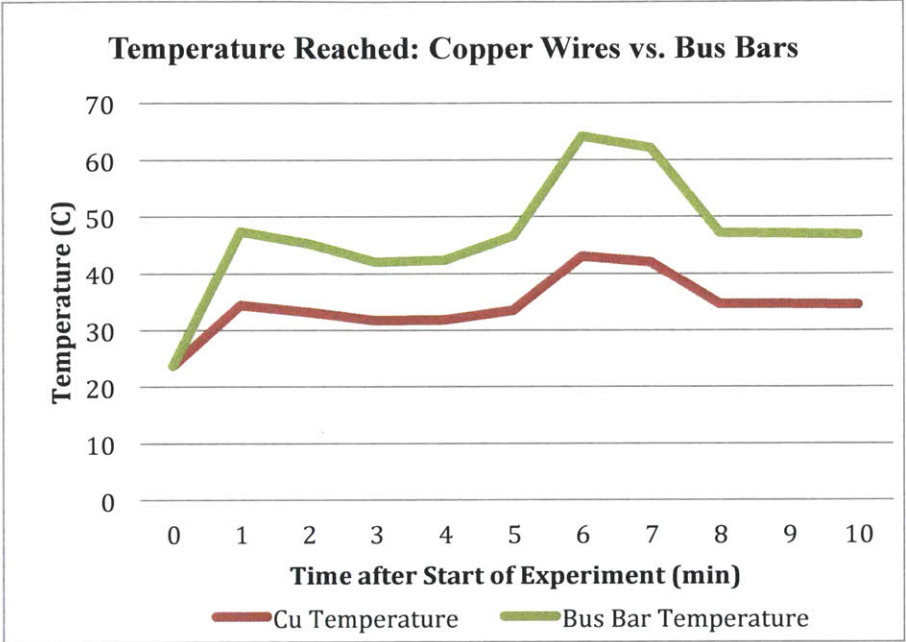


Figure 5-2 Temperature Achieved: Copper Wires vs. Bus Bars

In addition to the problem faced with hotspots, there are a few fluctuations in the temperature. During the first minute, the temperature spikes to 34°C for the copper wires and to 47°C for the bus bars. There is a second spike at the 6th minute when the temperature rises from 34°C to 43°C for the copper wires and from 46°C to 64°C for the bus bars. This may be due to a weak connection between the bus bars and the copper wires. In the current prototype the copper wires were simply wrapped over the bus bars and secured with electrical tape. Movement of the electrical tape comprised the connection and resulted in fluctuations of the temperature; when the connection is strong, the temperature is higher and naturally, when the connection is weak, the temperature is lower. This problem can be resolved with soldered connections between the tape and bus bars or, indeed, integrated tape and bus bars.

5.1. Conclusion

The beta prototype has proved to improve the design of ThermoCloud. Recalling the functional requirements of ThermoCloud, Table 1-1, the beta prototype is 95.3% transparent and it uses LDPE sheets with a thermal conductivity of 2.29 BTU*in/(hr*ft²*°F). In addition, it has an expected life determined by the power supply, in this case a 1.5kg, portable battery pack that showed no depletion after 70 minutes of testing. The polyethylene is a clean, smooth material

that can be sanitized using antibacterial cleaning supplies regularly found in hospitals. Most importantly, the new material is lighter, more flexible and softer than the PVC used in the first model of ThermoCloud.

While the beta prototype samples demonstrated hot spots, there is confidence that wider bus bars will eliminate this problem. Considering that the resistive network created by FrostFighter consisted of approximately 20 mm wide bus bars, it is expected that the resistive network of the beta prototype of ThermoCloud also require bus bars of similar width.

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