Fabrics as Thermal Insulators

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Abstract

Within this experiment, the insulation properties of polyester, cotton, and wool were investigated in order to determine which material is the most effective insulator. The experiment consisted of heating up water in an aluminum container and wrapping it with different insulators. The temperature of the water was then measured every five minutes for a period of 30 minutes. The experiment determined that, on average, the trials using insulators were able to keep the water warmer than the control trial with no insulator. Over 30 minutes, the temperature of the water with no insulator dropped by 19.3 degrees celsius. On average, the trials using cotton as an insulator led to the water's temperature dropping by an average of 12.4 degrees celsius over 30 minutes. When wool was used as an insulator, the temperature of the water dropper by 19.2 degrees celsius on average. With polyester as an insulator, the temperature of the water dropped by 13.9 degrees celsius on average. It was determined that cotton was the most effective insulator of the tested materials, followed by polyester and then cotton.

Introduction

Being uncomfortable in the heat or cold is a problem that many if not all people face. The standard remedy to issues of temperature is clothing. Centuries of development have lead to a wide variety clothing and fabrics, all of which are designed for different purposes. Synthetic materials such as rayon and polyester have been meticulously crafted to be as light and as breathable as possible. On the other end of the spectrum, insulated coats, gloves, and hats work to conserve the wearer's body heat during the harsh winter months. While researching winter clothing, the question arose of what commonplace fabric materials would be the best at keeping one warm. While the specially designed jackets, coats, gloves, etc. would obviously be more insulative than a cotton t-shirt, not everyone has easy access to or the need for heavy duty winter wear. This question is the basis for our experiment, the goal of which was to determine whether wool, polyester, or cotton, (all of which are very common fabrics that are available to most consumers), would be the best insulator. Determining which material is the most effective thermal insulator was the primary goal of the experiment while the secondary goal was to figure out how the Vernier temperature probe collects data and observe how effective it was for our experiment.

To understand what makes clothing or any material insulative, one must understand the basic principles of heat and thermal conductivity. Heat, in a basic sense, is the transfer of thermal energy from one object to another object ("Heat." The Gale Encyclopedia of Science). Heat always flows from a place of high concentration (or high temperature), to a place of low concentration (or low temperature). Heat will do this until an equilibrium is reached between the two objects, in which both objects will contain the same amount of thermal energy. This effect can be observed by placing a cold icecube on a room temperature table. Heat from the table will transfer itself to the ice, which has a lower temperature than the table. This process will continue until the table and the ice have reached equilibrium. Eventually, the ice will have melted, turning into water that has the same temperature as the table.

There are three methods of heat transfer. The first method is conduction. Conduction occurs when heat is transferred through physical contact (Gonzales). Heat transferred through conduction is what caused the ice to melt in the previous example. Conduction is also represented in Figure 1 by the heat that is transferred into the handle of the pot. The second method of heat transfer is convection. Convection is the transfer of thermal energy through a liquid or gas (Elert). When a liquid or gas is heated, the material expands and moves away from the heat source. In Figure 1, convection is shown through the water in the pot. When the thermal energy being conducted into the liquid is intense enough, the water will turn into water vapor and expand, moving away from the heat source. The final method of heat transfer is radiation. Radiation is heat transfer that does not occur through the physical connection between the heat source and the heated object ("How Does Heat Travel?"). An everyday example of radiation is the sun, which transfers heat to earth through radiation. In Figure 1, radiation is shown through the heat coming from the heated pad. Conduction, convection, and radiation form the basis of thermal translation, as well as the science of heat.

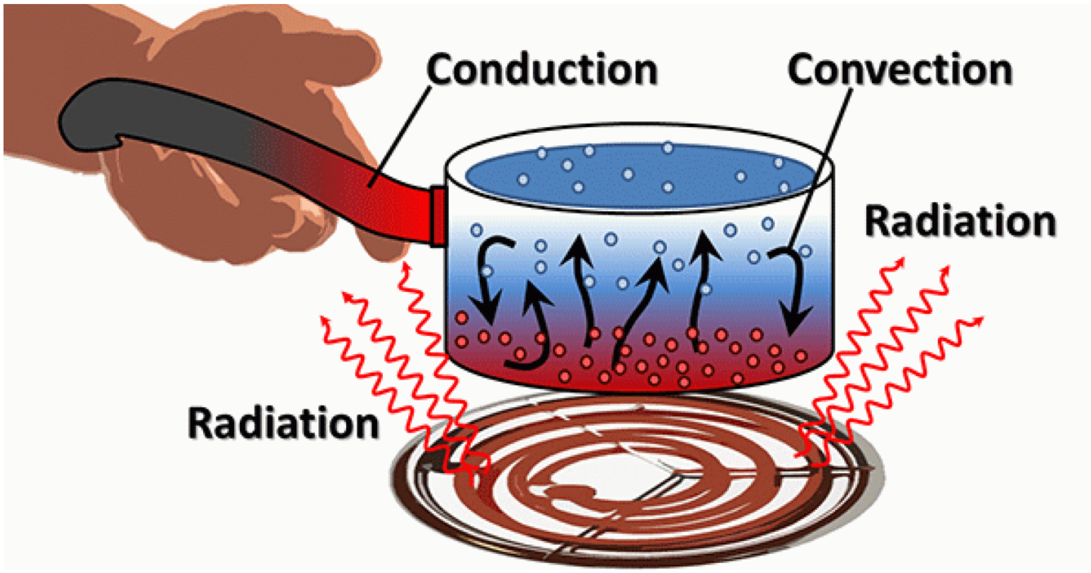


Figure 1: Diagram showing the different methods of heat transfer

While the transfer of heat as a concept stays the same for various materials, not all materials conduct heat with the same effectiveness. A material's ability to transfer heat relies on its thermal conductivity. Thermal conductivity is similar to electric conductivity, in that it is a measurement of how effectively a material is able to conduct or transfer energy ("What is Conductivity?"). In the case of thermal conductivity, the energy being transferred is heat energy. The equation for thermal conductivity is W/mk (Figure 2), which is the amount of heat that passes through a material, measured in watts per square meter in Kelvin, which is a unit of temperature with the same scale as celsius ("How to Calculate U Value"). This is also called the U value. As a general rule of thumb, materials that conduct electricity well such as copper and iron also conduct electricity well and vice versa.

$$k = W/mK$$

Figure 2: Equation for thermal conductivity

For our experiment, the crucial component was thermal insulation. Thermal insulation (or thermal resistance) is a material's ability to prevent or slow the aforementioned methods of heat transfer (Department of Energy - "Insulation"). A material's thermal resistance is measured in its R Value. The greater a material's R Value, the greater its thermal resistance. As can be seen in Figure 3, the R Value of a material is the material's thickness in meters divided by its thermal conductivity (the aforementioned U Value) ("How to Calculate U Value"). A material's R Value is inversely proportional to its thermal conductivity, so materials with high thermal conductivity (such as copper or iron) will have low R Values, while materials that have low thermal conductivity (such as rubber), will have high R Values. It is fairly easy to determine that conductive materials such as metals will have low R Values while not conductive materials such as rubber will have low R Values through background knowledge and basic understanding of electricity. However, it is more challenging to determine how well materials such as fabrics will act as insulators. Furthermore, it is difficult to determine how different fabrics will compare to each other as thermal insulators without experimentation. The experiment was designed around the need to answer this question.

$$R = m2K/W$$

Figure 3: Equation for thermal resistance

The three insulators we decided to test were wool, polyester, and cotton. This was primarily because there are very common so the results of our experiment are relatable to many people. Before experimenting with the materials, we decided to do some research on them. Wool is a fabric that is harvested from sheep or lamb. Wool fabric is very flexible and durable Comparing wool to other fabrics, wool can withstand over 20,000 bends while other fabrics such as silk, cotton, and rayon can only withstand under 3,000 bends. Not only that, but wool can easily absorb moisture without becoming damp. Wool will keep heat insulated by trapping dead air within its fibers However wool can make a person's skin irritated due to the microns within the fabric. If the wool is structurally rigid enough, it can result in a poking to the wearer's skin ("Why Wool"). Cotton is a very cheap fabric that is grown and used to produce clothing. Cotton is a very breathable fabric that can also transmit moisture away from the body. Just like wool, cotton is also absorbent. In the summer, cotton will keep the wearer cool and keep the cold out in the winter. This is due to the fact that the cotton fibers trap air between the fabrics fibers. This results with better insulation and higher comfort. Contrary to wool, cotton will rarely cause allergic reactions and is used for many other purposes. Due to cotton fabrics high tensile strength, the fabric is strong and durable and is more durable when wet (Peterman). Polyester is a synthetic material that is very durable. In fact, the fabric is practically plastic. Polyester is a fabric that doesn't shrink but can not hold its shape very well. Unlike cotton and wool, polyester is not absorbent. This allows polyester fabrics to dry faster. Also, unlike cotton, polyester isn't a breathable fabric which makes the wearer sweat more. For polyester to be insulative, the fibers are made hollow ("What is Polyester…"). This will allow warm air created by the body to be trapped inside the fiber. Usually polyester is combined with cotton to create a fabric that is ideal for many purposes such as athletic and hunting wear.

During the experiment, data was collected using a Vernier temperature probe. It is important to understand the workings of the probe in order to understand how the data was collected. The Vernier temperature probe is an electronic thermometer that does not use a mercury bulb that many older, less scientific thermometers use. It is instead classified as a stainless steel electron thermometer (“Stainless Steel Temperature Probe”). A stainless steel rod makes up a large majority of the probe itself. This rod is energized and has electricity flowing throughout it which is drawn from the outlet into which the probe must be plugged into. By placing the rod into a liquid or into an air sample, one can effectively measure the temperature of that sample. This is because as the temperature of the sample increases, electricity within the rod cannot flow as easily. This is because heat creates resistance for electricity and does not allow it to flow as easily (Woodford). The probe’s technological units then detect this resistance and convert this detected resistance into a temperature that is displayed on a computer using the Vernier Logger Pro software (“Stainless Steel Temperature Probe”).

After researching thermal insulation as well as the properties of our materials we would be testing which included polyester, cotton, and wool, we crafted a hypothesis. We hypothesized that wool would be the most effective insulator since it is naturally occurring in nature and used to keep sheep warm in the cold weather. Not only that, but wool has a significantly larger amount of air pockets which we believed would result in hot air being trapped more efficiently. We hypothesized that polyester would be the least insulative since it is a synthetic fiber that is often marketed as athletic wear for its top of the line breathability attributes. We also hypothesized that cotton would fall between polyester and wool in terms of insulation ability, but that all insulators we were testing would be more effective than no insulation at all.

Materials and Methods

Before testing each fabric material, a control test was conducted to examine the effect of time on the temperature of water. For this test, 200 mL of water were heated to 60 degrees celsius on a hot plate. 200 mL of water filled the aluminum cans approximately half a centimeter from full. Once the water reached 60 degrees celsius, it quickly poured into the can. The Vernier temperature probe, which was set up prior to heating the water, was inserted into the can. A timer was then set for 30 minutes. Every five minutes the temperature of the water was measured and recorded in a data table. Six measurements were taken over the 30 minute time.

To test the insulatory properties of the fabrics, a similar test was conducted. 600 mL of water was poured into a beaker and heated to 60 degrees celsius with a hot plate. The aluminum cans were placed into socks made of the three different fabric types, those being wool, cotton, and polyester. All of these socks were of the same thickness in order to test how material of an insulator affects insulation effectively, not thickness of an insulator. The bottom of the aluminum can, when placed on the table, rested on the heel of the sock. When the water was heated, 200 mL of water was poured to each aluminum can (3 in total). The tops of the socks were then rubber banded to close up the opening. A probe was then added to each sock covered can. Temperatures were measured with the same methods used in the control trial.

Many materials were utilized in order to carry out the experiment. The materials we used consisted of:

- 3 Smartwool 72% Wool socks
- 3 Under Armour 100% Cotton socks

- 3 Nike Dri Fit 80% Polyester socks
- 3 Stainless Steel Temperature probes (Vernier)
- Thermolyne Cimarec 2 hot plate
- 3 Aluminium containers (200mL)
- Logger Pro/Lab Quest
- Rubber Bands
- 1000ml Pyrex beaker

Results

Control Trials Results

Time Stamp (minutes)	Control (Celsius)
5	51.5
10	48
15	46.4
20	43.7
25	42.1
30	40.7
	Net temperature drop (Celsius)
	19.3

Table 1: Data showing the temperature of water with no insulation in relation to time.

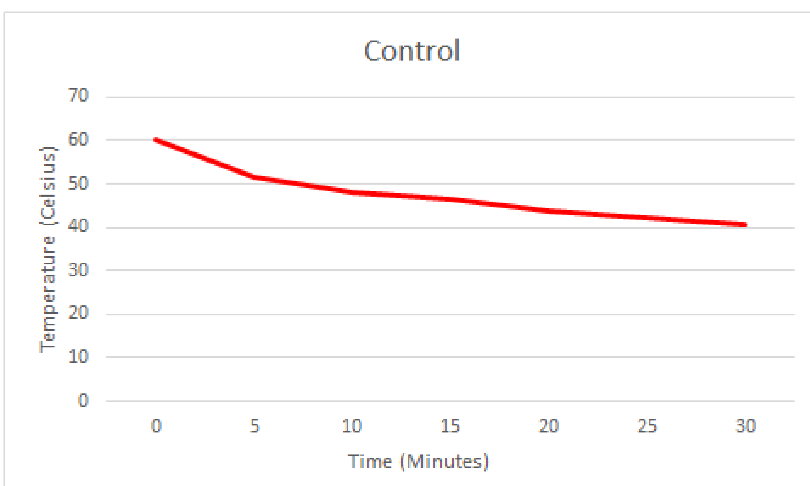


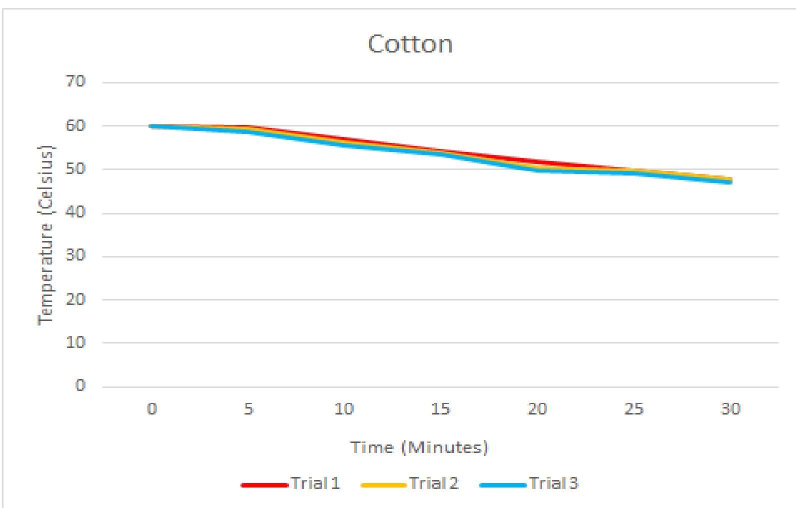
Figure 4. Graphical representation of control test data.

Cotton Trials Results

Time Stamp (minutes)	Cotton Trial 1 (Celsius)	Cotton Trial 2 (Celsius)	Cotton Trial 3 (Celsius)
5	59.6	59.4	58.6
10	56.8	56.3	55.6
15	54.2	54	48.6
20	51.8	50.4	45.9
25	49.8	49.7	42.5
30	47.8	47.8	41.1
	Net temperature drop (Celsius)	Net temperature drop (Celsius)	Net temperature drop (Celsius)
	12.2	12.2	12.9
	Average temperature drop (Celsius)	Standard Deviation	
	12.4	$\pm$0.4	

Table 2: Data showing the temperature of water insulated by cotton in relation to time

Figure 5. Graphical representation of cotton test data.



Wool Trials Results

Time Stamp (minutes)	Wool Trial 1 (Celsius)	Wool Trial 2 (Celsius)	Wool Trial 3 (Celsius)
5	53	56	57.1
10	46.3	52.9	53.98
15	41.5	50.2	51.3
20	38.3	46.4	48.4
25	36.9	44.6	46.3
30	33.7	43.1	45.1
	Net temperature drop (Celsius)	Net temperature drop (Celsius)	Net temperature drop (Celsius)
	26.3	16.9	14.9
	Average temperature drop (Celsius)	Standard Deviation	
	19.2	$\pm$6.8	

Table 3: Data showing the temperature of water insulated by wool in relation to time

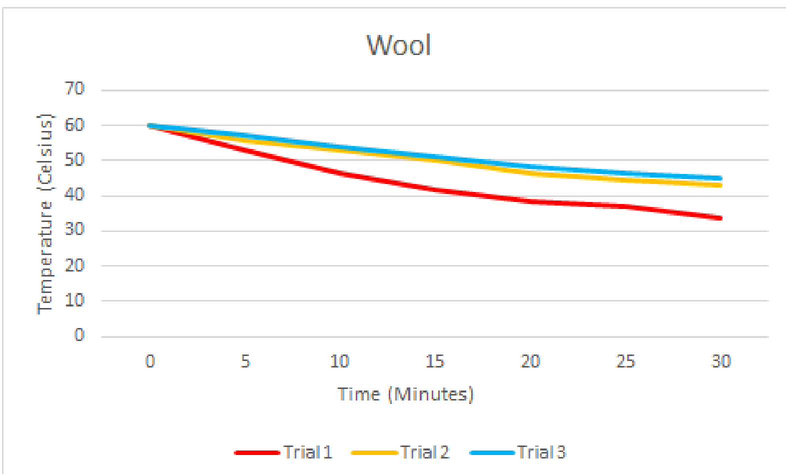


Figure 6. Graphical representation of wool test data.

Polyester Trials Results

Time Stamp (minutes)	Polyester Trial 1 (Celsius)	Polyester Trial 2 (Celsius)	Polyester Trial 3 (Celsius)
5	56.4	57.7	57.3
10	53.2	55.5	54.8
15	50.5	53.4	52.5
20	48.0	51.4	50.3
25	45.7	49.6	48.5
30	43.7	48.0	46.7
	Net temperature drop (Celsius)	Net temperature drop (Celsius)	Net temperature drop (Celsius)
	16.3	12.0	13.3
	Average temperature drop (Celsius)	Standard Deviation	
	13.9	$\pm$2.1	

Table 4: Data showing the temperature of water insulated by polyester in relation to time

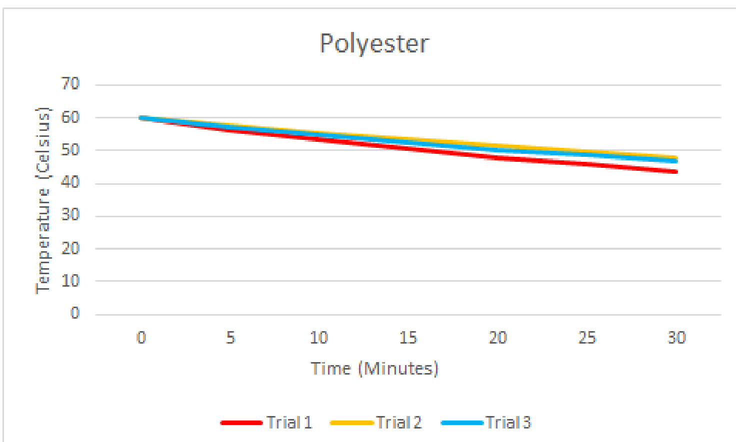


Figure 7. Graphical representation of polyester test data.

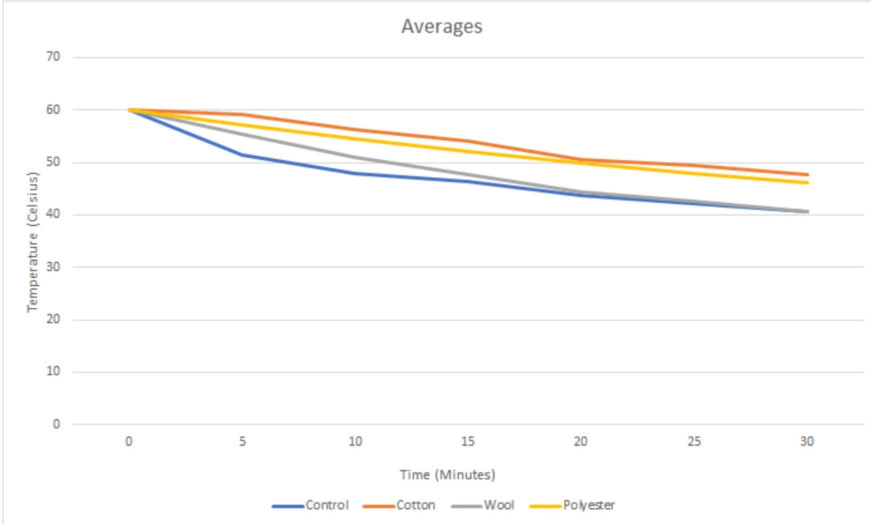


Figure 8. Graphical representation of average temperature of cotton, wool, polyester, and control tests

Through the results section, the net temperature drop was calculated by subtracting the temperature at the end of the 30 minute time span from the initial temperature of 60 degrees. To calculate the Standard Deviation, a datapoint was subtracted from the average of the set of data points, and then squared. The resultants of each datapoint was then added together and square rooted. Afterwards the sum was divided by the amount of data points used to find the standard deviation.

Discussion

Before experimentation had begun, the group had hypothesized that wool had the best thermal insulation. We had believed this because wool was the typical material used in clothing in the winter and it is also a naturally occurring material used to keep sheep warm. It was hypothesized that cotton would be the second best insulator and that polyester would be the least effective, as polyester is a synthetic fabric engineered for breathability and advertised for athletic usage. However, through experimentation, we had found that this was incorrect. Cotton was the most effective insulator, allowing the water within the aluminum container to drop by 12.4 degrees celsius on average. The second most effective insulator was polyester allowing the water within the aluminum containers to drop by 13.9 degrees celsius on average. The worst insulator of the three that were tested was wool which allowed the temperature of the water within the aluminum container to drop by 19.2 degrees on average.

Since the hypothesis was not correct, further research was conducted to determine the cause of the results. Considering that insulation effectivity is measured by an R value which is primarily based on the thermal conductivity of the material, it was believed that the results we received could have been related to the thermal conductivity of the various materials that were tested. Upon further research, the thermal conductivities of cotton, polyester, and wool were determined. These values can be seen in **Table 5** in comparison to their rank of insulation effectivity in the experiment..

Material	Rank of Insulation Effectivity in Experiment	Thermal Conductivity (w/mK)

Cotton	1	0.04
Polyester	2	0.05
Wool	3	0.07

Table 5. Statistics relating thermal conductivities of materials to how effectively they performed in the experiment.

From these statistics, there was a clear trend that the material with the highest known thermal conductivity was the worst insulator tested in the experiment, and that the insulator with the lowest known thermal conductivity was the most effective insulator. These statistics can help to explain why the data appeared as it did. The materials with higher thermal conductivity were generally not as effective insulators which caused the temperature of the water in the aluminum containers to drop more than compared to a material with a lower thermal conductivity. This is attributed to the fact that insulators with a higher thermal conductivity have a lower R value and are not effective insulators. Had this information been known before the experiment, we would have been able to accurately predict which insulators would be the most effective. While we only discovered it after performing the experiment, it was still reassuring to know that our experiment had likely been carried out with great accuracy since our results match those of similar data sets.

Designing the experiment, there were many issues with setting up the experiment. In fact, the experiment was designed from the ground up. This meaning that we had to work through trial and error to achieve results from our experiment. One issue we faced was that by using glass beakers instead of aluminum containers, the glass was so insulative that the additional sock insulator around the beaker had no effect on the change of the water's temperature over time. In order to combat this issue, we used thin aluminum containers rather than glass beakers since aluminum is not insulative. This in turn allowed us to measure the insulation properties of the sock material, not the water container. One other problem we ran into while performing the experiment was that the Vernier temperature probe had technical difficulties with measuring the temperature of a sample over a long period of time (30 minutes). Originally, we would have liked to monitor the temperature of the water continuously for 30 minutes. However, since that was not possible, we decided to only measure every 5 minutes over a 30 minute period. This was not the only issue that was faced with the Vernier temperature probe. The probe was not the most accurate and had a machine error of $\pm$ 0.3ºC from the actual measurement. While experimenting, we found that some of the socks wrapped around the aluminum containers dipped into the warm water and began to absorb the water. This moisture in the fabric then spread throughout the whole sock, making the insulator that was being tested damp. This happened noticeably on two trials which were the first polyester and first wool trials. We believe that the dampened insulators may have been less effective since both trials in which the insulators were known to become damp were considered outliers in our experiment since they were very far off from trials using the same material. In both of these outlier trials, the temperature of the water dropped relatively than other trials which can be seen in **Table 3 and Table 4** as well as **Figure 6 and Figure 7**.

While the data demonstrated a clear conclusion, it was not the most precise. The standard deviations of our data can be seen in **Table 6**.

Material	Standard Deviations Within Trial Sets

Cotton	0.4
Polyester	2.1
Wool	6.8

Table 6. Data showing the precision, measured in standard deviations of our trials.

As can be seen by observing **Table 6**, some of the data collected was precise while some was not. The data collected from the trials using cotton as an insulator was very precise, falling all within 0.4 standard deviations of each other. However, the data collected from the polyester and wool trials was relatively imprecise, as the data from the trials using polyester fell between 2.1 standard deviations within each other and the data from the wool trials were within 6.8 standard deviations of each other. We believed that the Vernier temperature was able to precisely collect data since the trials using cotton as an insulator yielded precise data and that this very imprecise data was attributed to two different outlier trials in the trial sets using wool and polyester as an insulator. These trials were polyester trial 1 and wool trial 1, which is believed to be caused by dampened socks that were previously explained.

To reduce error in the experiment, one measure that should be taken is to use lab grade materials. Instead of wrapping aluminum containers with socks made of the insulating material, custom made sleeves to fit around the aluminum containers should be used to ensure the insulator does not become damp and that all the containers are tied off at the top similarly. This way, every trial is ran the exact same and the data will become more precise. A more state of the art temperature probe should also be purchased, as the Vernier temperature probes are not especially accurate and also led to many technological struggles. This way, data can be collected with more precision, leading to more conclusive results. Since the conclusions from the results of the experiment were previously known, the experiment could be expanded to discover new information. One way in which this could be accomplished could be by testing how the amount of layers of insulation effects how effective the insulation is. Another possible extension idea could be to test how the amount of air pockets in an insulator affects how effective the insulator is. While both of these factors are known to determine how effective an insulator is, to our knowledge it has not yet been documented how these factors affect insulation in an experiment conducted similarly to ours.

The data that was collected from our experiment holds a very high social significance. It provides insight into what clothing materials are the best to wear outside. From our data shown above, cotton is the most effective insulator of the materials we tested and is therefore the best material to wear in the cold. This is because it is more effective at trapping heat than both polyester and wool. Our data is challenging to apply to the real world scenario of clothing as thermal insulators since often times wool clothing, which was the worst insulator of the ones we tested, is made to be thicker than cotton clothing. A one inch thick wool sweater will likely be a better insulator than a thin cotton T-shirt. Our experiment does however prove that if one was to wear a wool and cotton sweater of the same thickness, one wearing a cotton sweater would be able to better maintain their body temperature and stay safe in the cold. This information is important for people to know since they can then be aware of what clothing materials to wear in order to stay safe and avoid dangerous conditions such as frostbite in which extremities can freeze off due to inadequate covering of the skin by clothing (“Frostbite”).

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