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# FrostFlex

Isaac Edmondson
ile3@uakron.edu

Caleb Edmondson
cae50@uakron.edu

Joey Esker
jse35@uakron.edu

Nadine Salem
njs107@uakron.edu

# FROSTFLEX COOLING GLOVES FOR ATHLETIC PERFORMANCE

Caleb Edmondson
Isaac Edmondson
Joseph Esker
Nadine Salem

Final Report for MECE:461 Senior Design Project
Fall 2022 – Spring 2023
Faculty Advisor: Mr. David Peters
Faculty/Honors Advisor: Dr. D. Dane Quinn
Faculty/Honors Reader 1: Dr. Manigandan Kannan
Faculty/Honors Reader 2: Dr. Guo-Xiang Wang

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# Abstract

Research has shown that the majority of heat lost during physical exercise leaves the body through the hands, feet, and the face. Our design project seeks to develop cooling glove technology to increase the rate at which heat leaves the body during recovery from physical exertion. The goal of this project was to investigate different ways in which heat absorption through various mediums can be manipulated and scaled into an adaptable, flexible design in which athletes of all levels, from recreational to professional, can improve their physical performance with the use of our gloves. Deliverables include a functional prototype, product performance analysis, and research to support quality benchmarks.

# Contents

# 1. Introduction

## 1.1 Problem Statement

FrostFlex is a self-initiated design project that focuses on creating a product that provides an innovative solution to optimize physical performance. Research has shown that the cooling of an individual's hands between sets of resistive exercise increases work volume, and therefore facilitating heat transfer from the hands following physical exertion can lead to improved athletic performance [7]. Our team's goal was to design an effective, cost-efficient glove prototype that can enhance user performance, using existing research to validate our design. There are similar products that exist on the market today, but none are accessible or affordable to the average consumer. Our product targets consumers that consider themselves recreational athletes; however, other consumer groups, such as construction workers or sports teams, could benefit from the use of our product as well. The desired outcome of this project includes building a functional prototype and gathering experimental data. At the culmination of our design process, we will be able to present not only our solution, but also the methodology, research, and analysis that was performed throughout FrostFlex's genesis.

## 1.2 Product Definition

FrostFlex consists of engineered gloves and a cooling reservoir. The user puts on the gloves and holds the cold reservoir for 180 seconds to lower the core body temperature, thereby increasing performance output.  See Section 2.2 for additional information regarding product specifications.

## 1.3 Work Scope

Team FrostFlex utilized the engineering design process to create a working prototype for FrostFlex. The steps included the following: background research, conceptual design, embodiment design, engineering analysis, prototype building, and product testing.

# 2. Research & Specifications

## 2.1 Background Research

Exercise physiologists are continuously looking for novel methods to improve performance. A group of researchers at Stanford [7] discovered that periodic cooling of the palms provides a performance improvement on par with the improvements seen with the use of performance-enhancing drugs. The cooling, however, must occur above the temperature threshold that causes vasoconstriction, around 15°C [5]. Before vasoconstriction occurs, each hand and foot can dissipate 155-220 $W/m^2$ of heat. Once vasoconstriction is triggered, this value of heat flux approaches less than 0.1 $W/m^2$ [11]. During exercise, the human hand temperature can increase to 30°C [7]. Many concepts have entered the market based on these scientific principles to enhance performance; however, the current offerings are not user friendly, and many lack the ability to control temperature above the vasoconstriction temperature threshold. For example, the engineered device in the Stanford study [7] requires a large apparatus with a pump to flow water to provide the necessary cooling. Another concept that has been explored provides direct cooling to the hand but does not consider the issues of vasoconstriction, as the design uses a rapid cooling effect that would likely induce vasoconstriction.

## 2.2 Specifications

### 2.2.1 Product Specifications

The product was designed to be comparable in performance with the existing, expensive products on the market, while cutting down the cost of production and increasing ease of use. To be on par with the existing standards [7], FrostFlex was designed to cool hands from 30°C to 17°C in 180 seconds. This would theoretically reduce the core body temperature by approximately 0.5°C, one of the goals of our project.

### 2.2.2 User Requirements

Potential customers range from recreational to competitive athletes who want to improve their performance output. Therefore, it was up to our design team to create customer requirements for FrostFlex. Our team came up with the following: the product must be able to provide the necessary cooling to improve performance, while being easy to use, cheap, durable, and stylish. Our design process sought to maximize each of these parameters.

## 3. Other Considerations

Since FrostFlex directly impacts an individual's health and body temperature, safety was our utmost priority. This being the case, safety was given the largest weight when creating the decision matrix that would select our final conceptual design. Our team upheld safety standards by following a standardized treadmill test procedure during experimentation of FrostFlex gloves.

### 3.1 Societal Impact

FrostFlex is a product that will benefit society, providing relief and better performance for athletes, but can also extend its benefits to people with labor-intensive jobs such as construction workers. We want to create a positive impact on society by designing a product that promotes the importance of physical wellness. The individual will be more inclined to continue the habit of exercise if they recover adequately.

### 3.2 Environmental Concerns

There are variations of our product that do exist on the market currently, but they are larger-scale, less accessible, and more expensive. FrostFlex takes into consideration economic factors and provides a low-cost, effective product that's better geared towards the average consumer. While our goal was to create a functional, accessible product, we simultaneously considered environmental impact throughout the design process. We want to ensure that our product not only is harmless to society but also towards the environment. As engineers, we must uphold and understand the importance of protecting our environment — and incorporate environmental safety when necessary and within our means.

### 3.3 Ethics & Integrity

FrostFlex has potential to become a product that may have sizeable societal impacts. We hope to complete our deliverables with the intention of remaining ethical and safe. Although the methodology, research, and analysis are the key aspects of a successful design project, ethics and integrity are just as important and must be considered throughout the entire process. Overall, Team FrostFlex operated to lead with ethics and integrity — as these are the foundational aspects of successful and impactful engineering.

# 4. Design Process

## 4.1 Quality Function Deployment – Phase I, Ideation

We began project ideation well before the concept of FrostFlex was born. At the beginning of Autumn term, each group member brought ideas for a senior design topic, and those ideas were put into a ranked voting software upon which all team members voiced their opinion on the feasibility of the projects.

FrostFlex emerged as the victor in this ranked voting process and therefore became our official project.

In order to begin the design process, our team designed a function block diagram and a morphological chart. These documents allowed our ideation to follow a well-aligned procedure and for us to come up with various, differing solutions to the problem we are attempting to solve. The morphological chart is pictured in the figure below.

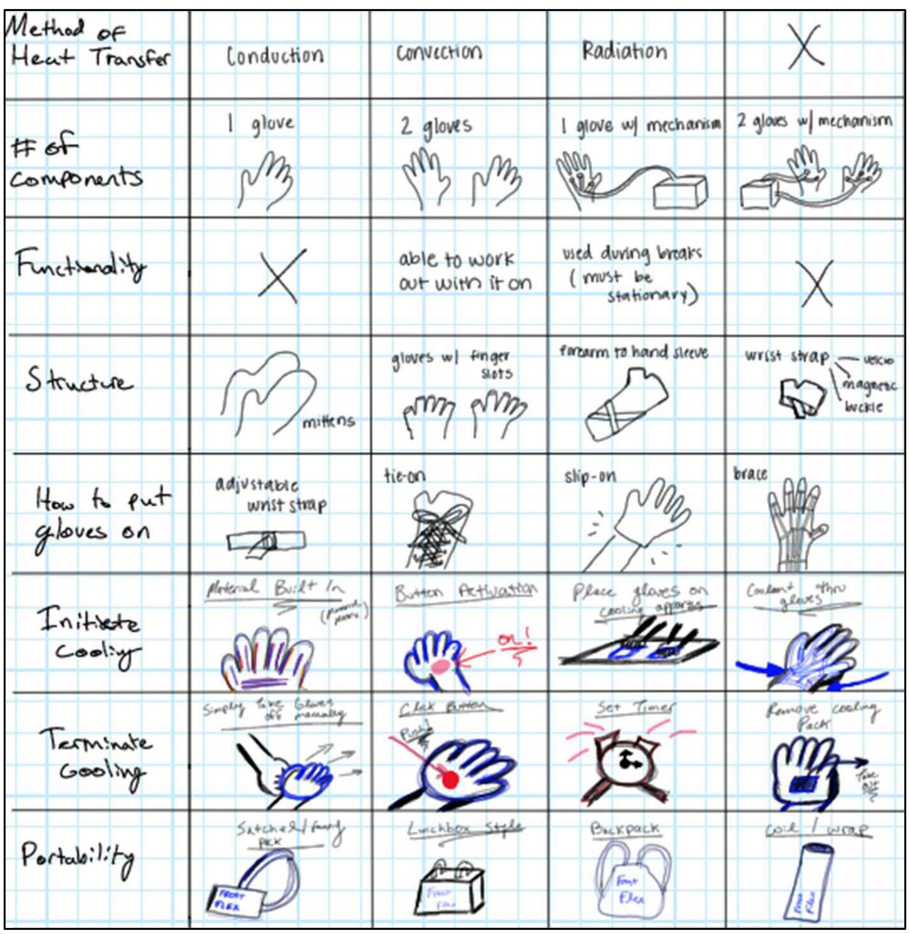


Figure 1: Morphological Chart

From this morphological chart, we were able to come up with seven feasible conceptual designs for FrostFlex.

## 4.2 Risk Assessment – Conceptual Design

Due to the nature of our project and its inherent interaction with human users, safety was key in the foundations of our design. In order to ensure we were taking all the proper considerations; we created an objective tree that outlined primary and secondary areas of focus for the evaluation of our design. That objective tree is pictured in the figure below.

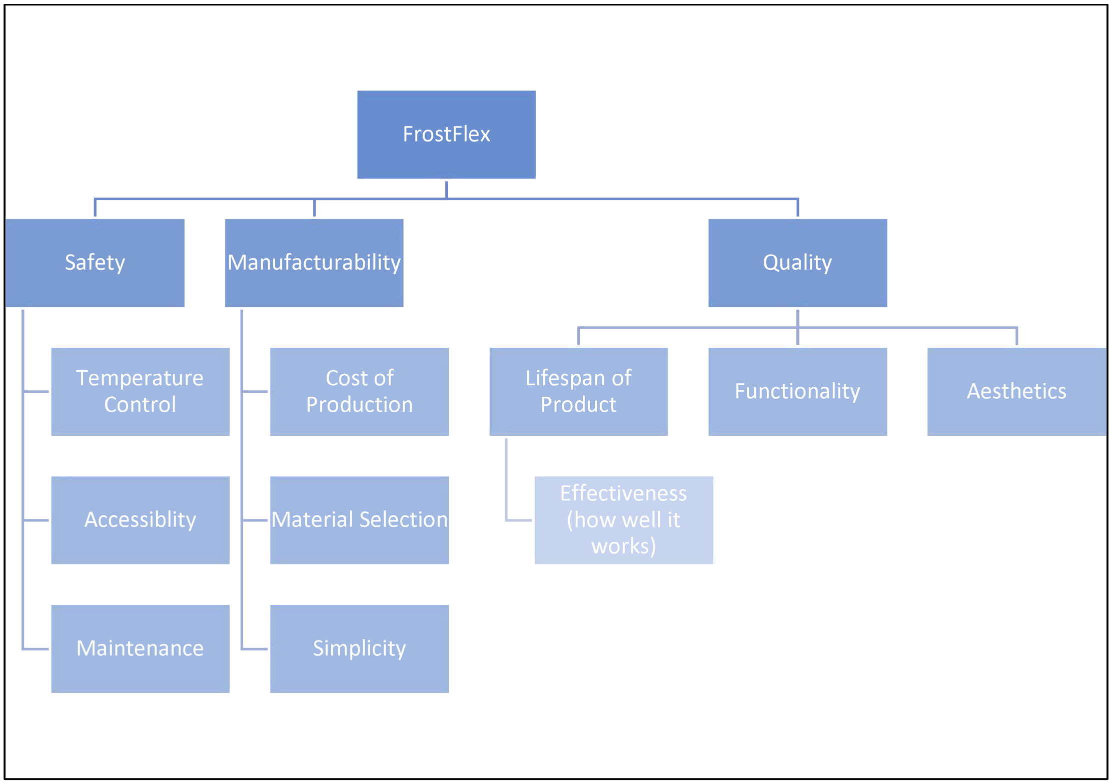


Figure 2: Objective Tree, Version 1

This objective tree was key in determining the feasibility and safety of our design ideas. It played a key role in determining the weights for the decision matrix that will be shown later in this report.

## 4.3 Engineering Constraints

Based on research conducted about the rate of heat transfer from the palms of the hands, it was determined that lowering the core body temperature of the user by 0.5 degrees Celsius would be sufficient for increasing athletic performance for the user [7]. In addition, when considering the possibility of vascular constriction occurring at lowered hand temperatures, it is imperative that FrostFlex users' skin temperature does not decrease below 15 degrees Celsius during use [11]. The gloves should be able to effectively facilitate heat transfer while maintaining durability with repeated use.

## 4.4 Brainstorming Solution Approaches

We were able to generate seven concepts for design given the previous process of designing our morphological chart, objective tree, and success parameters. Each of these design ideas was based on creating an efficient and safe method of transferring heat from the hot reservoir of the hands to a cold reservoir. While they may differ in appearance and function, the principal operation of each design is the same, and they all were created using the same criteria.

The seven solution approaches can be seen in the figures below.

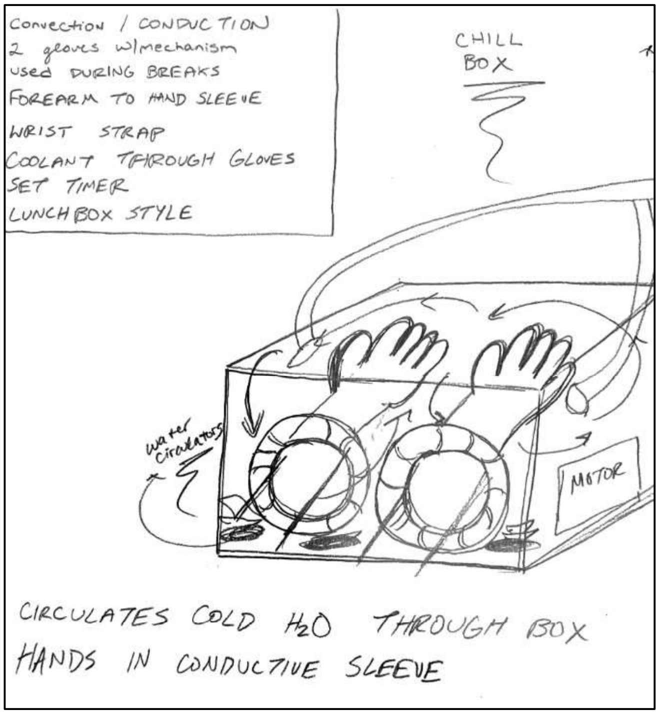


Figure 3: Design Concept Sketch I

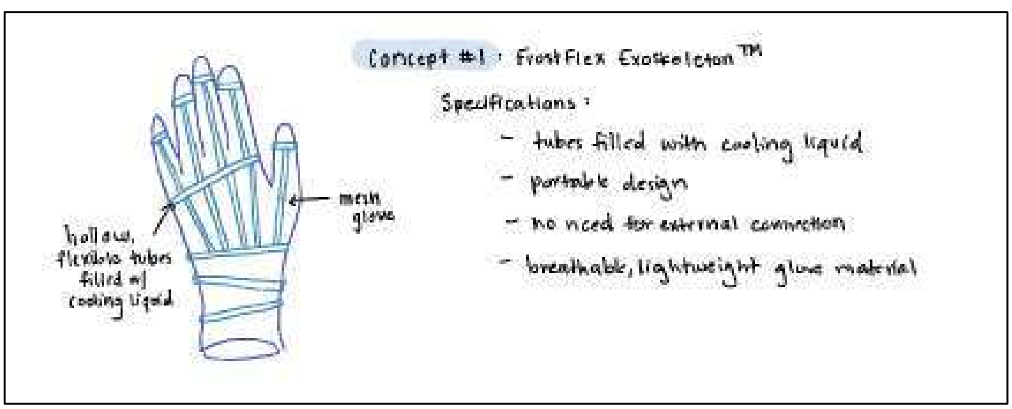


Figure 4: Design Concept Sketch II

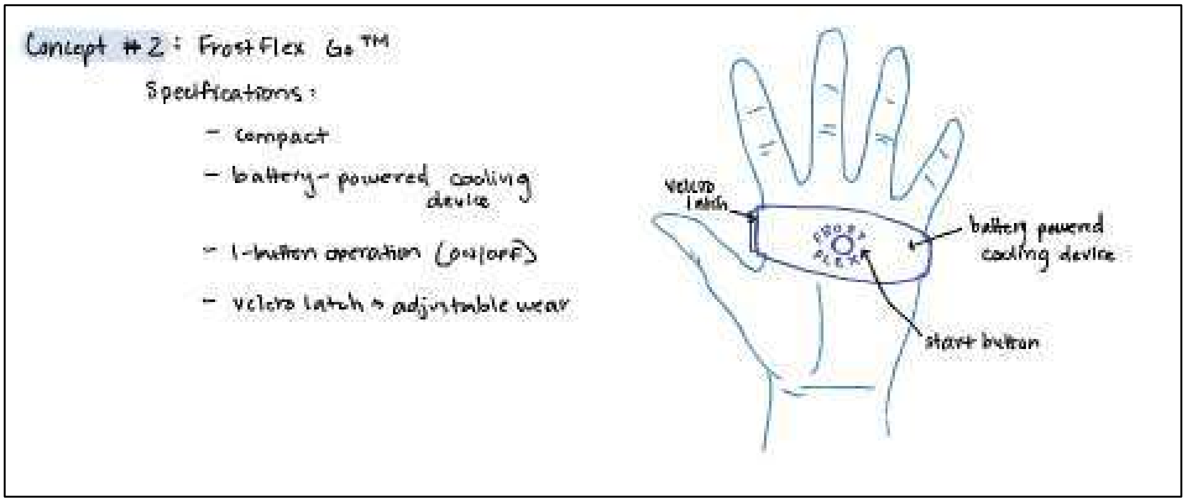


Figure 5: Design Concept Sketch III

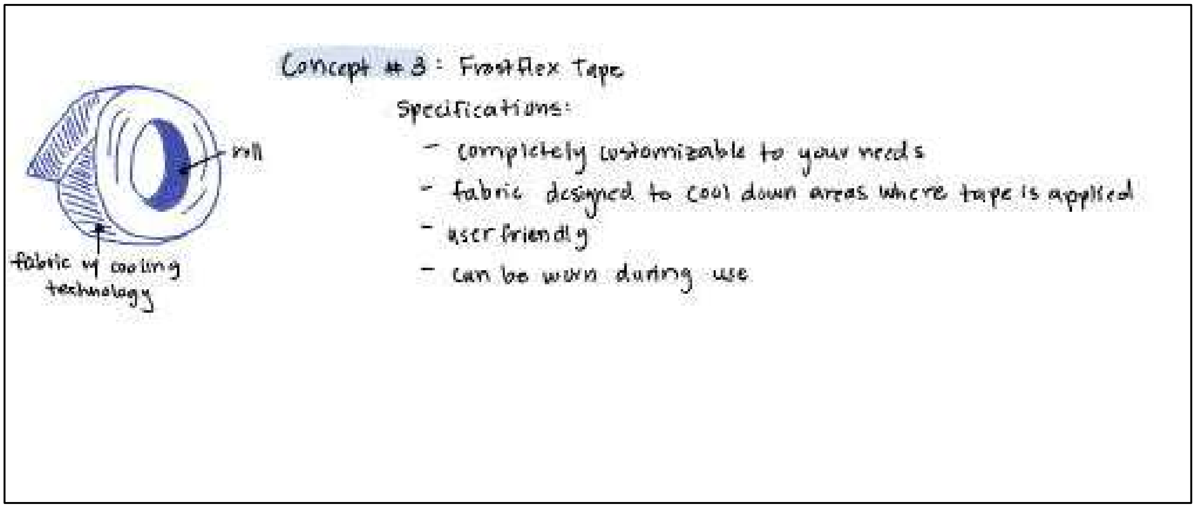


Figure 6: Design Concept Sketch IV

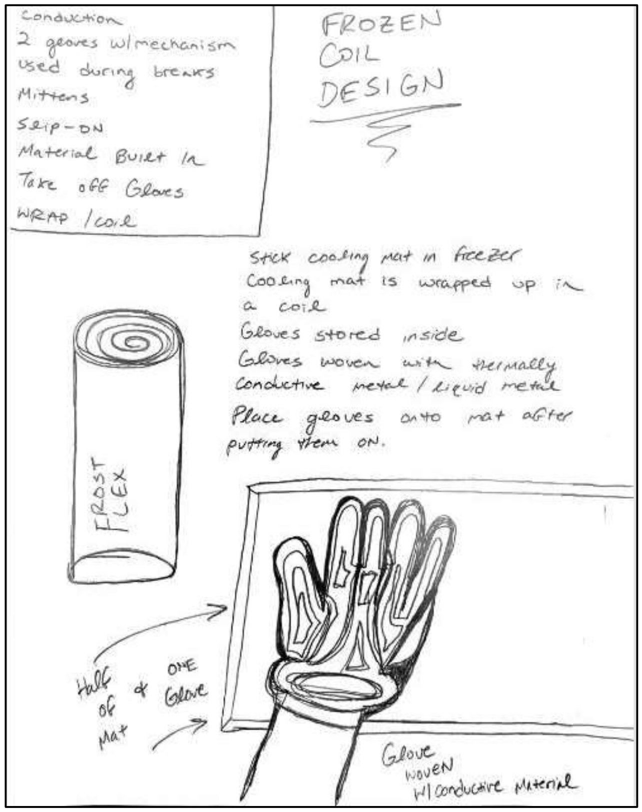


Figure 7: Design Concept Sketch V

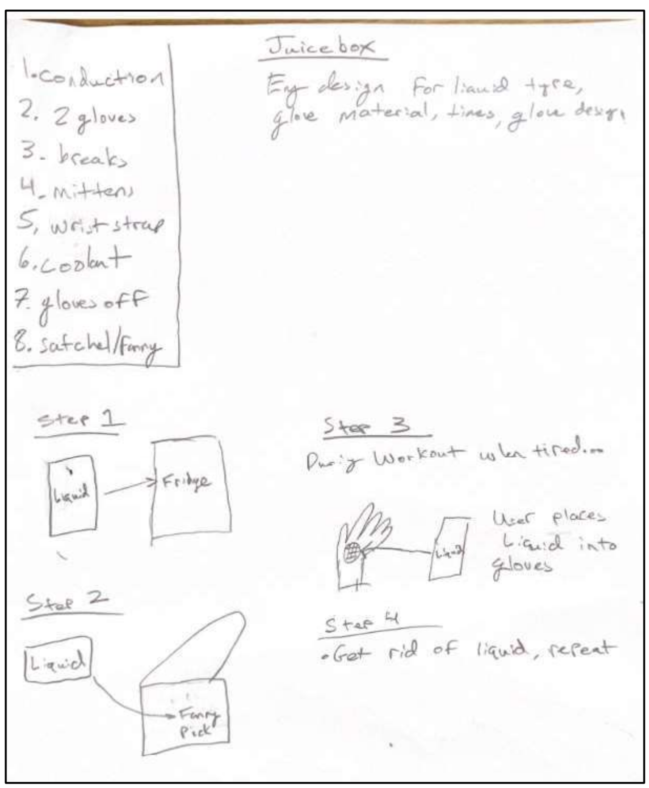


Figure 8: Design Concept Sketch VI

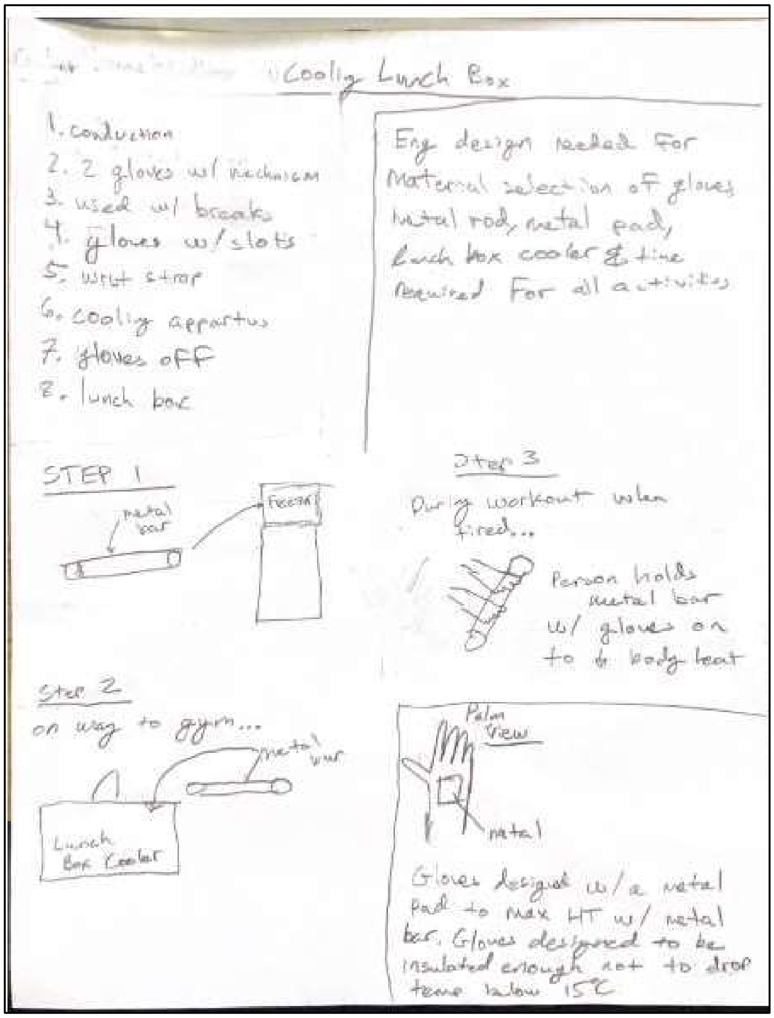


Figure 9: Design Concept Sketch VII

## 4.5 Quantitative & Qualitative Evaluation of Solution Approaches

A weighted decision matrix was designed in order to determine which conceptual design would become the method team FrostFlex would move forward with.
This weighted decision matrix defined the following five categories for success: effectiveness, ease of use, cost of production, lifespan of product, and aesthetics. Each of the seven proposed concept sketches were scored based on how well they met the requirements of the categories.

See Fig. 10 below for the simplified objective tree based on the five categories.

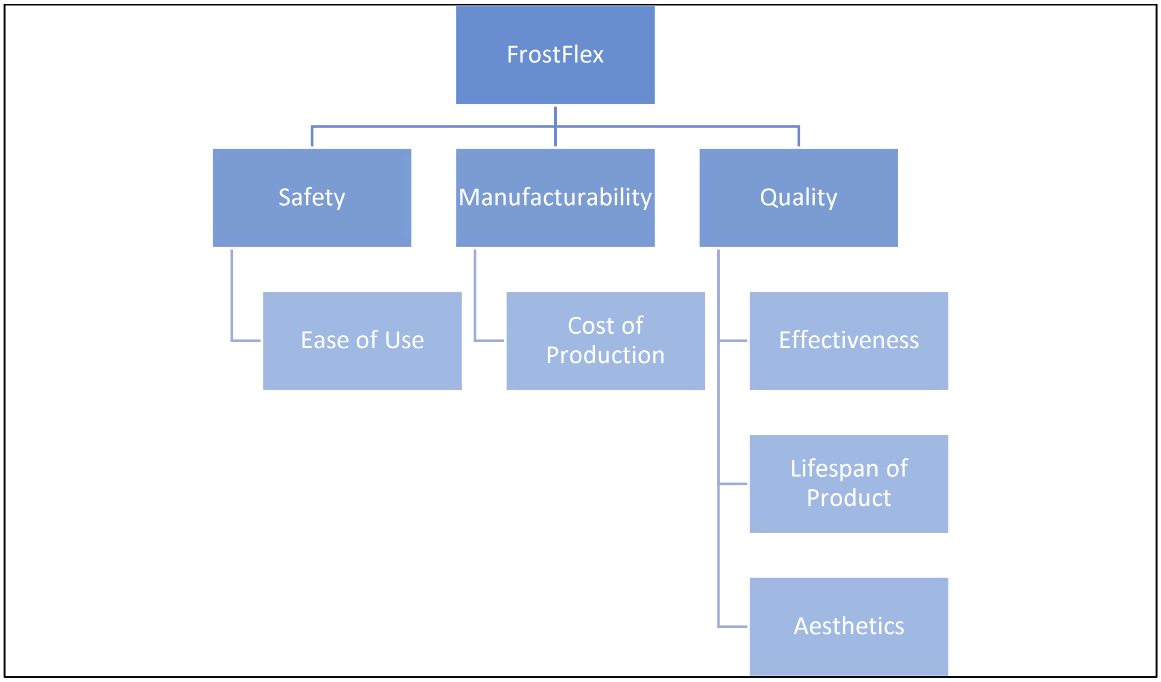


Figure 10: Objective Tree, Simplified

Below is a table showing the five design criteria and their assigned weight factors. They were weighted based off order of importance for our final design.

Table 1: Five Selected Design Criteria

| **Design Criterion** | **Weight Factor** |
|---|---|
| **Effectiveness** | 0.435 |
| **Ease of Use** | 0.175 |
| **Cost of Production** | 0.3 |
| **Lifespan of Product** | 0.0375 |
| **Aesthetics** | 0.0525 |
| TOTAL | 1 |

Table 2: Weighted Decision Matrix Results

| Concept Name | Design Criterion | Magnitude | Score | Rating | Final Rating |
|---|---|---|---|---|---|
| **CHILLBOX** | Effectiveness | Good | 3 | 1.305 | |
| | Ease of Use | Inadequate | 0 | 0 | |
| | Cost of Production | Weak | 1 | 0.3 | |
| | Lifespan of Product | Inadequate | 0 | 0 | |
| | Aesthetic | Inadequate | 0 | 0 | 1.605 |
| | | | | | |
| **JUICEBOX** | Effectiveness | Satisfactory | 2 | 0.87 | |
| | Ease of Use | Weak | 1 | 0.175 | |
| | Cost of Production | Good | 3 | 0.9 | |
| | Lifespan of Product | Satisfactory | 2 | 0.075 | |
| | Aesthetic | Good | 3 | 0.1575 | 2.1775 |
| | | | | | |
| **LUNCHBOX** | Effectiveness | Good | 3 | 1.305 | |
| | Ease of Use | Good | 3 | 0.525 | |
| | Cost of Production | Good | 3 | 0.9 | |
| | Lifespan of Product | Good | 3 | 0.1125 | |
| | Aesthetic | Satisfactory | 2 | 0.105 | 2.9475 |
| | | | | | |
| **FROZEN COIL** | Effectiveness | Good | 3 | 1.305 | |
| | Ease of Use | Good | 3 | 0.525 | |
| | Cost of Production | Good | 3 | 0.9 | |
| | Lifespan of Product | Good | 3 | 0.1125 | |
| | Aesthetic | Satisfactory | 2 | 0.105 | 2.9475 |
| | | | | | |
| **EXOSKELETON** | Effectiveness | Satisfactory | 2 | 0.87 | |
| | Ease of Use | Satisfactory | 2 | 0.35 | |
| | Cost of Production | Good | 3 | 0.9 | |
| | Lifespan of Product | Satisfactory | 2 | 0.075 | |
| | Aesthetic | Good | 3 | 0.1575 | 2.3525 |
| | | | | | |
| **TAPE** | Effectiveness | Satisfactory | 2 | 0.87 | |
| | Ease of Use | Good | 3 | 0.525 | |
| | Cost of Production | Weak | 1 | 0.3 | |
| | Lifespan of Product | Inadequate | 0 | 0 | |
| | Aesthetic | Good | 3 | 0.1575 | 1.8525 |
| | | | | | |
| **CONVECTION 2** | Effectiveness | Satisfactory | 2 | 0.87 | |
| | Ease of Use | Good | 3 | 0.525 | |
| | Cost of Production | Weak | 1 | 0.3 | |
| | Lifespan of Product | Good | 3 | 0.1125 | |
| | Aesthetic | Good | 3 | 0.1575 | 1.965 |

From this decision matrix, we decided to move forward with a combination of the "lunchbox" and the "frozen coil" design. These design ideas were very similar in terms of function and had the highest ratings across most parameters, so team FrostFlex determined the best elements of each conceptual design, combining them into what would become our final design selection.

### 4.5.1 Defined Constraints

A definition for each design criterion was developed for the evaluation of concept sketching.

1. Effectiveness:
   - FrostFlex will reduce user's core temperature by 0.5℃ in under 3 minutes, while keeping palm temperature above 15 ℃.
2. Ease of use:
   - FrostFlex will feature easy operation for the user. No more than three components for use, and able to begin use within fifteen seconds of initiation.
3. Cost of production:
   - FrostFlex has a goal of costing under $200 for proof of concept.
4. Lifespan of product:
   - FrostFlex must be a reusable product that can be used for at least 100 workouts before signs of wear appear.
5. Aesthetic:
   - FrostFlex must be made to be available in different styles with customization as an option, for easy marketability. FrostFlex appears to be a typical, everyday gym item.

## 4.6 Selection of Final Solution Approach

The final conceptual design incorporated two elements: gloves and a cold reservoir. This allows us to easily and effectively create a solution that smoothly implements theory learned in heat transfer to achieve our desired outcome. The following figures show our preliminary sketches for our final product.

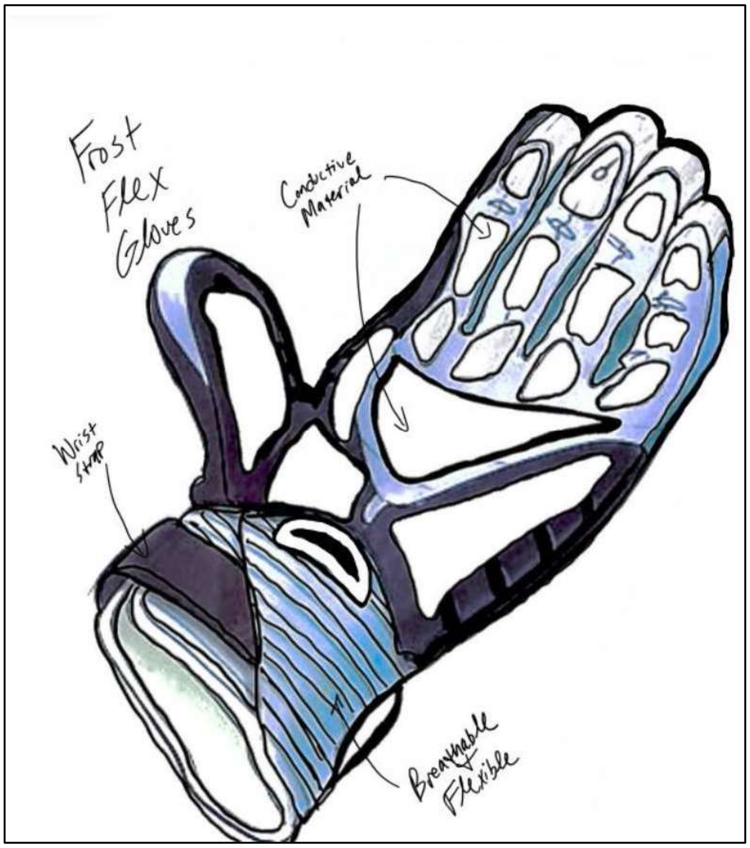

Figure 11: Final Design Sketch – Glove

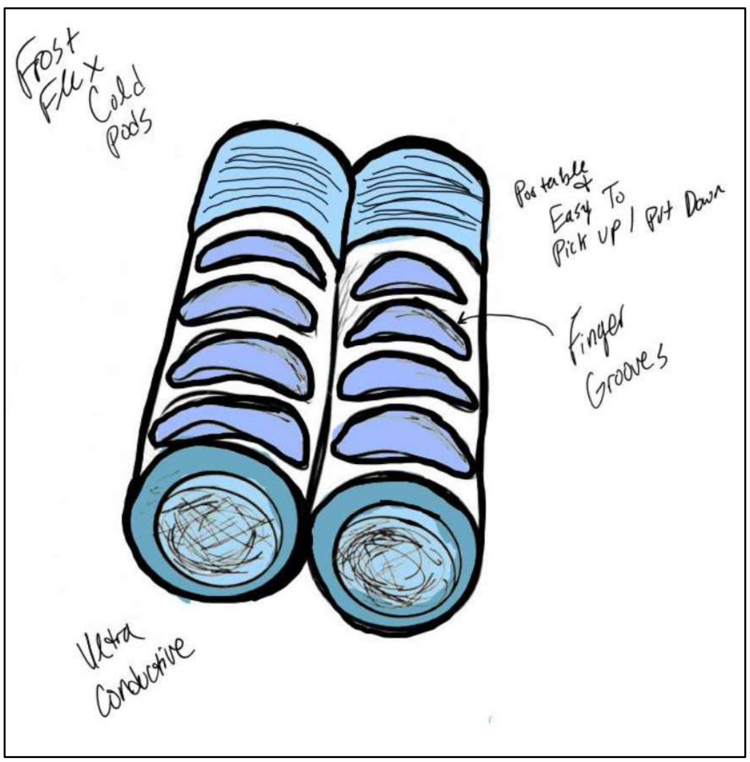

Figure 12: Final Design Sketch – Cold Reservoir

## 4.7 Thermal Simulation & Prototype Build

### 4.7.1 CAD Modeling

To begin our build, we sought to create a 3D model on SOLIDWORKS so that we could determine the necessary components for our build and run thermal analyses on our model. The following images show the 3D model that was created for our design.

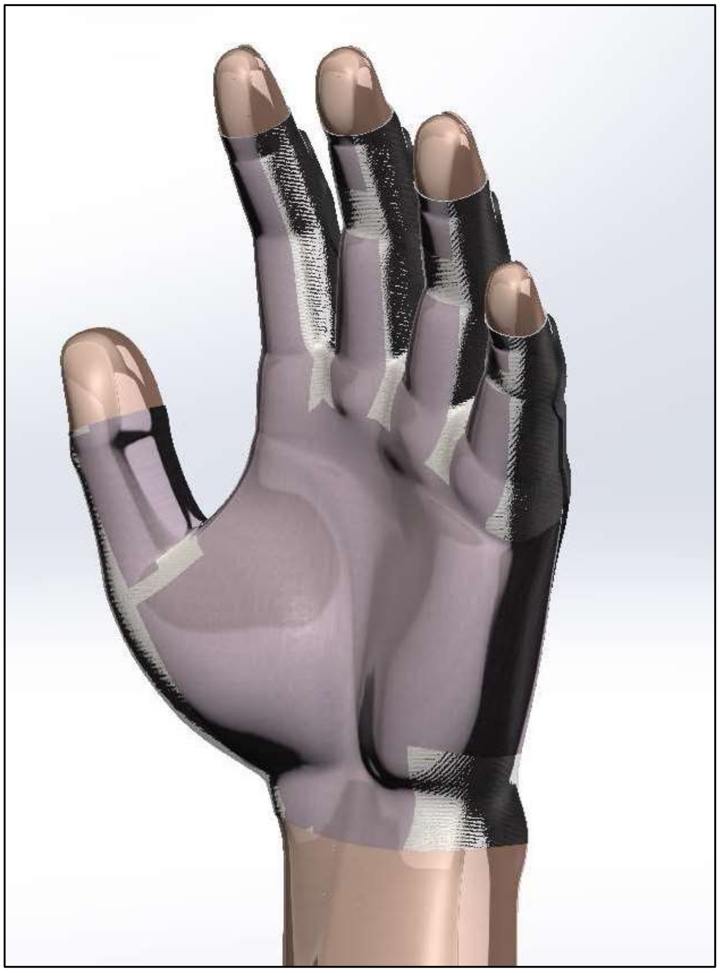

Figure 13: SOLIDWORKS Model

### 4.7.2 SOLIDWORKS Thermal Simulation

At the heart of our design lies the foundational principles of heat transfer through conduction. In order to determine materials that would sufficiently provide adequate heat transfer from a human hand to our cold reservoir, transient thermal simulations were performed through SOLIDWORKS simulation tools and ANSYS Workbench software.

In order to determine the feasibility of using thermal analysis software in our design, we began by performing a preliminary transient thermal analysis using SOLIDWORKS. The set up for the simulation included defining three layers of our human hand model. These layers represent the cold reservoir, the FrostFlex glove, and the human hand. The thickness of skin was set to 1.5

mm. Thicknesses for each layer were used throughout all thermal analyses in this report and were defined as follows.

Table 3: Layer Thicknesses

| | |
|---|---|
| **Cold Reservoir Thickness** | 4.0mm |
| **Glove Thickness** | 2.07mm |
| **Hand thickness (Skin Thickness)** | 1.5mm |

For the SOLIDWORKS analysis, a conductive thermal load of 0°C was applied to the outside of the cold reservoir and a conductive thermal load of 30°C was applied to the human hand layer. Connections between the layered materials were set to conduction, with thermal conductivities of the cold reservoir, glove, and hand as 0.595 $\frac{W}{m\,°C}$, 2.00 $\frac{W}{m\,°C}$, and 0.25 $\frac{W}{m\,°C}$, respectively. The simulation was performed for 180 seconds, the objective cooling time defined in our design. The following figures show the 0°C thermal load being applied to the palm of the model and also the result of the SOLIDWORKS simulation.

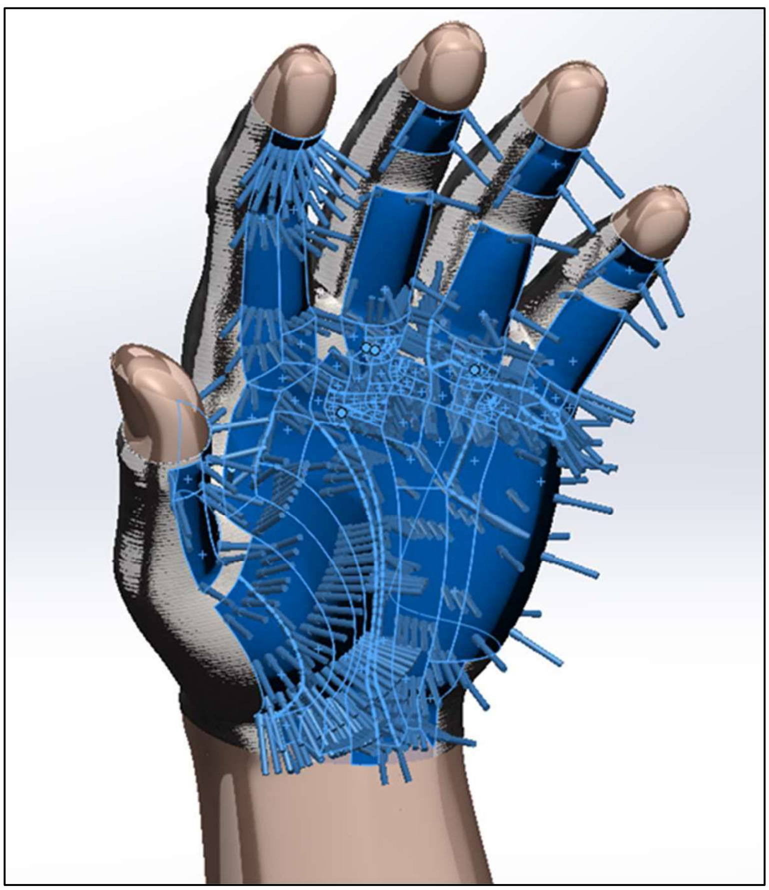

Figure 14: Cold Reservoir Thermal Load

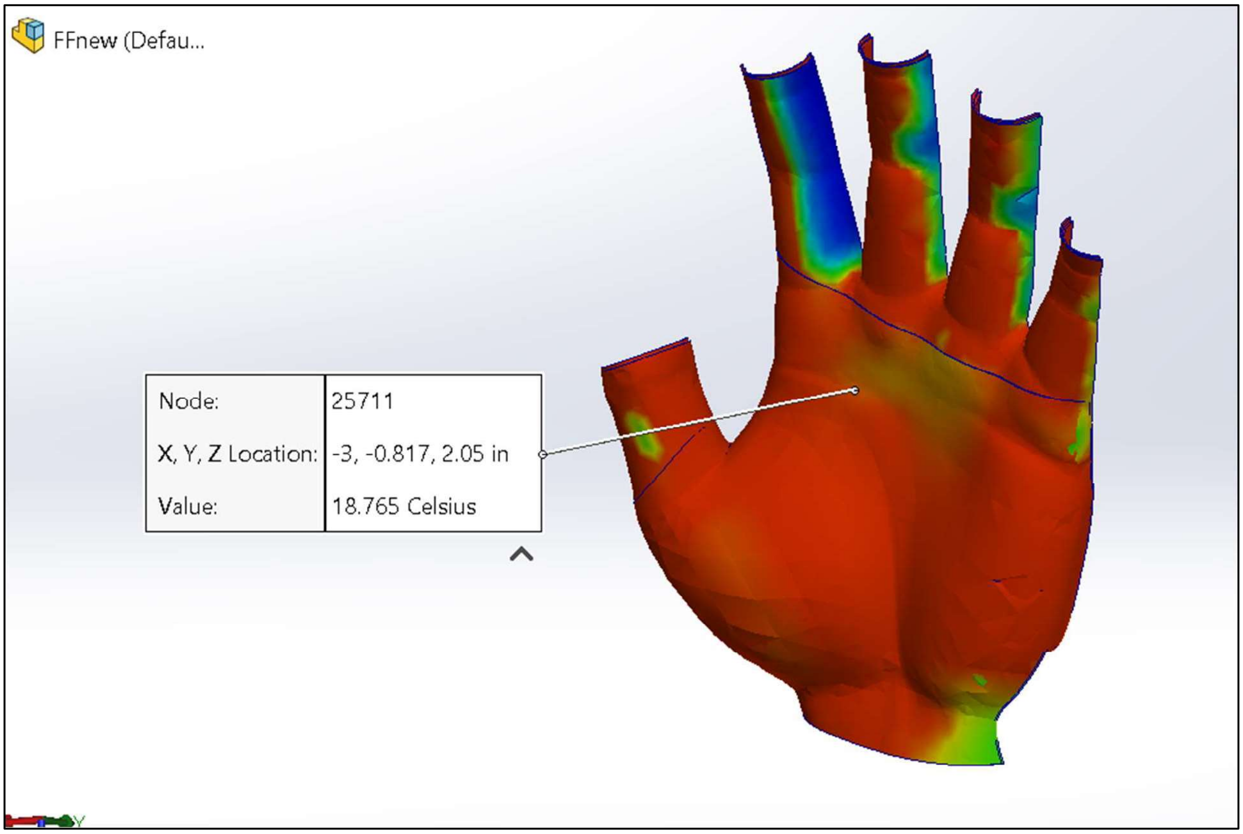


Figure 15: SOLIDWORKS Simulation Result

As evident in Fig. 15, The SOLIDWORKS simulation was able to perform the analysis with the defined parameters. Using the probe tool to find temperatures of the hand surface showed promising results in terms of our thermal analysis. In Fig. 15, the probe tool shows a temperature of 18.765°C. With our goal of achieving hand temperature of 17°C within 180 seconds of cooling, this preliminary simulation was successful and gave our group a baseline in terms of expectations for further studies.

Due to the complex geometry of our CAD model, we continued our study by using ANSYS Workbench for thermal simulations, due to its flexibility in incorporating different parameters and creating efficient customizations that would allow for larger data collection.

### 4.7.3 ANSYS Workbench Thermal Simulation

Repeated simulations were conducted using ANSYS Workbench Transient Thermal simulations. Throughout multiple trials, the hand's material (human skin), initial temperature and thickness remain constant. The defined parameters for design were the following: the glove material and thickness, the conductive material and thickness, and the cold reservoir material, thickness, and initial temperature. The goal of the insulation is to decrease the hand temperature to 17°C in three minutes. The thermal system was assumed to act as a plane wall and was modeled as shown in the following figure.

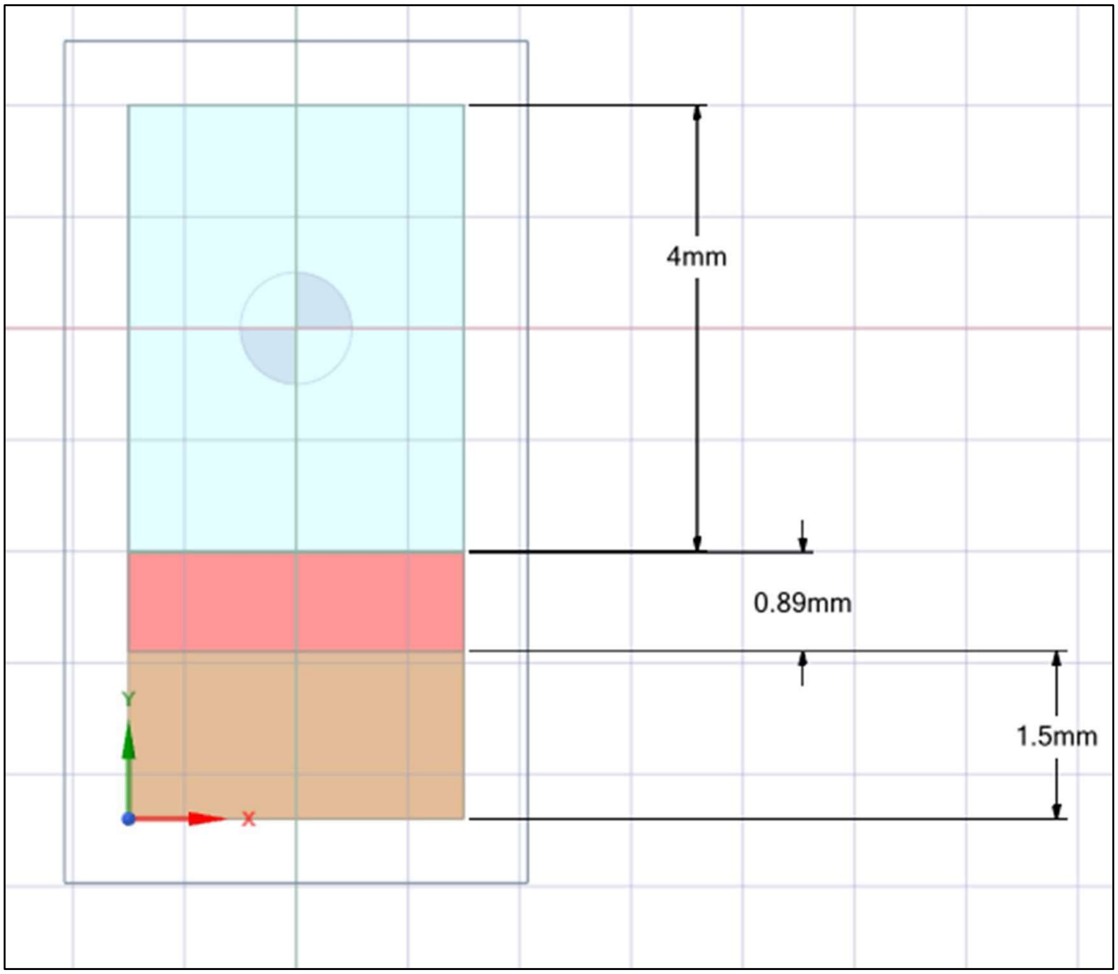

Figure 16: ANSYS Workbench Simulation Setup

The lower-level geometry represents the hand, the middle represents the glove, and the top layer serves as a representation of the cold reservoir. A conductive material was added between the glove and the cold reservoir in the simulation as the material that will be interlaced within the glove to improve thermal efficiency. Materials were assigned to each respective section of the plane wall model. Water was used as the cold reservoir, polyester as the glove material, and various materials were simulated as the conductive material. The thermal properties of the materials used in simulation are listed in the table below. See the following pages for properties of the conductive materials used.

Table 4: ANSYS Simulation Set-Up

| | Hand | Glove (polyester) | Cold Reservoir (water) |
|---|---|---|---|
| **Density (kg/m^3)** | 1230 | 1300 | 1000 |
| **Conductivity (W/ (m*C))** | 0.25 | 0.290 | 0.595 |

The following simulation results were run using transient thermal analysis for 180 seconds. Thickness of the conductive material differs throughout simulations, but the remaining parameters are held constant to ensure repeatibility and validity of the trials.

*Conductive Material: Aluminum, thickness 1.5mm, K = 250 W/m*K*

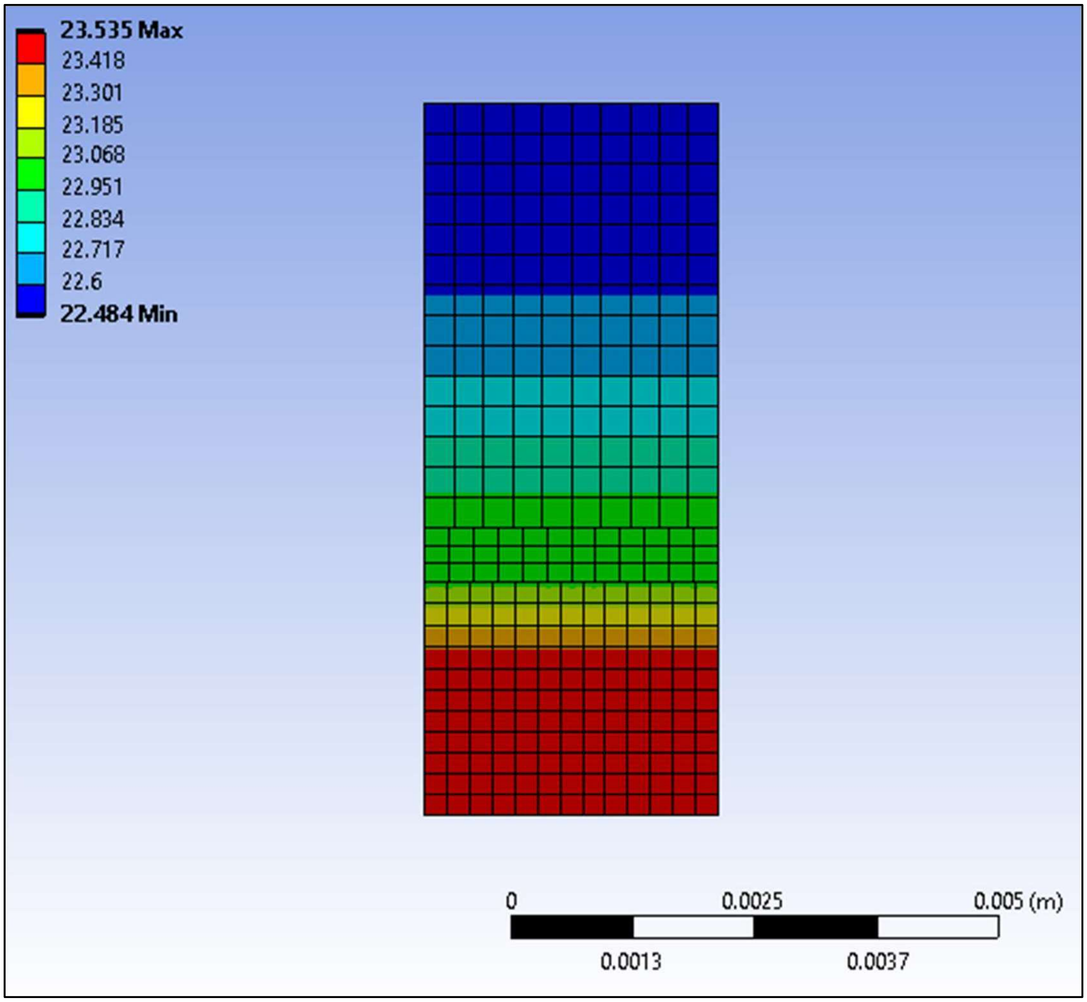


Fig 17: Aluminum ANSYS Simulation

*Conductive Material: Copper, thickness 1.5mm, K = 400 W/m*K*

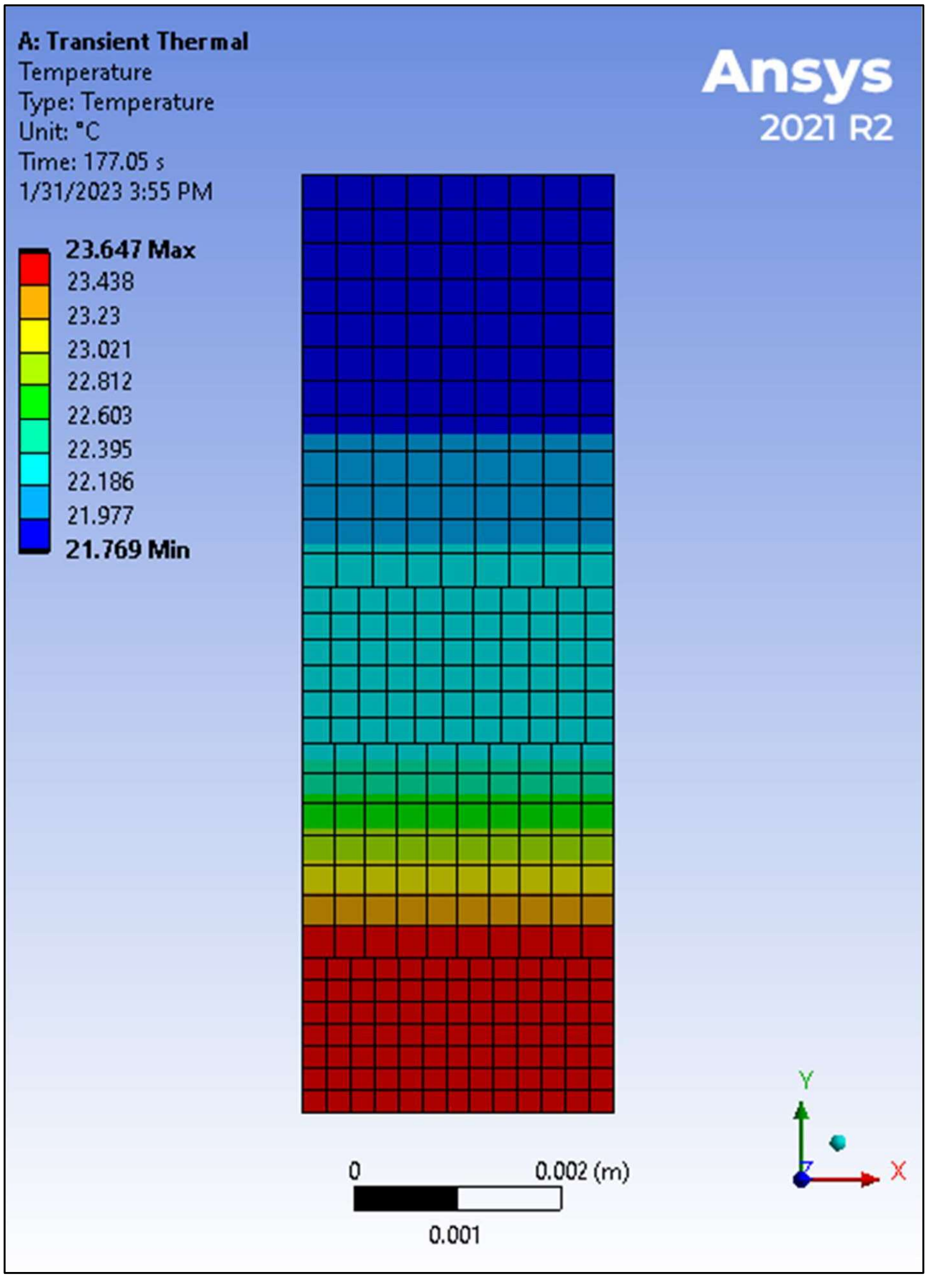


Fig 18: Copper ANSYS Simulation Result

*Conductive Material: Aluminum, thickness 1.5mm, K =250 W/m*K*

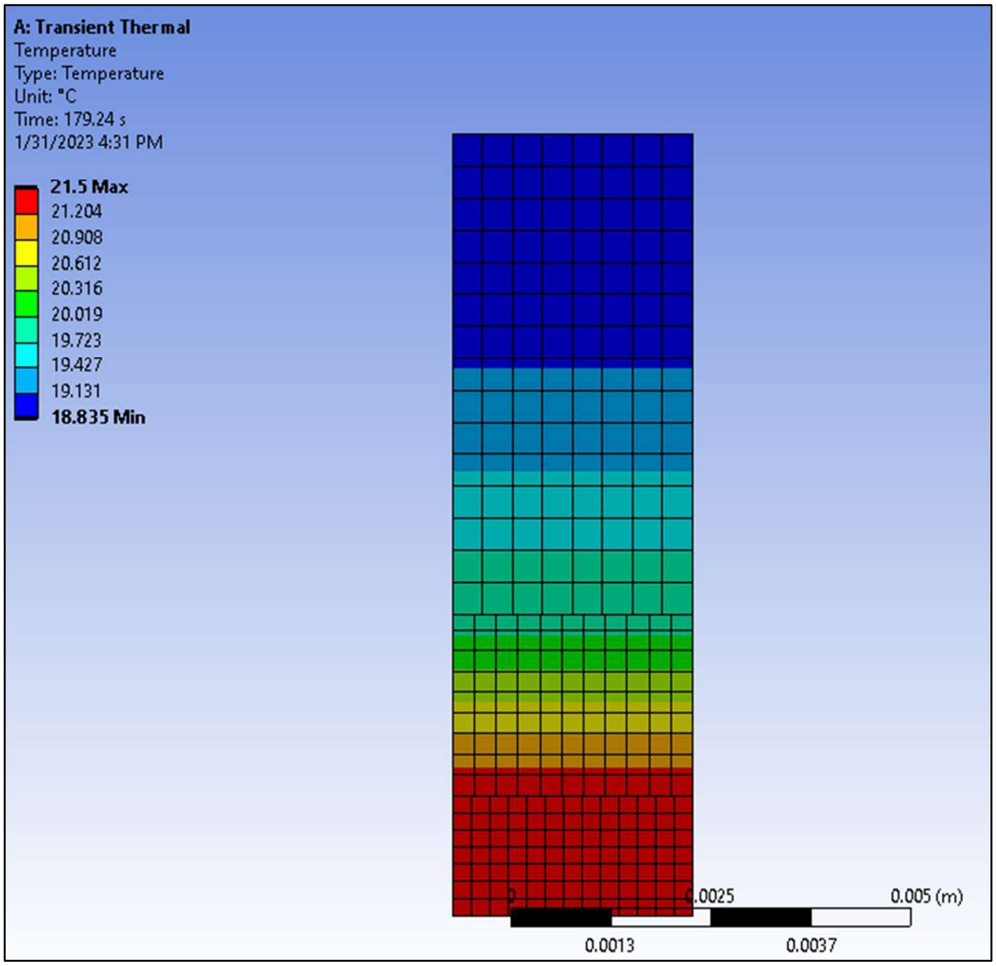

Fig 19: Aluminum ANSYS Simulation Result

As seen in the figures above, the goal of decreasing the human palm temperature to 17°C was not achieved through simulations with the active conductive material as metallic material, and glove material as polyester.

In the following section, the report covers how we were able to improve the results of our thermal simulations by using a different class of materials than metals as our conductive material that was to be built into our glove.

We determined it was necessary to find a material other than polyester to be used as the glove material. The remainder of this report builds on our work using metals and polyester, and explores a new class of materials for the base of our glove.

### 4.7.4 Dyneema Thermal Analysis

Through further research, our team discovered a subset of materials outside of conductive metal composites that was better suited for our design.

Researchers at Purdue University have developed Ultra-high Molecular Weight Polyethylene fabrics, one of them named "Dyneema." [4] These materials exhibit incredible thermal conductivity properties, while maintaining strong mechanical properties, with impressive elastic modulus, abrasion resistance, and flexibility characteristics [4]. Our group began to move forward using Dyneema in thermal analysis, seeing it is as a viable conductive material for our goal of decreasing the skin temperature to 17°C.

ANSYS transient thermal analysis was conducted with Dyneema as the glove material and a glove thickness of 1 millimeter. Dyneema allowed for the palm temperature to be cooled down to 18 degrees Celsius in 3 minutes; The results are shown below.

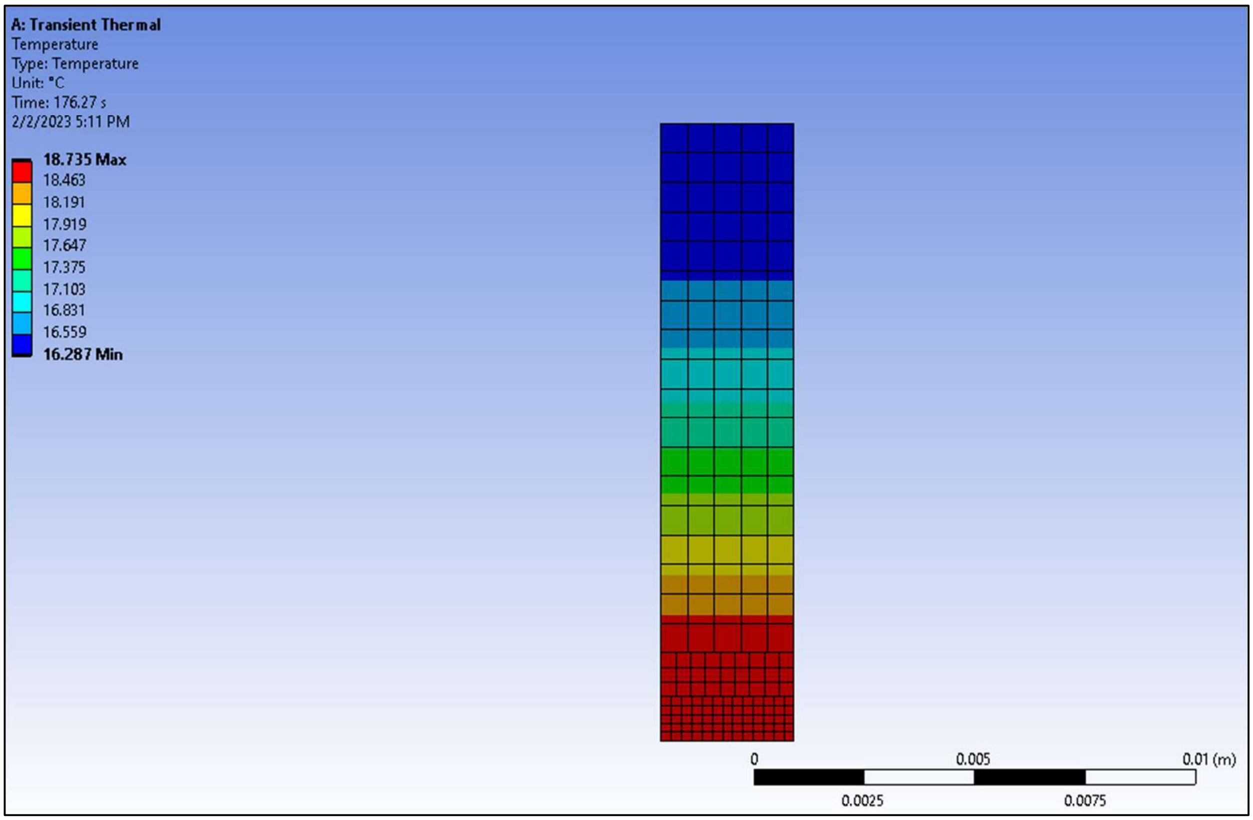

Figure 20: Dyneema ANSYS Simulation Result

### 4.7.5 Material Selection – ANSYS Granta EduPack

To confirm the selection of Dyneema as FrostFlex's thermally conductive material, we sought to use Granta EduPack Material selection software to confirm that Dyneema was a suitable material for our design.

In order to select a material index for our design, we referenced a database for different material indices given design outcomes.

For our design, we selected the index [1] that corresponded with the label in the following figure that states, "Minimum temp rise in specified time; thickness specified." However, our design sought to achieve maximum temperature rise in prescribed time, since this would indicate that the highest rate of controlled heat transfer had occurred in the 180 prescribed seconds. Therefore, we used the reciprocal of the given material index, and sought to find the material that maximized this index.

**Table C.6**

**Thermal and Thermo-Mechanical Design**

| Function and Constraints | Maximize |
|---|---|
| THERMAL INSULATION MATERIALS | |
| Minimum heat flux at steady state; thickness specified | $1/\lambda$ |
| Minimum temp rise in specified time; thickness specified | $1/a = \rho\, C_p/\lambda$ |
| Minimize total energy consumed in thermal cycle (kilns, etc.) | $\sqrt{a}/\lambda = \sqrt{1/\lambda\, \rho\, C_p}$ |

Fig 21: Material Index for Material Selection

**Material Index to Maximize:** $a = \frac{\lambda}{\rho C_p}$

Where $\rho$ is density ($\frac{kg}{m^3}$), $C_p$ is specific heat ($\frac{J}{kg*K}$), $\lambda$ is the thermal conductivity ($\frac{W}{m*K}$), $a$ is the thermal diffusivity ($\frac{m^2}{s}$)

Fig 22: Material Index Summary

As seen in the figure above, the index to be maximized includes the linear relationship between thermal conductivity over density multiplied by specific heat.

This material index was plotted in ANSYS Granta Edu Pack software. The materials compared in the following chart are natural and polymer fabrics. These materials were selected as they were potential candidates to be the thermally conductive material used in our design, due to their ability to be incorporated into the existing framework of a workout glove.

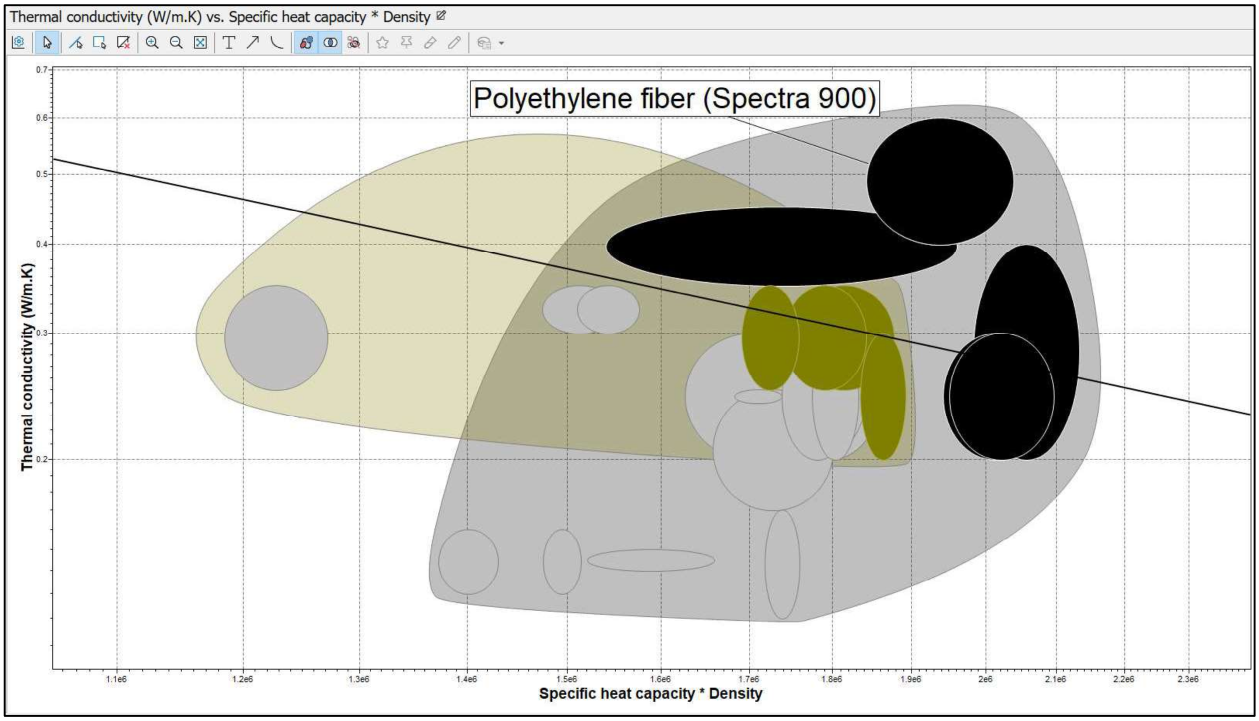

Fig 23: Granta Edu Pack Selection

After plotting the material index, it became clear that Dyneema (also known as Spectra 900) stood as the material that best exhibited the desired thermal properties for our conductive material.

Dyneema fabric was selected for implementation in the first prototype of FrostFlex.

### 4.7.6 Prototype Build

In order to build our prototype, we acquired traditional, polyester lifting gloves and sheets of Dyneema composite material. We then cut out the palms and portions of the fingers on these gloves and attached the Dyneema through various methods of hot fabric adhesives.
FrostFlex Version I can be pictured in the figures below. These were the prototypes used in the testing of our design.

Fig 24: FrostFlex Version I


Fig 25: FrostFlex Version I on User

Fig 26: FrostFlex Version I with Cold Resevoir Applied

The cost breakdrown for one pair of FrostFlex Version I gloves is as follows:

Table 5: Cost Breakdown

| **Item** | **Amount** | **Cost** |
|---|---|---|
| Dyneema composite | 1 sq ft | $6.50 |
| Workout gloves | 1 pair, medium | $15.99 |
| Ice packs | 2 | $8.00 |
| Hot glue gun | 1 | $6.00 |
| | TOTAL: | **$ 46.49** |

It cost approximately $46.50 to manufacture our first prototype.

# 5. Test & Results

## 5.1 Test Procedure

Our testing procedure involved human subjects and the use of heat monitoring devices to determine the cooling effect of our design on participants who are subject to physical exertion. The following outlines our proposed testing procedure:

Subject Inclusion Criteria:

- No known medical problems
- Are you under treatment for any medical problem?
- Not on medication
- Engage in physical exercise for a duration of > 30 minutes minimum 3 times a week for 6 months.
- Males aged to 20-25

Data Gathered from Subject:

- Age
- Height
- Weight

Subjects will participate in the following conditions:

1. HR at 90% Max Heart Rate

Instruments Used: Braun ThermoScan3 and ADC Pulse Oximeter Model 2200

Testing Protocol (Baalke's testing protocol):

a. Initial speed 3.4 mph, grade (0%)
b. Maintain a constant speed throughout entire test.
c. After the initial 2 min, increase grade by 2%
d. Thereafter, every 1 min increase grade by 1%
e. After each increase in grade, a pulse oximeter will measure the subject's HR. Data will be recorded.
f. Once the subject reaches the desired HR, the test will continue at the same speed and grade for 1 minute and will be stopped.
    a. HRmax = 220-age (Karvonen Formula)
g. If a 15% grade has been reached, mph will increase to 4mpH in a minute, and will increase by 0.5 mph every minute until desired HR is reached.
h. Once the test is complete, the subject's temperature will be measured.
i. Temperature will be measured every minute for 15 minutes.
j. The trial will be repeated with the same subject with at least a 72-hour rest period with FrostFlex gloves and cold reservoir applied for 3 minutes post treadmill exercise. Measurements will begin once gloves and cold reservoir are applied.

Product performance will be considered successful if both, or either, of the following metrics for success are achieved:

- Significantly different (p value less than 0.05) difference in body temp between control vs experimental group.

- Proves product works.
- 0.5°C difference between control and experiment group after 3 minutes of cooling.
  - Proves product at same standard as already existing product.

## 5.2 Results

Figure 27, pictured below, contains results showing the average change in temperature directly after the target heart rate was reached in the study.

The red line, labeled "control," shows the average temperature change over the fifteen-minute post workout measurement period. The blue line, labeled "experimental," shows the average temperature change over the fifteen-minute post workout measurement period when the FrostFlex gloves and cold reservoir were applied.

The shaded area shows the three minutes in which FrostFlex gloves and cold reservoir were applied during the induced cooling period within the experimental trials.

It is clear the average measured temperature for the experimental trials decreased at a faster rate than the control. This result was consistent with our expectations, as in the experimental trials, the FrostFlex gloves were applied, and therefore a temperature decrease was initiated due to the increased rate of heat transfer through the hands.

As the fifteen-minute measurement period continued, the average temperature for the experimental trials remained steadily below the control average temperature, except for a brief period at minute five.

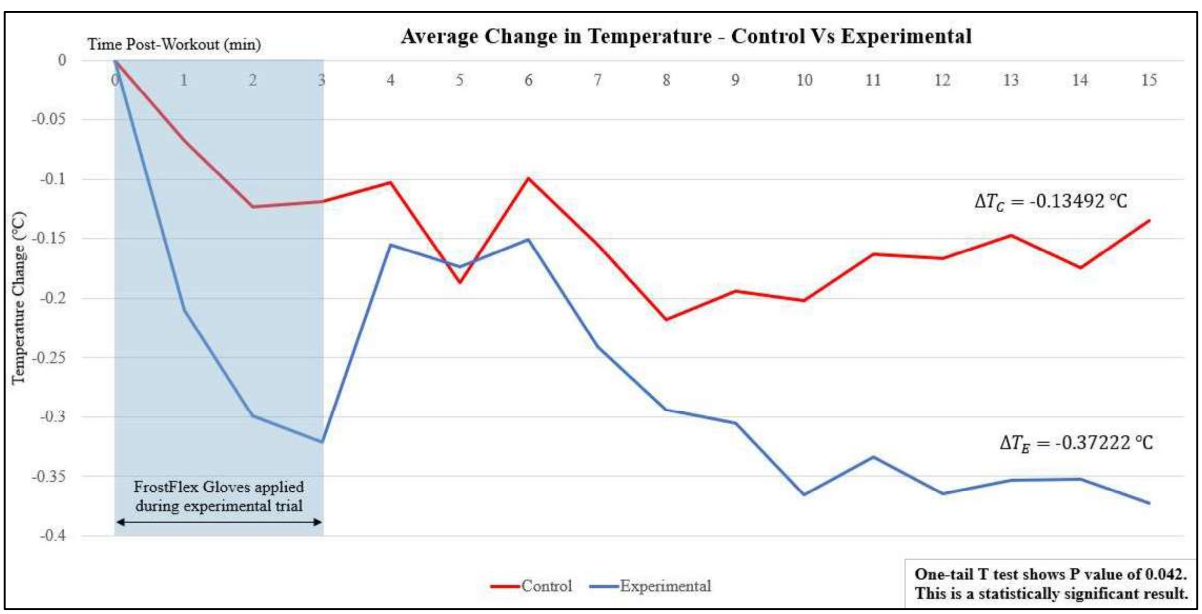


Fig 27: Average Temperature Comparison, Control & Experimental

Across the control trials, the average total temperature change was found to be -0.13492°C, while across the experimental trials, the average total temperature change was -0.37222°C. Though this result may not have achieved our initial goal of decreasing the body temperature by 0.5°C, when compared to the control group, the decrease in average temperature for the experimental group was found to be statistically significant.

A two-sample, one-tailed, paired t-test was set up as the following information describes.

- $\mu_1$: True mean of the control population
- $\mu_2$: True mean of the experimental population
- Null Hypothesis ($H_0$): $\mu_1 \neq \mu_2$
- Alternative Hypothesis ($H_1$): $\mu_1 > \mu_2$

The data was analyzed with Microsoft Excel Data Analysis tool. The results are shown in the following figure.

| | *Control* | *Experimental* |
|---|---|---|
| Mean | -0.134920635 | -0.372222222 |
| Variance | 0.152285986 | 0.088979107 |
| Observations | 14 | 14 |
| Hypothesized Mean Difference | 0 | |
| df | 24 | |
| t Stat | 1.807662778 | |
| P(T<=t) one-tail | 0.041605011 | |
| t Critical one-tail | 1.71088208 | |

Fig 28: Two-sample, one-tailed paired t-test results from Microsoft Excel

Since the P-value was found to be less than 0.5, our results were declared statistically significant.

# 6. Conclusion

## 6.1 Accomplishments

Over the course of the term, our team was successful in implementing the engineering design process to create a new consumer product. From the beginnings of preliminary design and embodiment design, to building a functional prototype and performing testing protocol, our team was able to complete our goals and overcome any setbacks encountered. By combining the foundational concepts of heat transfer with research on the human body and the methods in which it dissipates heat, our cooling glove technology was able to successfully decrease body temperature following strenuous physical activity.

It is important to keep in mind the original purpose and scope of FrostFlex. Throughout our initial research, we found multiple sources which cited increased work output following the lowering of the core body temperature. While there previously has been technology designed with the same goal of FrostFlex, these designs were incorporated into a laboratory setting, and did not consider the concept of creating a universally available product for recreational athletes and sports teams. FrostFlex was designed by keeping the consumer consistently in mind and putting aspects like ease of use, comfort, and cost at the forefront during design considerations.

At the beginning of our process, our team proposed two measures that would indicate FrostFlex was able to successfully decrease body temperature.

These benchmarks were the following:

I) Statistical significance. For a one-tail T-test comparing the change in body temperature between the control and experimental group, the p-value must be less than 0.05.
II) An observed 0.5°C difference between control and experiment group after 3 minutes of cooling.

After reviewing the data collected during our testing, we found that Benchmark I was met, while Benchmark II was not. Though meeting both success measures was the ideal outcome, by accomplishing our goal of statistical significance between the control and experimental trials, we have shown our FrostFlex prototype as being able to decrease the body temperature at an empirically significant rate.

## 6.2 Uncertainties

In continuation of the prior discussion concerning Benchmark II, FrostFlex was unable to meet our goal of decreasing the human body temperature by 0.5°C when compared to the control group. This could be due to a multitude of factors, however, we have determined the following to be the most likely cause of this result:

I) The Dyneema composite used in our prototype was not pure Dyneema, and therefore its heat conductivity may have been less than anticipated.
II) There was potential for human error throughout our measurements of body temperature, due to the thermometer used in testing being human operated.
III) Our sample size may not have been large enough to capture a complete picture of the cooling curves, both control and experimental.

## 6.3 Future Work

In less than a year, Team FrostFlex has taken an idea and transformed it into a fully working preliminary prototype. We completed our first round of testing, but in order to ensure that our product is universally functional and to reinforce our findings, we plan to expand our testing and sample sizes. Our first step would be to expand testing to females in the same age group, 20-25.

This would allow us to compare our findings to a different category of athletes and ensure the functionality of our product for all users.

Because our first prototype was functional, it was not in our scope to develop the second iteration although there are several improvements that could be made. This includes using pure Dyneema instead of the composite, which will allow higher heat conductivity and reduce uncertainties that may arose from the composite. We plan to look into better adhesives for the Dyneema to attach it to the workout glove, and potentially designing our own glove from scratch as well and sewing in the fabric.

During testing, we used a pulse oximeter and digital thermometer. In order to ensure the precision of our data collection, better, more expensive equipment may be in our future plans for continued testing.

## 6.4 Codes & Standards

Codes and standards were to be considered throughout our Senior Design Project.

ASTM D1388-18 is a standard test method for stiffness of fabrics.

The ASTM D1388-18 test method applies to most fabrics such as Dyneema which is the woven fabric used on the FrostFlex Glove. The standard covers measurements of stiffness properties of fabrics and the bending lengths and flexural rigidity of fabrics. When determining the composition of Dyneema, it was important for engineers to enhance mechanical, as well as thermal properties, in order to create a product that fit the needs of the applications it was composed for.

This standard is important to FrostFlex since the structural design and stiffness properties of the components incorporated into the FrostFlex glove can be studied to further improve our test results.

In addition to the ASTM D1388-18 standard, the experiments and prior research cited in this report also adhered to multiple standards in order to determine the thermal properties of fabrics. One important standard in determining the thermal properties of fabrics is ASTM D7984-21. This standard outlines procedure for measuring the thermal effusivity of fabrics, which is a measure of how a material exchanges heat with its immediate surroundings.

The research conducted in the referenced study [4], and the future work of thermal analysis using this standard, is a crucial part of FrostFlex, as thermal and mechanical properties for fabrics, such as Dyneema, is a key component of our design project.

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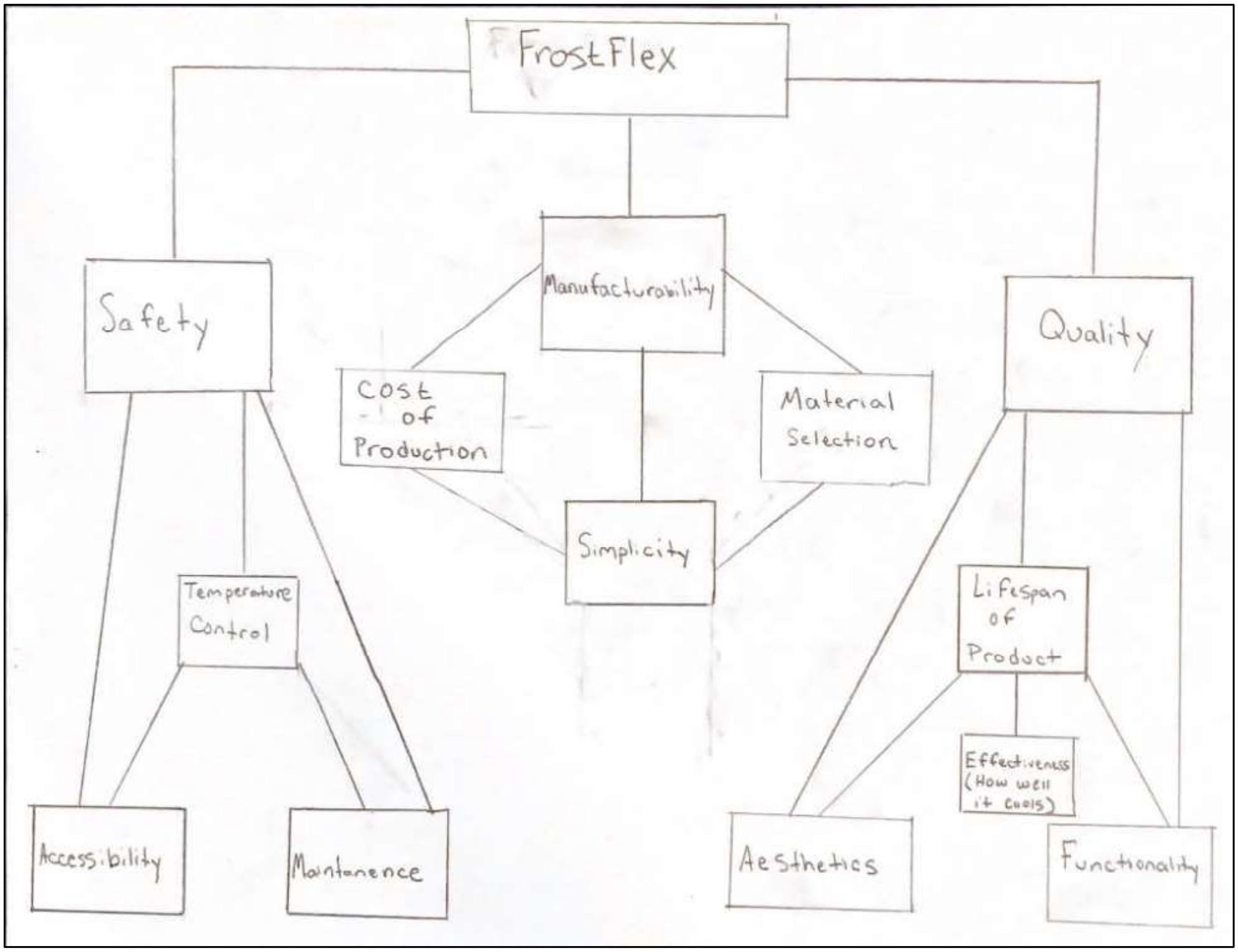
# Appendix

## Appendix A Objective Tree

Original photocopy of objective tree.



## Appendix B Weighted Decision Matrix

The following shows visuals from the Excel file used to develop design criteria and weighted decision matrix.

The labels list the names of preliminary design concepts, and the magnitudes of their scoring in each category is listed below.

| Design Criterion | Weight Factor |
|---|---|
| Effectiveness | 0.435 |
| Ease of Use | 0.175 |
| Cost of Production | 0.3 |
| Lifespan of Product | 0.0375 |
| Aesthetics | 0.0525 |
| | 1 |

| CHILLBOX | | | JUICEBOX | | | LUNCHBOX | | | FROZEN COIL | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Magnitude | Score | Rating | Magnitude | Score | Rating | Magnitude | Score | Rating | Magnitude | Score | Rating |
| Good | 3 | 1.305 | Satisfactory | 2 | 0.87 | Good | 3 | 1.305 | Good | 3 | 1.305 |
| Inadequate | 0 | 0 | Weak | 1 | 0.175 | Good | 3 | 0.525 | Good | 3 | 0.525 |
| Weak | 1 | 0.3 | Good | 3 | 0.9 | Good | 3 | 0.9 | Good | 3 | 0.9 |
| Inadequate | 0 | 0 | Satisfactory | 2 | 0.075 | Good | 3 | 0.1125 | Good | 3 | 0.1125 |
| Inadequate | 0 | 0 | Good | 3 | 0.1575 | Satisfactory | 2 | 0.105 | Satisfactory | 2 | 0.105 |
| | | 1.605 | | | 2.1775 | | | 2.9475 | | | 2.9475 |

| EXOSKELETON | | | FROSTFLEX TAPE | | | CONVECTION 2 | | |
|---|---|---|---|---|---|---|---|---|
| Magnitude | Score | Rating | Magnitude | Score | Rating | Magnitude | Score | Rating |
| Satisfactory | 2 | 0.87 | Satisfactory | 2 | 0.87 | Satisfactory | 2 | 0.87 |
| Satisfactory | 2 | 0.35 | Good | 3 | 0.525 | Good | 3 | 0.525 |
| Good | 3 | 0.9 | Weak | 1 | 0.3 | Weak | 1 | 0.3 |
| Satisfactory | 2 | 0.075 | Inadequate | 0 | 0 | Good | 3 | 0.1125 |
| Good | 3 | 0.1575 | Good | 3 | 0.1575 | Good | 3 | 0.1575 |
| | | 2.3525 | | | 1.8525 | | | 1.965 |

| Definition | |
|---|---|
| Effectiveness | FrostFlex will reduce your core temperature by 0.5 degrees C in under 3 minutes while keeping palm temperature above 15 degrees Celcius |
| Ease of Use | Easy operation (1-button), able to work out and complete other tasks with product still on |
| Cost of Production | FrostFlex has a goal of under $200 for proof of concept |
| Lifespan of Product | FrostFlex must be a reusable product that can be used for at least 100 workouts before failure |
| Aesthetics | FrostFlex can have many different looks and styles. Customization is an option-For easy marketablility, FrostFlex appears to be a typical everyday gym item. |

# Appendix C MATLAB Code

```
% FROSTFLEX
% 1.31.2023
% Thermal Resistance

clc,clear;
disp(' ')                                                    % page break
disp("Welcome to FrostFlex's Temperature Generator!");       % title
disp(' ');                                                   % page break
prompt = "     K value of first material:    ";              % input of Ka value
prompt
Ka = input(prompt);
prompt_1 = "     K value of second material:   ";           % input of Kb value
prompt
Kb = input(prompt_1);
prompt_2 = "     Thickness of material:        ";           % input of L value
prompt
L = input (prompt_2);
Tcr = FrostFlex(Ka,Kb,L);                                    % using function to
generate Tcr value based off of previous 3 inputs
disp(' ');                                                   % page break
fprintf('The temperature of the cold reservoir should be %.2f deg C',Tcr);  % display of final
answer, deg C
disp(' ');                                                   % page break

function [Tcr] = FrostFlex(Ka,Kb,L)                          % function defined by
3 inputs, Ka, Kb, and L ; to calculate temperature of cold reservoir, Tcr
TH=30;                                                       % temperature of hot
reservoir, deg C
Q=200;                                                       % heat transfer,
W/m^2
Aa=L^2;                                                      % cross-sectional
area of material A, m^2
Ab=L^2;                                                      % cross-sectional
area of material B, m^2
Ra=L/(Ka*Aa);                                                % resistance of
material A
Rb=L/(Kb*Ab);                                                % resistance of
material B
RTH=Ra+Rb;                                                   % total thermal
resistance
Tcr=(TH-(Q*RTH));                                            % calculation of Tcr,
deg C
end
```

## Appendix D Raw Data

Control Group

| | Body Temperature (Degrees Fahrenheit) | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Subject | 0 min | 1 min | 2 min | 3 min | 4 min | 5 min | 6 min | 7 min | 8 min | 9 min | 10 min | 11 min | 12 min | 13 min | 14 min | 15 min |
| 1 | 99.2 | 98.3 | 98.7 | 98.7 | 98.6 | 97.7 | 97.9 | 98.1 | 98.2 | 98.2 | 98.2 | 98.2 | 98.1 | 98.1 | 98.0 | 97.9 |
| 2 | 98.4 | 98.4 | 98.5 | 98.6 | 98.7 | 98.6 | 98.6 | 98.7 | 98.6 | 98.6 | 98.7 | 98.7 | 98.8 | 98.7 | 98.6 | 98.6 |
| 3 | 98.5 | 98.4 | 98.2 | 97.3 | 98.2 | 97.9 | 97.8 | 96.8 | 96.9 | 96.6 | 96.2 | 97.0 | 97.7 | 98.0 | 97.8 | 97.8 |
| 4 | 98.4 | 98.3 | 98.2 | 98.0 | 97.9 | 97.9 | 98.1 | 98.1 | 97.9 | 98.0 | 98.1 | 98.2 | 98.0 | 98.0 | 98.1 | 97.8 |
| 5 | 99.3 | 99.3 | 98.0 | 99.0 | 98.9 | 98.7 | 98.8 | 98.8 | 98.7 | 98.6 | 98.5 | 98.5 | 98.4 | 98.5 | 98.4 | 98.5 |
| 6 | 99.4 | 99.4 | 99.3 | 99.3 | 99.1 | 98.9 | 99.1 | 98.9 | 98.7 | 98.5 | 98.7 | 98.8 | 98.9 | 99.0 | 99.2 | 98.9 |
| 7 | 98.1 | 98.1 | 98.3 | 98.3 | 98.3 | 98.4 | 98.5 | 98.5 | 98.6 | 98.5 | 98.4 | 98.5 | 98.4 | 98.4 | 98.2 | 98.3 |
| 8 | 98.4 | 98.3 | 98.2 | 98.3 | 98.4 | 98.4 | 98.3 | 98.3 | 98.3 | 98.3 | 98.4 | 98.4 | 98.4 | 98.4 | 98.4 | 98.3 |
| 9 | 97.6 | 97.8 | 98.0 | 98.1 | 98.2 | 98.1 | 98.2 | 98.2 | 98.1 | 98.1 | 98.1 | 98.1 | 98.0 | 98.0 | 98.0 | 98.1 |
| 10 | 99.4 | 98.5 | 98.3 | 98.1 | 98.3 | 98.1 | 98.5 | 98.5 | 98.5 | 98.6 | 98.4 | 98.4 | 98.4 | 98.3 | 98.3 | 98.3 |
| 11 | 98.3 | 98.1 | 98.3 | 98.1 | 98.0 | 97.9 | 97.9 | 97.9 | 97.9 | 98.0 | 97.9 | 97.9 | 97.8 | 98.0 | 97.8 | 97.8 |
| 12 | 99.9 | 99.6 | 99.4 | 99.5 | 99.3 | 99.1 | 99.2 | 99.4 | 99.4 | 99.4 | 99.2 | 99.3 | 99.0 | 99.4 | 99.2 | 99.2 |
| 13 | 99.6 | 100.1 | 99.3 | 99.2 | 99.3 | 99.2 | 100.5 | 99.5 | 98.6 | 99.8 | 99.6 | 99.6 | 99.6 | 99.5 | 99.4 | 99.4 |
| 14 | 98.4 | 98.4 | 99.1 | 99.1 | 98.7 | 98.5 | 98.5 | 99.1 | 98.5 | 98.4 | 98.8 | 98.6 | 98.4 | 98.4 | 98.4 | 98.5 |

Experimental Group

| | Body Temperature (Degrees Fahrenheit) | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Subject | 0 min | 1 min | 2 min | 3 min | 4 min | 5 min | 6 min | 7 min | 8 min | 9 min | 10 min | 11 min | 12 min | 13 min | 14 min | 15 min |
| 5 | 98.7 | 98.5 | 98.5 | 98.5 | 98.5 | 99.4 | 99.4 | 99.3 | 99.2 | 99.1 | 99.1 | 99.3 | 98.5 | 98.7 | 98.6 | 98.6 |
| 1 | 98.3 | 98.3 | 98.2 | 98.3 | 98.5 | 98.7 | 98.5 | 98.5 | 98.1 | 98.1 | 97.8 | 97.8 | 97.8 | 97.9 | 97.8 | 97.9 |
| 4 | 98 | 97.9 | 97.5 | 97.4 | 97.1 | 98 | 97.8 | 97.8 | 97.9 | 98.1 | 98.2 | 98.1 | 98.1 | 98.1 | 98 | 98 |
| 2 | 99.5 | 98.6 | 98.1 | 98.7 | 99.5 | 99.3 | 99.3 | 98.7 | 98.9 | 98.8 | 98.7 | 98.8 | 98.7 | 98.6 | 98.6 | 98.5 |
| 3 | 99.3 | 98.5 | 98.6 | 98.3 | 98.4 | 98 | 98.8 | 97.6 | 97.5 | 97.6 | 96.4 | 97 | 97.2 | 98 | 97.3 | 97.7 |
| 6 | 98.6 | 98.6 | 99.0 | 98.6 | 98.6 | 98.4 | 98.6 | 98.4 | 98.6 | 98.6 | 98.6 | 98.6 | 98.4 | 98.6 | 98.4 | 98.4 |
| 7 | 99.2 | 98.3 | 98.2 | 98.2 | 98.1 | 98 | 97.9 | 97.7 | 97.9 | 97.6 | 98 | 98.1 | 98.1 | 97.9 | 98.6 | 97.8 |
| 8 | 98.8 | 98.5 | 98.4 | 98.5 | 98.9 | 98.9 | 98.8 | 98.5 | 98.6 | 98.6 | 98.5 | 98.5 | 98.3 | 98.4 | 98.4 | 98.3 |
| 9 | 98.5 | 98.5 | 97.5 | 97.5 | 97.5 | 97.7 | 97.7 | 98 | 97.8 | 97.5 | 97.5 | 97.8 | 97.9 | 97.3 | 97.3 | 97.3 |
| 11 | 100 | 99.2 | 99 | 99.2 | 99.9 | 99 | 99 | 99.2 | 98.7 | 98.9 | 98.7 | 98.6 | 98.4 | 98.4 | 98.5 | 98.6 |
| 14 | 98.9 | 98.4 | 98.4 | 98.3 | 99.0 | 98.7 | 98.8 | 98.6 | 98.5 | 98.5 | 98.4 | 98.4 | 98.3 | 98.3 | 98.3 | 98.5 |
| 12 | 98.8 | 98.5 | 98.3 | 98.3 | 98.6 | 98.5 | 98.2 | 98.3 | 98.3 | 98.2 | 98.3 | 98.3 | 98.3 | 98.3 | 98.3 | 98.3 |
| 13 | 98.7 | 98.3 | 98.4 | 98.2 | 99.0 | 98.4 | 99.1 | 99.0 | 98.3 | 98.4 | 98.4 | 98.3 | 98.4 | 98.3 | 98.4 | 98.4 |
| 10 | 98.4 | 98.3 | 98.1 | 97.6 | 98.2 | 98.3 | 98.0 | 98.0 | 98.0 | 98.0 | 97.9 | 97.7 | 98.1 | 98.0 | 98.3 | 98.0 |