Duocel® Metal Foam Display Cases

Final Design Review (FDR)

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Executive Summary

This Final Design Review (FDR) report outlines the senior design project that was conducted by a team of four mechanical engineering students at California Polytechnic State University-San Luis Obispo for ERG Materials and Aerospace Corporation. The goal of this project was to design displays that showcase the properties of ERG's Duocel® foam at tradeshows and client meetings. To better understand the needs of our sponsor, the team researched Duocel®'s capabilities, related technologies, and relevant standards and regulations. With this information, we further defined the problem by creating a problem statement and a set of engineering specifications through a Quality Function Deployment (QFD) process. The first step we took in tackling our design challenge was to determine which properties of the Duocel® foam would be suitable for table-top displays and be most beneficial to our sponsor. It was found that the thermal and fluid flow properties of the foam were most important to our sponsor. Though a series of ideation and idea refinement processes the team designed a Flow Control Display and a Thermal Conductivity Display. The Flow Control Display demonstrates the varying flow resistance of different porosity Duocel® foams using a manual air-pump system. The Thermal Conductivity Display is comprised of heating and cooling elements that demonstrate the heat dissipation ability of Duocel® foam. To verify the feasibility of our designs, we built concept prototypes. With sponsor approval, the team moved forward with the Flow Control Display and redesign the Thermal Conductivity Display. The team created detailed designs for both displays, complete with engineering drawings and wiring diagrams. Additionally, manufacturing plans, testing procedures, and structural prototypes were developed for each design. Confirmation prototypes were manufactured based on the final designs on staggered timelines. First, the Flow Control Display was assembled and tested. The test results revealed that this display did not function as intended. The team proceeded to troubleshoot the display and determined that the functionality issues were a result of insufficient velocity of air flow. Next, the Thermal Conductivity Display was manufactured and calibrated. Once it was satisfactorily assembled, the display was tested and met all the engineering specifications identified at the beginning of the project. This document contains the research, ideation processes, design decisions, design outcomes, manufacturing processes, test results, and project management associated with this senior project.

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1. Introduction

ERG Materials and Aerospace Corporation, a company specializing in the manufacturing of a proprietary metal foam, has been struggling to reach new clients using passive displays at tradeshows and would like our team to design displays that showcase the metal foam's capabilities.

Our team, Team Tetrakai, is comprised of four Mechanical Engineering students at California Polytechnic State University. The team includes Syed Hasan, Ben Swanson, Kate Goldsworthy, and Katherina Prodanov. Each of us came on board excited for the project's challenges, its room for creativity, and the ability to work with ERG Material's metal foam and its various properties. Our goal was to find a solution to this problem by designing a series of up to three displays that showcase properties or applications of Duocel® foam in an interactive, educational, and intuitive way.

The following document will lay out the background of the problem, objectives, and project management. The background will explain what we already know about the project and the company/product based on our technical research and sponsor interviews. The objectives section is an outline of the design specifications and design constraints that need to be met to successfully complete the project. The Concept Designs section describes the ideation process, design decisions, and chosen displays. The project management section describes the project plan, timeline of deliverables, and expected schedule moving forward; this section is broken down into more specific tasks in our Gantt Chart in Appendix A. This document serves as a Final Design Review for the project sponsor, ERG Materials and Aerospace Corporation.

After the submission of the Scope of Work, the team updated the Background and Objectives sections based on feedback from the project sponsor and advisor. Section 2.2 (Related Technology) now includes additional information on useful patents. Section 3.2 (Engineering Specifications) features a more thorough explanation of the Quality House of Function and an updated set of specifications.

After the submission of the Preliminary Design Review, the team moved forward with two designs—the Flow Control Display and the Thermal Conductivity Display. The Electrical Conductivity Display was eliminated based on sponsor feedback. Due to this major change, section 4.2.3 (Electrical Conductivity Design) of this report was moved to Appendix I.

The Critical Design Report included three new sections—Final Design, Manufacturing Plan, and Design Verification Plan. The Final Design section outlined the full detailed design, justification of design decisions, safety, and maintenance. The Manufacturing Plan section outlined the expected procurement, manufacturing, and assembly of each display. The Design Verification Plan section described how the team planned to test the designs to check if specifications were met. Additionally, the Project Management section was updated to reflect the project timeline.

This Final Design Report includes major changes to the Final Design, Manufacturing, Testing, Project Management, and Conclusion Sections. The Final Design section has been updated to reflect design changes made during the confirmation prototype manufacturing. The Manufacturing and Testing sections have been updated to include the results of the confirmation prototype, as well as lessons learned during this process. The Project Management section reflects the final project timeline and includes a reflection on what worked and did not work during this project. Finally, the conclusion section has been expanded to explain all project outcomes, lessons learned, and recommendations for the displays going forward.

2. Background

There is a niche market for metal foam, so most people do not know what it is or what it can be used for. In order to showcase its various applications, we researched what people would potentially find interesting about the product and how we could relate it to already existing technology. Since the displays must be carried in a commercial flight, TSA regulations were examined as well. To have a complete understanding of the background, our team researched the customer's needs, related technology, and any applicable codes/standards.

2.1 Customer Needs

ERG Aerospace Corporation has been manufacturing their Duocel® metal foams since 1967; these foams can be made with a variety of materials and have many different applications [1]. Their early customer base was largely military until the mid-1990's when they made their product available to the public and expanded their potential consumer base. A great way to meet new customers is to attend expos and tradeshows while showcasing their product and its applications. ERG believes that their current displays can be improved.

Figure 1. ERG Materials & Aerospace Corporation display in use at a tradeshow.

Currently, ERG's display uses a combination of mostly passive and limited active/hands-on experiences to showcase their product. Their primary hands-on display is various aluminum blocks that showcase their product's relative densities. Another hands-on display that ERG uses is a "baffle tube" that demonstrates their product's ability to keep mass distribution under control. They also use flashcards with a picture of the individual passive displays that can be seen on the table in Figure 1. These flashcards discuss how the product is used in the real world. Unfortunately, these displays still leave a lot of potential customers wondering what the metal foam can do and can require a lot of explaining by those working the display booth.

Our team's preliminary meeting with ERG Materials & Aerospace was useful to gather this information and other problems that are faced with their current methods. Despite the various displays and the explanation available via the flashcards, their representatives at the display continue to face the question: "What does this do?" They made it clear that they want a display that can speak for itself and showcase an application for the foam. ERG mentioned that they were thinking we could do three individual displays with each one showcasing a different application. Later in the design process, we would bring our ideas and ERG's ideas together and then choose the ones we would all like to work on. ERG would like the displays to be portable, intuitive, memorable, and able to showcase their metal foam's capabilities.

2.2 Related Technology

Since the project deals with the display and understanding of the metal foam rather than the engineering behind it, the focus of our technical research was on the different uses of the foam we intend to demonstrate. Non–technical research was also done on the marketing and understanding of engineering products

Metal foam has a wide range of properties and can be used in many applications. One challenge we faced was figuring out which applications were most common and easiest to understand. The journal article *"Commercial Applications of Metal Foams: Their Properties and Production"* [2] from the scientific journal *Materials* explains the structural and functional applications of metal foams. The article states "the most remarkable mechanical properties of foams are their lightweight, the relative strength in compression, the bending stiffness, and the energy absorption". It also says that metal foams are "known for their thermal insulation properties, especially ceramic, glass and polymeric foams".

To demonstrate the energy absorption properties, we investigated a paper on an experiment conducted at Senman University [3]. The paper outlines the results of an experiment analyzing the metal foam's high performance in dispersing energy while being lightweight.

Another display will show the thermal capabilities of the metal foam. To do this, it is helpful to understand the use of the metal foam as a heat exchanger and to model its effectiveness. *"A synthesis of fluid and thermal transport models for metal foam heat exchangers"* [4] explains the factors that affect the performance of the foam as a heat exchanger, which will be helpful when building the display.

As we design our product, it will be important to keep similar existing products in mind. Not only should our product accomplish our customer needs better than existing alternatives, but these alternatives can be used as inspiration. If an existing design meets one or more customer needs very well, we can emulate its positive aspects. One existing product is ERG's crush display currently used at tradeshows. While this display is very intuitive, it is not interactive or eye-catching. Their density comparison display has the opposite strengths; it is interactive, but not necessarily intuitive. Similarly, the metal foam applications display is eye-catching and interesting, but not intuitive nor interactive. Ultimately, we would like to combine the best aspects of each of these displays.

Figure 2. Yaskawa trade show display with moving parts and bright colors.

There are also existing products not currently being used by ERG. For example, there is another company called Foam Core that displays a similar product using detailed design photos. While this display is eye-catching, it is not intuitive or interactive. On the other hand, a company called Yaskawa displays their product using working robots that are eye-catching and intuitive but not interactive as shown in Figure 2.

In addition to considering similar products, we will be drawing inspiration from patented technology. Table 1 shows five patents and their associated patent numbers. Each of these patents is correlated to a possible display design. Should the design warrant it, these products could be incorporated into the final prototype rather than manufacturing a similar device ourselves.

Table 1. Existing patents that relate to heat transfer, flame arrester, or circuit display designs.

Patent Name	US Patent Number	Description
Active thermoelectric pad with thermal sensor [6]	US20180101203A1	A pad that detects thermal changes and outputs analysis. Similar technology could be used for a thermal display.
Shape memory polymer material-based fire trigger alarm device [7]	CN 106846702 A	Material that is set off by specific temperatures and used to trigger an alarm.
Transparent thermal insulating system [8]	US 3953110 A	Transparent insulation that can be used in a thermal display to prevent the outside of the display from reaching dangerous temperatures.
Flame Arrester Apparatus [9]	US 5415233 A	A small version of a flame arrester that could be adapted to display flame arresting capabilities of metal foam.
Electronic toy and teaching aid safety device [10]	US 7144255 B2	Safe battery holder that limits current made for quick-connect assemblies.

The first three patents listed in Table 1 will be considered as part of a heat transfer display. The “active thermoelectric pad with thermal sensor” [6] and “shape memory polymer material-based fire trigger alarm device” [7] are two possible devices to detect thermal changes within the foam. These changes could then be displayed to the viewer to explain the foam’s ability to dissipate heat effectively.

Another display design is a small flame arrester that shows Duocel’s® ability to dissipate heat quickly. The “transparent thermal insulating system” [8] could be used to insulate a flame arrester system to keep viewers safe from the excessive heat. The “flame arrester apparatus” [9] is a good reference in the design of a small flame arrester that can be displayed at a trade show.

Finally, the “electronic toy and teaching aid safety device” [10] is a device that would be implemented or emulated in a circuit-completion design. This device would prevent too much current from being supplied to the foam connection point for the safety of the user.

2.3 Applicable Codes and Standards

As the displays must be suitable for travel on a commercial flight, they must comply with the Transportation Security Administration (TSA) standards and regulations. TSA regulations are extensive and as such are not fully detailed in this document. A full, detailed list of the regulations can be found on the Department of Homeland Security’s TSA website [5]. Table 2 below shows a partial list of the restricted potential heating or energy storage elements.

Table 2. A partial list of restricted items per TSA regulations.

Item / Material	Permitted in Carry-on Baggage?	Permitted in Checked Baggage?
Arc Lighters	No	No
Plasma Lighters	No	No
Electronic Lighters	No	No
Butane	No	No
Disposable/Zippo Lighters	Yes	Yes*
Fuels	No	No
Fire-Extinguishers	No	No
Lithium Batteries <100 W-hrs.	Yes	Yes*
Lithium Batteries <100 W-hrs.	Yes*	No
Non-spilling Wet Batteries	Yes*	Yes
Power Banks	Yes	No
Propane	No	No

* Item/material has special instructions associated with it. See TSA website for details [5]

Table 2 covers a variety of materials that we thought would be useful for us to know regarding their TSA status. Included are various fuels and power sources that could be used in our displays. This table determined a few items that we likely cannot consider and gave early consideration for design decisions.

It is also important to note that all checked baggage must measure no more than 62 linear inches (sum of length, width, and height) and weigh no more than 50 pounds. Almost all codes and standards expected to be followed at a tradeshow setting overlap with regulations required by TSA. Additional guidelines outline minimum safety distances for moving machinery and handling of high voltage electrical equipment. These guidelines do not apply to our displays.

3. Objectives

In the objectives section the problem is fully defined by a problem statement, a boundary sketch, and design specifications that correspond to the sponsor's needs. This section gives a foundation to the problem we are facing and outlines the criteria that need to be met in order to properly solve the problem.

3.1 Problem Definition

ERG Materials and Aerospace Corporation, a company specializing in the manufacturing of a proprietary metal foam, has been struggling to reach new clients using passive displays at tradeshows. They need a better way to reach new clients by showcasing the capabilities of their foam using interactive and intuitive displays. Because they need to travel to meet clients, our design must fit in a suitcase and comply with TSA regulations.

To better define the problem, a pictorial representation of the project scope, known as a "boundary sketch", was created. The boundary sketch can be seen in figure 3 below. It shows the anticipated operating environment of our design, which includes the people and objects the design may interface with. The elements encompassed by dashed lines are the portions of the environment that our team has control over, i.e. the portions which fall into our scope of work. The elements outside of the dashed lines, on the other hand, influence our design decisions but are not part of the scope of the project.

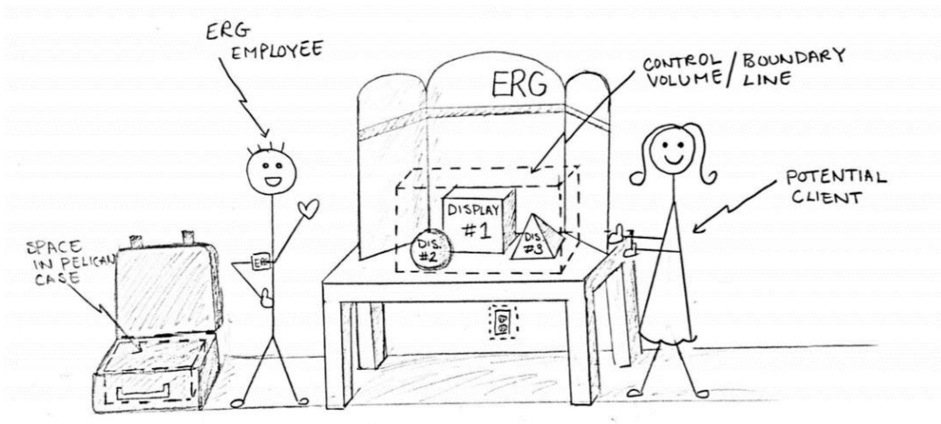

Figure 3. Boundary sketch of Duocel® metal foam displays.

As can be seen in Figure 3, the focus of the project will be to create one to three table-top displays. The display will interface with the table, ERG's existing trade show displays, potential power sources, ERG employees, and potential clients. They will also be stored in a pelican case and transported as checked baggage on commercial flights.

Based on discussions with our sponsor, we compiled a list of our sponsor's needs/wants shown below:

- Features Duocel® metal foam
- Showcases Duocel®'s properties
- Includes an interactive user interface
- Intuitive
- Eye-catching
- Holds user's attention
- Able to be taken on a flight
- Portable
- Easy to assemble
- Safe for users and operators
- Reusable/repeatable
- Durable
- Cost-effective

3.2 Engineering Specifications

To ensure that we are solving the correct problem and that all the necessary design specifications are met, we performed a Quality Function Deployment (QFD) process. The QFD chart seen in Appendix B considers our sponsor's wants and needs and provides measurable design specifications while considering the various people interacting with the design and other display styles. From this analysis, we paired customer needs with corresponding specifications—for example, the need for portability would correspond with weight, size, and durability specifications.

The QFD allowed us to compare the customer requirements and the specifications required to meet them. This comparison shows strong correlations for requirements such as “weight” and “portability”. One requirement that did not necessarily need to be quantified is the ability to take it on a flight. That can be considered a design specification that must be met for each display. Another particularly important specification that we got out of this was our user test for determining if a display was eye-catching. This test is important as we cannot measure or build to a certain strength ourselves but must test and reiterate for as the project goes on.

Table 3 below gives the project specifications drafted from the customer needs list and QFD analysis. Each specification has a target value, as well as a tolerance ad risk associated with this value. These specifications are also assigned at least one compliance method—Test (T), Analysis (A), Inspection (I), or Similarity to an existing design (S)—which will be used to determine whether each target is met.

Table 3. Project specification, testing, and risk information

#	Specification Description	Target	Tolerance	Compliance	Risk
1	Weight	50 lbs.	max	I	L
2	Time for Assembly	20 mins	max	T	L
3	Dimensions	62 in linear	max	I	L
4	Reset time	10 min	max	T	M
5	Cost	$4,000	max	A	M
6	Users report eye-catching	60% agree	min	T, A	L
7	User understanding	60% pass	min	T, A	H
8	Users interact easily	70% w/o assistance	min	T, A, S	L
9	Reaction time	5 secs	max	T, A, I	M

In Table 3, the “Risk” column represents the importance of the specification on a scale of Low Risk (L), Medium Risk (M), or High Risk (H). Low-risk specifications have targets that will be very simple to meet. High-risk specifications have targets that will be more challenging to meet; the team must design specifically with high-risk specifications in mind. Our highest-risk specification was “User understanding”. This specification is critical for our project because the displays are useless if they are not understood by the audience. It will be difficult to meet this specification because different people will have different background knowledge. To meet this specification, designs will use simple visuals and properties that can be easily understood.

Due to the nature of our project, many of the design specifications are user opinions and therefore difficult to measure. These specifications will be evaluated using product tests in which users interact with the prototype and then answer a survey about their experience. A complete list of testing notes is given below.

- **Weight:** This weight limit is imposed by TSA guidelines. The total weight of the displays and carrying case will be measured using a scale and must stay below 50lbs.

- **Time for Assembly:** In order to ensure setup of displays can be completed in a reasonable time, we have chosen a 20-minute max time for assembly. This includes everything from unpacking the case to using the displays. We will measure this using a stopwatch to time un-practiced users while they set up the displays.
- **Dimensions:** The displays must fit into the carrying case, which shall have dimensions of less than 62 linear inches (calculated as the sum of length, width, and height). This will be measured with a measuring tape.
- **Reset Time:** The time for the display(s) to be reset and able to be used again shall not exceed 10 minutes. This will be measured by timing an un-practiced user resetting the display.
- **Cost:** The total cost of this project shall not exceed the project budget of $4,000.
- **Eye-Catching:** Our user tests will also include a survey comparing the aesthetic of our displays versus the older displays; our displays should be considered more eye-catching by at least 60% of users.
- **Users Report Understanding:** For our displays to be effective, at least 60% of users should understand what the displays are trying to convey on a basic level. We will conduct a questionnaire during our user testing to assess the number of users who comprehend the basic principles presented (such as heat transfer, flow distribution, etc.).
- **Users interact easily:** Our displays should not require an ERG employee to explain how to interact with them. Greater than 70% of users during user testing shall be able to interact with the displays without any verbal or written instructions besides what is part of the display itself.
- **Reaction time:** To hold user attention, the displays shall have a reaction (defined as a noticeable change in the system) within 5 seconds. The reaction times of the displays will be measured using a stopwatch.

These testing procedures will be further defined as the display designs take shape. When considering design specifications, there is a list of constraints that the team must meet to consider the project acceptable. Our constraints are as follows:

- Includes Metal Foam
- Displays Up to Three Different Uses
- Must Meet TSA Requirements
- Is Safe, Cannot Harm Users
- Fits in a Pelican Case

For the designs to be considered successful, every constraint specification listed above must be met.

4. Concept Design

The purpose of this section is to describe the preliminary designs chosen by the project team. First, it describes the ideation process and initial concepts. Then, it explains the criteria and reasoning behind design decisions. Finally, it describes the three chosen displays in detail. This includes an explanation of components selected using Pugh Matrices, physical and computer-aided models, hazard analysis, and potential design issues for each display.

4.1 Display Type Selection

The team brainstormed design concepts through a series of ideation sessions both individually and as a team. The two main ideation methods the team used were sketching under a time limit and classic group brainstorming on a whiteboard. Sketching under a time limit allowed individuals to fully explore their own ideas while classic brainstorming allowed the team to build on those ideas together. Initially, ideation focused on big-picture concepts such as properties and applications of the foam that could be displayed. From there, the team developed several ideas of how to display those properties and applications. Finally, these ideas took shape as detailed concept designs. Sketches generated during the ideation sessions, a complete list of design ideas, and concept model photos are included in Appendix C.

The concepts listed in Appendix C were narrowed down using feedback from the project sponsor about the feasibility of each design and importance of the properties being displayed. For example, the team created several concept designs to demonstrate the acoustic properties of the foam, but the designs were eliminated because the sponsors were not interested in displaying this property. The team considered seven top concept designs.

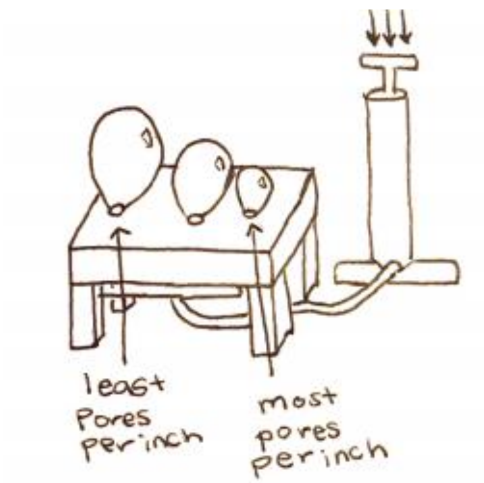

Figure 4. Flow Control Display with a user-operated air pump.

The first top concept the team considered is the Flow Control Display shown in Figure 4. This display features a series of balloons connected to a user-operated air pump. Each balloon’s air supply has a piece of metal foam of different pore size impeding the flow. As the user supplies air to the system, the balloons inflate at different rates as the flow is distributed based on pore size. This display is useful in visualizing the fluid flow control properties of the metal foam.

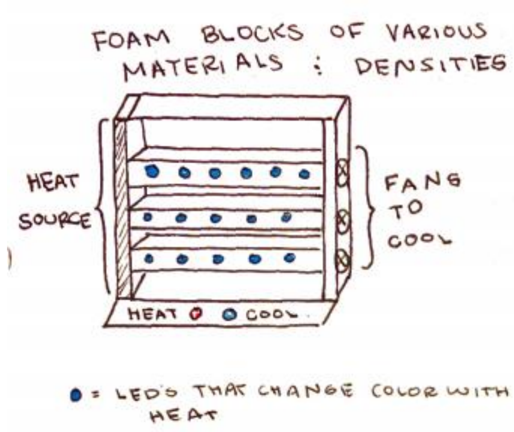

Figure 5. Thermal Conductivity Display concept sketch with LED indicators.

The second top concept the team considered is the Thermal Conductivity Display shown in Figure 5. This display includes a set of metal foam blocks of different materials and densities. Each block has a heat source on one side and a cooling mechanism on the other. Two buttons allow the user to choose whether to heat or cool the foam. LED indicator lights along the foam blocks indicate the relative temperature at that location. This display would be useful in showing each metal foam's ability to dissipate heat efficiently.

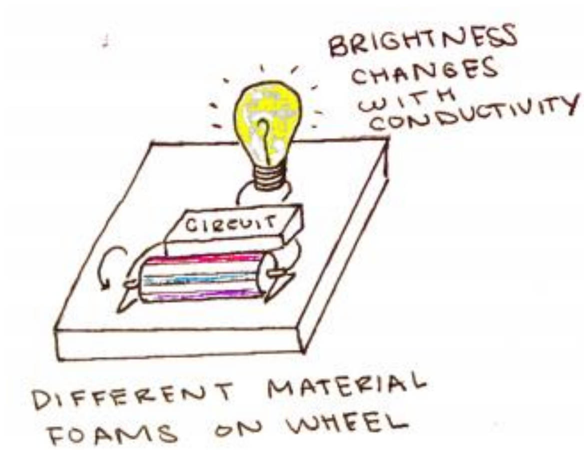

Figure 6. Electrical Conductivity Display with rotating wheel.

The third top concept the team considered is the Electrical Conductivity Display shown in Figure 6. This display features a set of foam blocks of various materials on a rotating wheel. As the wheel is rotated by the user, a different foam completes the circuit at predetermined connection points. The circuit lights up a light bulb—or series of lightbulbs—differently depending on the level of conduction across the foam. This display would be useful in showing that some materials conduct better than expected (e.g. carbon) and some materials conduct worse than expected (e.g. aluminum).

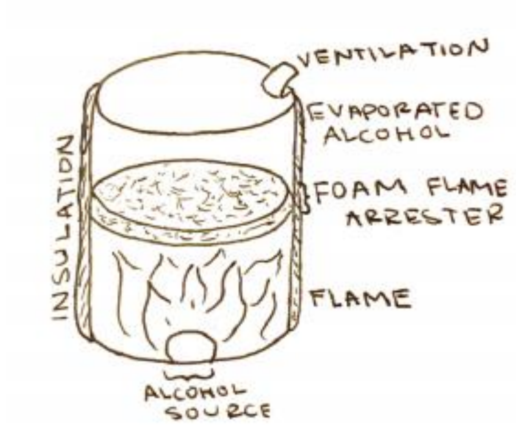

Figure 7. Flame Arrester Display with alcohol-based flammable gas.

The fourth top concept the team considered is the Flame Arrester Display shown in Figure 7. The team consulted with Dr. Richard Emberley—a Fire Protection Engineer and Cal Poly Professor—on the details of this design to ensure feasibility and safety. This display features a clear tank with a source of alcohol supplied to the system. The alcohol evaporates, creating a flammable gas within the tank. Alcohol was chosen for this purpose because other flammable gases would not be allowed through TSA. The gas in the lower region of the tank is ignited with an electric spark, creating a flame. The metal foam flame arrester dissipates heat so quickly that the flame is not spread to the gas in the upper chamber. The combustion products are expelled through the top ventilation. This display shows off the heat transfer properties of the foam and is extremely eye-catching but user safety is a concern.

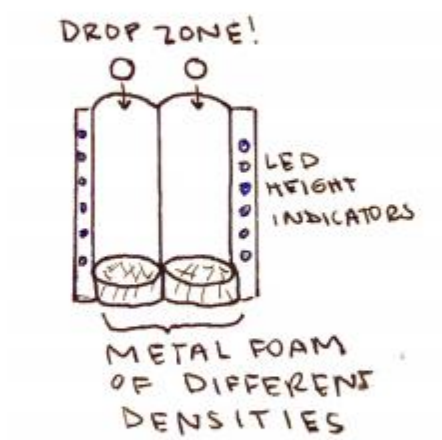

Figure 8. Energy Absorption Display with interchangeable foam for comparison.

The fifth top concept the team considered was the Ball Drop Energy Absorption Display shown in Figure 8. In this design, users drop ping pong balls onto disks of metal foam and observe the difference in bounce height. Balls dropped onto foam of different densities and materials will react differently based on the ability to absorb energy. The bounce height is indicated by motion-sensor-triggered LEDs along the wall of the display. This design would display an important property but would be destructive over time and need regular metal foam changes.

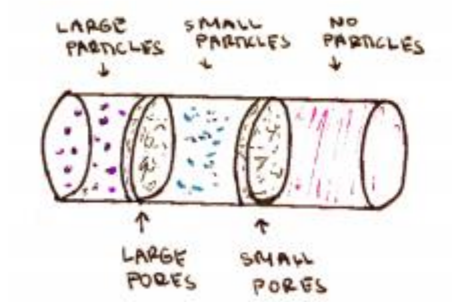

Figure 9. Particle Filter Display with three chambers.

The sixth top concept that the team considered was the Particle Filter Display shown in Figure 9. This display features three chambers separated by metal foam. One disk of foam has large pores, while the other has small pores. Particles of two sizes and colored water fill the system such that when flipped upside down, the top chamber holds the large particles, the middle chamber holds the small particles, and the bottom chamber holds water only. This display would show off the foam's ability to separate materials of different sizes and allow fluid to flow through.

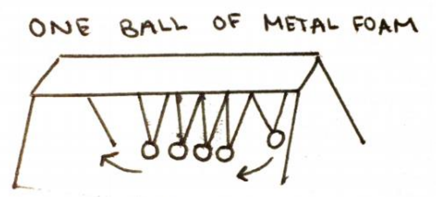

Figure 10. Newton's Cradle Display with several pendulums.

The seventh top concept the team considered was the Newton's Cradle Display shown in Figure 10. This display features a series of pendulums fixed so that when one pendulum is set in motion the energy is transferred through to the other side. This design features one pendulum that could be switched between solid aluminum and aluminum foam. When aluminum foam is used the energy is absorbed and the motion dies out quickly.

Once a list of the top designs was established, the team built the concept models pictured in Appendix C to better understand the functionality and aesthetic of each design. During this process, the team decided that some designs were far more eye-catching than others. Additionally, the team realized there were some components of the Flame Arrester Display that had not been fully considered (such as ventilation requirements).

After completing concept models, the team received additional feedback from the sponsor indicating they want at least one heat transfer display and one fluid flow display. The third display could show any property of the team's choosing. The team created a decision matrix split into three categories (heat transfer, fluid flow, and other) and chose the design that scored highest in each category. Some of the most important criteria the team considered are whether the design is eye-catching, attention-holding, educational, useable at a trade shown, and appropriate for the time and skill expected for a project of this magnitude.

The complete design decision matrix is shown in Appendix D. The Thermal Conductivity Display with LED indicator lights was the clear choice for the heat transfer category. It scored well on every criterion except for reaction time but still meets the minimum requirement for the reaction time specification. The Flow Control Display was selected for the fluid flow category because it had the highest total score for this category by a wide margin. The "other" category—which included energy absorption and miscellaneous designs—was the only category without one clear winner. The decision matrix for this category is shown in Table 4.

Table 4. Decision matrix for energy absorption and miscellaneous options.

		ENERGY ABSORPTION						MISCELLANEOUS			
		Bounce Test		Push Back		Newton's Cradle		EMI Shielding		Electrical Conductivity	
CRITERIA	WEIGHTING	*Score*	*Total*	*Score*	*Total*	*Score*	*Total*	*Score*	*Total*	*Score*	*Total*
Dimensions	2	2	4	2	4	5	10	5	10	3	6
Reaction Time	2	5	10	4	8	5	10	5	10	5	10
Eye-catching	4	3	12	3	12	2	8	1	4	4	16
Cost	3	3	9	3	9	5	15	5	15	3	9
Holds Attention	5	3	15	4	20	3	15	2	10	4	20
Interactive	4	4	16	5	20	2	8	1	4	5	20
Intuitive	3	4	12	4	12	4	12	2	6	4	12
Educational	5	4	20	4	20	5	25	4	20	5	25
Manufacturability	4	4	16	3	12	5	20	5	20	4	16
Portable	2	2	4	2	4	5	10	5	10	4	8
TSA eligibility	3	5	15	3	9	5	15	5	15	4	12
Repeatable	3	5	15	5	15	5	15	5	15	5	15
Usable at a tradeshow	4	5	20	3	12	5	20	2	8	5	20
Time/skill-appropriate	5	4	20	3	15	2	10	1	5	3	15
	TOTAL SCORE:	188		172		193		152		204	

The two highest-scoring designs from this category are the Electrical Conductivity Display and the Newton's Cradle Display. Both designs meet the minimum requirements of our design specifications and scored highly in most categories. However, the Electrical Conductivity Display scored higher in the categories with the highest weight such as "eye-catching" and "holds attention" and thus a slightly higher overall score. Additionally, the Electrical Conductivity Display is far more time and skill appropriate because it would require both mechanical and mechatronic components; the Newton's Cradle design was deemed too simple for a project of this magnitude. Ultimately, the Electrical Conductivity Display was chosen as the third and final design.

4.2 Display Design

The purpose of this subsection is to describe each of the three chosen displays in detail. First, it will discuss the functions and components of the display. Then, it will present physical and computer-aided models that the team completed to verify the function and aesthetics of the displays. Finally, it will address potential hazards and problems that must be considered going forward.

4.2.1 Flow Control Display

Duocel® metal foam can be used to control fluid flow by providing flow control. The foam's porosity can be chosen in order to adjust the flow. The Flow Control Display demonstrates Duocel®'s flow resistance capabilities by comparing the various options in porosity and density that can be used to control flow.

This display features a set of up to five balloons, each contained in an acrylic case, and attached to a metal or plastic nozzle leading to a pump. The balloons will be set up in a line using a wooden stand with air tubes hidden underneath. Each balloon's air supply will have a piece of metal foam impeding the flow, where different porosities cause different flow resistances.

Air pressure will be supplied using a foot or bike pump that is operated by the customer. The air pressure will be divided equally between the balloons so that the balloon with the lowest flow resistance (corresponding to the lowest pores-per-inch) will inflate first. Once it expands to the size of its acrylic case, the balloon with the next lowest flow resistance will begin to inflate. This process will repeat until all balloons are fully inflated. A release valve will be used to deflate the balloons as needed.

This display is both interactive and eye-catching. The customer will be drawn in either by the bright balloons or the interactive pump. This display is highly repeatable as balloons can be replaced when needed. The response time will be small because the balloon with the least flow resistance will begin to inflate immediately.

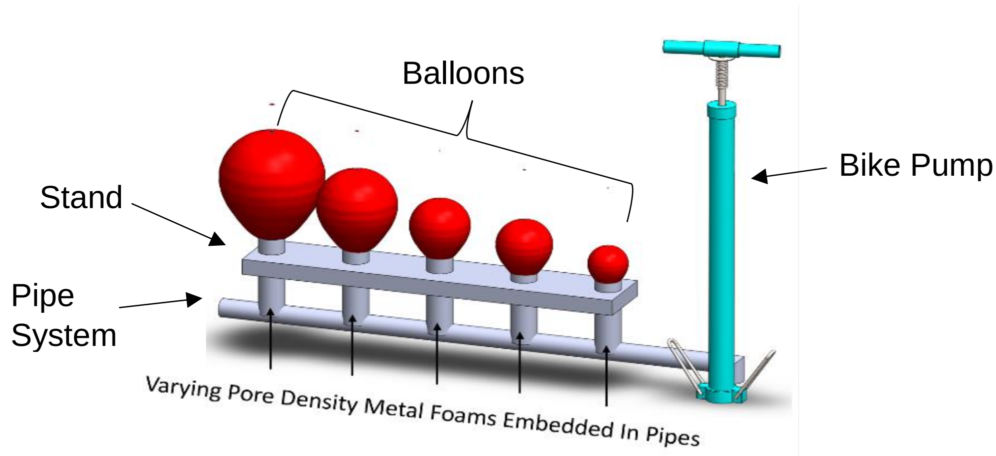

Figure 11. Preliminary CAD model for the Flow Control Display

Figure 11 shows a preliminary CAD model the Flow Control Display. The design will order the balloons from lowest flow resistance to highest flow resistance (or vice versa). Simple charts and information cards will accompany the display for customers who want additional information.

As the balloons fill up, the customer will be able to observe that foams with the low pores-per-inch (PPI) offer some resistance but much less than the higher PPI foams. The foams embedded in the tubing will also be displayed in front of each balloon, as seen in Figure 12.

Figure 12. Functional prototype of the Flow Control display.

For our Preliminary Design Report, the team constructed a functional prototype of this display that demonstrates the behavior and set-up of two foams that differ in pore size. The resistance of the higher PPI foam was simulated by manipulating the tube to create a flow resistance on one side. The balloon with the least resistance (displayed with the 10 PPI foam sample on the right) filled while the flow-resistive 40 PPI balloon (left) did not. The team plans to include charts like the one seen in Figure 12 to our display in order to appeal to a more technical audience. These charts give a pressure drop per length of metal foam for a given flow rate; They can be found on ERG's website as well as Appendix E and serve to corroborate the feasibility of the design concept.

The design was broken down into three sub-functions; air supply mechanism, metal foam placement, and display method. The team created a Pugh matrix for each to evaluate and optimize features and derive multiple potential design solutions. The Pugh matrix shown in Table 5 indicates methods by which the display can convey the differences in airflow to the customer. Each method is evaluated using sponsor requirements as well as ease of implementation/compatibility. Results from the matrix show the balloon display having the highest score; the streamers a close second.

Table 5. Pugh matrix showing results for our method of displaying airflow.

SUB-FUNCTION:	Display Airflow				
CRITERIA	*Datum* **Airflow meter**	*Option 1* **Balloons**	*Option 2* **Streamers**	*Option 3* **Pitot Tube**	*Option 4* **Floating Ball**
Readability	s	-	-	s	-
Eye-catching	s	+	+	-	+
Portability	s	+	+	s	+
Compatibility	s	+	-	-	-
Cost	s	+	+	s	+
Repeatability	s	+	+	+	-
TOTALS	**0**	**4**	**2**	**1**	**3**

Other subfunctions were evaluated similarly. For the air supply mechanism, the bike pump had the highest score but both hand pump and foot pump had competitive scores. The team chose to go with a bike pump. As for the metal foam placement, we considered interchangeable methods for the metal foam, but the matrix strongly favored the option to display multiple different foams at once. The full Pugh matrices for other subfunctions can be found in Appendix F.

This display is appropriate for a trade show setting because it displays how various foams resist fluid flow, an important application of the metal foam. Inflation of the balloons is a great way to catch people's attention. Because the user is the one supplying the air, the display is both interactive and hold's users' attention. The row of balloons allows the customer to clearly visualize the differing airflows as well as offer a side-by-side comparison between different metal foams, furthering the customer's understanding of the effect of the PPI and/or densities. The proposed display does not require any materials that are restricted by TSA guidelines, but it will be important to build it as compact and portable as possible.

There are two key challenges with this display. One is supplying an equal amount of air pressure to each of the tubes leading to the balloons. Splitting up the single line from the pump into multiple lines with equal pressure will be a challenge during the build.

There are three main hazards associated with this display; projectiles/stored energy, display falling hazards, and noise levels. The balloons will be pressurized and could become a projectile if not attached properly. Since our design calls for an acrylic case covering each balloon, the balloon should be unable to harm the customer. Secondly, to stop the display from slipping off the table, rubber pads will be added to the base. The last hazard is the possibility of noise over 90 decibels if the balloon pops. Fortunately, the acrylic cases that the team will use will restrict the balloon to a volume below its limit. Additionally, if the balloon does pop the case will muffle the sound such that it does not harm the customers' ears. A full list of the hazards considered can be seen in the Hazards Check List presented in Appendix G.

4.2.2 Thermal Conductivity Display

Duocel® metal foam is often used in heat transfer applications because its high porosity allows efficient convective cooling. The Thermal Conductivity Display demonstrates Duocel®'s heat transfer capabilities as well as highlights the difference in thermal efficiencies between materials and densities.

This display features five bars, each made of a different material or density, in an acrylic case. On one end of the bars is a set of heat sources and on the other is a set of fans. A single heating plate or fan is not used for all the bars to avoid any variation in heating of the plate itself or the proximity of the bars to the fan. The individual plates and fans can be activated ensuring all bars get the same initial heat at the same time.

At the push of a button, the heat sources are activated. As the bars heat up, a series of LEDs along each bar will indicate when the temperature at that location crosses a threshold. The LEDs will highlight the varying rates at which the heat transfers through the bar.

Once the bars are heated, heat dissipation properties can also be shown. At the push of another button, fans on the opposite end of the bars will activate and cool them down. Again, the customer can visualize the cooling capabilities with the help of LEDs. A computer-aided model of this design is shown in Figure 13.

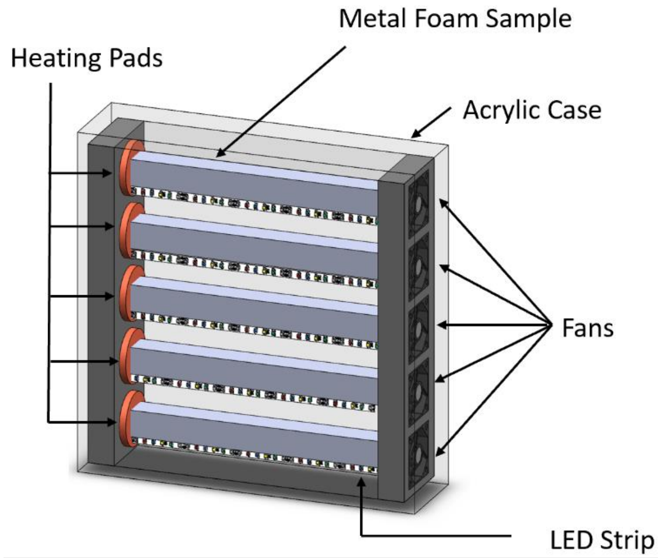

Figure 13. Preliminary CAD model Thermal Conductivity Display

Additionally, the team constructed a concept prototype of this design to demonstrate the components and aesthetic of the display as shown in Figure 14.

Figure 14. Concept prototype showing placement of bars and LEDs

The design was broken down into three sub-functions; heat source, detection method, and display method. The team created a Pugh matrix for each to evaluate and optimize features and derive multiple potential design solutions. The Pugh matrix for the heat display is shown in Table 6.

Table 6. Pugh matrix showing results for heat display subfunction.

SUB-FUNCTION:	Heat Display					
	Datum	*Option 1*	*Option 2*	*Option 3*	*Option 4*	*Option 5*
CRITERIA	**Mercury**	**LEDs**	**Digital readout**	**Color Strip**	**Wax**	**Tactile**
Eye-catching	s	+	-	+	+	-
Intuitive	s	+	+	+	+	s
Compatibility	s	+	s	+	-	-
Range	s	s	+	-	-	-
TOTALS	**0**	**+3**	**+1**	**+2**	**0**	**-3**

The matrix shows multiple methods by which the team can convey the temperature as well as the rate of temperature change of the bars to the customer. Each method is evaluated using sponsor requirements as well as ease of implementation. Results from the matrix show the LEDs having the highest score with the color strip a close second. Other subfunctions were evaluated similarly. A heating plate as a heat source and thermocouples for heat detection was decided. Pugh matrices for other subfunctions can be found in Appendix F.

This display is appropriate for a trade show setting because it exhibits heat transfer - one of the most useful properties of the metal foam. It allows interaction with the display as the customer heats and cools the bars. The LEDs allow the customer to clearly visualize the flow of heat as well as offer a side-by-side comparison between different bars, furthering the customer's understanding of the effect of pore sizes. The proposed display does not require any materials that are restricted by TSA guidelines and has a small enough footprint to be carried while traveling.

Initially, our goal is for the fastest heating metal to take about 10 seconds to heat the entire bar assuming one-dimensional heat flow. The pure aluminum rod is potentially the bar with the highest thermal conductivity. A quick initial calculation, detailed in Appendix H, shows that the bar would need to be sized 1in x1in x 12in and would need to be heated to 40°C for the heat to reach the end of the rod in 8.6 seconds. This shows that the team will need to alter dimensions going forward.

The key challenge with this display is reading the temperatures. Thermocouples are fragile and need to be installed correctly and safely as to ensure the function of the display. The color and density of the LED lights will be decided when parts are sourced prior to the Critical Design Review.

There are three main hazards associated with this display: hot metal, high-speed fans, and falling hazards. Metal bars are heated in the display and can burn someone if touched. The bars will be encased in an acrylic box with ventilation to prevent contact with the customer. Similarly, with the fans, a customer might hurt their fingers if they touch spinning fan blades. A wire mesh will be placed on the back of the fans to allow airflow but also preventing contact with the fans. Finally, to avoid the displays from slipping off the table, rubber pads will be added to the base. A full list of the hazards considered can be seen in the Hazards Check List presented in Appendix G.

4.2.3 Electrical Conductivity Display

An Electrical Conductivity Display was designed and presented at the Preliminary Design Review. However, this design was rejected due to the lack of significance to the project sponsor. Additionally, by removing this design the team will have the necessary time to complete the remaining two designs prior to the Critical Design Review.

For a full explanation of the Electrical Conductivity Display, see the concept design detailed in Appendix I.

5. Final Design

The purpose of this section is to outline the full design of each display unit. This includes detailed descriptions of the design, justification of design decisions, and a discussion of safety and maintenance.

5.1 Final Flow Control Display

The Flow Control Display demonstrates Duocel®'s flow control capabilities by comparing the amount of airflow that passes through foams of varying porosity. This property is visualized for the users through the inflation of balloons as shown in Figure 15.

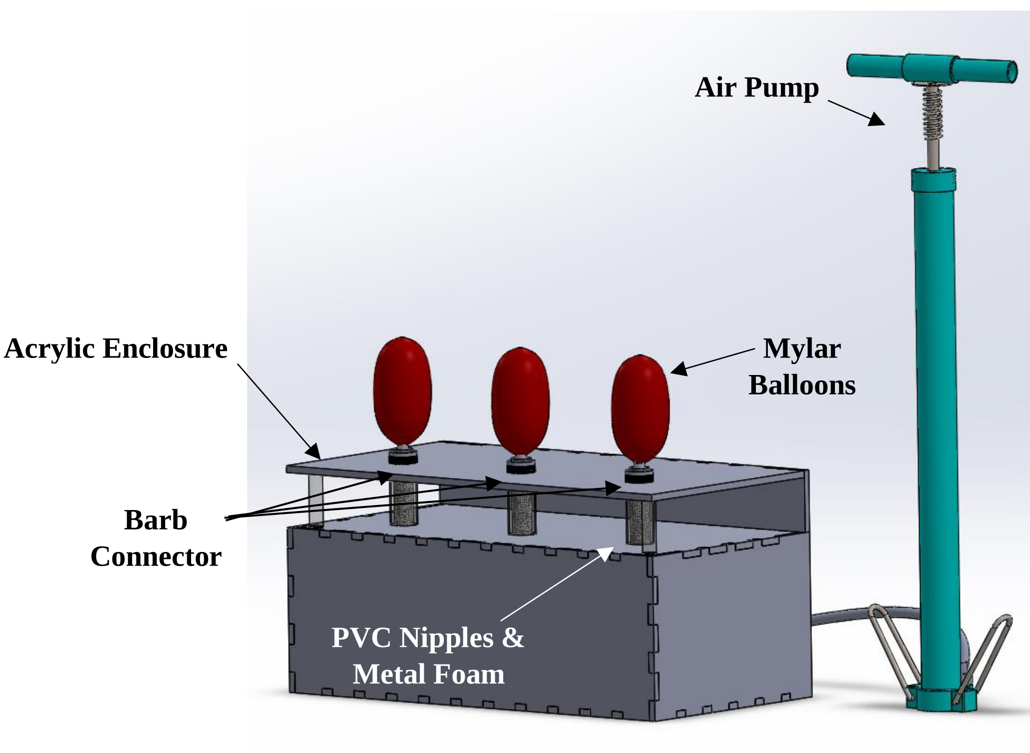

Figure 15. CAD Model of the Flow Control Display.

5.1.1 Flow Control Detailed Design

As can be seen in Figure 15, this display has two major subsystems: the flow path and the enclosure. The flow path subsystem is made entirely of sourced parts and begins with the pump through which users create airflow. This air travels through roughly 7 feet of 3/8" diameter vinyl tubing until it meets a check valve. The valve allows for air to enter the manifold through a small section of 3/8" tubing without permitting backflow. The manifold is attached to the tubing by a male-to-male converter and a 3/8" barb connector. It has four outlets, each with a built-in valve. One of the four outlets is left unconnected, so it can act as a release valve, while the other three are fitted with a 3/8" barb connector. The connector attaches each outlet to 4" of vinyl tubing leading to a brass L-joint (to avoid pinching in the tubes) which then goes to another 4" on vinyl tubing before reaching the PVC nipple containing one of the three chosen air-flow-controlling foams. The threaded PVC nipple interfaces with two barbed connectors (one on each end). The first connector attaches the nipple to the vinyl tubing while the other attaches to the mylar balloons.

The second subsystem is the enclosure. The enclosure is primarily made of black acrylic and has several main components: a box, supports, and a stage as shown in Figure 16.

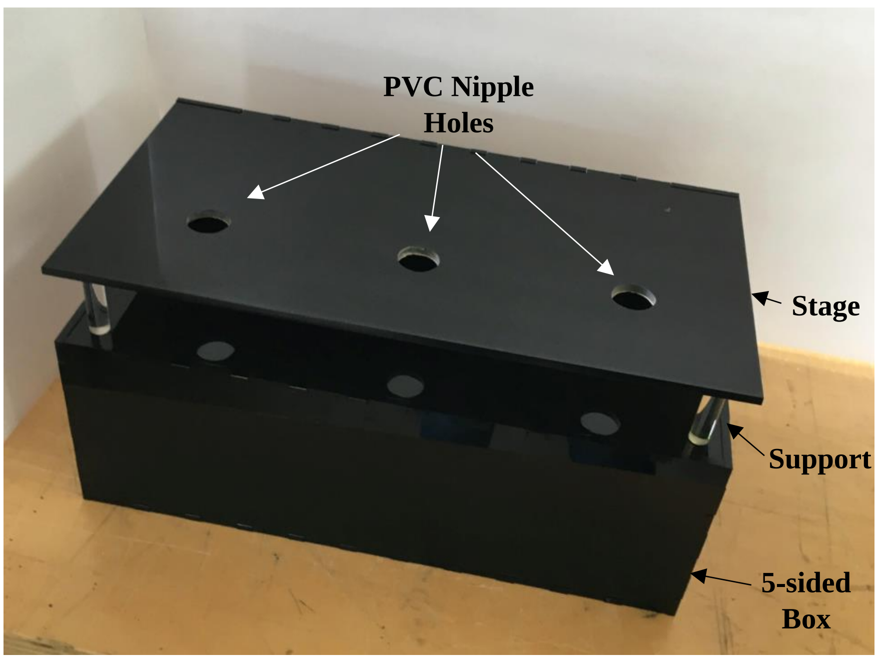

Figure 16. Black acrylic enclosure for Flow Control Display.

The first component is a five-sided box which serves to hide the bulk of the flow path subsystem. The box has no back panel, allowing for easy maintenance and assembly of the flow path. The top of the 5-sided box has three evenly spaced holes which allow the PVC nipples to pass through. Next are the supports which rest on the top of the box and hold up the stage up. The supports are comprised of two 2" clear acrylic rods placed on the front corners of the box and a black acrylic support panel along the back. On top of the supports is a black acrylic stage with identical holes to those created on the box's top panel. These holes allow for the metal foam filled PVC nipples to sit between the top of the box and the stage, rendering them visible to users. The barb connectors that are attached to the balloons rest on top of the stage.

The purpose of this design is to show a difference in flowrate for metal foams of different PPI. When the user pumps air into the flow path using an air pump, the balloons will begin filling according to the resistance the metal foam provides. The airflow will favor the path with the least resistance, so the mylar balloon connected to the foam with the lowest PPI will begin filling first. Once this balloon expands to its maximum volume, the airflow will naturally divert to fill the balloon connected to the next lowest PPI. In this way all three balloons will fill, demonstrating Duocel®'s flow control capabilities. Once the demonstration is complete, the user can open the release valve on the manifold and the balloons will deflate. Following the closure of the release valve, the demonstration can be repeated.

5.1.2 Flow Control Display Justification

The team made material and geometry choices based on the design specifications defined in Section 3.2. We sourced parts that would create an easily transportable, cost effective, and visually appealing product. Our flow path subsystem is modular to allow for easy maintenance. It is primarily made up of flexible tubing and detachable fittings, so the subsystem can be disassembled and stored compactly for easy transportation. Additionally, the off-the-shelf parts are specified for fluid flow applications and follow industry standards. After the flow path subsystem was designed, the geometry of the enclosure subsystem was optimized to its 6"x9"x17" dimensions to comfortably house the flow path while reducing its footprint within the carrying case. The enclosure is made of black acrylic for aesthetic and budgeting reasons. The opaque acrylic hides the components of the flow path while providing a clean finish to the box. The black color not only allows for the ERG and descriptive decals to standout but also creates a contrast drawing the user's attention to the colorful balloons. Acrylic was the material of choice because it would allow us to manufacture the highly customized enclosure in-house for a fraction of what it would cost to outsource the manufacturing.

5.1.3 Flow Control Display Safety and Maintenance

There are no major safety concerns regarding the Flow Control Display because there are no moving or high-voltage components. One minor safety concern is the display being knocked off the table at a trade show and hurting someone. To counter this, rubber pads have been placed at the bottom of the display to provide more friction and prevent slipping. The updated safety/hazard checklist for this display can be found in Appendix G. A complete list of safety risks and implemented preventative measures can be found in Appendix R.

The sponsor will need to maintain or repair any issues that come up during a trade show. The first potential problem is that the balloons do not inflate. First, the tubes should be checked for tanged or pinched sections. Second, the connections between the tube should be checked to make sure there are no leaks. If there is a leak, replace the tube and the barbed connector. If the balloons do not stay inflated, check to see if any of them have a tear and replace damaged balloons. The spring in the check valve might loosen over time and not restrict airflow. Check the valve and replace it if it malfunctions. If any part of the acrylic enclosure breaks, acrylic cement can be used to fix it temporarily, but a new piece will have to be cut to replace it later. A summary of recommended maintenance procedures is provided in the FMEA report in Appendix J.

5.1.4 Flow Control Display Cost

We were given a budget of $4000 to build both displays. Our goal was to spend less than $2000 on each display. The purchases are broken down by subassembly and summarized in Table 7.

Table 7. Cost breakdown of subsystems in Flow Control Display.

Subsystem	Description	Price
Acrylic Box	Acrylic sheets, acrylic rods, Acrylic cement	$91.19
Airflow System	Tubes, Barbed connectors, manifold, check valve	$114.2
Visual Components	Balloons, ~~Acrylic Cylinders,~~ PVC nipple	$65.75
Pumps	Hand, and foot pumps	$28.41
	Total:	**$299.50**

The airflow subsystem is the most expensive one due to the ten barb connectors at $6.30 each. The acrylic box includes the only raw material in the list: the acrylic sheets. Since we already have access to a laser cutter, we have no additional manufacturing costs. The various pumps were bought off the shelf.

The primary vendor for this display was Amazon, however the acrylic sheets were sourced from US Plastics and the PVC nipples were sourced from ePlastics. The total cost of materials at the time of critical design review is $300. The estimated cost of all purchased parts can be found in the project budget in Appendix K.

5.2 Thermal Conductivity Display

The Thermal Conductivity Display demonstrates Duocel®'s heat dissipation capabilities by comparing the temperature of the aluminum Duocel® foam (6-8% density, 10 PPI) and solid aluminum blocks measuring 4"x5"x1". Both the foam and solid blocks are uniformly heated and then cooled by forced convection provided by overhead fans. The difference in heat dissipation is visualized for the users through illuminated LEDs and a digital temperature readout. A rendering of our final design is shown in Figure 17.

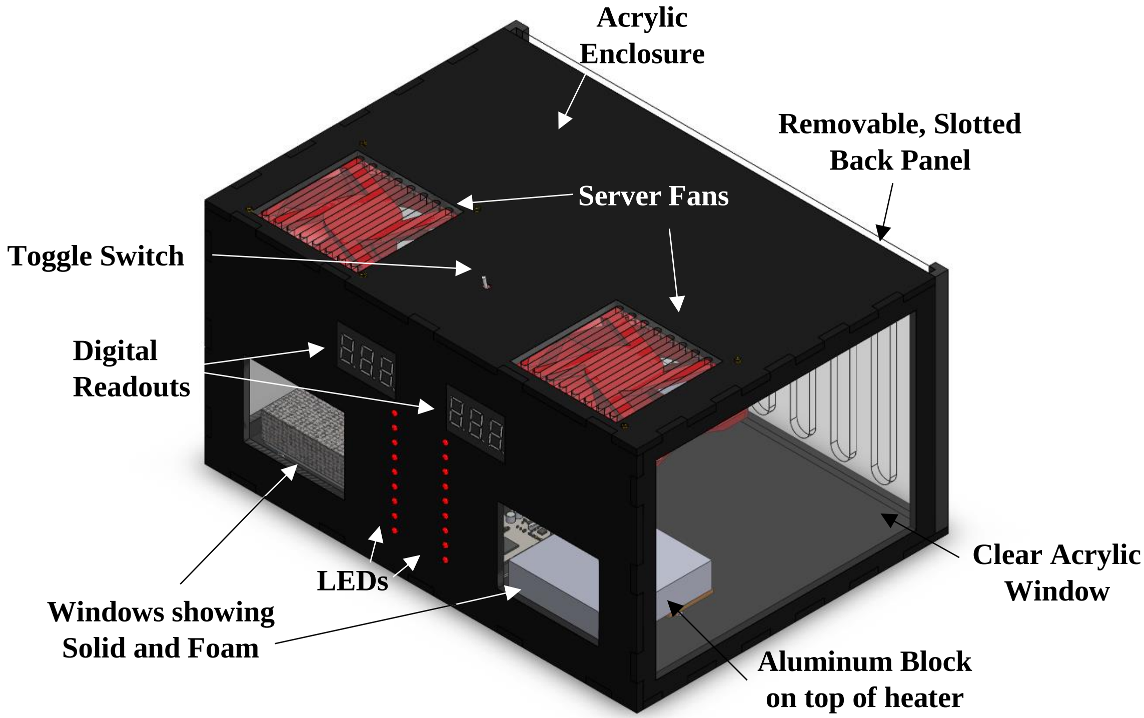

Figure 17. CAD Model of the Thermal Conductivity Display enclosure.

5.2.1 Thermal Conductivity Display Detailed Design

This display has four subsystems: an enclosure, a fan circuit, a heating circuit, and a measurement and display circuit. The enclosure, shown in Figure 17, is a six-sided box with dimensions of 17”x12”x9”. It is primarily comprised of ¼” thick black and clear acrylic. The black acrylic is lined with insulation to protect the acrylic from overheating. The black acrylic front panel houses two self-contained digital temperature readouts and two LED displays. Additionally, clear acrylic windows are set into the black acrylic to allow users to see the aluminum foam and solid aluminum blocks. The sides of the enclosure contain similar clear acrylic windows so that users can see the display’s internal components. The top of the enclosure is made of black acrylic with clear acrylic windows slotted to permit airflow. Additionally, the top panel serves as a mounting location for the server fans with size 6-32 heat-set inserts (threaded tubes set into the acrylic surface) allowing for fastener attachment. The back of the box is a clear acrylic sliding hatch. It has slots to promote convection currents and allow for easy maintenance.

The first electrical subsystem is the fan circuit. The fan circuit allows the users to cool the aluminum foam and solid aluminum blocks by means of force convection. It is comprised of the 12-volt portion of a duel 5V/12V power supply, two fans, and a double-pole double-throw (DPDT) toggle switch. A wiring diagram for the fan circuit is shown in Figure 18.

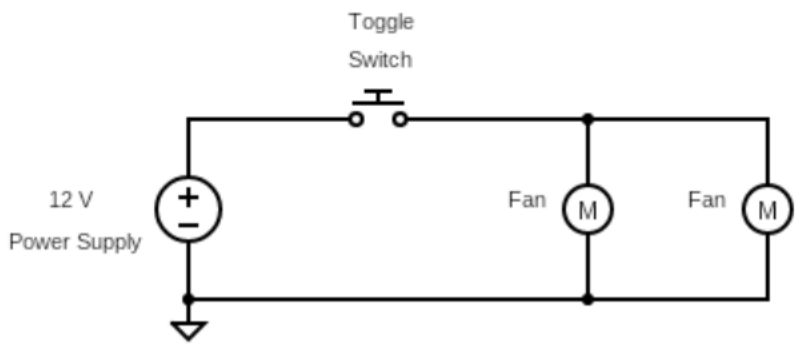

Figure 18. Wiring diagram of the fan circuit.

In this circuit, two fans are powered in parallel by a 12-volt AC-to-DC power supply. The circuit is controlled by a DPDT toggle switch with three positions. The first switch position powers the fan in this subsystem, the second acts as an off position, and the third powers the heaters described in the heating circuit subsystem to follow. When the switch is toggled into the first position the fan circuit is completed, allowing current to be drawn by the fans and turning them on. An analysis of the current draw can be found in Appendix L and the links for the manufacturer specifications for the components are provided in Appendix M.

The second electrical subsystem is the heating circuit. The heating circuit provides uniform heat to the aluminum foam and solid aluminum blocks. It is comprised of a 24-volt power supply, two 30W thin-film heating elements, and a DPDT toggle switch. A wiring diagram for the heating circuit is shown in Figure 19.

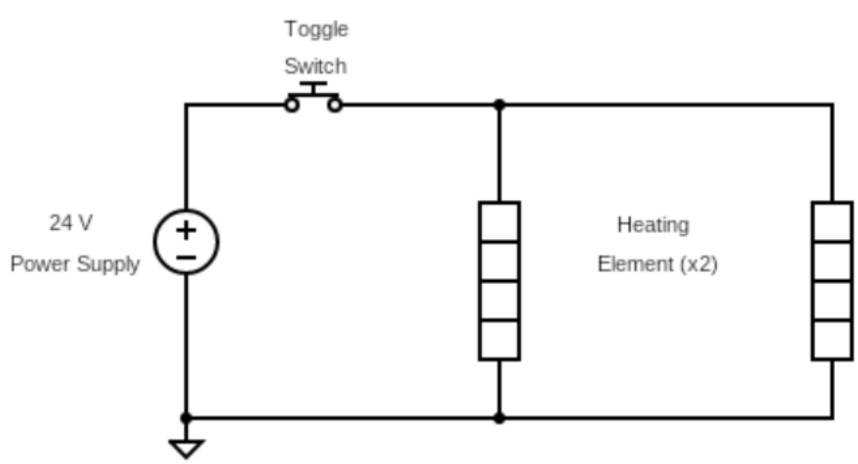

Figure 19. Wiring diagram of the heating circuit.

As seen in the heating circuit wiring diagram, two thin filmed heating elements are powered in parallel by a 24-volt AC-to-DC power supply. The circuit is controlled by a DPDT toggle switch where the third position completes the heating circuit and the heating elements draw current. An analysis of the current draw can be found in Appendix L and the links for the manufacturer specifications for the components are provided in Appendix M.

The third electrical subsystem is the measurement and display circuit. The measurement and display circuit measures the temperature of the aluminum foam and solid aluminum blocks and lights up the LED displays accordingly. The higher the temperature reading, the more LEDs are illuminated. It is comprised of the 5-volt portion of a duel 5V/12V power supply, an Arduino Mega 2560 micro controller, two 10-ohm thermistors, two 2.9-kohm resistors, and 14 red LEDs with corresponding 360-ohm resistors. A wiring diagram for the measurement and display circuit is shown in Figure 20.

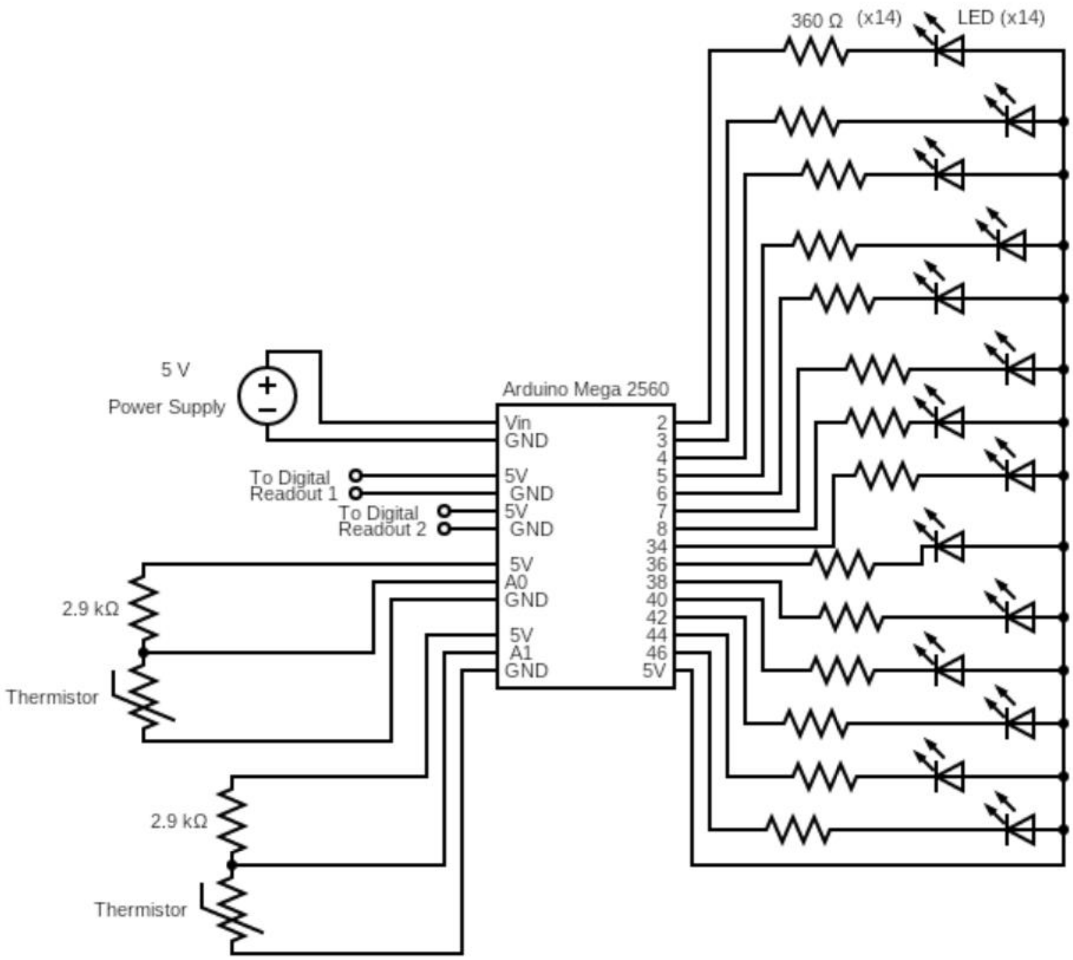

Figure 20. Wiring diagram of the measurement and display circuit.

As seen in this wiring diagram, the entire subsystem is powered by a 5-volt AC-to-DC power supply. The thermistors are resistor-like components which allow the subsystem to take temperature readings from the aluminum blocks. There is one thermistor for each block. As the thermistors are non-linear, a pair of voltage dividers are created containing a thermistor and a 2.9 kΩ resistor each. This divider allows for accurate changes of thermistor resistance to be fed to the Arduino Mega 2560 controller. Each change in resistance corresponds to a change in temperature. The correlation for voltage and temperature in degrees Celsius can be found in Appendix H. The Arduino Mega 2560 controller collects the voltage readings and powers the red LEDs accordingly. There are a fourteen total LEDs, with seven corresponding to each block. As the temperature reading for each block increases, the Arduino will power more LEDs with the maximum temperature reading resulting in all seven LEDs lit and the minimum temperature reading resulting in only one LED lit. An analysis of the current draw can be found in Appendix L and the links for the manufacturer specifications for the components are provided in Appendix M.

For this circuit to operate as intended, the Arduino requires instructions provided by Arduino code. A flow chart of our code can be seen in Figure 21.

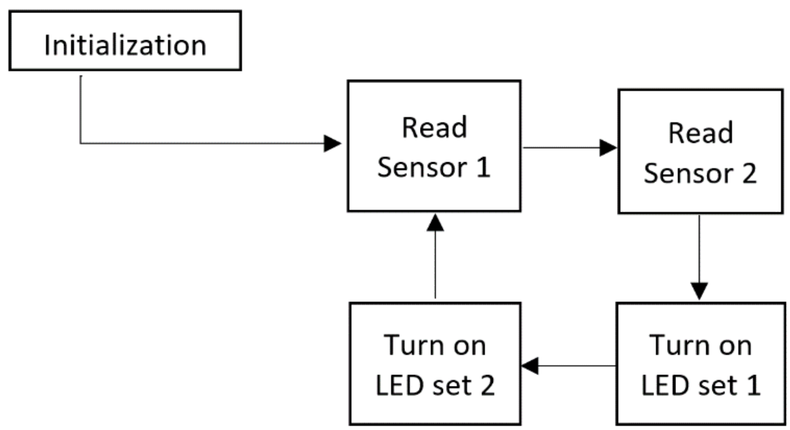

Figure 21. Flow chart of Arduino code.

The flow chart in Figure 21 provides a general overview of the Arduino code. After initialization, the program will obtain voltage readings from the thermistor sensors by means of the voltage dividers. This is denoted in the flow chart by the blocks labeled "Read Sensor 1" and "Read Sensor 2". After obtaining the reading, the appropriate number of LEDs will be turned on for each set of seven. This is denoted by the blocks labeled "Turn on LED set 1" and "Turn on LED set 2". From there the cycle continues, with periodic sensor readings and LED activation. The final Arduino code and original pseudo-code are provided in Appendix N.

A flow chart of how these electrical subsystems interact can be seen in the flow chart in Figure 22. The blue, orange and green boxes correspond to the fan circuit, heating circuit, and measurement and display circuit respectively.

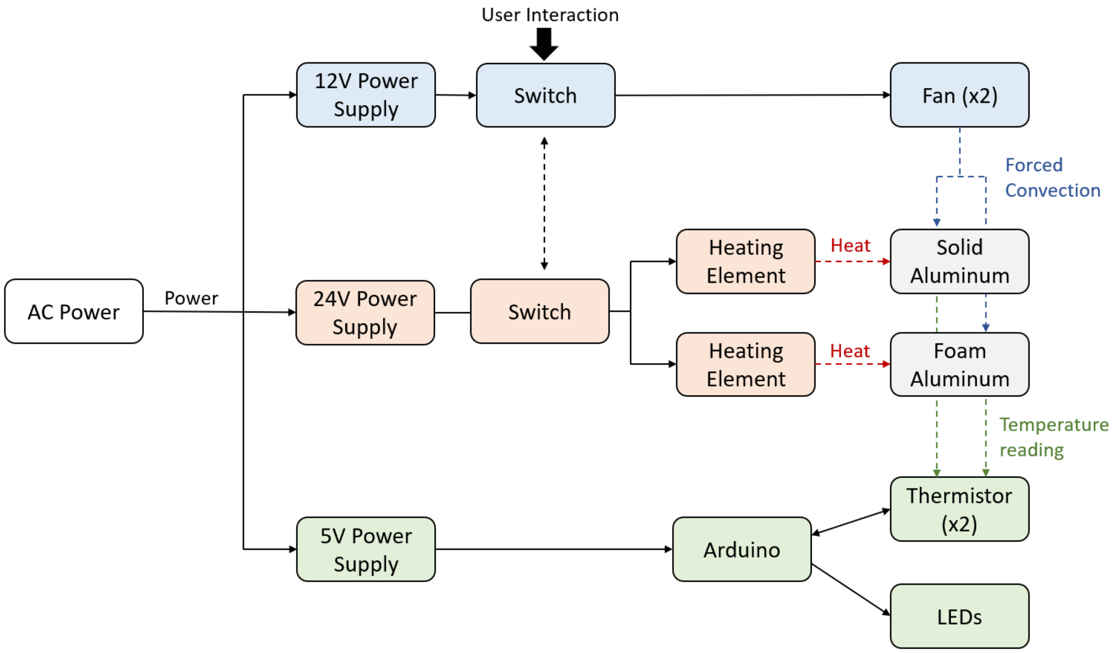

Figure 22. Flow chart of Thermal Conductivity Display operation.

The system is powered using AC 120-volts from a wall outlet carried by a power cable to 12-volt, 24-volt, and 5-volt AC-to- DC power supplies. When the system is plugged in 5-volt subsystem will run continuously allowing the Arduino to take voltage readings from the thermistor circuitry and illuminate the LEDs accordingly. The user can change the position of the toggle switch to either turn on the fans via the 12-volt power supply, turn on the heating elements via the 24-vot power supply, or keep both subsystems off. When the heating elements are on they will provide uniform heat to the solid aluminum and aluminum foam blocks. As the temperature of the blocks increases, users will be able to visualize the speed and extent of the temperature change through increasing number of illuminated LEDs. Conversely, when powered the fans will create a forced convection current within the system, cooling the aluminum blocks. As the temperature of the blocks drops, users will be able to visualize the speed and extent of the temperature change through decreasing number of illuminated LEDs.

5.2.1 Thermal Conductivity Display Justification

A conservative Finite Element Analysis (FEA) simulation was conducted in Solidworks. The simulation showed that with a 60 W power input (double what is used in the final design) and natural convection, the solid aluminum block will reach a steady-state temperature of 117 ̊C while the Duocel® block will reach a steady-state temperature of 34 ̊C. The FEA simulation results can be seen in Appendix O.

In order to verify that this design will work as expected, the team conducted a thermal profile test on January 29, 2019 under the supervision of Cal Poly Mechanical Engineering Professor Glen Thorncroft. A heat plate was used to heat two aluminum blocks (one solid aluminum and one aluminum foam). The steady-state thermal profiles were captured using a thermal camera. A fan was introduced to the system to create forced convection and the transient response was recorded using the thermal camera. This test confirmed that under equal conditions, the Duocel® material would have a lower steady-state temperature. The solid aluminum block was not visibly affected by the addition of forced convection, whereas the temperature of the Duocel® block dropped significantly. These results were consistent with the team's simulation and confirm the Thermal Conductivity Display will function as designed. The full test can be found in Appendix P.

A radiation simulation was conducted using Engineering Equation Solver (EES) based on thermal resistance calculations. The enclosure was assumed to be fully closed and the walls were modeled as black surfaces, with an emissivity of one. The heater temperature was set to the maximum that a set of two thin-film heaters could provide (77 ̊C). Under these conditions, the walls of the enclosure will reach a maximum temperature of 55.5 ̊C. This simulation confirms that the acrylic walls will not reach their melting temperature of approximately 160 ̊C. The EES code used to run this simulation and full results can be found in Appendix Q.

The team designed the Thermal Conductivity Display to meet the engineering specifications outlined in Section 3.2. The size of the enclosure and internal components were sourced to meet the volume and weight constraints; the combination of both displays will stay under 62 linear-inches and 50 lbs. The clear acrylic windows will be implemented to increase user understanding. The system will require little on-site assembly to minimize the assembly time. The bright LEDs and red switch were selected to be eye-catching and make user-interaction intuitive.

5.2.3 Thermal Conductivity Display Safety and Maintenance

This display has a few potential safety concerns. This includes heated components, electrical currents, and high-speed parts. A complete list of safety risks and implemented preventative measures can be found in Appendix R.

Heating elements have the inherent potential to burn users. To minimize this safety concern, we have implemented several preventative measures, including heating element calibration, reduced access to the heating elements, and insulative materials. We have calibrated the thin film heaters so that no component reaches a steady state temperature of higher than 42°C. A minimum temperature of 44°C is required to burn human skin under extended exposure. So, our 42°C calibration ensures that even in a case extreme misuse, where a user touches a heating element directly, the user will not sustain a burn. Even so, the acrylic enclosure prevents any users from coming into contact with any of the heating or heated components. To ensure that the enclosure itself does not experience a significant change in temperature, two types of insulation will be implemented—a radiation shield and silicon pads to prevent conduction.

Another safety concern is the electrical currents which have the potential to electrically shock a user. To protect against shock, all electronics are bounded in an enclosure preventing users from accessing them directly. Additionally, high quality electrical components and power sources from reputable brands were sourced to reduce the chance of malfunction. The power sources are also individually encased in manufacturer-provided enclosures and supply no more than 24VDC. There is no bare wire used in the system and all wire-to-wire connections are incased in shrink tubing.

The rotating fans can cause possible injury if a user were to encounter the fan blades directly. Our acrylic enclosure protects users from accessing the fan blades, as the fans are set inside the enclosure and covered by slotted clear acrylic. The updated safety/hazard checklist for this display can be found in Appendix G.

The team designed the system with replaceable parts and a sliding back plate to allow for maintenance. If there is no reading using external display, the sponsor should first check to see if the corresponding thermocouple is in the correct position in the block. If there is no temperature reading shown on either the LEDs or the external display, this means that the metal blocks are not heating up. This could be due to loss of power, in which case inspect where the heating elements are plugged in. It could also be improper contact to the heating element to the metal, which can be fixed by readjusting the block(s) on top of the heating element. If the fans are not spinning, check to see if there are any foreign objects caught in the blades. If not, check if the fans are connected properly to a power supply. Also, be sure that the display is plugged into a 120-volt AC outlet.

In the case the LEDs are not lighting, remove the burnt-out LEDs and replace with new LEDs. If all the LEDs are not working, check to see if the thermistor is making proper contact with the metal blocks. If the thermistor is placed properly, this could indicate an issue with the microcontroller. First, make sure that the microcontroller is plugged in and receiving power. Next, check the pin connections on the board to make sure all the wired connections are soldered and intact. A summary of recommended maintenance procedures is given in the FMEA report in Appendix J.

5.2.1 Thermal Conductivity Display Cost

As previously stated, the team has a budget of $4000 to build both displays. Our goal was to spend less than $2000 on each display. The purchases planned for the thermal display are broken down by subassembly and function, summarized in Table 8.

Table 8. Cost breakdown of subsystems in the thermal display.

Subsystem	Description	Price
Acrylic Box	Acrylic sheets, Heat-set inserts, Acrylic cement, Thermal Paste and Insulation	$293.17
Fan Circuit	Fans, Button (Powered by 12V Supply)	$61.93
Heating Circuit	24V Supply, Flexible film heating element, Heat Shrink Tubing, Thermal Switches	$47.55
Display Circuit	5&12 V Power supply, Power cord, Arduino, 10kohm Thermistor, 2.49kohm Resistors, Pins, Wires, Jumbo LEDs and LEDs, Max6682 Chip + Breakout board, Digital thermocouple readout	$165.81
	Total:	**$568.46**

The acrylic box enclosure is the most expensive subsystem mainly due to the price of acrylic sheets. The only custom component will be manufactured by the team using Cal Poly resources, so no manufacturing costs apply.

A large portion of the electronics needed for this display will be bought from Digikey and Jameco. Our button for the fan system is sourced from Adafruit while our heat-set inserts are sourced from McMaster. The metal foam block that we will be using is provided by our sponsor ERG. The acrylic sheets will be bought from US Plastics. The total cost of materials at the time of our critical design review is approximately $570. The estimated cost of all purchased parts can be found in the project budget in Appendix K.

6. Manufacturing

In order to test the final design, the team set out to build two functioning confirmation prototypes that will be presented at the spring Senior Project Expo. These confirmation prototypes were assembled from a combination of purchased and custom-manufactured parts. The purpose of this section is to describe the entire manufacturing process from procurement of parts and raw materials through final assembly, with enough detail that it can be replicated as needed. Additionally, this section concludes with suggestions for improvement and lessons learned during the manufacturing process.

6.1 Flow Control Build

The Flow Control confirmation prototype was manufactured and assembled prior to the Critical Design Report and presented at a Manufacturing and Test Review on February 5, 2019. The following sections outline the full manufacturing process used to create the confirmation prototype.

6.1.1 Flow Control Procurement

The Flow Control Display is comprised of off-the-shelf parts, with the exception of the display enclosure for which acrylic sheets were procured. The majority of components were sourced from Amazon due to the variety of components available and low cost. However, the PVC nipples and sheet of black acrylic were sourced from US Plastics Corp and ePlastics respectively. The metal foam inserts were manufactured by the project Sponsor, ERG. For a full list of procured parts with vendor and cost information, see the Indented Bill of Materials in Appendix S.

Table 9. Flow Control Final Cost Summary

Subsystem	Description	Price
Acrylic Box	Acrylic sheets, acrylic rods, Acrylic cement, Rubber feet	$ 100.16
Airflow System	Tubes, Barbed connectors, manifold, check valve, L-barbs	$ 132.03
Visual Components	Balloons, PVC nipples, Acrylic cylinders	$ 87.26
Pumps	Hand, foot, and tire inflator pumps	$ 78.40
	Total:	**$ 397.85**

As shown in Table 9, the final cost for the Flow Control Display was $397.85. This is $98.35 more than the initial estimated cost of $299.50 presented in Table 7 at the Critical Design Review stage. This over-shoot of the estimated costs is attributed the parts required for troubleshooting the display, namely additional tubing, connectors, and a tire-inflator pump costing $49.99. Even with the unexpected costs the display is still well within the $2,000 budget.

All materials and components are procured through the project sponsor, ERG Aerospace, and delivered to the Cal Poly machine shop. No outsourcing is required for this display.

6.1.2 Flow Control Manufacturing Plan

A diagram of the manufacturing and assembly for the Flow Control Display is shown in Figure 23. A step-by-step instruction manual is provided in Appendix T for recreating the display if necessary.

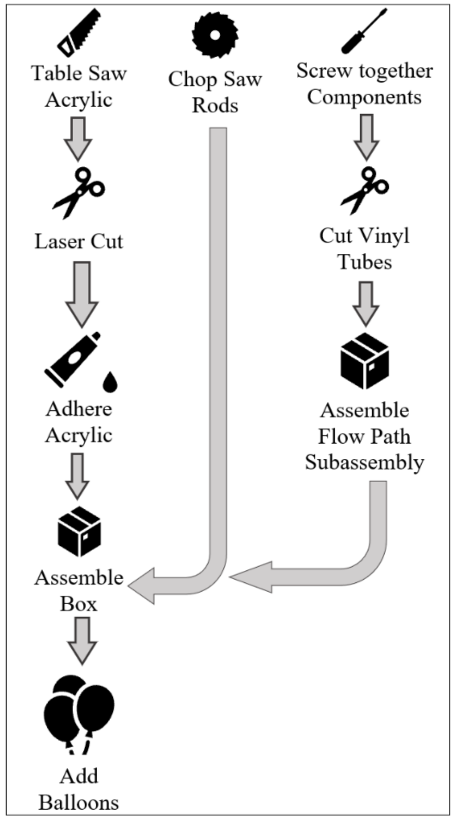

Figure 23. Manufacturing diagram for Flow Control Display.

The only custom manufactured component of the Flow Control Display is the acrylic enclosure. The raw materials required for this component included a ¼"x2'x4' black acrylic sheet, a 1/8"x1'x1' red acrylic sheet, and a 1/5" diameter clear acrylic rod that is at least 4" long.

The black acrylic was first cut into three pieces—two measuring 18"x24" and one measuring 12"x24"—using a table saw. The purpose of these cuts was to make the black acrylic fit onto the 18"x32" bed of the laser cutter.

Once the black acrylic sheet was cut to size, the laser cutter was used to cut out the enclosure pieces. Illustrator drawings used to make these cuts are attached in Appendix U. A total of seven pieces were cut: one front, one top, one middle, one bottom, one back support, and two sides.

The clear acrylic rods were cut to 2" lengths using a miter saw. The ends of the rods were filed to a flatness tolerance of 0.1".

The box was assembled using acrylic cement as an adhesive. This was done by squeezing a thin line of cement onto one notched surface and then pressing the surfaces together. The surfaces were held together for at least 30 seconds to ensure a strong bond.

During the manufacturing of the Flow Control Display, the team learned that the optimal fit for notched components is achieved by sizing the components to the same dimension. The laser cutter left the components approximately 0.001” smaller than dimensioned; this created a gap between the components that was filled by the acrylic cement during the bonding process.

Additionally, the team learned that when using acrylic cement, you must be careful to apply only a small bead on joined surface to avoid excess cement seeping out. The cement cannot be removed once applied, so apply with caution. For critical joints, an additional bead of cement was applied to the inside of the enclosure to increase joint strength.

6.1.3 Assembly of Flow Control Display

After the acrylic enclosure has been built, the full display was assembled.

First, the team attached a hose-to-barb adaptor to one end of the 4” length tube. Then, an L-joint connected another 4” tube to a hose-to-barb adaptor. This is shown in Figure 24. Then, they screwed a PVC nipple onto one adaptor and insert a metal foam cylinder inside the PVC nipple. The PVC nipple was held through the back of the enclosure and up through a hole such that the top threads poke out the top of the display. Another hose-to-barb adaptor as screwed onto the threads and release your hold on the subassembly. The metal foam was visible inside the clear PVC from the front of the display. This process was repeated at two other hole locations, ensuring the foam with the highest PPI is on one end and the lowest PPI is on the other.

The free end of each subassembly was attached to the manifold by screwing the barb connector onto a manifold outlet. The male-to-male adaptor was screwed onto the manifold inlet and another bard connector on the free end of the male-to-male adaptor. At this point, there was only one outlet of the manifold without any additional components attached—this served as the release valve.

Figure 24. Air flow manifold and the metal foam pathways.

One end of the 1” tube was attached to the inlet of the manifold and the other end to the black side of the check valve. One end of the 6’ tube was attached to the white side of the check valve and the other to the pump. A balloon was placed onto the end of each barb connector so that it sat normal to the top surface of the enclosure, as shown in Figure 25.

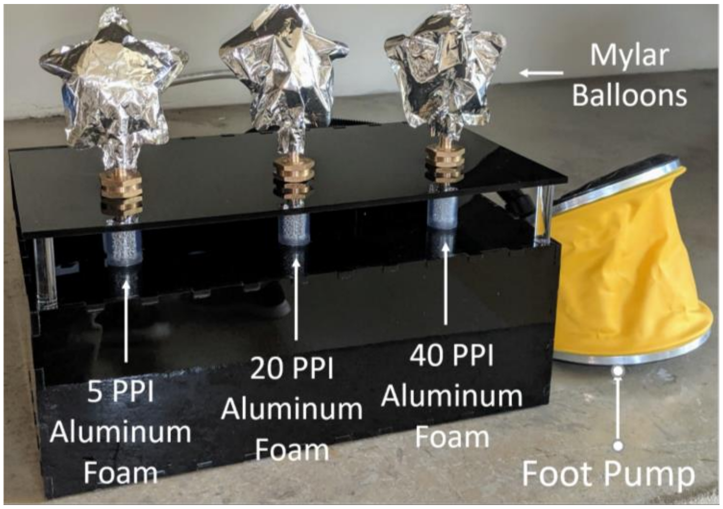

Figure 25. Finished Build of the Flow Control Display

6.2 Thermal Conductivity Build

The Thermal Conductivity confirmation prototype was manufactured and assembled following the Critical Design Report. The following sections outline the full manufacturing process used to create the confirmation prototype.

6.2.1 Thermal Conductivity Procurement

The Thermal Conductivity Display is comprised of mostly off-the-shelf parts, with the exception of the display enclosure for which acrylic sheets were procured. The majority of components were sourced from Jameco and Digikey because high quality electrical components are required. However, the black acrylic sheets were sourced from ePlastics and the digital readouts and flexible heaters were sourced from Amazon. The metal foam block will be manufactured by the project Sponsor, ERG Aerospace. For a full list of procured parts with vendor and cost information, see the Indented Bill of Materials in Appendix S.

Table 10. Thermal Conductivity Final Cost Summary

Subsystem	Description	Price
Acrylic Box	Acrylic sheets, Heat-set inserts, Acrylic cement, Thermal Paste, Insulation, Command strips	$ 301.42
Fan Circuit	Fans, Button (Powered by 12V Supply)	$ 85.48
Heating Circuit	24V Supply, Flexible film heating element, Heat Shrink Tubing, Thermal Switches	$ 98.93
Display Circuit	5&12 V Power supply, Power cord, Arduino, 10kohm Thermistor, 2.49kohm Resistors, Pins, Wires, Jumbo LEDs and LEDs, Max6682 Chip + Breakout board, Digital thermocouple readout	$ 194.62
	Total:	**$ 680.45**

As shown in Table 10, the final cost for the Thermal Conductivity Display was $680.45. This is $111.99 more than the initial estimated cost of $568.46 presented in Table 8 at the Critical Design Review stage. This over-shoot of the estimated costs is attributed the components required for reworking electrical subsystems fried or broken during manufacturing. Some of these components included a 24-vlot power supply, Max6682 chips, toggle switches, and solder paste. Even with the unexpected costs the display is still well within the $2,000 budget.

Materials and components are procured through the project sponsor, ERG Aerospace, and delivered to the Cal Poly machine shop. No outsourcing is required for this display.

6.2.2 Thermal Conductivity Manufacturing Plan

A diagram of the manufacturing and assembly for the Thermal Conductivity Display is shown in Figure 26. A step-by-step instruction manual is provided in Appendix V for recreating the display if necessary.

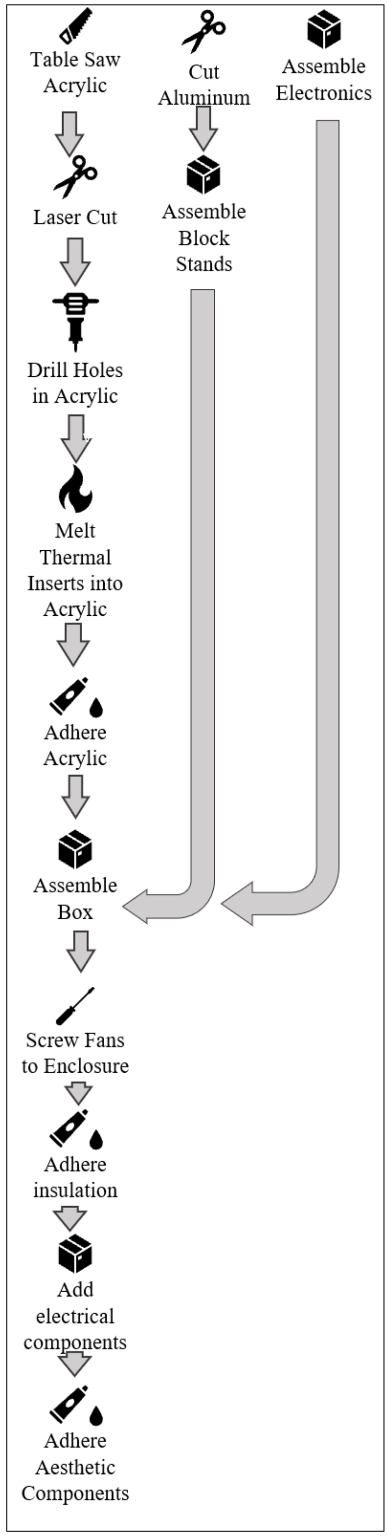

Figure 26. Thermal Conductivity Display manufacturing diagram.

The main custom manufactured component of the Thermal Conductivity Display was the acrylic enclosure. The raw materials required for this component included two ¼"x2'x4' black acrylic sheets, a 1/4”x2’x4’ clear acrylic sheet, one 1/8”x18”x18” red acrylic sheet, radiation insulation, and conduction insulation.

The black acrylic sheets and clear acrylic sheet were first cut into three pieces—two measuring 18”x24” and one measuring 12”x24”—using a table saw. The purpose of these cuts was to make the acrylic fit onto the 18”x32” bed of the laser cutter.

Once the acrylic sheet was cut to size, the laser cutter was used to cut out the enclosure pieces from Illustrator drawings. Similarly, the clear components were cut from clear acrylic and the lettering was cut from red acrylic.

The team drilled 5/32” holes with a 1/8” depth in the top and bottom surfaces of the enclosure as shown in the drawing package in Appendix X. The threaded thermal inserts were placed on top of the holes and the tip of a soldering iron was used to melt them into the surface as seen in Figure 27.

Figure 27. Thermal inserts in top sheet.

To build the block stand, the team cut an aluminum sheet into two 4”x5” sheets using a step shear. Then, a size 6-32 hole was drilled through each corner of each sheet. The team assembled the block stands and screwed them into the thermal inserts in the bottom surface. The blocks were placed onto these block stands. Thermocouple and thermistor devices were inserted into block holes using thermal paste for a tight fit.

The box was assembled using acrylic cement as an adhesive. To attach the clear acrylic windows, the clear pieces were inserted into the black cutouts and a thin layer of acrylic cement was applied to the inside edge. The walls were attached by squeezing a thin line of acrylic cement onto one notched surface before pressing the interfacing surfaces together. The surfaces were held together for at least 30 seconds to ensure a strong bond. The back surface was left unbonded to allow it to slide up and down freely.

Once the box was completed, the insulation was applied. Conduction insulation was applied between the blocks and the block stands. Radiation insulation was applied to all black inside surfaces. The insulation was cut to size as needed and pressed onto surfaces using the pre-applied adhesive.

During the manufacturing of this display, the team learned that the insulation should not be handled without gloves and safety glasses. When cut to size, the composite material produces small fibers that are painful to touch. To prevent any insulation threads from coming loose in the box, the team covered the edges of the insulation with black tape.

Additionally, the team learned that the easiest way to produce clean edges when using acrylic cement is to apply painters' tape around the edge of the clear acrylic. Then, a thin bead of cement was applied on the inside edge only. This prevented any messy cement from being seen through the windows. Figure 28 shows a successfully glued window.

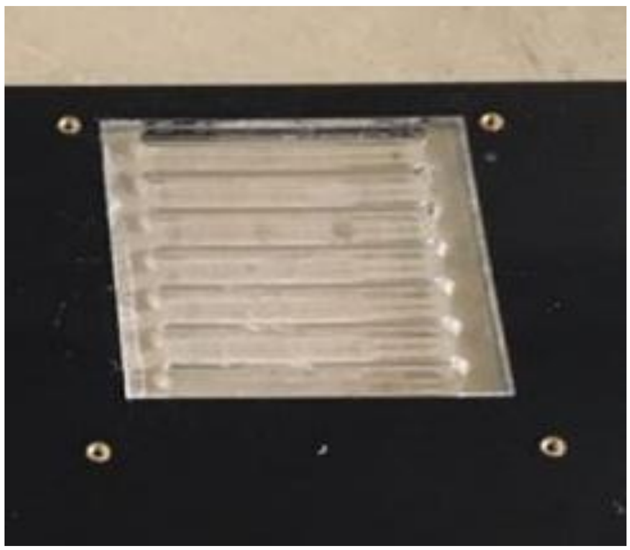

Figure 28. Finished glued window with no glue showing on the outside of the acrylic.

In parallel with the enclosure manufacturing, the team built the electrical subsystems. First the two power sources were connected to a common AC power cord. This was done by jumping appropriately rated wire from the 12V/5V power source's live, neutral, and ground terminals to the respective terminals on the 24V power source. At the 24V power source's terminals corresponding AC cable leads were also attached. This assembly is shown in Figure 29, below.

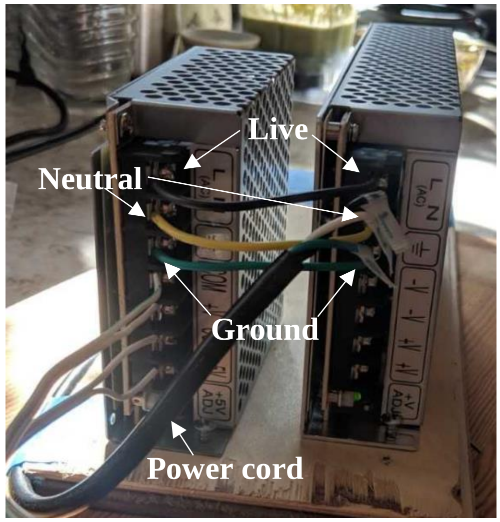

Figure 29. Power supply final assembly.

The team noticed that the screw mechanism used to secure wires at each terminal was prone to releasing the wires if not adequately tightened. Thus, special care was taken to tighten the mechanisms as far as possible. Additionally, the power cord was secured to the substrate to prevent users from pulling the cord leads out of the power source. These measures were later implemented in the final assembly within the enclosure.

The team began by assembling all the circuits individually on breadboards to test for functionality before soldering on protoboards. These breadboard functionality assemblies proved prudent as there were several lessons learned and design tweaks made in the process. First, the fan circuit was assembled as described in the design section. This circuit functioned as expected, so a final circuit was soldered onto protoboard according to the original circuit diagram. A detailed manufacturing plan can be found in Appendix V. A side-by-side image of the functioning breadboard fan circuit set up and the completed protoboard is shown in Figure 30.

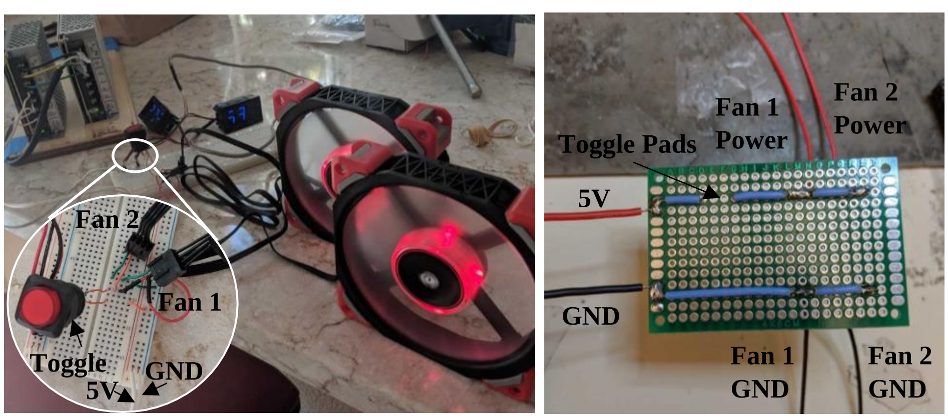

Figure 30. Fan circuit breadboard and final protoboard assemblies.

Next the heating circuit was assembled. At first the circuit was built according to the original design shown in Appendix X which featured two 30 W heating elements in parallel for each block. The resulting power was 60 W per block. From initial calibrations it was determined that the steady state temperature was too high in this circuit configuration for the fans to make a timely difference in block temperature. The team decided that one 30 W flexible heater would be used instead. The resulting maximum steady state temperature was 42℃. This design temperature allowed for the fans to reasonably cool the blocks, while also providing an additional safety precaution- users cannot be burned even if they touch the heater directly. To further increase the reaction time of the display, a Double Pole Double Throw (DPDT) switch was added between the heating and fan circuits so that when the fans are on the heaters are off and vice versa. Satisfied with our assembly, the team soldered the circuit and covered the wire connections with shrink tubing.

To assemble the measurement and display circuit the team first need to solder the Max 6682 chip onto a breakout board. Due to the chip's size, electrostatic charge, and temperature sensitivity it was very difficult to solder without damaging. See Figure 31 for a size comparison of the chip and breakout board as compared to a penny.

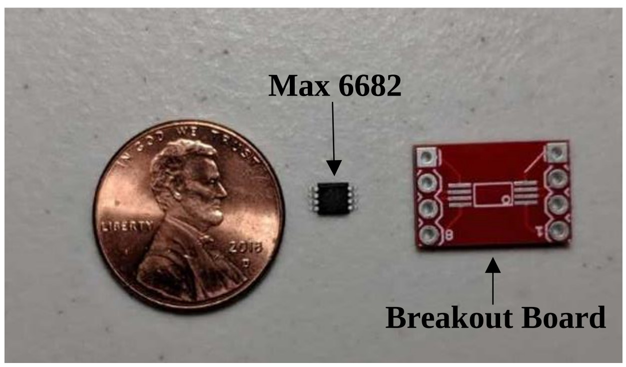

Figure 31. Max 6682 chip and breakout board size as compared to penny.

Multiple methods of soldering the chip were attempted including conventional solder, solder paste, and protective thermal tape. Unfortunately, neither the team nor a consultant with advanced skills in soldering were able to viably solder the chip to the breakout-board. It was determined that our skills and equipment were not sophisticated enough to employ the Max 6682 chip in our device, so the design was changed to include a voltage divider instead.

The voltage divider including the thermistor sensors, Arduino, and LEDs were assembled on breadboards. Once the team was satisfied with the measurement and display circuit's functionality, it was soldered together. First, two sets of voltage dividers comprised of a thermistor and a 2.9 kΩ were soldered onto a protoboard. The power, ground, and reading wires from each divider were then soldered to the 5V, GND, and analog reading pins respectively on the Arduino protoboard shield. Additionally, fourteen uniquely colored jumper cables were soldered to the shield's digital pins 2 through 8 and 34 through 46 to connect to the LED protoboards. Figure 32 below shows the final Arduino shield configuration.

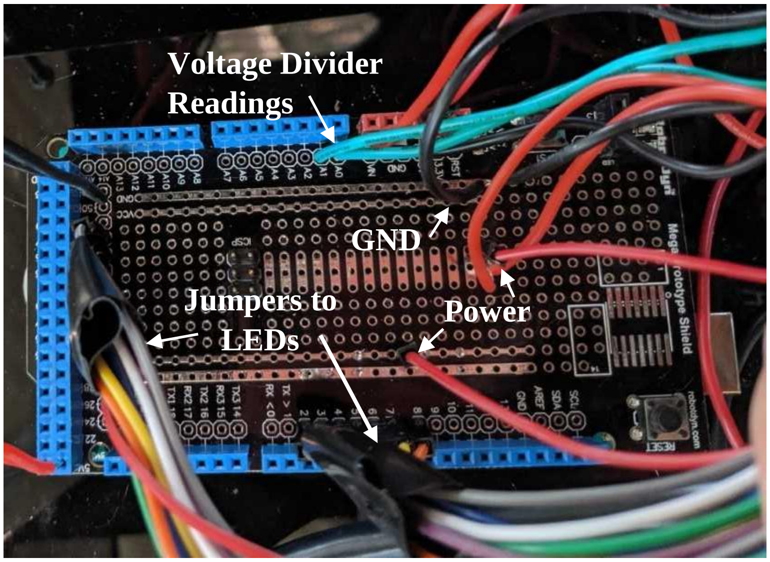

Figure 32. Arduino protoboard shield with final soldered components.

Two sets of LED protoboards were soldered next. The team assembled both protoboards so that there were seven LEDs in parallel each in series with a 360Ω resistor and a jumper cable colored to match a corresponding jumper connected to the Arduino shield. A wire was connected to each LED branch to function as a common ground. Unfortunately, it was found that the anode and cathode of all the LEDS were flipped so the circuit could not function if grounded through the common wire. The team decided to instead apply 5-vots to both the connecting wire and jumper cables and turn the LEDs on by means of the Arduino code powering off the jumper cables. This unintended design change is reflected in our final wiring diagram, the original can be found in Appendix X.

The electrical subsystems were a challenging portion of the design and manufacturing of this display. As such, the team gained new skills in soldering, coding, and electrical troubleshooting. Additionally, we learned safety precautions that should be taken around electrical components such as Electrostatic-discharge-safe workspaces and avoiding wearing metal jewelry around live components.

6.2.3 Assembly of Thermal Conductivity Display

After the acrylic enclosure was built, the full display was assembled.

The fans were attached by placing them under the top surface and fastening in place with size 6-32 bolts. There should be four bolts used to attach each fan. Additionally, the toggle switch was threaded through the loose-fit hole in the top panel in the display. A nut and rubber washer were used to secure the switch in place. A view of the top surface of the display can been seen in Figure 33.

Figure 33. Top of Thermal Conductivity display.

The thin film heaters were placed between the blocks and the conduction insulation layer. The digital readouts and LEDs were pushed into the holes in the front of the enclosure. Interference fits ensured a stable hold without adhesive so that these components can be replaced if necessary.

The Arduino was secured down behind the solid block using Velcro. Next to the Arduino, both power sources were screwed into the acrylic and further attached to the floor of the enclosure with Velcro. The power cord was also clamped down. A picture of the internal display set-up can be seen in Figure 34.

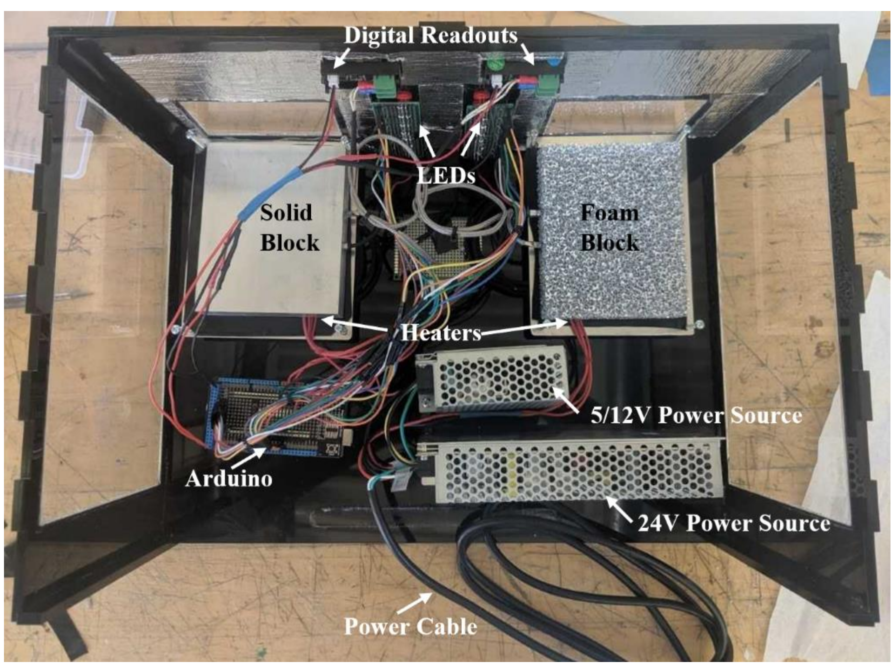

Figure 34. Internal display set-up.

Finally, the decals were attached to the front and top surfaces of the display with acrylic cement as shown in Figure 35. The most effective method for placing the letters is to use tape to line up the letters prior to applying the cement.

Figure 35. Front and top surface decals.

6.3 Manufacturing Reflections

If this display was to be built again, the team would make some minor changes to the manufacturing process. For instance, when manufacturing began, we had limited laser-cutting skills and thus made avoidable mistakes. After completing this project, we have a better understanding of the laser cutting process and applications. If we were to manufacture this display again, we could use these skills to cut cleaner pieces using less material.

The team found that some electrical components, such as the Max 6682 chip, required more specialized equipment and skills. As such, if we were to do this again, we would not attempt to use that component in the electrical design. Additionally, due to the inconsistency in the sourced self-contained digital readouts we would have implemented temperature readouts that can be programed through the Arduino. This would have reduced the number of sensors required from two to one per block and ensured that the LEDs and digital readouts were presenting the same reading.

7. Design Verification Plan

After the confirmation prototypes were built for each display, we conducted a series of tests and other procedures that will confirm the displays work as intended and meet the design specifications. The Design Verification Plan and Report (DVP&R) details all specifications that were tested for each display. It can be found in Appendix W.

7.1 Flow Control Display Specifications and Test Results

The purpose of this subsection is to describe the specifications, test procedures, and test results for the Flow Control Display. A large portion of the specifications for the two displays are the same, but each display has its own unique specifications that it must also meet. The design specifications for our Flow Control Display are intended to ensure that the display functions properly and consistently. It also aims to make the system easy to transport, set up, and understand to fulfill its purpose as a trade show display.

There two specifications that consider the combined effect of both displays. These are maximum weight and total linear dimensions. The maximum combined weight specification is set at 50 pounds. The total linear dimensions of the display are set at 62 linear-inches maximum. This specification describes the combined width, depth, and height of both displays when partially disassembled and arranged into the intended travel configuration.

While there are no special equipment or facilities necessary for testing our specifications, some basic equipment was needed to obtain to run these tests. The maximum weight test required weighing each display and their respective components on a scale. The total linear dimension specification test required a tape measure to complete. As these tests were run with both the Flow Control and Thermal Conductivity Displays, the combined test results are discussed in the following section 7.2.

A specification unique to the Flow Control Display was that the balloons fill according to the foam porosity, with the lowest PPI foam filling first and highest PPI foam filling last. This specification required a simple functional test to make sure our display worked consistently. While simple, this test was essential, as the specification was considered “high risk” and determined if the display was functional.

Unfortunately, the display failed this basic functionality test. The balloons would not fill according to the porosity of the metal foam in the path, rather filling in an apparently random order. Despite many troubleshooting efforts involving various parts of the flow path, pump, and balloons, the balloon continued to fill in an inconsistent order. As a result, Flow Control Display was unable to pass the specification. The team did not have sufficient time to completely redesign the display, so recommendations for a potential solution are detailed in Section 9. As the Flow Control Display is not functional, the remaining tests were not completed. The DVP&R for the Flow Control Display can be found in Appendix W.

7.2 Thermal Conductivity Display Specifications and Test Results

The purpose of this subsection is to describe the specifications, test procedures, and test results for the Thermal Conductivity Display. For this display, all specifications that were listed in the specification section of the report were tested and the results are described below. Unlike the Flow Control Display, all specifications were able to be tested and confirmed. The combined specifications for maximum weight and total linear dimensions of the display specifications are the same as described for the Flow Control Display in Section 7.1. The completed DVP&R for the Thermal Conductivity Display can be found in Appendix W.

The first set of tests performed was the maximum weight and total linear dimensions test. For these tests, the specifications were meant to describe the combined total between both the flow control and thermal displays. To see if our final design passed these specifications, we went ahead and tested them together as intended. The maximum weight test included weighing each display separately and adding the total together. This was done on a Circuits and Systems SX1000 scale. To make up for the precision uncertainty of each weigh-in, uncertainty analysis was performed for this test. The resulting data is shown in in Table 11, and the uncertainty analysis can be found in Appendix AA. We also tested the total linear dimensions. To do this, we put each display down next to each other (in a configuration that they were intended to travel in) and used a tape measurer to take the height, width, and length of the layout and added them together to make sure the specification was met. These results are also in Table 11.

The Thermal Conductivity Display also has individual specifications including time for assembly, time to 'reset', display reaction time, and several user-based specifications. The time to assemble, reaction time, and time to reset tests all require a timer to complete. These tests were performed by different members of our team to confirm that someone who is familiar with the system (such as the project sponsor) can assemble or reset it in the designated amount of time.

The time to assemble the display was specified at a 20-minute maximum. Meaning that it should take no longer than 20 minutes for someone who is familiar with the display to set it up. As with all the time-based test, a stopwatch was used to take the measurements in this test. The testing procedure required a team member to assemble the display from its travel configuration. First the team member set the display on a table and removed the power cord from the enclosure by lifting the back cover. Then, they plugged the power cord into an extension cord which they proceeded to plug into a wall outlet. Finally, they set the display to the “heat” option by flipping the switch. The display passed this test as it only took about three minutes to complete.

The time to ‘reset’ test was specified at a 10-minute maximum. Meaning that it should take no longer than 10 minutes for someone who is familiar with the display to reset it. This specification was tested by timing how long the metal foam would take to heat up to maximum steady state temperature from its cooled state. The test was performed by a team member who toggled the switch to heating mode from cooling. It took just under two minutes for the metal foam to reach the maximum steady state temperature, so the display also meets this specification.

The reaction time of display was specified at a 5-second maximum. Meaning that the display should produce a visible response less than five seconds after user input. This specification was tested by timing how long it took for the fans to respond to user input. The test was performed by a team member who toggled the switch to cooling mode from heating. The display passed this test as the fans reacted to user input in less than two seconds.

The last set of specifications tested related to users' experience of the display. These specifications included user reports of eye-catching, user understanding, and user reports of ease of interaction. To test these specifications the team needed a user survey and willing volunteers to complete the survey after interacting with the display. The team tested these specifications by setting up a table with the display (seen in Figure 36) and asking people on campus to interact with the display. The participants were then asked to fill out a survey with questions that corresponded to each specification. A copy of this survey and the complete results can be found in Appendix Z.

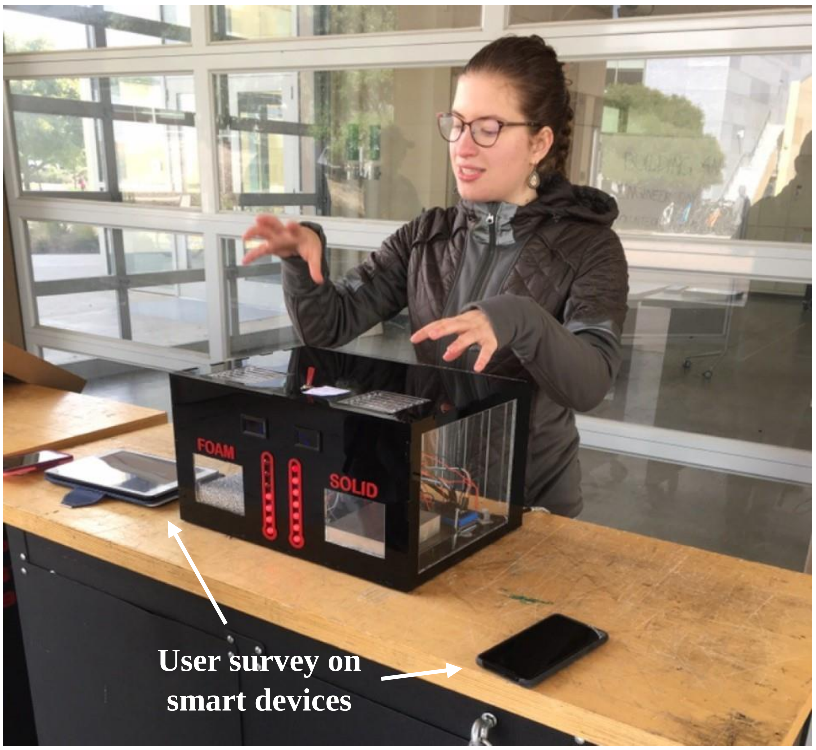

Figure 36. Katherina Prodanov running the user testing of the Thermal Conductivity Display.

We gathered 50 responses over the course of the testing session. From the results of the survey, it was determined that the display met all three specifications. The "users report eye-catching" specification required at least 60% of users to find the display eye-catching. The survey results showed that 96% of the users agreed that the display was eye-catching. The "user understanding quiz" specification required at least 60% of the users to correctly answer questions designed to assess their understanding. The survey results showed that 78% of the users answered the questions correctly. The "users interact easily" specification requires that at least 60% of users report that they can comfortably and appropriately run the system without significant aid. The survey results showed that 96% of the users found the display easy to use. The complete testing results for the Thermal Conductivity Display are shown in Table 11.

Table 11. Specification Testing Results for the Thermal Conductivity Display.

Spec #	Test Description	Acceptance Criteria	Quantity Tested	Data	Qty. Pass	Qty. Fail	Result
1	Maximum Weight	50 lbs. max	1	25.4 ± .14 lbs.	1	0	PASS
2	Time for assembly of display	20 mins max	1	3 min, 5 sec.	1	0	PASS
3	Total linear dimensions of display	62 linear in. max	1	56 in.	1	0	PASS
4	Time to 'reset' display	10 mins max	1	1 min, 55 sec.	1	0	PASS
6	Users report eye-catching	60% agree min	50	96% agree	48	2	PASS
7	User understanding quiz	60% pass min	50	78% pass	39	11	PASS
8	Users interact easily	70% interact min	50	96% agree	48	2	PASS
9	Reaction time of display	5 seconds max	1	<2 sec.	1	0	PASS

All nine specifications were met for the Thermal Conductivity Display. With these results, we consider this display to be successful.

8. Project Management

The purpose of this section is to outline the steps taken to complete this project. This includes a description of the design process, a timeline of major deliverables, a detailed project schedule, and a project management refection.

Due to the nature of this senior project course, there was a pre-determined timeline of major tasks and deliverables. However, special project circumstances—namely the design and manufacturing of two separate systems—required an adjusted timeline authorized by our senior project advisor, Sarah Harding.

8.1 Design Process

The senior project class was split up into three phases over the course of the school year. The first phase focused on defining the problem, brainstorming design ideas, and choosing a design to proceed with. It began with researching the project, understanding the problem that needed to be solved and outlining the project's Scope of Work. Once the Scope of Work was approved by the sponsor, the team completed extensive ideation to brainstorm design possibilities. The team built basic concept models to further investigate the feasibility of these designs. Through a series of design matrices, the team selected three display designs to pursue and built a prototype of each concept. The submission of this Preliminary Design Report marked the end of the first phase of this project.

The second phase focused on finalizing detailed designs and creating a manufacturing plan. Finalizing the design included performing Failure Modes and Effects Analysis, adjusting the design for manufacturability, and creating complete solid models. Then, the team sourced parts and wrote a manufacturing plan for each design. With sponsor approval, the team manufactured a complete Flow Control Display, which serves as a Critical Design Prototype. Thermal testing and simulations were performed to confirm the Thermal Conductivity Display would function as intended.

The final phase of this project included manufacturing the Thermal Conductivity Display and testing both displays. Once our sponsors agreed with our manufacturing plans, we ordered the necessary parts. While the team was waiting for part delivery, we finished the build and began the testing of the Flow Control Display. The team then manufactured the Thermal Conductivity Display. All three displays were tested as described in Section 7 and redesigned/adjusted as necessary. The team then wrote a comprehensive Operator's Manual shown in Appendix AB and ensured all designs were safe prior to delivery. The third phase of this project was preparing for the Spring Senior Project Expo and Final Design Review. This was also an important step as it served as a reflection on our design process and allowed us to make recommendations and suggestions on how we would do the project differently.

8.2 Timeline of Deliverables

The team constructed a Gantt Chart that outlines the project timeline as shown in Appendix A. The first phase of the Gantt Chart includes tasks completed prior to the submission of the Preliminary Design Report. The second phase outlines a detailed schedule of tasks that were completed up to the Critical Design Report. The final phase outlines the detailed manufacturing and testing procedures that were completed prior to Senior Project Expo. The major project deliverables are shown in Table 12.

Table 12. Estimated timeline for major deliverables.

Deliverable	Description	Deadline
Scope of Work	Outline of entire project, including background, specifications, and estimated timelines.	10/19/18
Preliminary Design Report	Description of project process including initial concept sketches, analysis, and research as needed.	11/16/18
Critical Design Report	Full report of project design including all necessary information to manufacture components.	2/28/19
Final Design Report	Report of completed project including fully manufactured prototype and test results.	5/31/19
Project Expo	Final project presentations open to the public. Will also serve as a simulated tradeshow environment for a final round of user testing.	5/31/19

Certain deadlines were altered as needed to fit the project; for example, the Critical Design Report was delayed compared to the typical senior project schedule, allowing the team to redesign the Thermal Conductivity Display. The Senior Project Expo featured only the Thermal Conductivity Display as the Flow Control Display was not functional. The Expo also features a large poster board to summarize the most important features and steps in the design process. After the Senior Project Expo, our sponsors at ERG Aerospace shall take the displays and any necessary components/materials with them for their own use.

8.3 Special Processes

Our senior design project has some unique requirements that set it apart from traditional projects. Because we planned to manufacture two displays, our manufacturing schedule deviated from the traditional class timeline. We built our first full design prior to the Critical Design Report as a substitute for the Critical Design Prototype. This allowed us the necessary time after the Critical Design Report to manufacture the second display. We chose the Flow Control Display to manufacture first because we predicted that it would be relatively simple to complete before the Critical Design deadline. This would then be followed by the Thermal Conductivity Display after the completion of the CDR.

Along with the engineering aspect, we must also deal with consumer interaction. Since our goal is to attract people to the displays and make them understand the product, surveys will play a major part in deciding if we have met those goals. The team wrote a survey (mentioned in Section 7) and completed user testing using Cal Poly students and faculty by setting up the thermal display in a courtyard on campus.

Toward the end of the project, we had the manufacturing of the thermal display deadline pushed up so that our sponsor ERG Aerospace could take it to a tradeshow and become familiar with the display before Expo. Since we were on track with the manufacturing, this deadline to complete the display was met and ERG was able to pick it up on time and was able to return it in time to prepare the display for Expo.

8.4 Project Management Reflection

Due to both unexpected redesigns and designing two separate displays, the project timeline was somewhat unconventional. To allow time for troubleshooting and redesign, some deadlines were delayed (such as the Critical design Review) while others were moved up (such as the Flow Control Manufacturing and Test Review). The team was able to successfully juggle two displays while meeting all course requirements in the allotted time by diligently setting deadlines and meeting them. Though the Flow Control Display was not functional at the completion of this project, we feel that the team did an exceptional job of managing our time considering the project goals.

However, if we were to do this project again, we would simplify the project goals early on to allow more time for troubleshooting and redesign. If the team had focused on only two displays at the beginning, additional time could have been used to test the Flow Control Display functionality before manufacturing the full display.

Additionally, the team would adjust the way we split up responsibilities. At the beginning of the project, almost every assignment was completed as a group. This wasted a lot of time, as many assignments only required one or two people. As we neared the end of the project, we began splitting up the work such that each team member specialized in one aspect of the project, while having little to no influence on other aspects. For example, one team member completed all of the solid modeling while another team member completed all of the electrical design and manufacturing. Though this method was more efficient, it created problems when not all team members understood the full design, manufacturing, and testing of the display. If we were to do this project again, we would continue splitting up assignments for efficiency, but would vary the assignments each week such that everyone gets to work on every aspect of the display.

9. Conclusion

The purpose of this document is to provide a complete account of the process of building and testing the display boxes. The following section contains a description of the final product that was achieved, what could have been done differently, and possible next steps for improving the project. For a complete list of operating instructions, see Appendix AB.

9.1 Flow Control Display Results and Recommendations

The team was able to complete the manufacturing and testing of our final flow resistance display. The acrylic box was successfully manufactured, and the piping system was adjusted so they would fit in the box without them twisting or getting pinched. The air successfully flows from the pump to inflate the balloons as planned.

After multiple tests and iterations, we concluded that the final design would not provide the required results. Initial tests on our first design showed the balloons did not inflate in the expected order. We assumed that the elasticity of the rubber balloons might be affecting our results. We then replaced them with non-elastic mylar balloons, but the problem persisted. Other attempts to fix the displays included using more metal foam, removing any bias in the piping system and using different types of pumps.

The failure of the system could be traced to the basic concept of the design itself. We built the display with the confidence airflow would be affected by different porosities of metal foam. Unfortunately, the initial flow rate of air required to show any measurable changes was too high. The required flowrate could have been achieved with a pressurized air pump. Following TSA restrictions, it was not possible to carry compressed air while traveling, and so we used an electrical pump, which could not provide a high enough flow rate.

The following are some suggested changes that the sponsor can implement once the displays are handed over. One proposed idea is to use water as the liquid in the system instead of air. The balloons could be replaced with some sort of measuring equipment such as a graduated cylinder to measure fluid output. Another suggestion is to use a lot more metal foam in the piping systems, that would increase the volume of foam that the air has to pass through and may show a difference in flow rates.

Through this manufacturing and testing process, we learned that testing the basic concept of the project very early on is important. We should have asked for the metal foam test pieces much earlier in the process and made sure there was a difference in air flow. We should also have focused on just one or two displays from the beginning of the project instead of having to cut down from three displays during the design stages. This would have given us the necessary time to do comprehensive tests prior to building the display.

9.2 Thermal Conductivity Display Results and Recommendations

The Thermal Conductivity Display was successfully manufactured and tested in the allotted time. Manufacturing the electric circuits was by far the most difficult portion of this project. However, the team was able to produce functional and robust circuitry. At the time of hand-off to the project sponsor, the display was able to successfully heat and cool the metal blocks while outputting the temperature both digitally and visually. In user testing, the surveys showed that users not only understood the purpose of the display, but also thought the display was eye catching and easy to use.

However, there is still significant room for improvement. The digital temperature outputs are less accurate than desired and should be replaced with a higher-end product. Additionally, in the shipment to ERG prior to the Senior Project Expo, some components were dislodged. To prevent this issue in the future, the power sources and blocks should be strapped down prior to transport; the team is currently using packing tape for this, but a permanent strap should be implemented.

If we had to do this project over again, we would allot more time and resources to the circuit manufacturing. The circuits ended up taking much longer to assemble, test, and reassemble than we expected. Additionally, the team would have implemented further transportation safety measures prior to shipping the display to ERG. This would include taping down additional components and adding Styrofoam corner protection.

10. Acknowledgements

The team could not have completed this project without the help of those around us. First and foremost, we would like to thank ERG Aerospace representatives Denver Schaffarzick and Jake Puppo for their guidance throughout this project. We would also like to acknowledge Dr. Vladimir Prodanov and Daniel Kasman for their electrical consultations on the Thermal Conductivity Display. Above all, we would like to thank our project advisor, Sarah Harding, for her unwavering support every step of the way.

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Appendix A: Gantt Chart

35 - Team Tetrakai	start	end
Problem Definition	**09/29/18**	**10/18/18**
Initial Design	**10/19/18**	**11/27/18**
Ideation	**10/19/18**	**10/27/18**
Ideation Session 1	10/19	10/19
Ideation Session 2	10/20	10/21
Ideation Session 3/4 (In class)	10/22	10/27
Sponsor Dinner	10/24	10/24
Meeting with Sponsor	10/25	10/26
Concept Model Preparation	10/26	10/26
Concept Model	**10/27/18**	**11/05/18**
Concept Model Sketches	10/27	10/27
Gather Concept Model Resources	10/28	10/29
Build Concept Model(s)	10/30	10/30
Pugh Matrices	11/01	11/02
Decision Matrix	11/04	11/05
Concept Prototype	**11/03/18**	**11/11/18**
Concept Prototype Sketching	11/03	11/06
Concept Prototype Materials	11/07	11/07
Build Concept Prototype	11/08	11/08
Rough CAD	11/09	11/11
Design Decisions	**10/31/18**	**11/12/18**
Component Research	10/31	11/11
Design Refinement	11/12	11/12
Design Sketches	11/10	11/11
PDR	**11/09/18**	**11/27/18**
Fix SOW Issues	11/09	11/13
Hazard Evaluation	11/09	11/11
Write Preliminary Design Review	11/09	11/12
Prepare Preliminary Design Present...	11/09	11/12
In-class PDR Presentation	11/13	11/13
PDR Peer Review	11/15	11/15
Submit PDR to Sponsor	11/16	11/16
Present PDR to Sponsor	11/27	11/27
Preliminary Design Review	11/27	11/27

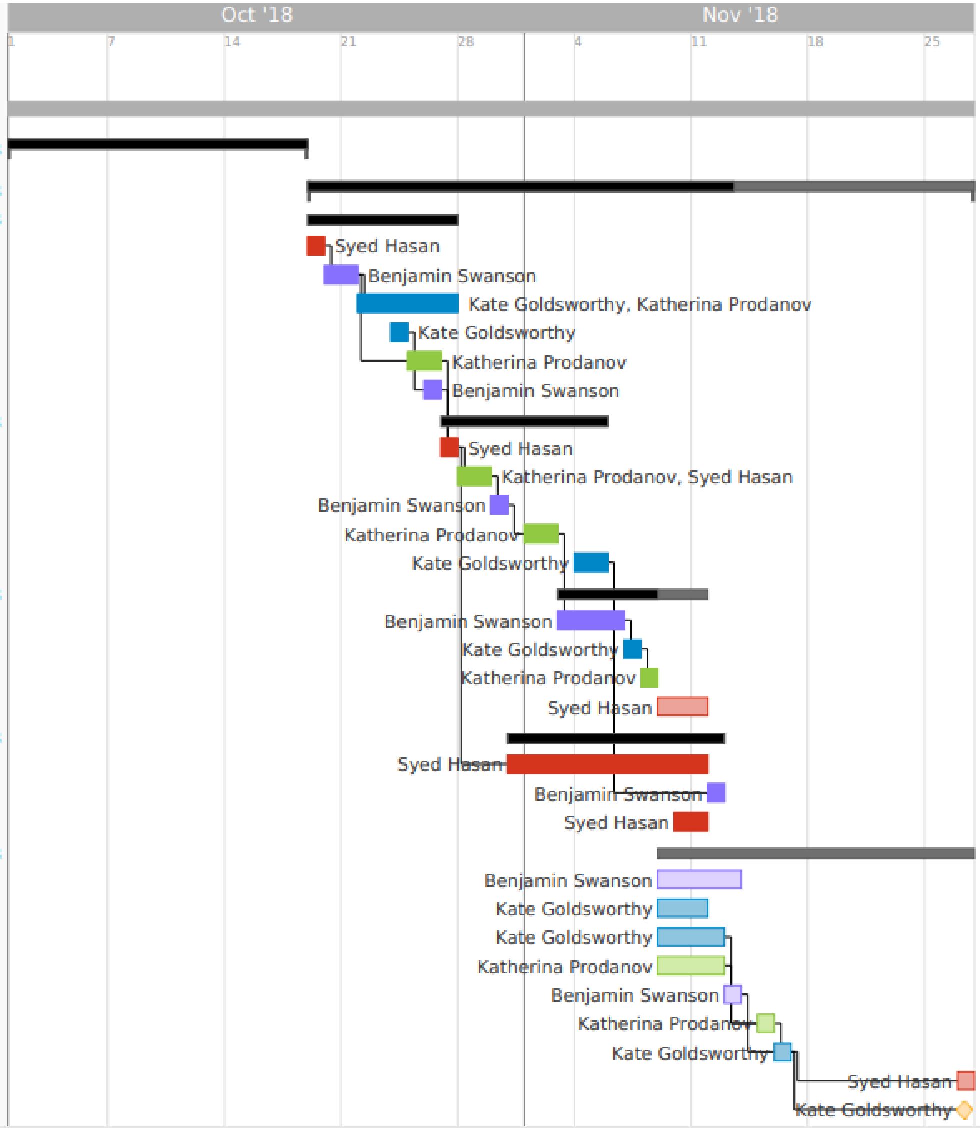


Figure A.1. Gantt chart for the first quarter of project tasks through Preliminary Design Report.

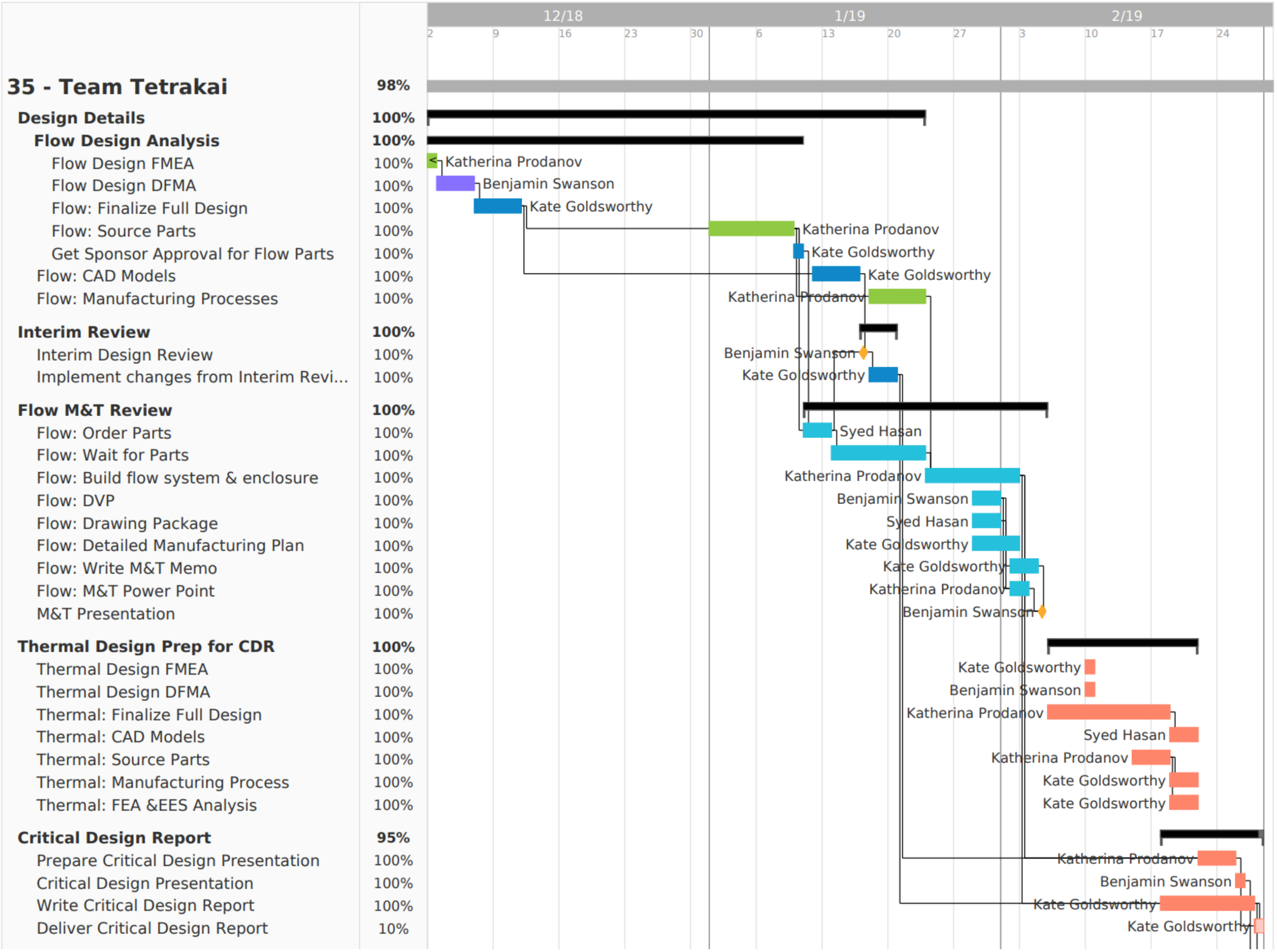


Figure A.2. Gantt chart for Preliminary Design Report through Critical Design Report.

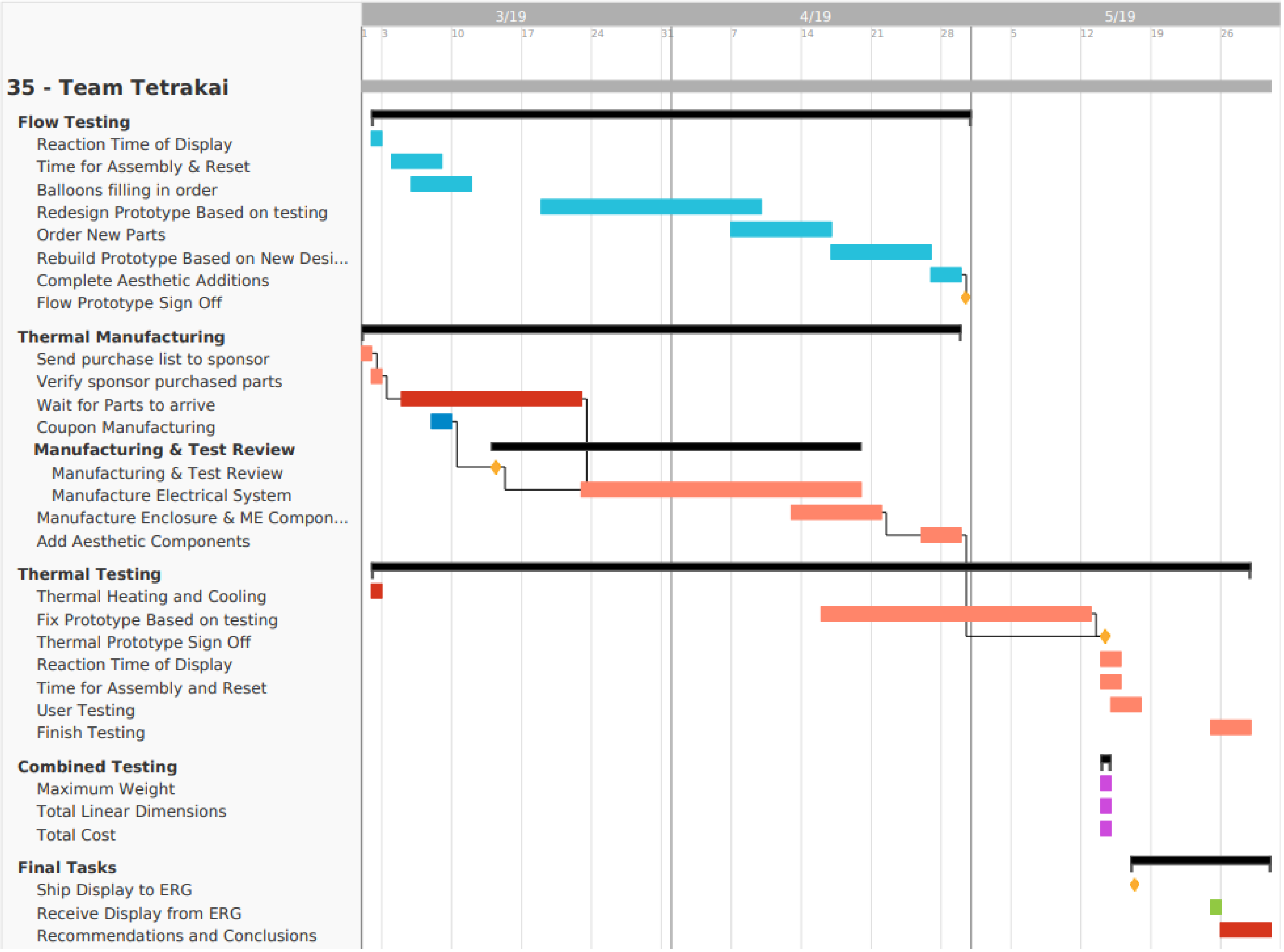
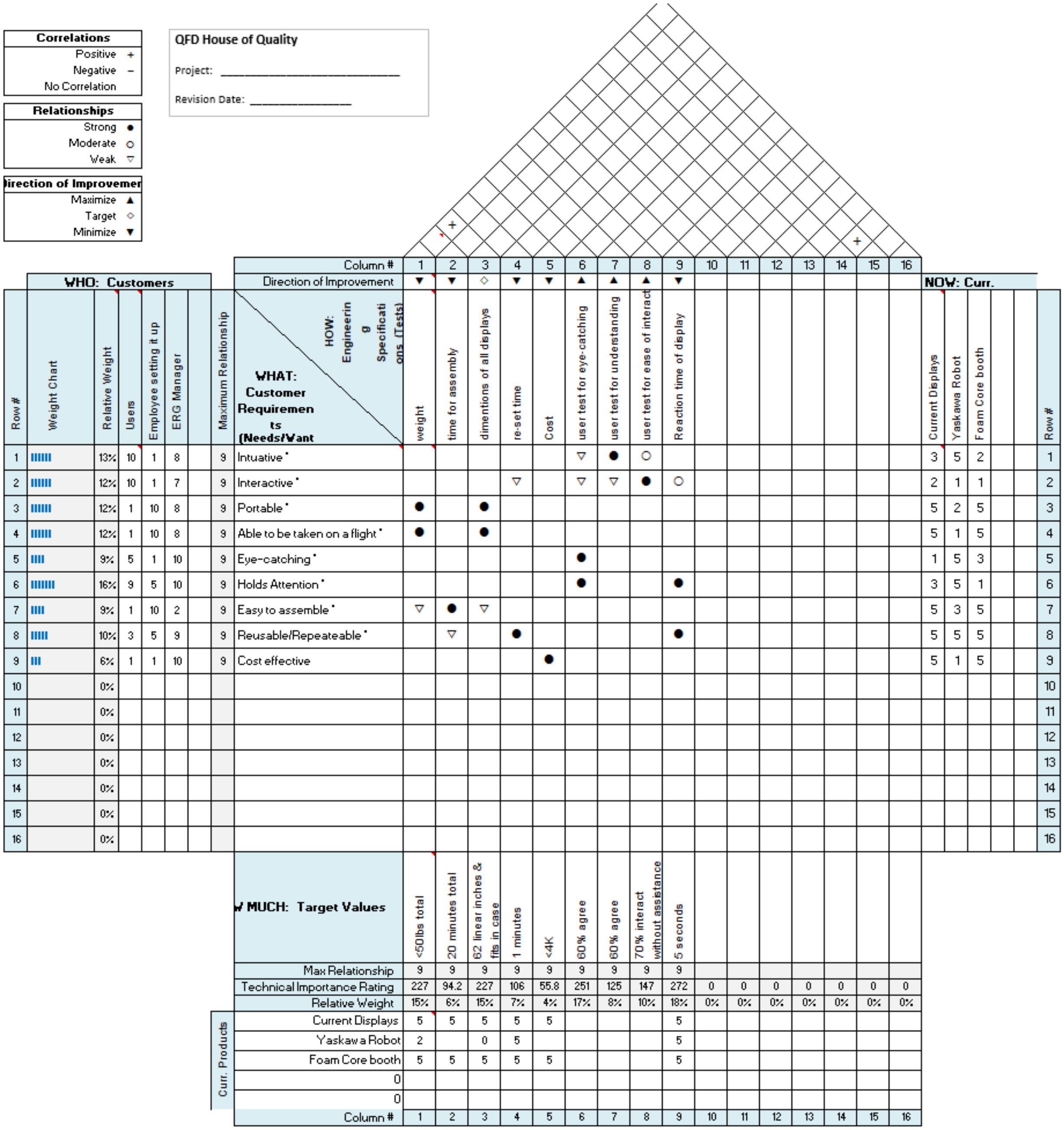


Figure A.3. Gantt chart for Critical Design Report through Project Expo.

Appendix B: QFD House of Quality



Correlations	
Positive	+
Negative	−
No Correlation	

Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼

QFD House of Quality

Project: ____________________________

Revision Date: ________________

Row #	Relative Weight	Users	Employee setting it up	ERG Manager	Maximum Relationship	WHAT: Customer Requirements (Needs/Wants)	1 weight (▼)	2 time for assembly (▼)	3 dimentions of all displays (◇)	4 re-set time (▼)	5 Cost (▼)	6 user test for eye-catching (▲)	7 user test for understanding (▲)	8 user test for ease of interact (▲)	9 Reaction time of display (▼)	Current Displays	Yaskawa Robot	Foam Core booth	Row #
1	13%	10	1	8	9	Intuative						▽	●	○		3	5	2	1
2	12%	10	1	7	9	Interactive				▽		▽	▽	●	○	2	1	1	2
3	12%	1	10	8	9	Portable	●		●							5	2	5	3
4	12%	1	10	8	9	Able to be taken on a flight	●		●							5	1	5	4
5	9%	5	1	10	9	Eye-catching						●				1	5	3	5
6	16%	9	5	10	9	Holds Attention						●			●	3	5	1	6
7	9%	1	10	2	9	Easy to assemble	▽	●	▽							5	3	5	7
8	10%	3	5	9	9	Reusable/Repeateable		▽		●					●	5	5	5	8
9	6%	1	1	10	9	Cost effective					●					5	1	5	9
10	0%																		10
11	0%																		11
12	0%																		12
13	0%																		13
14	0%																		14
15	0%																		15
16	0%																		16

Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
HOW MUCH: Target Values	<50lbs total	20 minutes total	62 linear inches & fits in case	1 minutes	<4K	60% agree	60% agree	70% interact without assistance	5 seconds							
Max Relationship	9	9	9	9	9	9	9	9	9							
Technical Importance Rating	227	94.2	227	106	55.8	251	125	147	272	0	0	0	0	0	0	0
Relative Weight	15%	6%	15%	7%	4%	17%	8%	10%	18%	0%	0%	0%	0%	0%	0%	0%
Curr. Products: Current Displays	5	5	5	5	5				5							
Yaskawa Robot	2		0	5					5							
Foam Core booth	5	5	5	5	5				5							
0																
0																

Figure B.1. Full QFD chart.

Column #	1	2	3	4	5	6	7	8	9
Direction of Improvement	▼	▼	◇	▼	▼	▲	▲	▲	▼
HOW: Engineering Specifications (Tests) / **WHAT: Customer Requirements (Needs/Wants)**	weight	time for assembly	dimentions of all displays	re-set time	Cost	user test for eye-catching	user test for understanding	user test for ease of interactior	Reaction time of display
Intuative *						▽	●	○	
Interactive *				▽		▽	▽	●	○
Portable *	●		●						
Able to be taken on a flight *	●		●						
Eye-catching *						●			
Holds Attention *						●			●
Easy to assemble *	▽	●	▽						
Reusable/Repeateable *		▽		●					●
Cost effective					●				

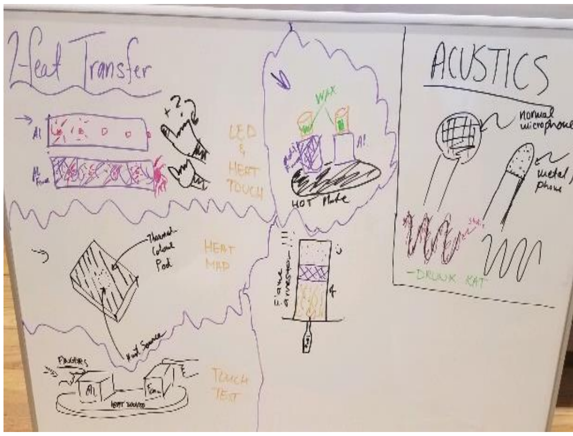
Figure B.2. Want and how sections of QFD chart.

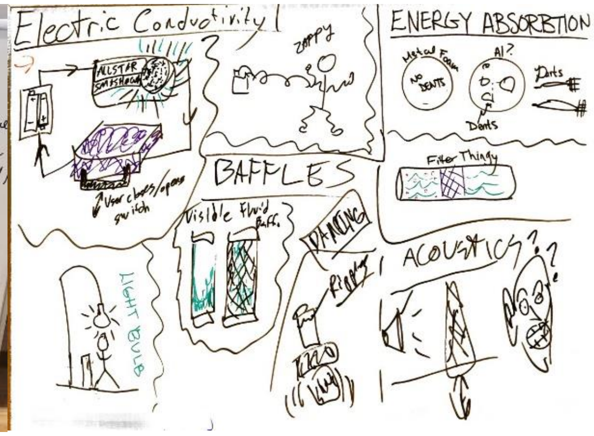
	HOW MUCH: Target Values	<50lbs total	20 minutes total	62 linear inches & fits in case	1 minutes	<4K	60% agree	60% agree	70% interact without assistance	5 seconds
	Max Relationship	9	9	9	9	9	9	9	9	9
	Technical Importance Rating	227	94.23	227	105.7	55.8	251.4	125.5	146.9	271.5
	Relative Weight	15%	6%	15%	7%	4%	17%	8%	10%	18%
Curr. Products	Current Displays	5	5	5	5	5				5
	Yaskawa Robot	2		0	5					5
	Foam Core booth	5	5	5	5	5				5
	0									
	0									
	Column #	1	2	3	4	5	6	7	8	9

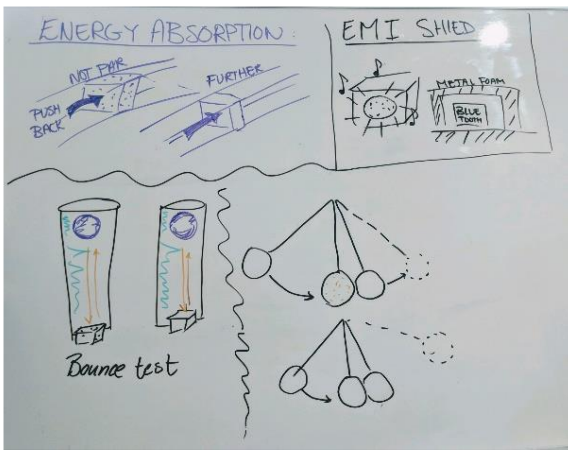
Figure B.3. Target value and current product sections of QFD chart.

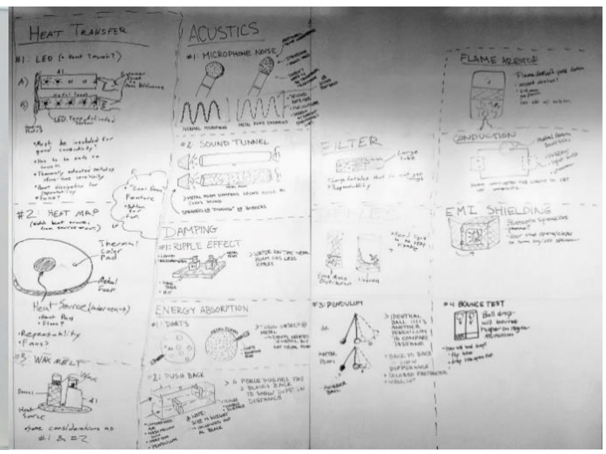
Appendix C: Complete List of Design Ideas

Ideation Sketches:





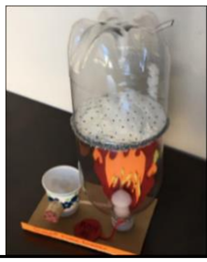
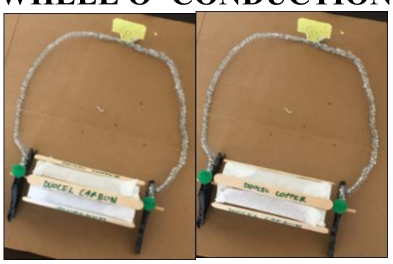




General Ideas List:

- LED heat transfer
- Wax melt heat transfer
- Color changing strip heat transfer
- Color changing pad heat map
- Butter melting heat transfer
- Tactile heat display
- Microphone acoustics
- Sound tunnel acoustics
- Ripple effect damping
- Balloon flow distribution
- Streamers airflow visual
- Dartboard energy absorption
- Push-back energy absorption
- Golfing energy absorption
- Newton's cradle energy absorption
- Particle filter
- Baffle
- EMI shielding
- Circuit conductivity
- Flame arrester
- Bounce test
- Rotating Baffle

Appendix C continued: Concept Models

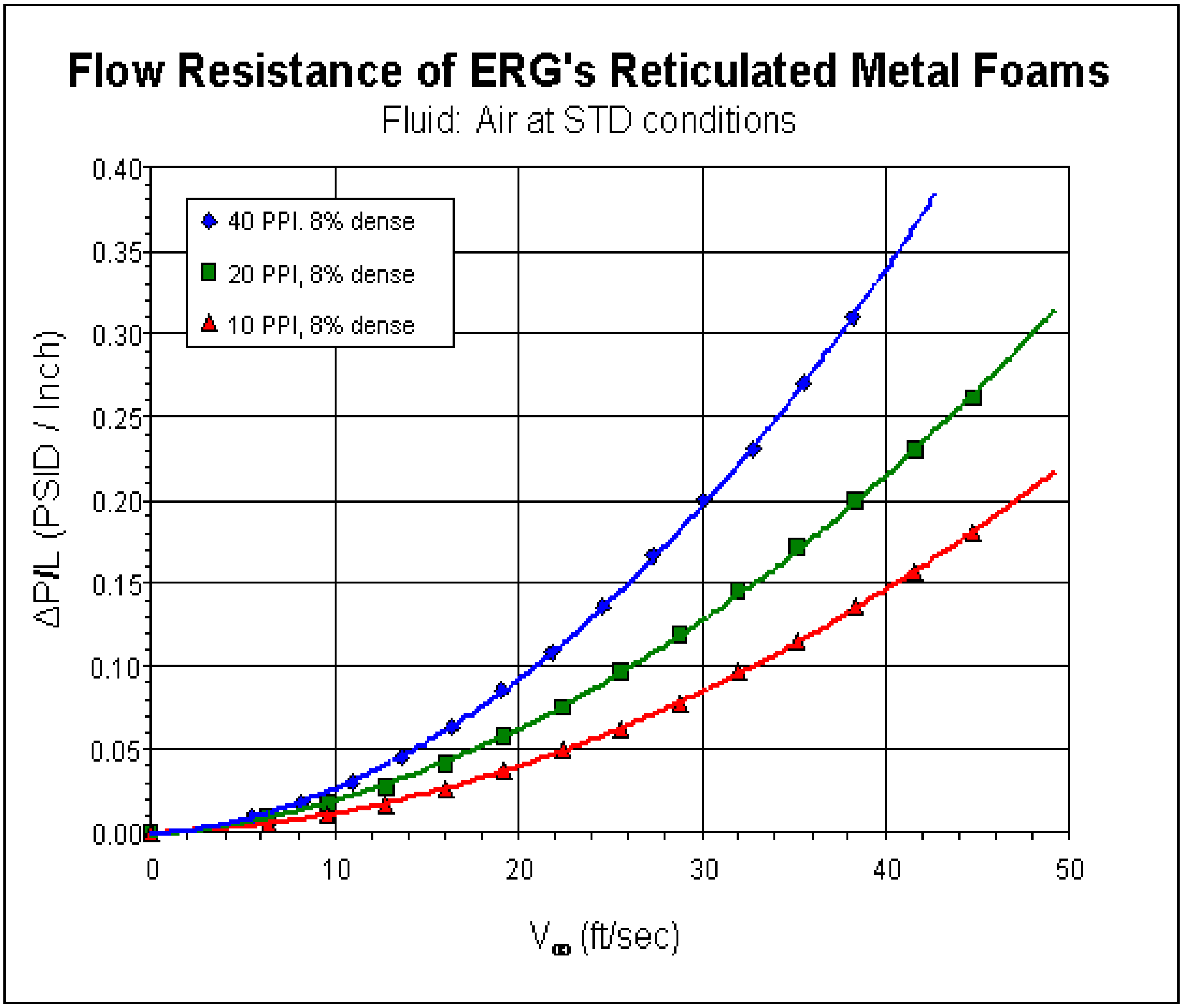
Concept Prototype	Description
"DE-ENERGIZER" DISPLAY 	**Main Concept: Energy Absorption** • Two tunnels for dropping ping-pong balls onto pieces of metal foam • Bounce height will change based on foam density/material • Foam blocks interchangeable (can compare types) • LED's along the inner walls light up when the ball passes to make the difference more visible
FLAME ARRESTER 	**Main Concept: Heat Dissipation** • Alcohol supplied to bottom of chamber and evaporated • Alcohol ignited with electric spark triggered by "PUSH ME" button • Flame will consume alcohol on bottom section but will not pass flame arrester foam • Vent at top of chamber to expel combustion products
WHEEL O' CONDUCTION 	**Main Concept: Conduction** • Electric circuit completed by metal foam to display conduction capabilities • Can rotate out different materials, coatings, etc • Light with change brightness depending on how well the material conducts • May also play sounds/have additional effects to draw attention
NEWTON'S CRADLE 	**Main Concept: Energy Absorption** • Newton's cradle where metal foam ball can be added/removed for comparison • With metal foam, energy will damp out quickly • Could have different materials or densities to compare
PARTICLE FILTER 	**Main Concept: Filtering** • Clear tube with compartments separated by metal foam of decreasing pore size • Liquid mixture with particles of various sizes/materials • When you flip over the filter, different size particles will make it through different levels, separating them out • Particles of the same size will be the same color
ROTATING BAFFLE 	**Main Concept: Baffle Application** • Two tubes with colored water (one with baffle and one without) on pivot points • When you flip the tube, you can see and feel the difference in flow • Very similar to current design with additional elements

Appendix D: Decision Matrix

CRITERIA	WEIGHTING	HEAT TRANSFER								ENERGY ABSORPTION					
		LED Heat Transfer		Heat Map		Wax Melt		Flame Arrestor		Bounce Test		Push Back		Newton's Cradle	
		Score	*Total*	*Score*	*Total*	*Score*	*Total*	*Score*	*Total*	*Score*	*Total*	*Score*	*Total*	*Score*	*Total*
Dimensions	2	4	8	3	6	3	6	2	4	2	4	2	4	5	10
Reaction Time	2	2	4	2	4	1	2	3	6	5	10	4	8	5	10
Eye-catching	4	4	16	3	12	2	8	5	20	3	12	3	12	2	8
Cost	3	3	9	2	6	4	12	1	3	3	9	3	9	5	15
Holds Attention	5	3	15	4	20	2	10	5	25	3	15	4	20	3	15
Interactive	4	3	12	3	12	2	8	2	8	4	16	5	20	2	8
Intuitive	3	4	12	4	12	3	9	4	12	4	12	4	12	4	12
Educational	5	4	20	5	25	4	20	5	25	4	20	4	20	5	25
Manufacturability	4	3	12	2	8	4	16	1	4	4	16	3	12	5	20
Portable	2	3	6	2	4	2	4	1	2	2	4	2	4	5	10
TSA eligibility	3	4	12	4	12	4	12	1	3	5	15	3	9	5	15
Repeatable	3	4	12	4	12	3	9	2	6	5	15	5	15	5	15
Usable at a tradeshow	4	5	20	5	20	5	20	2	8	5	20	3	12	5	20
Time/skill-appropriate	5	5	25	4	20	3	15	1	5	4	20	3	15	2	10
	TOTAL SCORE:	183		173		151		131		188		172		193	

CRITERIA	WEIGHTING	Fluid Flow												MISCELLANEOUS			
		Filter		Floating Foam		Flow Resistance		Hour Glass		Streamer Airflow		Rotating Baffle		EMI Shielding		Electrical Conductivity	
		Score	*Total*	*Score*	*Total*	*Score*	*Total*	*Score*	*Total*	*Score*	*Total*	*Score*	*Total*	*Score*	*Total*	*Score*	*Total*
Dimensions	2	5	10	1	2	3	6	4	8	3	6	4	8	5	10	3	6
Reaction Time	2	4	8	5	10	4	8	5	10	5	10	4	8	5	10	5	10
Eye-catching	4	2	8	4	16	4	16	2	8	3	12	2	8	1	4	4	16
Cost	3	4	12	2	6	4	12	4	12	2	6	4	12	5	15	3	9
Holds Attention	5	3	15	2	10	3	15	2	10	2	10	2	10	2	10	4	20
Interactive	4	3	12	2	8	5	20	3	12	2	8	3	12	1	4	5	20
Intuitive	3	5	15	3	9	4	12	5	15	2	6	2	6	2	6	4	12
Educational	5	2	10	3	15	3	15	2	10	3	15	3	15	4	20	5	25
Manufacturability	4	2	8	2	8	4	16	3	12	3	12	5	20	5	20	4	16
Portable	2	4	8	1	2	4	8	4	8	1	2	5	10	5	10	4	8
TSA eligibility	3	5	15	2	6	4	12	5	15	2	6	5	15	5	15	4	12
Repeatable	3	4	12	5	15	4	12	5	15	5	15	5	15	5	15	5	15
Usable at a tradeshow	4	5	20	3	12	5	20	5	20	3	12	5	20	2	8	5	20
Time/skill-appropriate	5	3	15	4	20	3	15	2	10	4	20	2	10	1	5	3	15
	TOTAL SCORE:	168		139		187		165		140		169		152		204	

Appendix E: Fluid Flow Control Chart



Appendix F: Pugh and Morphological Matrices

SUB-FUNCTION:	Air pump mechanism				
	Datum	*Option 1*	*Option 2*	*Option 3*	*Option 4*
CRITERIA	**Compressed air**	**Hand pump**	**Bike pump**	**Foot pump**	**Air compressor**
Cost	s	+	+	+	+
Transportability	s	+	+	+	-
TSA Allowable	s	+	+	+	+
Flowrate	s	-	-	-	s
Power Source	s	+	+	+	-
Compatibility	s	-	s	-	s
TOTALS	**0**	**+2**	**+3**	**+2**	**0**

SUB-FUNCTION:	Display Airflow				
	Datum	*Option 1*	*Option 2*	*Option 3*	*Option 4*
CRITERIA	**Airflow meter**	**Balloons**	**Streamers**	**Pitot Tube**	**Floating Ball**
Readability	s	-	-	s	-
Eye-catching	s	+	+	-	+
Portability	s	+	+	s	+
Compatibility	s	+	-	-	-
Cost	s	+	+	s	+
Repeatability	s	+	+	+	-
TOTALS	**0**	**+4**	**+2**	**1**	**3**

SUB-FUNCTION:	Metal Foam Placement		
	Datum	*Option 1*	*Option 2*
CRITERIA	**Switchable Foam**	**3+ Displays**	**Slide Selector**
Ease of Use	s	+	s
Eye-Catching	s	+	s
Interactive	s	s	s
Cost Effective	s	-	-
Ease of Understanding	s	+	-
Portability	s	-	-
TOTALS	**0**	**+1**	**-3**

SUB-FUNCTION	*Flow Resistance Display*				
Air Pump	Compressed air	Hand pump	Bike pump	Foot pump	Air compressor
Metal Foam Placement	Switchable Foam	3+ Displays	Slide Selector		
Display Airflow	Airflow meter	Balloons	Streamers	Pitot Tube	Floating Ball

SUB-FUNCTION:	Heat Source			
	Datum	*Option 1*	*Option 2*	*Option 3*
CRITERIA	**Heat Plate**	**Flame**	**Hair Dryer**	**Hot Fluid**
Time to Heat	s	+	-	s
Consistency	s	-	-	+
TSA Allowable	s	-	s	s
Portability	s	-	+	-
Power Source	s	-	s	-
TOTALS	**0**	**-3**	**-1**	**-1**

SUB-FUNCTION:	Heat Detection				
	Datum	*Option 1*	*Option 2*	*Option 3*	*Option 4*
CRITERIA	**Thermometer**	**Thermocouples**	**Tactile**	**Wax**	**MEMs**
Precision	s	+	-	-	+
Size	s	+	+	s	+
Sensitivity	s	+	-	-	+
Cost	s	+	+	+	-
Compatibility with display	s	+	-	s	+
Accurate	s	+	-	-	+
TOTALS	**0**	**+5**	**-2**	**-2**	**+4**

SUB-FUNCTION:	Heat Display					
	Datum	*Option 1*	*Option 2*	*Option 3*	*Option 4*	*Option 5*
CRITERIA	**Mercury**	**LEDs**	**Digital readout**	**Color Strip**	**Wax**	**Tactile**
Eye-catching	s	+	-	+	+	-
Intuitive	s	+	+	+	+	s
Compatibility	s	+	s	+	-	-
Range	s	s	+	-	-	-
TOTALS	**0**	**+3**	**+1**	**+2**	**0**	**-3**

SUB-FUNCTION	*Thermal Conductivity Display*					
Heat Source	Heat Plate	Flame	Hair Dryer	Hot Fluid		
Heat Detection	Thermometer	Thermocouples	Tactile	Wax	MEMs	
Heat Display	Mercury	LEDs	Digital readout	Color Strip	Wax	Tactile

SUB-FUNCTION:	How to switch materials			
	Datum	*Option 1*	*Option 2*	*Option 3*
CRITERIA	**Building Blocks**	**Flat Wheel**	**Sliding**	**Barrel Wheel**
Interactive	S	S	S	S
Eye-catching	S	S	S	+
Ease of use	S	+	S	+
Reliability	S	-	-	-
Ease of labeling	S	+	+	+
Level of containment	S	+	S	+
TOTALS	**0**	**+2**	**0**	**+3**

SUB-FUNCTION:	How to display conductivity					
	Datum	*Option 1*	*Option 2*	*Option 3*	*Option 4*	*Option 5*
CRITERIA	**Multimeter**	**Lightbulb**	**LEDs**	**Sound/music**	**Van de Graff**	**Magnetic Particles**
Eye-catching	S	+	+	+	+	+
Range	S	-	S	-	-	-
Cost	S	S	S	S	-	-
Feasibility	S	S	S	S	-	-
TOTALS	**0**	**0**	**+1**	**0**	**-2**	**-2**

SUB-FUNCTION	*Electrical Conductivity Display*					
Switching Materials	Building Blocks	Flat Wheel	Sliding	Barrel Wheel		
Display Voltage	Multimeter	Lightbulb	LEDs	Sound/Music	Van de Graff	Magnetic Particles

Appendix G: Hazard Checklists

<u>Display: Flow Control</u>

Y	N	
☐	✔	1. Will the system include hazardous revolving, running, rolling, or mixing actions?
☐	✔	2. Will the system include hazardous reciprocating, shearing, punching, pressing, squeezing, drawing, or cutting actions?
☐	✔	3. Will any part of the design undergo high accelerations/decelerations?
☐	✔	4. Will the system have any large (>5 kg) moving masses or large (>250 N) forces?
✔	☐	5. Could the system produce a projectile?
✔	☐	6. Could the system fall (due to gravity), creating injury?
☐	✔	7. Will a user be exposed to overhanging weights as part of the design?
☐	✔	8. Will the system have any burrs, sharp edges, shear points, or pinch points?
☐	✔	9. Will any part of the electrical systems not be grounded?
☐	✔	10. Will there be any large batteries (over 30 V)?
☐	✔	11. Will there be any exposed electrical connections in the system (over 40 V)?
✔	☐	12. Will there be any stored energy in the system such as flywheels, hanging weights or pressurized fluids/gases?
☐	✔	13. Will there be any explosive or flammable liquids, gases, or small particle fuel as part of the system?
☐	✔	14. Will the user be required to exert any abnormal effort or experience any abnormal physical posture during the use of the design?
☐	✔	15. Will there be any materials known to be hazardous to humans involved in either the design or its manufacturing?
✔	☐	16. Could the system generate high levels (>90 dBA) of noise?
☐	✔	17. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, or cold/high temperatures, during normal use?
☐	✔	18. Is it possible for the system to be used in an unsafe manner?
~~☐~~	~~☐~~	~~19. For powered systems, is there an emergency stop button?~~
☐	✔	20. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

Display: Thermal Conduction

Y	N	
✔	☐	1. Will the system include hazardous revolving, running, rolling, or mixing actions?
☐	✔	2. Will the system include hazardous reciprocating, shearing, punching, pressing, squeezing, drawing, or cutting actions?
✔	☐	3. Will any part of the design undergo high accelerations/decelerations?
☐	✔	4. Will the system have any large (>5 kg) moving masses or large (>250 N) forces?
☐	✔	5. Could the system produce a projectile?
✔	☐	6. Could the system fall (due to gravity), creating injury?
☐	✔	7. Will a user be exposed to overhanging weights as part of the design?
☐	✔	8. Will the system have any burrs, sharp edges, shear points, or pinch points?
☐	✔	9. Will any part of the electrical systems not be grounded?
☐	✔	10. Will there be any large batteries (over 30 V)?
☐	✔	11. Will there be any exposed electrical connections in the system (over 40 V)?
☐	✔	12. Will there be any stored energy in the system such as flywheels, hanging weights or pressurized fluids/gases?
☐	✔	13. Will there be any explosive or flammable liquids, gases, or small particle fuel as part of the system?
☐	✔	14. Will the user be required to exert any abnormal effort or experience any abnormal physical posture during the use of the design?
☐	✔	15. Will there be any materials known to be hazardous to humans involved in either the design or its manufacturing?
☐	✔	16. Could the system generate high levels (>90 dBA) of noise?
☐	✔	17. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, or cold/high temperatures, during normal use?
✔	☐	18. Is it possible for the system to be used in an unsafe manner?
✔	☐	19. For powered systems, is there an emergency stop button?
✔	☐	20. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

Appendix H: Preliminary Calculations

Thermal Conduction Timing:

One dimensional heat flow equation,

$$\frac{\Delta Q}{\Delta t} = \frac{k A (\Delta T)}{\Delta x}$$

$Q = 150W$ [Spec. for heating pad]

$k_{AL} = 205\ W/mK$

$A = 1in \times 1in\ [0.0254m \times 0.0254m]$

$\Delta T = 40$ [Pad temp − Room temp]

$\Delta x = 12in \approx 0.3048$

$$t = \frac{\Delta Q\ \Delta x}{k\ A\ \Delta T}$$

$$= \frac{(150\,W)(0.3048\,m)}{\left(205\,\frac{W}{mK}\right)(0.0254)m^2(40)}$$

$$= 8.64 \text{ seconds}$$

DESIGN DISPLAY 3		CALCULATED BY:
ELECTRICAL CONDUCTIVITY	POWER CONSUMPTION	KATHERINA PRODANOV

HARDWARE & SPECIFICATIONS:

- ARDUINO MEGA 2560
  - → $I_{AM} = 52\,mA$
  - → 54 digital input/output pins
  - → DIRECT 5V OR USB
- ADAFRUIT LED DRIVER BREAKOUT BOARD
  - → 24 independent LED drivers
  - → $I_{LED} = 2$ to $80\,mA$
- POWER BANK
  - → $V_{OUT} = 5\,V$
  - → $I_{OUT} = 1000\,mA$
  - → Capacity = 2200 mAh

BASED ON THE ARDUINO, 24 WHITE LEDS, AND THE POWER BANK RATING, THE LED CURRENT & MAX ON TIME FOR THE DEVICE WILL BE DETERMINED.

$$I_{LED_{TOTAL}} = N_{LED}\, I_{LED}$$

WERE $N_{LED} \equiv$ number of LEDs
$I_{LED} \equiv$ LED current in mA

$$I_{LED_{TOTAL\,MAX}} = \frac{B_{CAP}}{t_{RUN}} - I_{AM}$$

WHERE $B_{CAP} \equiv$ capacity of power bank in mAh
$t_{RUN} \equiv$ time the device can run undisturbed
$I_{AM} \equiv$ Arduino current draw in mA

$$I_{LED_{TOTAL}} = I_{LED_{TOTAL\,MAX}}$$

$$N_{LED}\, I_{LED} = \frac{B_{CAP}}{t_{RUN}} - I_{AM}$$

REARRANGE SUCH THAT LED CURRENT IS A FUNCTION OF t_{RUN}

$$I_{LED} = \frac{\left(\frac{B_{CAP}}{t_{RUN}}\right) - I_{AM}}{N_{LED}}$$

$$I_{LED} = \frac{1}{N_{LED}}\left[\left(\frac{B_{CAP}}{t_{RUN}}\right) - I_{AM}\right]$$

LET $t_{RUN} = 8\,h$
$N_{LED} = 24$
$B_{CAP} = 2200\,mAh$
$I_{AM} = 52\,mA$

$$I_{LED} = \frac{1}{24}\left[\left(\frac{2200\,mAh}{8\,h}\right) - 52\,mA\right]$$

$\therefore I_{LED} = 9.29\,mA$ ✓ WITHIN RANGE

Appendix I: Electrical Conductivity Display Design

The third concept selected was an Electrical Conductivity Display. This design features an LED panel that lights up according to the electrical conductivity each Duocel® foam material (i.e. copper, aluminum, carbon, and coated metal). It serves to showcase the variety of conductivity levels available from ERG. The user interacts with the display by rotating a wheel with foams of various materials mounted to it. When the foam is lined up with metal contacts, a circuit is completed turning on LEDs that spell "ERG". The number of LEDs turned on by each foam segment will be normalized such that the most conductive material lights up the entire display and the least conductive segment will turn on no LEDs. Figure 15 shows the preliminary computer-aided model with a single light bulb representing a series of LEDs.

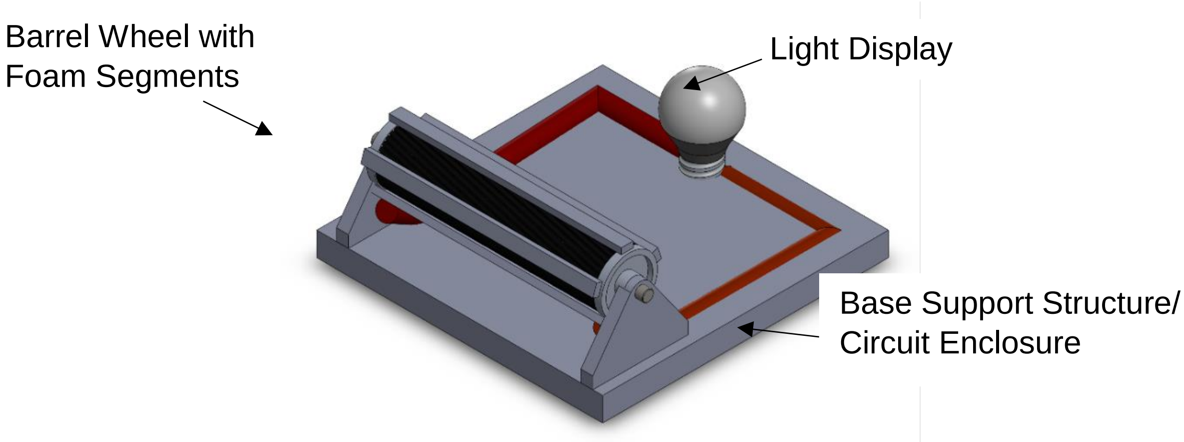


Figure 37. Preliminary CAD model of the electrical conductivity display.

In order to better visualize the final product, the team built an aesthetic concept prototype for this display. Figure 16 shows the LED panel spelling out "ERG" as well as the rotating wheel of foams.

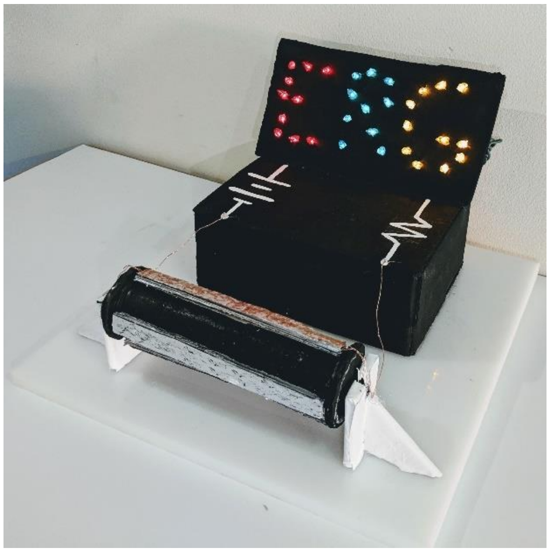


Figure. Preliminary concept prototype of the electrical conductivity display.

Pugh matrices were used to decide the way the conductivity levels would be displayed and the method by which the user would switch between the foams. The Pugh matrix used to determine the foam switching method resulted in a rotating barrel wheel as the top choice. This matrix can be seen in Appendix F. Table 7 shows the Pugh matrix for the "how to display conductivity" sub-function.

Table 13. Pugh matrix for ways to display conductivity

SUB-FUNCTION:	How to display conductivity					
	Datum	*Option 1*	*Option 2*	*Option 3*	*Option 4*	*Option 5*
CRITERIA	**Multimeter**	**Lightbulb**	**LEDs**	**Sound/music**	**Van de Graff**	**Magnetic Particles**
Eye-catching	S	+	+	+	+	+
Range	S	-	S	-	-	-
Cost	S	S	S	S	-	-
Feasibility	S	S	S	S	-	-
TOTALS	**0**	**0**	**+1**	**0**	**-2**	**-2**

The Pugh matrix analysis resulted in LEDs being the top display choice, as compared to the multimeter datum, a single light bulb, sound/music, a Van de Graff machine, and movement of magnetic particles. Each idea was compared to the multimeter datum according to the listed criteria: eye-catching, range, cost, and feasibility, where range indicates how obvious the difference in conductivity will be to the user. The Van de Graff machine and movement of magnetic particles ideas, although eye-catching, proved to be undesirable due to their potential lack of range, high cost, and complexity. The single light bulb and sound/music were shown to be more eye-catching than the multimeter but were less desirable due to their lack of range. As compared to the multimeter, LEDs come out as slightly more favorable due to a greater visual appeal. Additionally, through circuitry and programming, we can have control over each sperate LED resulting in a similar range as the multimeter, at a similar cost and feasibility. As such, LEDs were selected.

The component materials under consideration for the base supporting structure are acrylic, wood, and metal. Light emitting diodes will make up the light display, and the wheel will be made of acrylic or other plastic to prevent current loss between the foam and apparatus. The LED display will be controlled by an Adafruit LED Driver and an Arduino which will also serve as a meter for the metal conductivity. The exact circuit, control configuration, programming, and foam-to-circuit contacts are currently unknown.

This design meets our sponsor's needs by showcasing a property of their foam in an interactive way. Additionally, the variable LED display promotes company name recognition and an understanding of the various conductivity levels available. According to the preliminary power consumption calculations presented in Appendix H, the display can be self-contained and run for 8 hours with a 5 volt, 2200 mAh rated power bank. This allows the display to be portable and TSA compliant. The design will require minimal assembly and, due to the longevity of the preliminary material selections, to be highly reusable.

The anticipated hazards for this design are minimal. We anticipate the potential for a pinch point at the point of rotation of the barrel wheel. This hazard will be mitigated by orienting the wheel to minimize access to the pinch point and creating guards to discourage users from encountering the pinch point. The display will be designed to minimize sharp edges, and special care will be taken to remove burrs and smooth sharp edges on machined components. As this is a tabletop display, there is the potential for it falling off the table resulting in an injury. We will minimize this possibility by providing instructions on proper placement of the design on the table (i.e. away from the edges) and creating a design with a low center of gravity to prevent tipping. Finally, the greatest potential from misuse of the device is the use of an improper power source. This could result in damage to the system and a hazardous malfunction. As the system will only be specified to power a microcontroller and LEDs, any power source which has a higher than specified voltage has the potential to be hazardous. We will enclose the power source and electronics to prevent tampering and provide proper instructive and warning labels for battery changes. A full list of the hazards considered can be seen in the Hazards Check List presented in Appendix G.

Appendix J: FMEA

Display: Flow Control

												Action Results			
System / Function	Potential Failure Mode	Potential Effects of the Failure Mode	Severity	Potential Causes of the Failure Mode	Current Preventative Activities	Occurence	Current Detection Activities	Detection	Priority	Recommended Action(s)	Responsibility & Target Completion Date	Actions Taken	Severity	Occurence	Criticality
Flow/ Deliver air	Tubes pinched	Balloons don't inflate	7	Tubes Tangled Something heavy on tubes	Short Tubes, Rigid Tubes	1	Visual	2	14						
	Air leaks	Balloons don't inflate	8	Badly connected junctions Punctures	Rigid Tubes Sealent at Junctions	3	Visual	4	96	Provide leak detector. Use strong sealant and teflon tape. Use interference fit.	Syed Feb. 8. 2019	Used interference fit barbs to create seal.	8	1	4
Flow/ Maintain Pressure	Valve breaks	Balloons don't stay inflated	5	Spring loosens over times	Make Valve Replacable	2	Visual	4	40						
Balloon/Display Property	Ballons break/get stuck	Balloons don't inflate	8	Old balloons	Balloons are Switchable	4	Visual	1	32						
Balloon/ Prevent unlimited expansion	Balloons pop	Property not shown	10	Balloon expands to much	Balloons are Switchable	1	Visual	1	10						
	Enclosure Breaks	Other balloons don't inflate	6	Impact forces		1	Visual	1	6						
Stand/ Maintain stability	Leg breaks	a) Display falls over b) Sharp edges exposed	9	Heavy object placed on display Display falls	No Exposed Surface to Place Anything On	2	Visual	1	18						
	No traction	Display falls off table	5	Someone pushes display	High-friction pads on feet	3	Test on surface	3	45						
General/ Holds Parts together	Loose fasteners	Display comes apart	10	Vibrations in transport	Self-Locking Fasteners	2	Tactile shake test	4	80	High-Quality Fasteners, Check for "Back Out", Avoid Fasteners When Possible	Ben Swanson Feb 8, 2019	Did not use fastensers, the system was designed to fit together.	7	1	2
	Adhesive doesnt bond	Display comes apart	10	Moisture content or temperature changes	Avoid Adhesive Critical Areas	2	Visual	4	80	Use high quality adhesive for proper bonding	Kate Goldsworthy Feb. 2019	Acryllic cement adhesive bonded the system together	7	1	2
General/ Maintains appearance	Surfaces are damaged	Display looks worn out	4	Wear over time	Sealant over paint	3	Visual	1	12						

Display: Thermal

System / Function	Potential Failure Mode	Potential Effects of the Failure Mode	Severity	Potential Causes of the Failure Mode	Current Preventative Activities	Occurence	Current Detection Activities	Detection	Priority	Recommended Action(s)	Responsibility & Target Completion Date	Actions Taken
Heat/ Heat metals	Loss of power	Element doesn't heat up	10	Bad connections Low battery	Excellent soldering Replacable batteries	2	Tempurature Read out	1	20			
	Metal blocks dislodged	Blocks don't heat up	9	External force	Internal fixures	1	Visual	1	9			
Heat/ Insulate surfaces	Melting or burning	Damaged enclosure	6	Insulation not thermally resistant	Extra insulation	2	Visual	1	12			
Heat/ Provide convective cooling	Loss of power	Fans don't spin	8	Bad connections Low battery	Excellent soldering Replacable batteries	2	Visual	1	16			
	Obstruction of fans	Fan don't spin	8	Foreign objects	Fan covering	2	Visual	1	16			
Measurement/ read tempurature	Thermistor is disloged	incorrect temperature reading	9	External force	Internal fixure	3	Tempurature Read out	3	81	Use aheasive and fixture to keep in place	Ben Swanson April 2019	
	Wires are disconnected	no temperature reading	10	Bad connections external force	Excellent soldering Internal fixtures	2	Tempurature Read out	2	40	Excellent solder bond with shrink tubes	Katherina Prodanov April 2019	
Display/ visulaize temperature	Wires are disconnected	Property not shown	10	Bad connections External force	Excellent soldering Internal fixtures	2	Visual	2	40	Excellent solder bond with shrink tubes	Kate Goldsworthy April 2019	
	LED blulb burns out	Property not shown	5	Incorrect power application	Replacable LEDs	1	Visual	1	5			
Enclosure/ Maintain stability	No traction	Display falls off table	4	Someone pushes display	High-friction pads on feet	3	Test on surface	2	24			
Enclosure/ Allow for air flow	Ventilation obstructed	Gets too hot	4	Foreign objects	Warning signs User training	2	Tactile	2	16			
General/ Holds Parts together	Loose fasteners	Display comes apart	3	Vibrations in transport	Self-Locking Fasteners	2	Tactile shake test	2	12			
	Adhesive doesnt bond	Display comes apart	5	Moisture content or temperature changes	Avoid Adhesive Critical Areas	2	Visual	3	30			
General/ Maintains appearance	Surfaces are damaged	Display looks worn out	2	Wear over time	Sealant over paint	3	Visual	1	6			

Appendix K: Project Budget (Venders and Links Shown in Appendix Y)

Table K.1. Project Budget for the Flow Control Display

ITEM	DESCRIPTION	QTY.	UNIT PRICE	TOTAL PART PRICE
Tubing	10ft, 3/8" ID x 1/2" OD PVC flexible plastic tubing.	1	$ 7.89	$ 7.89
Check Valve	2Pcs 10mm 3/8" ABS	1	$ 8.98	$ 8.98
Splitter & release valve	4 Way Heavy Duty Hose Splitter	1	$ 22.47	$ 22.47
Barb tube connectors	Female Garden Hose Thread with 3/8" Barb	11	$ 6.36	$ 69.96
Male to male converter	Double male 3/4-inch male on both ends.	1	$ 4.86	$ 4.86
Acrylic Cylinders	4"x8" diameter clear plastic cylinders 4 pack	1	$ 28.99	$ 28.99
Adhesive	Acrylic Cement, 5 Ounce Tube, Clear	1	$ 7.19	$ 7.19
Small Balloons	5" Red Latex Ballons 72 pack	1	$ 7.24	$ 7.24
Large Balloons	10" Red Latex Ballons 72 pack	1	$ 7.99	$ 7.99
Foot pump	High volume foot bellows	1	$ 9.97	$ 9.97
Hand pump	19.8 x 9.1x 15.2"pump	1	$ 18.44	$ 18.44
Red Acrylic Sheet	1/8" 12x12 cast red acrylic sheet	1	$ 9.99	$ 9.99
Black Acrylic Sheet	0.250" 24x48 black acrylic sheet	1	$ 64.66	$ 64.66
Acrylic rod	6' x 0.5" DIA. clear rod	1	$ 9.35	$ 9.35
PVC Nipple	3/4" x 3" Clear PVC Pipe Nipple	4	$ 5.38	$ 21.52
			TOTAL PRICE	$ 299.50

Table K.2. Project Budget for the Thermal Display

ITEM	DESCRIPTION	QTY.	UNIT PRICE	TOTAL PART PRICE
Flexible Heater	Mxfans 4.5x10cm 24V 30W PI Plastic Heating Film Heater Adhesive Back	4	$ 2.35	$ 9.40
Digital Thermocouple Readout	UCTRONICS -30-800 Degree Centigrade Digital Temperature Meter Blue LED Display K-type Thermocouple Temp Sensor 2-wires Reverse Polarity Protection with Black Case	2	$ 10.49	$ 20.98
Aluminum Block	6061 Aluminum 1" Thick x 4" Wide x 6" Long	1	$ 21.90	$ 21.90
Metal Foam Block	1" Thick x 4" Wide x 4" Long	1	$ -	$ -
Thermistor	THERM NTC 10KOHM 3435K PROBE	3	$ 7.57	$ 22.71
Resistors	RES 2.94K OHM 1/4W 1% AXIAL (Vishay Dale)	5	$ 0.67	$ 3.35
Arduino	ARDUINO MEGA 2560 REV3 [A000067]	1	$ 30.50	$ 30.50
Jumbo LEDs	10mm Jumbo Diffused LED Super Red	20	$ 0.55	$ 11.00
LEDS	LED Uni-Color Red 635nm 2-Pin T-1 3/4 (Lite-on)	20	$ 0.12	$ 2.40
Fans	Corsair ML120 Pro LED, Red, 120mm Premium Magnetic Levitation Cooling Fan CO-9050042-WW	2	$ 27.99	$ 55.98
Heat Shrink Tubing	560PCS Heat Shrink Tubing 2:1, Eventronic Electrical Wire Cable	1	$ 8.99	$ 8.99
Button	Adafruit: Large Arcade Button with LED - 60mm Red	1	$ 5.95	$ 5.95
Protoboard Sheild	RobotDyn - Mega Protoshield Prototype Shield with Mini breadboard, for Arduino Mega 2560 (Assembled)	1	$ 8.99	$ 8.99
Wires	Striveday™Flexible Silicone Wire 18awg Electric wire 18 gauge	1	$ 18.99	$ 18.99
Pins	DEPEPE 30 Pcs 40 Pin 2.54mm Male and Female Pin Headers for Arduino Prototype Shield	1	$ 5.99	$ 5.99
Heat-Set Inserts	Brass Heat-Set Inserts for Plastic ; 6-32 Thread Size, 0.150" Installed Length	1	$ 9.25	$ 9.25
Black Acrylic Sheet	0.250" 24x48 black acrylic sheet	2	$ 64.66	$ 129.32
Clear Acryllic Sheet	0.250" X 24" X 48" CLEAR ACRYLIC SHEET	1	$ 69.08	$ 69.08
24V power supply	150W 24V 6.5A Enclosed Switchable AC-to-DC Power Supply	1	$ 23.40	$ 23.40

ITEM	DESCRIPTION	QTY.	UNIT PRICE	TOTAL PART PRICE
5 & 12V power supply	54W Dual Output 5V 6A and 12V 2A Enclosed Switching Power Supply	1	$ 14.95	$ 14.95
Power Cord	6 Foot 3 Conductor SVT Power Cord with Pigtails	1	$ 4.95	$ 4.95
Thermal Switch	Resettable thermal switch Bourns Inc.	3	$ 1.92	$ 5.76
MAX6682 chip	IC THERMISTOR TO DGTL 8UMAX	3	$ 4.05	$ 12.15
Max6682 breakout board	SSOP TO DIP ADAPTER - 8-PIN (Spark fun)	3	$ 2.95	$ 8.85
Thermal Paste	Noctua NT-H1 Pro-Grade Thermal Compound Paste (Gray) 1.4 ml	1	$ 7.90	$ 7.90
Conductivity Insulation	Black Heat Resistant Thin Silicone Grade Rubber Gasket Sheet 12 by 12 inch	1	$ 11.59	$ 11.59
Radiation insulation	Thermo-Tec 13575 Adhesive Backed Aluminized Heat Barrier, 12" x 24"	2	$ 18.47	$ 36.94
			TOTAL PRICE	$ 519.30

Appendix L: Current Draw for Thermal Display Circuits

CURRENT DRAW FOR FAN CIRCUIT:

SERVER FAN: 0.299 A /fan — 12V SOURCE: 2A availible

BUTTON: NEGLIGABLE

$I_{TOTAL} = (0.299A)(2) = \underline{0.598A}$

$I_{AVAILIBLE} = \underline{2A}$

$I_{TOTAL} < I_{AVALIBLE}$ ✓

CURRENT DRAW FOR HEATING CIRCUIT:

HEATING ELEMENTS: 30 W /element — 24V SOURCE: 6.5A

THERMAL SWITCHES: NEGLIGIBLE

$P = IV$

$I = \frac{P}{V} = \frac{30\,W}{24\,V}$

$I = 1.25\,A$

$I_{TOTAL} = 4(1.25A) = \underline{5A}$

$I_{AVALIBLE} = \underline{6.5A}$

$I_{TOTAL} < I_{AVALIBLE}$ ✓

CURRENT DRAW FOR MESUREMENT/DISPLAY CIRCUT:

LEDs: 180 mA — 5V SOURCE: 6A

ARDUINO: 500 mA

MAX6682: NEGLIGIBLE

THERMISTORS/RESISTORS: NEGLIGIBLE

$I_{TOTAL} = 14 I_{LED} + I_{ARDUINO}$
$= 14(180\,mA) + 500\,mA$

$I_{TOTAL} = 3.02A$

$I_{AVALIBLE} = 6A$

$I_{TOTAL} < I_{AVALIBLE}$ ✓

Appendix M: Thermal Display Circuits Manufacturer's Specifications

Fan Circuit	
Part	Data Sheet Link
Server Fan	https://www.corsair.com/us/en/LED-Color/Fan-Size/Package-Quantity/ml-pro-led-config/p/CO-9050042-WW
Toggle Button	https://www.adafruit.com/product/1190
12V Power Supply	https://www.jameco.com/Jameco/catalogs/c181/P106.pdf

Heating Circuit	
Part	Data Sheet Link
Heating Element	https://www.amazon.com/dp/B07H4TKNFR/?coliid=I3R6DHMWKLXPMN&colid=2KWA66KIBS0FE&psc=0&ref_=lv_ov_lig_dp_it
Thermal Switch	https://www.bourns.com/docs/Product-Datasheets/AA.pdf
24V Power Supply	https://www.jameco.com/Jameco/catalogs/c181/P106.pdf

Display Circuit	
Part	Data Sheet Link
Arduino	https://store.arduino.cc/usa/mega-2560-r3
MAX6682	https://datasheets.maximintegrated.com/en/ds/MAX6682.pdf
5V Power Supply	https://www.jameco.com/Jameco/catalogs/c181/P106.pdf
Thermistor	media.digikey.com/pdf/Data%20Sheets/TEWA/TT08-10KC8-T105-1500.pdf
LEDs	https://www.jameco.com/Jameco/Products/ProdDS/2152155.pdf
Resistor	http://www.vishay.com/docs/31018/cmfind.pdf

Appendix N: Thermal Display Arduino Code

Final Arduino Code:

```
#define VOLT_THRESH_1 1.12

#define VOLT_THRESH_2 1.20

#define VOLT_THRESH_3 1.28

#define VOLT_THRESH_4 1.35

#define VOLT_THRESH_5 1.43

#define VOLT_THRESH_6 1.50

void setup() {

  // put your setup code here, to run once:

  Serial.begin(9600);

  pinMode(A0, INPUT);

  pinMode(A1, INPUT);


  pinMode(2, OUTPUT);    //pinMode(pin #, INPUT or OUTPUT): sets pin 2 as an output

  pinMode(3, OUTPUT);    //sets pin 3 as an output

  pinMode(4, OUTPUT);    //sets pin 4 as an output

  pinMode(5, OUTPUT);    //sets pin 5 as an output

  pinMode(6, OUTPUT);    //sets pin 6 as an output

  pinMode(7, OUTPUT);    //sets pin 7 as an output

  pinMode(8, OUTPUT);    //sets pin 8 as an output


  pinMode(46, OUTPUT);

  pinMode(44, OUTPUT);

  pinMode(42, OUTPUT);

  pinMode(40, OUTPUT);

  pinMode(38, OUTPUT);

  pinMode(36, OUTPUT);

  pinMode(34, OUTPUT);


  digitalWrite(2, LOW); //digitalWrite(pin#, HIGH or LOW) : sets pin 2 as on

  digitalWrite(3, HIGH); //sets pin 3 as on

  digitalWrite(4, HIGH); //sets pin 4 as on
```

```
  digitalWrite(5, HIGH); //sets pin 5 as on
  digitalWrite(6, HIGH); //sets pin 6 as on
  digitalWrite(7, HIGH); //sets pin 7 as on
  digitalWrite(8, HIGH); //sets pin 8 as on

  digitalWrite(46, LOW);
  digitalWrite(44, HIGH);
  digitalWrite(42, HIGH);
  digitalWrite(40, HIGH);
  digitalWrite(38, HIGH);
  digitalWrite(36, HIGH);
  digitalWrite(34, HIGH);
}
void loop() {
  // put your main code here, to run repeatedly:
  float voltage = get_voltage(A0);
  turn_on_leds_left(voltage);
  Serial.print("Left Voltage: ");
  Serial.println(voltage);

  voltage = get_voltage(A1);
  turn_on_leds_right(voltage);
  Serial.print("Right Voltage: ");
  Serial.println(voltage);

  delay(1000);
}
float get_voltage(int pin)
{
  float voltage = analogRead(pin);
  voltage = voltage / 1023.0;
  voltage = voltage * 5.0;
  return voltage;
}
```

```
void turn_on_leds_left(float voltage)
{
  digitalWrite(44, HIGH);
  digitalWrite(42, HIGH);
  digitalWrite(40, HIGH);
  digitalWrite(38, HIGH);
  digitalWrite(36, HIGH);
  digitalWrite(34, HIGH);

  if (voltage >= VOLT_THRESH_1)
  {
    digitalWrite(44, LOW);
  }
  if (voltage >= VOLT_THRESH_2)
  {
    digitalWrite(42, LOW);
  }
  if (voltage >= VOLT_THRESH_3)
  {
    digitalWrite(40, LOW);
  }
  if (voltage >= VOLT_THRESH_4)
  {
    digitalWrite(38, LOW);
  }
  if (voltage >= VOLT_THRESH_5)
  {
    digitalWrite(36, LOW);
  }
  if (voltage >= VOLT_THRESH_6)
  {
    digitalWrite(34, LOW);
  }
}
```

```
void turn_on_leds_right(float voltage)
{
  digitalWrite(3, HIGH); //sets pin 3 as on
  digitalWrite(4, HIGH); //sets pin 4 as on
  digitalWrite(5, HIGH); //sets pin 5 as on
  digitalWrite(6, HIGH); //sets pin 6 as on
  digitalWrite(7, HIGH); //sets pin 7 as on
  digitalWrite(8, HIGH); //sets pin 8 as on

  if (voltage >= VOLT_THRESH_1)
  {
    digitalWrite(3, LOW);
  }
  if (voltage >= VOLT_THRESH_2)
  {
    digitalWrite(4, LOW);
  }
  if (voltage >= VOLT_THRESH_3)
  {
    digitalWrite(5, LOW);
  }
  if (voltage >= VOLT_THRESH_4)
  {
    digitalWrite(6, LOW);
  }
  if (voltage >= VOLT_THRESH_5)
  {
    digitalWrite(7, LOW);
  }
  if (voltage >= VOLT_THRESH_6)
  {
    digitalWrite(8, LOW);
  }
}
```

Arduino Pseudo-code:

```
func main:
      initialize global variables
      initialize SPI driver
      while True:
            input1 = readsensor1()
            input2 = readsensor2()
            updateLedSet1(input1)
            UpdateLedSet2(input2)
      end while
end func

func updateLedSet1(float input):
      set all LEDs off
      If input > 20, Then turn on Led1
      If input > 25, Then turn on Led2
      If input > 30, Then turn on Led3
      If input > 35, Then turn on Led4
      If input > 40, Then turn on Led5
      If input > 45, Then turn on Led6
      If input > 50, Then turn on Led7
end func
```

Appendix O: Thermal FEA Simulation

Description: Finite Element Analysis simulation of solid aluminum and metal foam blocks.

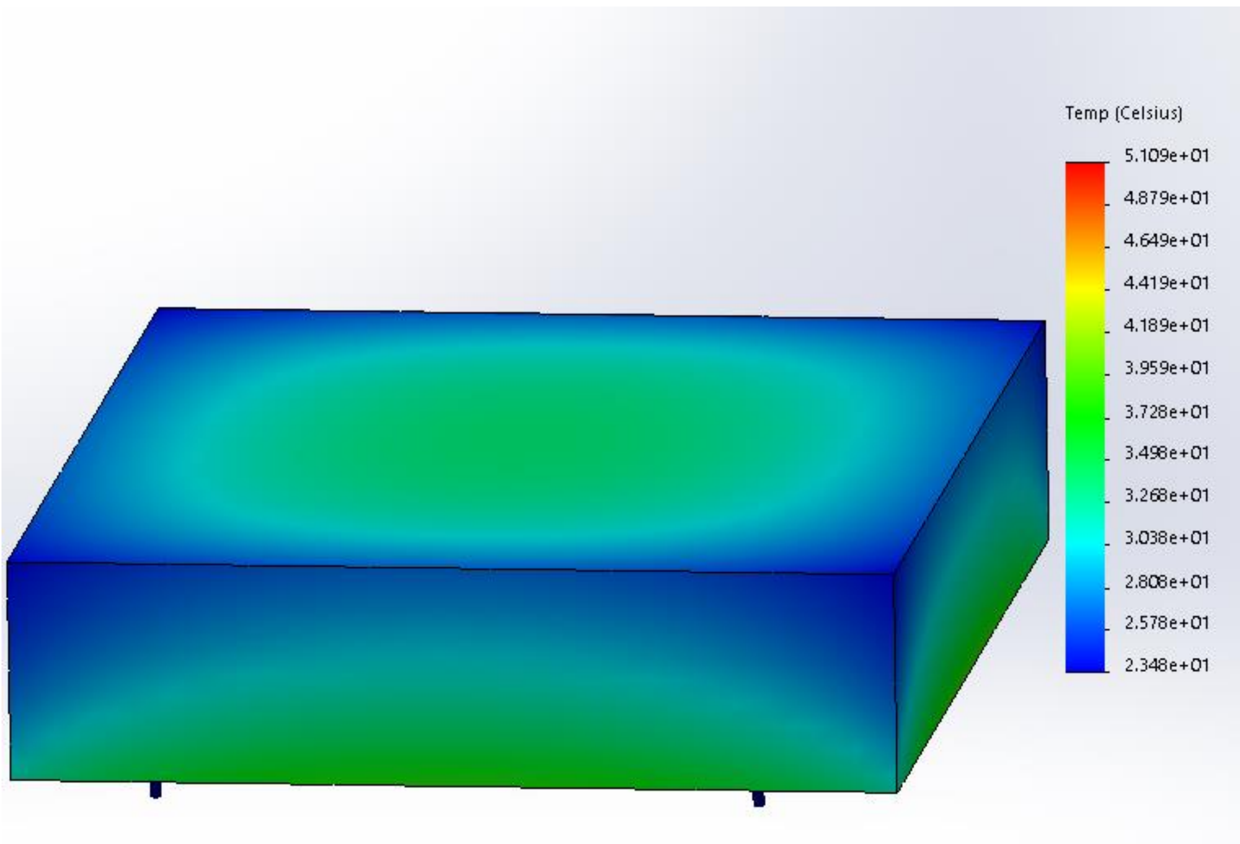
Inputs:

- 60 W power to bottom surface
- Free convection on other surfaces (25 W/m^2*K)
- 7% density aluminum foam properties
- 293 K ambient temp

Simulation 1: Aluminum Foam

Results with 25*9.5 w/m^2K

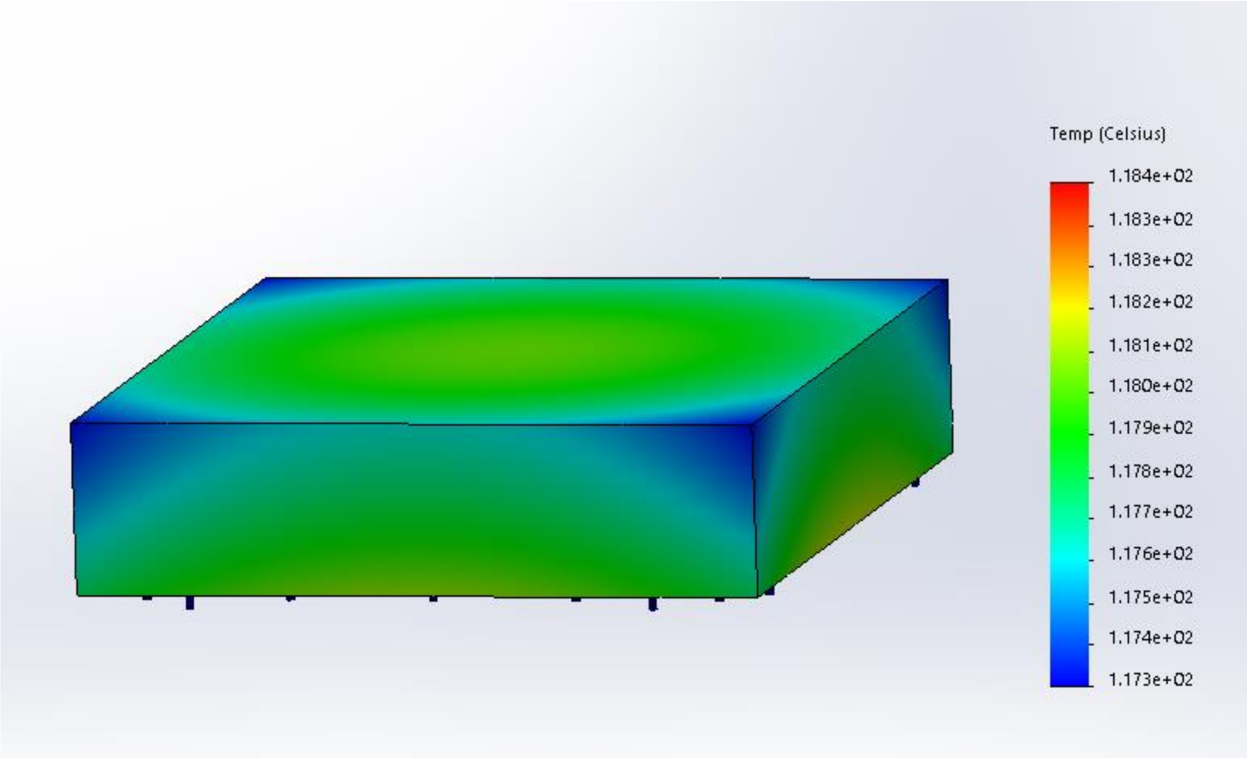
- Heater temp: 51.1 ̊C
- Middle of top surface temp: 34 ̊C
- Low temp: 23.5 ̊C



Simulation 2: Solid Aluminum

Results:

- Heater temp: 118.4 ̊C
- Middle of top surface temp: 117 ̊C
- Low temp: 117 ̊C



Appendix P: Thermal Display Confirmation Setting

Testing Conditions:
Location: Cal Poly ME Thermal Sciences Lab
Test performed by: Kate Goldsworthy and Katherina Prodanov
Supervised by: Glen Thorncroft, Ph. D
Test Materials:

- Solid Aluminum block, 1”x4”x6”
- Duocel® Aluminum block, 6% density, 1”x3”x6”
- Heat Plate
- Fan, 5” diameter
- IR Thermometer
- Thermal Camera iPhone attachment
- iPhone

Test Procedure:

1. Plug in heat plate and set temperature to 100 ̊C.
2. Place solid aluminum and Duocel® aluminum blocks on heat plate equidistant from center of plate.
3. Wait approximately 10 minutes for steady state conditions. Check temperature using IR thermometer to ensure steady state prior to proceeding.
4. Use the thermal camera to take a picture of the thermal profile at steady state conditions.
5. With the thermal camera recording, introduce the fan to the system by holding it approximately 1” above the blocks and centered between the two.
6. Repeat experiment to confirm results.

Test Results:

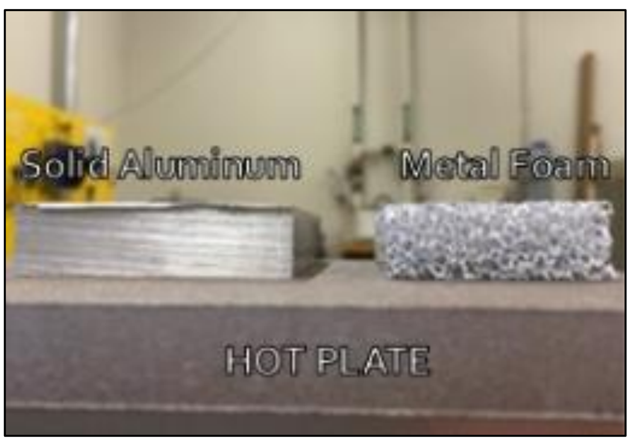


Figure 1. Test setup with solid aluminum and Duocel® aluminum on a hot plate.

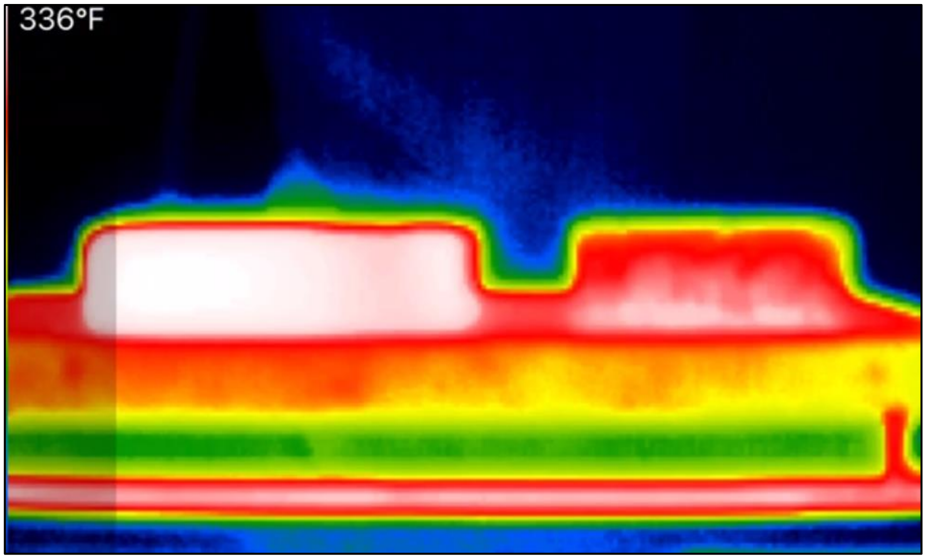


Figure 2. Thermal profiles of blocks with natural convection.

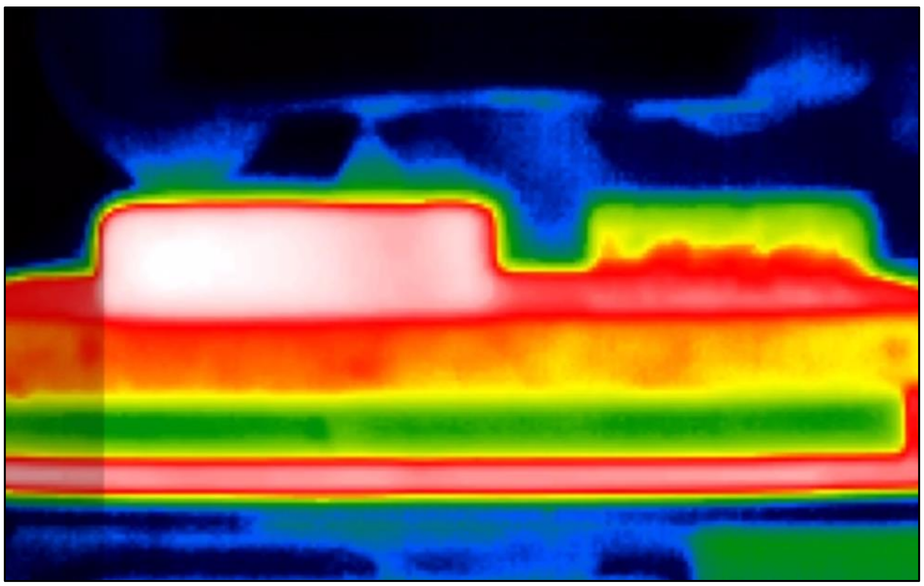


Figure 3. Thermal profiles of blocks with forced convection.

Conclusion:

The thermal profiles show that at natural convection, the Duocel® material has a much lower steady-state temperature. With forced convection, the Duocel® block cools significantly, while the solid aluminum does not experience significant change. This is consistent with the expected results, confirming the concept behind this design.

Appendix Q: EES Radiation Simulation

"Notes:

Surface 1: floor at 77 C (shutoff temp)

Surface 2: Black surfaces, insulated, front and bottom

Surface 3: Clear surfaces, Sides back

Surface 4: Black surface non insulated, top

Assume 0.2286 m tall, 0.30.5 m long, 0.432 m wide

conservative assumption: no holes in box"

"Geometry"

L = 0.305 [m]

w = .432 [m]

h = .2286 [m]

e1 = 0.95

"assume all other surfaces are black bodies or insulated”

A1 = L/4*w "third of floor is heated"

A2 = 3*L/4*w+ w*h "black insulated surfaces"

A3 = 2*L*h + w*h "clear surfaces"

A4 = L*w "black top"

"Given Values"

T1 = 350 [K]

sigma = 5.67e-8 [W/(m^2*K^4)]

q1 = 120 [W]

q2 = 0

q4 = 0

q3 = 0

"View Factors"

F12 = **f2d_12**(L/4,h)

F21 = F12*A1/A2

```
F23 = 2*f2d_12(w,h)+f2d_12(L,h)
F32 = F23*A2/A3
F13 = 1-F14-F12
F31 = F13*A1/A3
F14 = f2d_14(L,L/4,h,0)
F41 = F14*A1/A4

F42 = f2d_12(L,h)+f2d_14(L,3*L/4,h,0)
F24 = F42*A4/A2

F34 = F43*A4/A3
F43 = 1-F41-F42
"Resistances"
R1 = (1-e1)/(e1*A1)
R12 = 1/(A1*F12)
R13 = 1/(A1*F13)
R14 = 1/(A1*F14)
R31 = 1/(A3*F31)
R32 = 1/(A3*F32)
R34 = 1/(A3*F34)
R43 = 1/(A4*F34)
R42 = 1/(A4*F42)
R41 = 1/(A4*F41)
R21 = 1/(A2*F21)
R23 = 1/(A2*F23)
R24 = 1/(A2*F24)

"Heat Balance"
q1 = (Eb1-J1)/R1
q2 =(J2-J1)/R21+(J2-J3)/R23+(J2-J4)/R24
"q1 = (J1-J2)/R12+(J1-J3)/R13+(J1-J4)/R14"
q3 = (J3-J2)/R32+(J3-J4)/R34+(J3-J1)/R31
q4 = (J4-J1)/R41+(J4-J3)/R43+(J4-J2)/R42
```

"Solve for Temps"

Eb1 = sigma*T1^4

J2 = sigma*T2^4

J3 = sigma*T3^4

J4 = sigma*T4^4

Unit Settings: SI C kPa kJ mass deg

A1 = 0.03294	A2 = 0.1976	A3 = 0.2382	A4 = 0.1318
e1 = 0.95	Eb1 = 850.9	F12 = 0.4188	F13 = 0.4662
F14 = 0.115	F21 = 0.06982	F23 = 0.6477	F24 = 0.4235
F31 = 0.06447	F32 = 0.5372	F34 = 0.1859	F41 = 0.02875
F42 = 0.6351	F43 = 0.3361	h = 0.2286 [m]	J1 = 659.1
J2 = 659.1	J3 = 659.1	J4 = 659.1	L = 0.305 [m]
q1 = 120 [W]	q2 = 0	q3 = 0	q4 = 0
R1 = 1.598	R12 = 72.49	R13 = 65.12	R14 = 264
R21 = 72.49	R23 = 7.814	R24 = 11.95	R31 = 65.12
R32 = 7.814	R34 = 22.58	R41 = 264	R42 = 11.95
R43 = 40.82	σ = 5.670E-08 [W/(m^2*K^4)]	T1 = 350 [K]	T2 = 328.4
T3 = 328.4	T4 = 328.4	w = 0.432 [m]	

Appendix R: Risk Analysis Reports

designsafe Report

Application: Flow Control

Description:

Product Identifier:

Assessment Type: Detailed

Limits:

Sources:

Risk Scoring System: ANSI B11.0 (TR3) Two Factor

Analyst Name(s):

Company: ERG Materials and Aerospace

Facility Location:

Guide sentence: When doing [task], the [user] could be injured by the [hazard] due to the [failure mode].

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
1-1-1	All Users Common Tasks	slips / trips / falls : falling material / object Display falling off table	Serious Unlikely	Medium	Attach rubber pads at the base to provide more grip	Minor Remote	Negligible	Complete [4/29/2019]
1-1-2	All Users Common Tasks	ergonomics / human factors : excessive force / exertion Placing wieght on the display will break the acrylic	Serious Remote	Low	Place a warning on enclosure to not put weight on it	Minor Unlikely	Negligible	On-going [Daily]
1-1-3	All Users Common Tasks	noise / vibration : noise / sound levels > 80 dBA Balloons poping	Moderate Likely	Medium	Acrylic cylinder will contain the noise of the balloon poping	Minor Remote	Negligible	TBD
1-1-4	All Users Common Tasks	material handling : stacking / storing Acrylic cylinders are fragile and can break in transport	Moderate Unlikely	Low	Fill acrylic cylinders with packing paper so that it doent squeeze and break	Minor Remote	Negligible	TBD
1-1-5	All Users Common Tasks	fluid / pressure : high pressure air pump provides high pressure in the system	Moderate Likely	Medium	release valve if pressure too high in the system	Minor Unlikely	Negligible	Complete [4/29/2019]
1-1-6	All Users Common Tasks	fluid / pressure : explosion / implosion Baloons can explode	Moderate Likely	Medium	Cylinders to limit balloon volume, extra balloons on hand	Minor Unlikely	Negligible	TBD

designsafe Report

Application: Thermal Conductivity Display

Description:

Product Identifier:

Assessment Type: Detailed

Limits:

Sources:

Risk Scoring System: ANSI B11.0 (TR3) Two Factor

Analyst Name(s):

Company: ERG Materials and Aerospace

Facility Location:

Guide sentence: When doing [task], the [user] could be injured by the [hazard] due to the [failure mode].

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
1-1-1	All Users Common Tasks	mechanical : cutting / severing High speed fans	Catastrophic Remote	Low	Shield fans with acrylic vents	Catastrophic Remote	Low	
1-1-2	All Users Common Tasks	mechanical : drawing-in / trapping / entanglement High speed fans	Catastrophic Remote	Low	Shield fans with acrylic vents	Catastrophic Remote	Low	
1-1-3	All Users Common Tasks	electrical / electronic : energized equipment / live parts High voltage heating pads	Serious Unlikely	Medium	Place high voltage equipment within enclosure	Serious Remote	Low	
1-1-4	All Users Common Tasks	electrical / electronic : lack of grounding (earthing or neutral) High speed fans and heating element	Serious Unlikely	Medium	Ground electrical systems	Serious Remote	Low	
1-1-5	All Users Common Tasks	electrical / electronic : shorts / arcing / sparking High volatge current	Moderate Likely	Medium	Built in fuse, will trip if wires short	Moderate Unlikely	Low	
1-1-6	All Users Common Tasks	electrical / electronic : improper wiring High speed fans	Moderate Unlikely	Low	Built in fuse, will trip if wires short	Moderate Unlikely	Low	
1-1-7	All Users Common Tasks	electrical / electronic : unexpected start up / motion Heating / Cooling button malfunction	Serious Unlikely	Medium	Master power swith to turn off all systems immediatly	Serious Remote	Low	

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
1-1-8	All Users Common Tasks	electrical / electronic : power supply interruption High voltage power supply required	Moderate Unlikely	Low	Master power swith to turn off all systems immediatly	Moderate Remote	Negligible	
1-1-9	All Users Common Tasks	fire and explosions : hot surfaces Heating pads / affected surfaces	Moderate Likely	Medium	Inside of enclosure lined with thermal paper to stop acrylic from heating	Moderate Unlikely	Low	
1-1-10	All Users Common Tasks	heat / temperature : burns / scalds If user tries to touch metal / heating pad	Serious Unlikely	Medium	Heating elements placed inside enclosure	Serious Remote	Low	
1-1-11	All Users Common Tasks	heat / temperature : radiant heat Heat to outer surfaces	Moderate Unlikely	Low	Provide sufficient ventillation in box with vents	Moderate Remote	Negligible	
1-1-12	All Users Common Tasks	heat / temperature : severe heat Heaing pads	Serious Unlikely	Medium	Thermal switch will turn off heating element if too hot	Serious Remote	Low	
1-1-13	All Users Common Tasks	heat / temperature : inadequate heating / cooling Keep heat contained	Moderate Likely	Medium	Provide sufficient ventillation in box with vents	Moderate Unlikely	Low	
1-1-14	All Users Common Tasks	ventilation / confined space : confined space Hot air in small box	Moderate Unlikely	Low	Provide sufficient ventillation in box with vents	Moderate Unlikely	Low	
2	operator <None>	<None>						
3	maintenance technician <None>	<None>						

Appendix S: Indented Bill of Materials

<u>Flow Control Display</u>

		Indented Bill of Material (BOM)									
		Flow Control Display Assembly									
Asm. Lvl	**Part ID**	**Part #**	**Description**				**Material**	**Vendor**	**Qty**	**Cost**	**Ttl Cost**
			Lvl0	Lvl1	Lvl2	Lvl3					
0		F	Flow Control Assembly					------			
1	n/a	F1		Acrylic Display Case				------	1		$ -
2	B0182IIPEO	F1.1			Clear Acrylic Cylinders		Acrylic	Amazon	3	$ 7.00	$ 20.99
2	ACREXR0.500	F1.2			Clear Acrylic Rod		Acrylic	ePlastics	1	$ 9.35	$ 9.35
2	----	F1.3			Acrylic Cement			Amazon	1	$ 7.19	$ 7.19
2	ACRY20250.250PM	F1.4			Black Acrylic Sheet, 2'x4'		Acrylic	ePlastics	1	$ 64.66	$ 64.66
2	X001CUYO1J	F1.5			Red Acrylic Sheet		Acrylic	Amazon	1	$ 9.99	$ 9.99
1	n/a	F2		Flow Pathway				------	1		$ -
2	X001P2BPO3	F2.1			Clear Flexible Tubing, Vinyl		Vinyl	Amazon	1	$ 8.65	$ 8.65
2	X000RD2V17	F2.2			4-way valve splitter		Aluminum, plastic	Amazon	1	$ 22.47	$ 22.47
2	80015AOREO	F2.3			Male-to-male adaptor		Brass	Amazon	1	$ 4.86	$ 4.86
2	B0064OJ7HE	F2.4			Hose-to-tube adaptor		Brass	Amazon	10	$ 6.36	$ 63.60
2	B000P91RVK	F2.5			Hand Pump		Plastic	Amazon	1	$ 18.44	$ 18.44
2	34351	F2.6			PVC Nipples, Clear		PVC	US Plastics	3	$ 5.38	$ 16.14
2	----	F2.7			Foam Inserts		Duocel®	ERG Aerospace	3	$ 10.00	$ 30.00
2	X001P7RMOP	F2.8			Red Balloons, 5"		Latex	Amazon	3	$ 0.10	$ 0.31
2	B07H6B5272	F2.9			Check Valves		Plastic, Alu	Amazon	1	$ 4.49	$ 4.49
								Purchased Parts Total:			**$ 281.14**

Thermal Display

			Indented Bill of Material (BOM) Thermal Display Assembly								
Asm. Lvl	Part ID	Part #	Description				Material	Vendor	Qty	Cost	Ttl Cost
			Lvl0	Lvl1	Lvl2	Lvl3					
0		T	Thermal System Assembly								
1	n/a	T1		Acrylic Enclosure							
2	----	T1.1			Acrylic Cement		Paste	Amazon	1	$ 7.19	$ 7.19
2	ACRY20250.250PM24X48	T1.2			Black Acrylic Sheet, 2'x4'		Acrylic	ePlastics	2	$ 64.66	$ 129.32
2	944589A280	T1.3			Heat-Set Inserts		Brass	McMaster	1	$ 9.25	$ 9.25
2	ACRYCLR0.250PM24X48	T1.4			Clear Acrylic Sheet, 2'x4'		Acrylic	ePlastics	1	$ 69.08	$ 69.08
2	LMSTF	T1.5			Thermal Insulation Pad 12"x12"		Silicone	Amazon	1	$ 11.59	$ 11.59
2	NT-H1	T1.6			Thermal Paste 1.4 ml		Paste	Amazon	1	$ 7.90	$ 7.90
2	13575	T1.7			Radiation insulation 1'x2'		Adhesive Backed Alumininum	Amazon	2	$ 18.47	$ 36.94
2	n/a	T1.8			Metal Foam Block 1"x4"x4"		Duocel®	ERG Aerospace	1	$ -	$ -
2	8975K242	T1.9			Aluminum Block 1"x4"x6"		Aluminum	Amazon	1	$ 21.90	$ 21.90
1	n/a	T2		Fan Circuit (Powered by 12V Supply)							
2	CO-9050042-WW	T2.1			Fans		Plastic	Amazon	2	$ 27.99	$ 55.98
2	1190	T2.2			Button		Plastic	Adafruit	1	$ 5.95	$ 5.95
1	n/a	T3		Heating Cicuit							
3	323855	T3.1			24V power supply			Jame Co.	1	$ 23.40	$ 23.40
2	M3180903031	T3.2			Flexible Heater		Plastic	Amazon	4	$ 2.35	$ 9.40
2	ET1002	T3.3			Heat Shrink Tubing			Amazon	1	$ 8.99	$ 8.99
3	AA72A10-ND	T3.4			Thermal Switch		Plastic	Digikey	3	$ 1.92	$ 5.76
1	n/a	T4		Display Circuit/Electronics							
2	n/a	T4.1			Power						
3	323425	T4.1.1				5 & 12V power supply		Jame Co.	1	$ 14.95	$ 14.95
3	37997	T4.1.2				Power Cord		Jame Co.	1	$ 4.95	$ 4.95
2	A000067	T4.2			Arduino MEGA			Amazon	1	$ 30.50	$ 30.50
3	1912-1037-ND	T4.2.1				10kohm Thermistor		Digikey	3	$ 7.57	$ 22.71
3	CMF2.94KQFCT-ND	T4.2.2				2.49 kohm Resistors		Digikey	5	$ 0.67	$ 3.35
3	B071JDRGGR	T4.2.3				Protoboard Sheild		Amazon	1	$ 8.99	$ 8.99
3	----	T4.2.4				Wires	Silicone	Amazon	1	$ 18.99	$ 18.99
3	DE37566	T4.2.5				Pins		Amazon	1	$ 5.99	$ 5.99
3	MAX6682MUA+-ND	T4.2.6				MAX6682 chip		Digikey	3	$ 4.05	$ 12.15
3	1568-1093-ND	T4.2.7				Max6682 breakout board	Plastic	Digikey	3	$ 2.95	$ 8.85
2	n/a	T4.3			Display						
3	COMINHKPR125520	T4.3.1				Digial Thermocouple Readou	Plastic	Amazon	2	$ 10.49	$ 20.98
3	2152155	T4.3.2				Jumbo LEDs	Plastic	Jame Co.	20	$ 0.55	$ 11.00
3	790081	T4.3.3				LEDs	Plastic	Jame Co.	20	$ 0.12	$ 2.40
								Purchased Parts Total:			$ 568.46

Appendix T: Flow Control Display Manufacturing Plan

Subassembly 1: Custom Display Box

Step 1.1: Use a table saw to cut two 18”x 24” pieces and one 12”x 24” piece of ¼” thick black acrylic.

Step 1.2: Laser cut the black acrylic sheets according to Adobe Illustrator diagram provided with drawing package. There should be 11 total black acrylic pieces cut from the sheet.

Step 1.3: Laser cut 1/8” red acrylic sheet according to Adobe Illustrator diagram provided with the drawing package. There should be three total red acrylic pieces (spelling “ERG”) cut from the sheet.

Step 1.4: Laser Cut decals from white transfer paper.

Step 1.5: Cut four 2” lengths of clear acrylic rod using a chop saw. File ends of rod smooth.

Step 1.6: Assemble box as indicated in assembly drawing using notches as shown in Figure 1. Confirm box appears as shown in Figure 1 before proceeding to the next step.

Figure 1. Assembled Custom Display Box Subsystem

Step 1.7: Apply acrylic cement between all acrylic surfaces and press together. This includes on the notched joints, on the rod ends, and under the acrylic rings. Do not move components once cement has been applied for at least ten minutes.

Subassembly 2: Fluid Flow System

Step 2.1: Screw a brass adaptor onto the end of each threaded PVC tube.

Step 2.2: Place threaded PVC tubes through the 1” holes on top of the display such that the tubes hang parallel to the clear acrylic rods.

Step 2.3: Fill each clear PVC tube with a foam insert, then close the bottom of the tube with another brass adaptor. The foam inserts should be placed in order of pore size, such that the 40 PPI foam is on the left and the 10 PPI foam is on the right.

Step 2.4: Screw the male-to-male adaptor into the inlet of the manifold. Screw a brass adaptor onto release valves 1, 3, 4, and the exposed end of the male-to-male adaptor as indicated in the drawing package.

Step 2.5: Cut three lengths of vinyl tubing of approximately 4”, four lengths of approximately 1”, and one length of approximately 3’.

Step 2.6: Attach one end of three 1” length tube onto a PVC tube-adaptor and the other end to a release-valve-adaptor. Attach an L-joint to those tube. On the other side of the L-joints, attach the three 4” tubes and connect them with the PVC nipples. Attach the 1” length tube to the inlet-valve-adaptor. Attach one end of the 6’ tube to the black end of the plastic check valve and the other end to the pump.

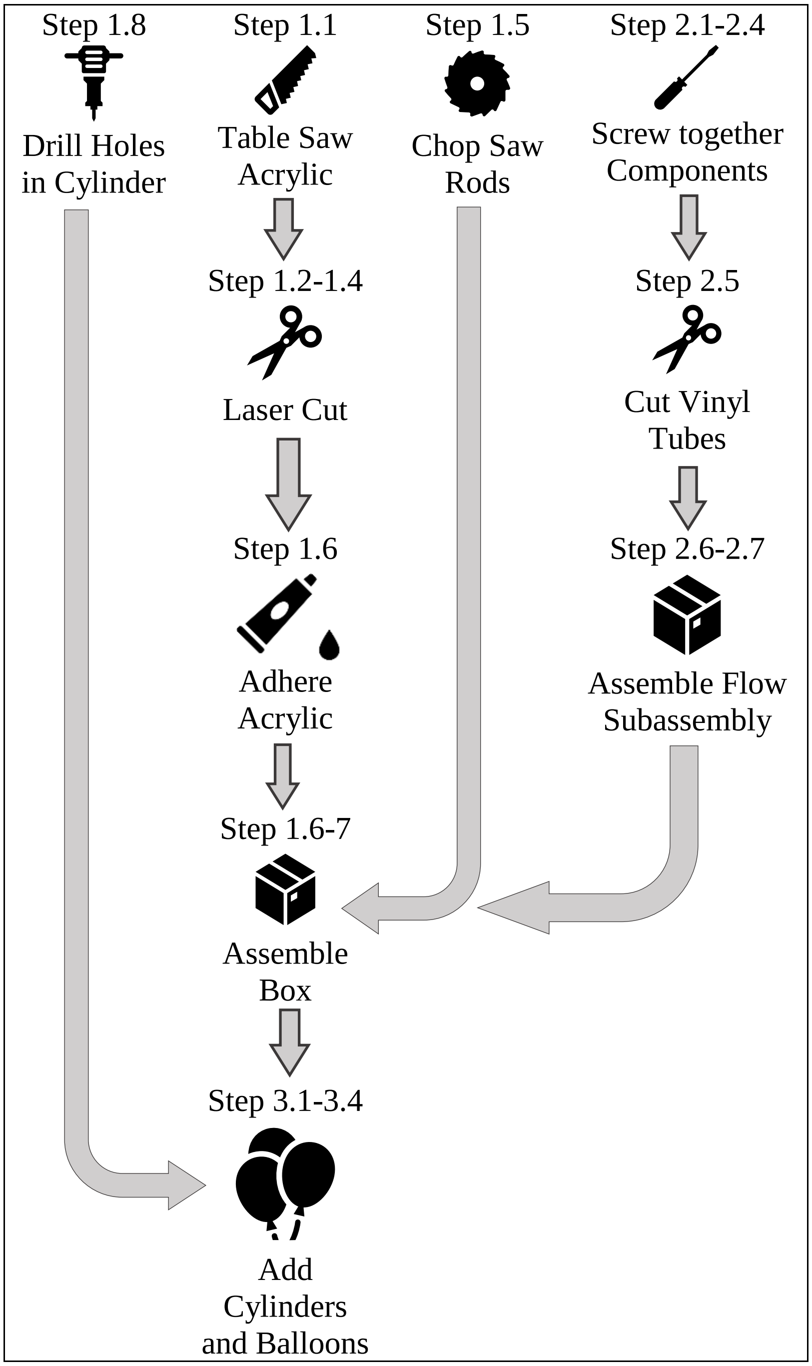
Step 2.7: Attach the white end of the plastic check valve to the open end of the 1” tube. Place the manifold such that it is hidden from view when standing opposite the display.

Subassembly 3: Display Components

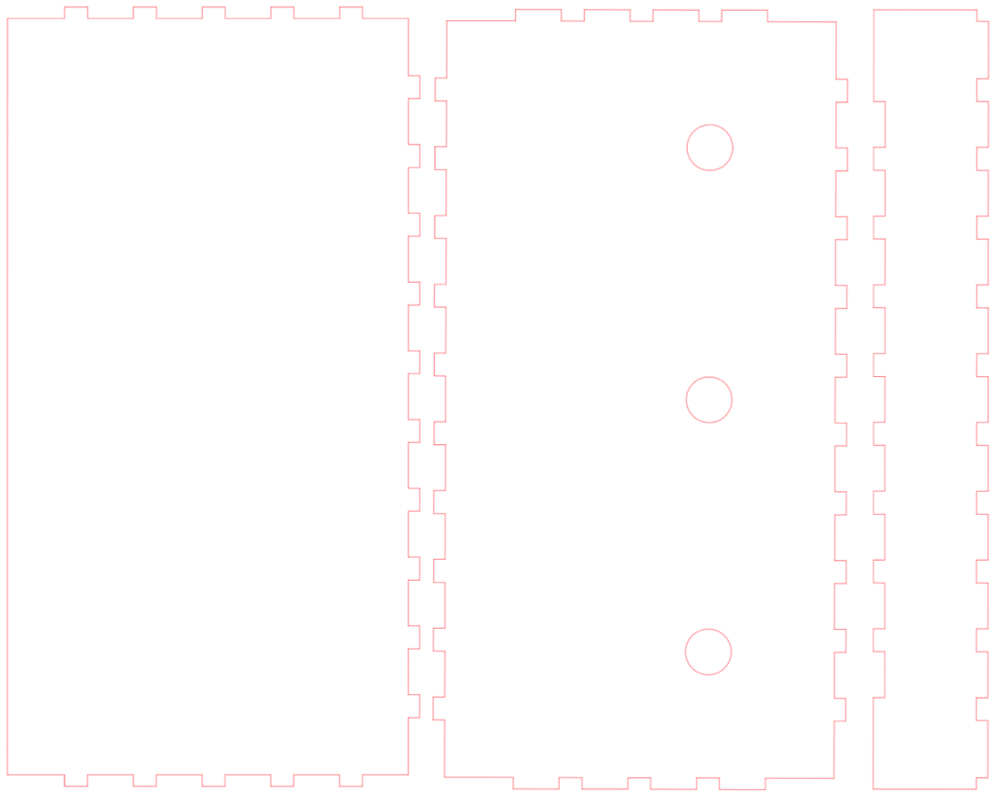
Step 3.1: Attach decals to front and top surfaces as needed and rubber pads to the bottom surface.

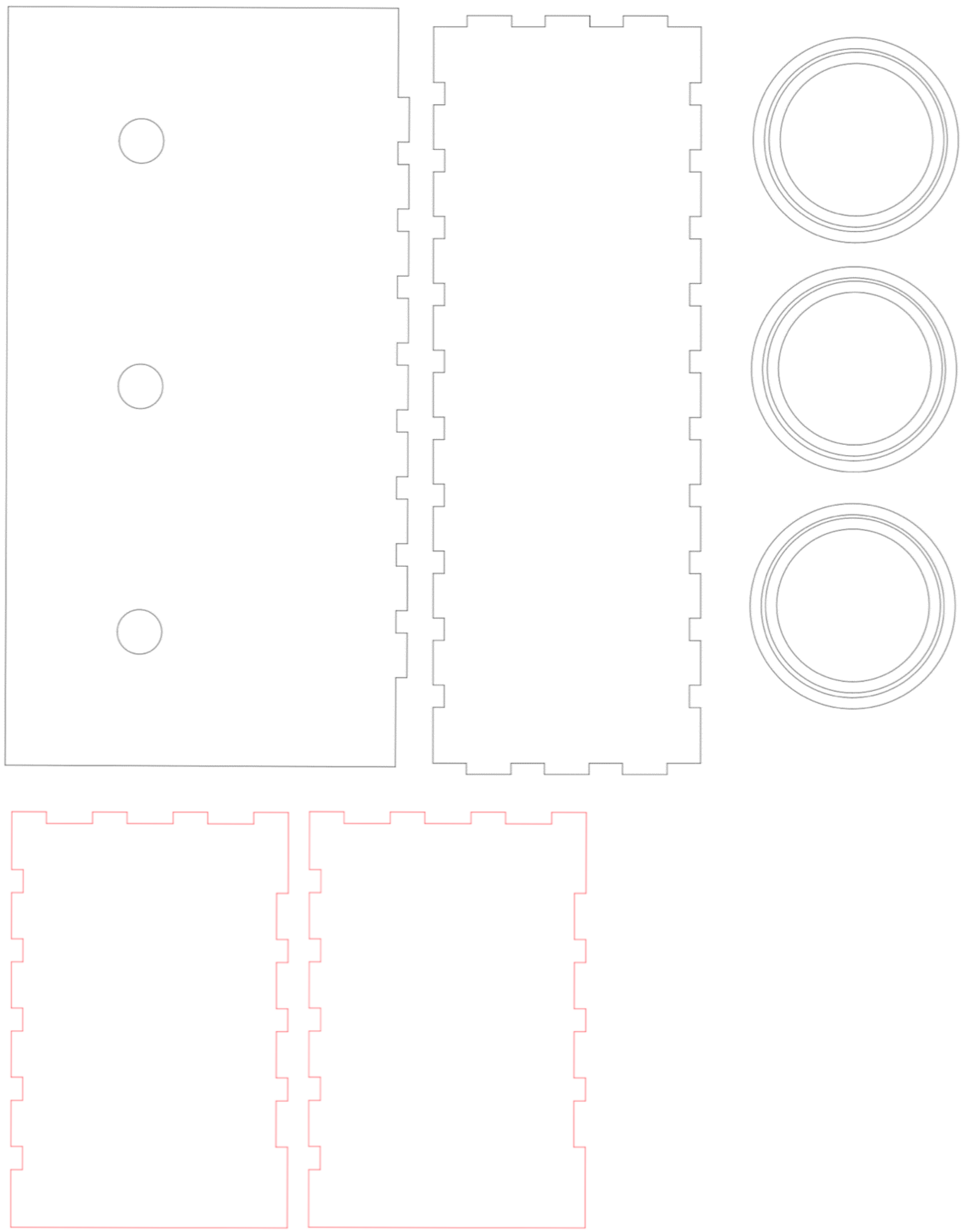
Step 3.2: Place the display on a sturdy table with the pump next to it.

Step 3.3: Attach a balloon to each of the three brass adaptors exposed above the display surface.


Step 1.8
Drill Holes in Cylinder
Step 1.1
Table Saw Acrylic
Step 1.5
Chop Saw Rods
Step 2.1-2.4
Screw together Components
Step 1.2-1.4
Laser Cut
Step 2.5
Cut Vinyl Tubes
Step 1.6
Adhere Acrylic
Step 2.6-2.7
Assemble Flow Subassembly
Step 1.6-7
Assemble Box
Step 3.1-3.4
Add Cylinders and Balloons

Appendix U: Illustrator Drawings





Appendix V: Thermal Display Manufacturing Plan

Subassembly 1: Custom Display Box

Step 1.1: Use a table saw to cut ¼” thick black acrylic into 1’x2’ sheets.

Step 1.2: Laser cut the black and clear acrylic sheets using Adobe Illustrator diagrams.

Step 1.3: Laser Cut decals from white and red transfer paper to represent the thermometers and label the materials.

Step 1.4: Insert clear acrylic pieces into the black acrylic cutouts and apply a thin layer of acrylic cement along edges. Do not move components once cement has been applied for at least ten minutes.

Step 1.5: Assemble box by interlocking the notches.

Step 1.6: Insert thermal inserts approximately 1/8” in from the top cutouts such that the insert is accessible from inside the box.

Step 1.7: Apply acrylic cement between all acrylic surfaces and press together. This includes on the notched joints, on the rod ends, and under the acrylic rings. Do not move components once cement has been applied for at least ten minutes.

Subassembly 2: Heating Components

Step 2.1: Attach the two fans to the inside top surface using four screws each. Ensure the fans are oriented such that they blow air into the box during operation.

Step 2.2: Lay conduction insulation on the bottom surface of the box.

Step 2.3: Remove adhesive backing from radiation insulation and apply to all non-clear surfaces.

Step 2.4: Remove adhesive backing from thin film heaters and attach in the position shown in the drawing package.

Step 2.5: Drill two ¼" diameter holes in the solid aluminum block, approximately 1” in from the edge.

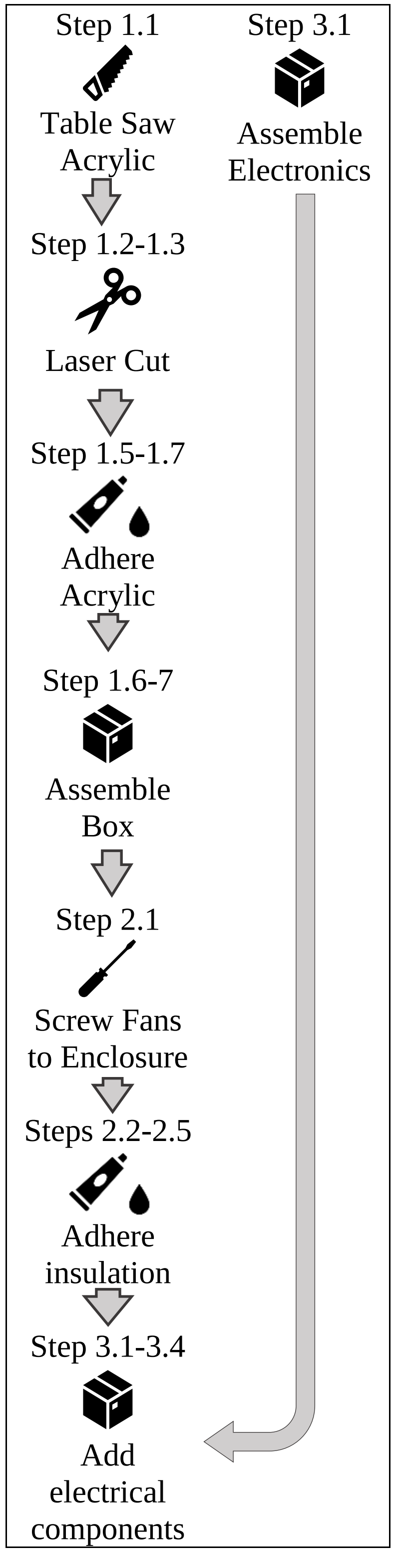
Step 2.6: Place metal blocks on top of the thin film heaters so that one surface is visible through the front windows.

Subassembly 3: Electrical Components

Step 3.1: Assemble electrical components according to the wiring diagrams provided in Appendix L.

Step 3.2: Thread LED bulbs and digital readouts through holes in front surface of enclosure and secure with adhesive.

Step 3.3: Place thermistors on side of each metal block and secure with adhesive.


Step 1.1
Table Saw Acrylic
Step 1.2-1.3
Laser Cut
Step 1.5-1.7
Adhere Acrylic
Step 1.6-7
Assemble Box
Step 2.1
Screw Fans to Enclosure
Steps 2.2-2.5
Adhere insulation
Step 3.1-3.4
Add electrical components
Step 3.1
Assemble Electronics

Appendix W: DVP&R

Flow Control Display DVP&R

Senior Project DVP&R													
Date: 5/21/19	Team: Team TetraKai		Sponsor: ERG Aerospace			Description of System: Flow Control Display					DVP&R Engineer: Ben Swanson		
TEST PLAN										TEST REPORT			
						SAMPLES		TIMING		TEST RESULTS			
Item No	Spec #	Test Description	Acceptance Criteria	Test Responsibility	Test Stage	Quantity	Type	Start date	Finish date	Test Result	Quantity Pass	Quantity Fail	NOTES
1	1	Maximum Weight	50 lbs. maximum	Ben	FP	1	Sys	5/7/2019	5/9/2019				*Will be used for
2	2	Time for assembly of display	20 mins maximum	Kate	FP	1	Sys	5/7/2019	5/9/2019				
3	3	Total linear dimensions of display	62 linear in. maximum	Kat	FP	1	Sys	5/7/2019	5/9/2019				
4	4	Time to 'reset' display	10 mins maximum	Syed	FP	1	Sys	5/7/2019	5/9/2019				
5	5	Total cost	$4,000 maximum	Syed	FP	1	Sys	5/31/2019	5/31/2019				Not a "Test", will check
6	6	Users report eye-catching	60% agree minimum	Kat	FP	50	Sys	5/9/2019	5/16/2019				
7	7	User understanding quiz	60% pass minimum	Kate	FP	50	Sys	5/9/2019	5/16/2019				
8	8	Users interact easily	70% interact w/o assistance minimum	Ben	FP	50	Sys	5/9/2019	5/16/2019				
9	9	Reaction time of display	5 seconds maximum	Syed	SP	10	Sys	1/30/2019	1/30/2019	<1 sec	1	0	Clear response almost immediately after pumping air
10	10	**Ballons filling according to foam porosity**	**Lowest PPI fills first, highest PPI last**	**Ben**	**SP**	**5**	**Sub**	**4/20/2019**	**5/1/2019**	**FAIL**	**0**	**5**	**Critical misfunction of display, no consistant or expected fill order.**

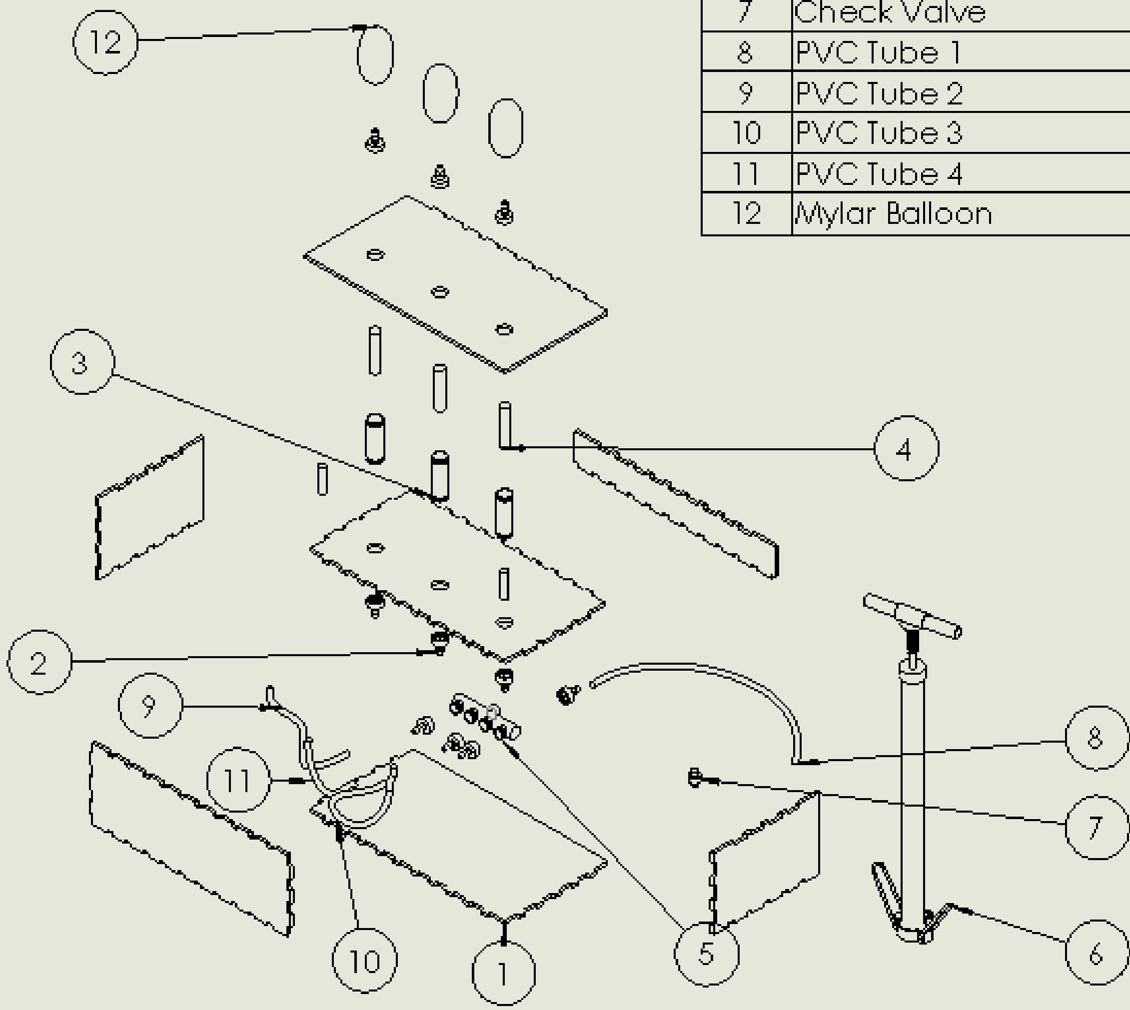
Thermal Display DVP&R

Senior Project DVP&R														
Date: 5/21/19		Team: Team TetraKai	Sponsor: ERG Aerospace			Description of System: Thermal Display						DVP&R Engineer: Ben Swanson		
TEST PLAN										TEST REPORT				
Item No	Spec #	Test Description	Acceptance Criteria	Test Responsibility	Test Stage	SAMPLES		TIMING		TEST RESULTS			NOTES
						Quantity	Type	Start date	Finish date	Test Result	Quantity Pass	Quantity Fail	
1	1	Maximum Weight	50 lbs. maximum	Ben	FP	1	Sys	5/7/2019	5/14/2019	PASS	1	0	*Will be used for uncertainty analysis
2	2	Time for assembly of display	20 mins maximum	Kate	FP	1	Sys	5/7/2019	5/16/2019	PASS	1	0	SEE TEST PROCEDURES FOR OBSERVATIONS
3	3	Total linear dimensions of display	62 linear in. maximum	Kat	FP	1	Sys	5/7/2019	5/14/2019	PASS	1	0	SEE TEST PROCEDURES FOR OBSERVATIONS
4	4	Time to 'reset' display	10 mins maximum	Syed	FP	1	Sys	5/7/2019	5/16/2019	PASS	1	0	SEE TEST PROCEDURES FOR OBSERVATIONS
5	5	Total cost	$4,000 maximum	Syed	FP	1	Sys	5/31/2019	5/31/2019	-	-	-	Not a "Test", will check at end of
6	6	Users report eye-catching	60% agree minimum	Kat	FP	50	Sys	5/9/2019	5/16/2019	PASS	48	2	SEE TEST PROCEDURES FOR OBSERVATIONS
7	7	User understanding quiz	60% pass minimum	Kate	FP	50	Sys	5/9/2019	5/16/2019	PASS	39	11	SEE TEST PROCEDURES FOR OBSERVATIONS
8	8	Users interact easily	70% interact minimum	Ben	FP	50	Sys	5/9/2019	5/16/2019	PASS	48	2	SEE TEST PROCEDURES FOR OBSERVATIONS
9	9	Reaction time of display	5 seconds maximum	Syed	SP	1	Sys	5/9/2019	5/16/2019	PASS	1	0	SEE TEST PROCEDURES FOR OBSERVATIONS
10	10												

Appendix X: Drawing Package & Wiring Diagrams

Exploded View Assembly Drawings

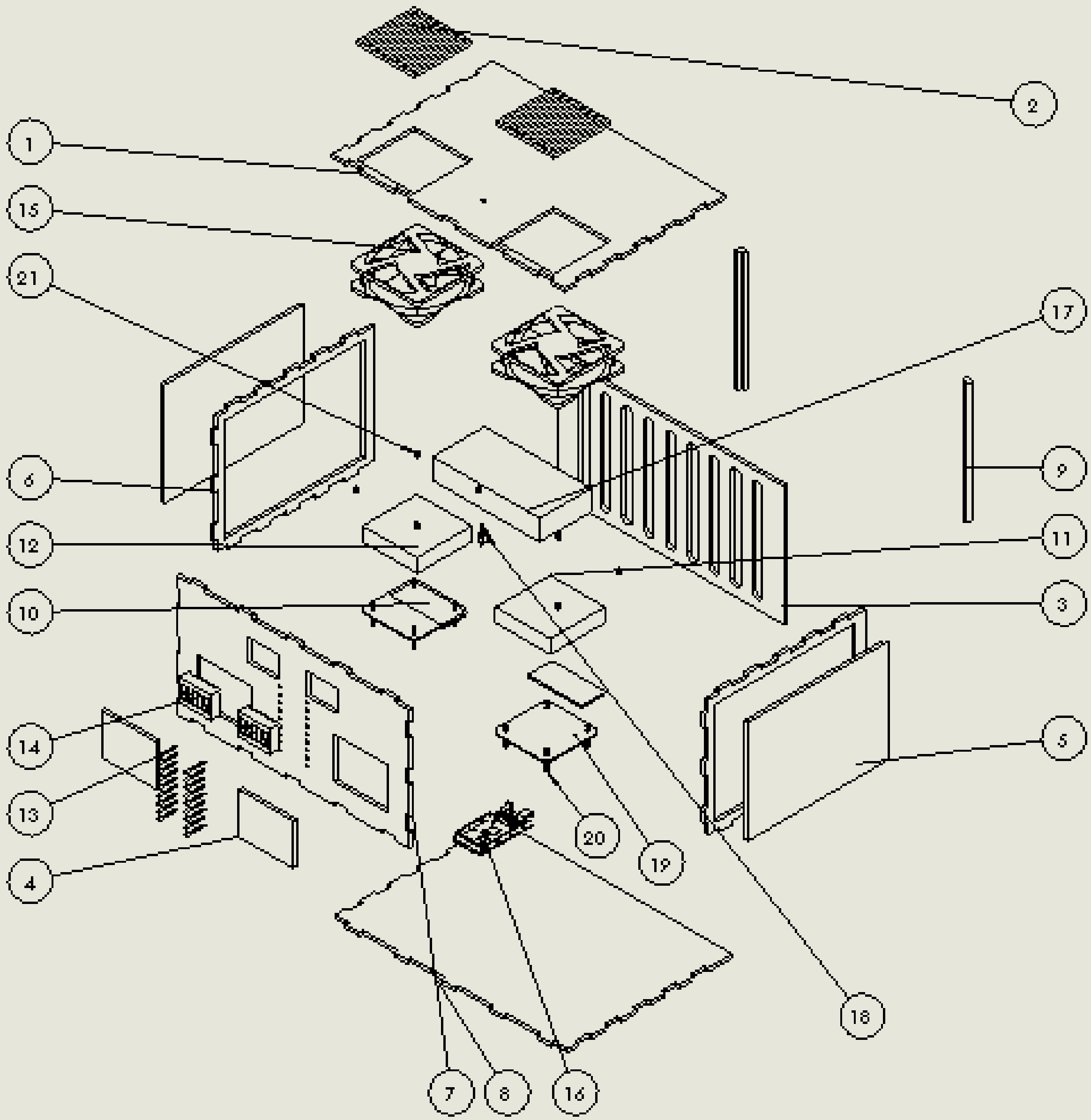
ITEM NO.	PART NUMBER	QTY.
1	Acrylic Display Box	1
2	Barb Tube Connector	10
3	PVC Nipple	3
4	Metal Foam Insert	3
5	4 Way Split Valve	1
6	Air Pump	1
7	Check Valve	1
8	PVC Tube 1	1
9	PVC Tube 2	1
10	PVC Tube 3	1
11	PVC Tube 4	1
12	Mylar Balloon	3



FLOW RESISTANCE DISPLAY EXPLODED VIEW

	NAME	DATE	SIZE	DWG. NO.	REV
DRAWN	S HASAN	2/3/17	A	200	7

SCALE: 1:10

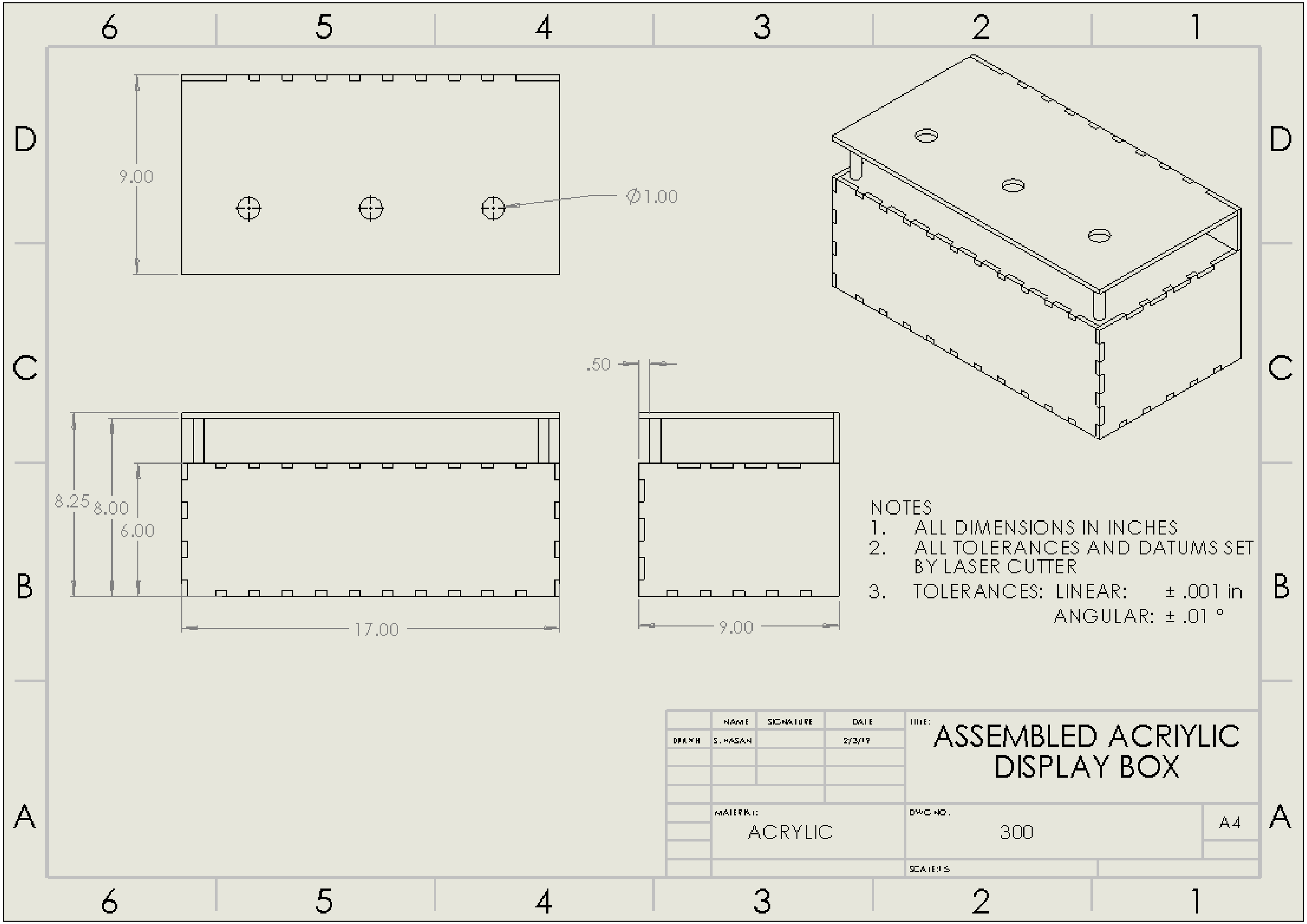


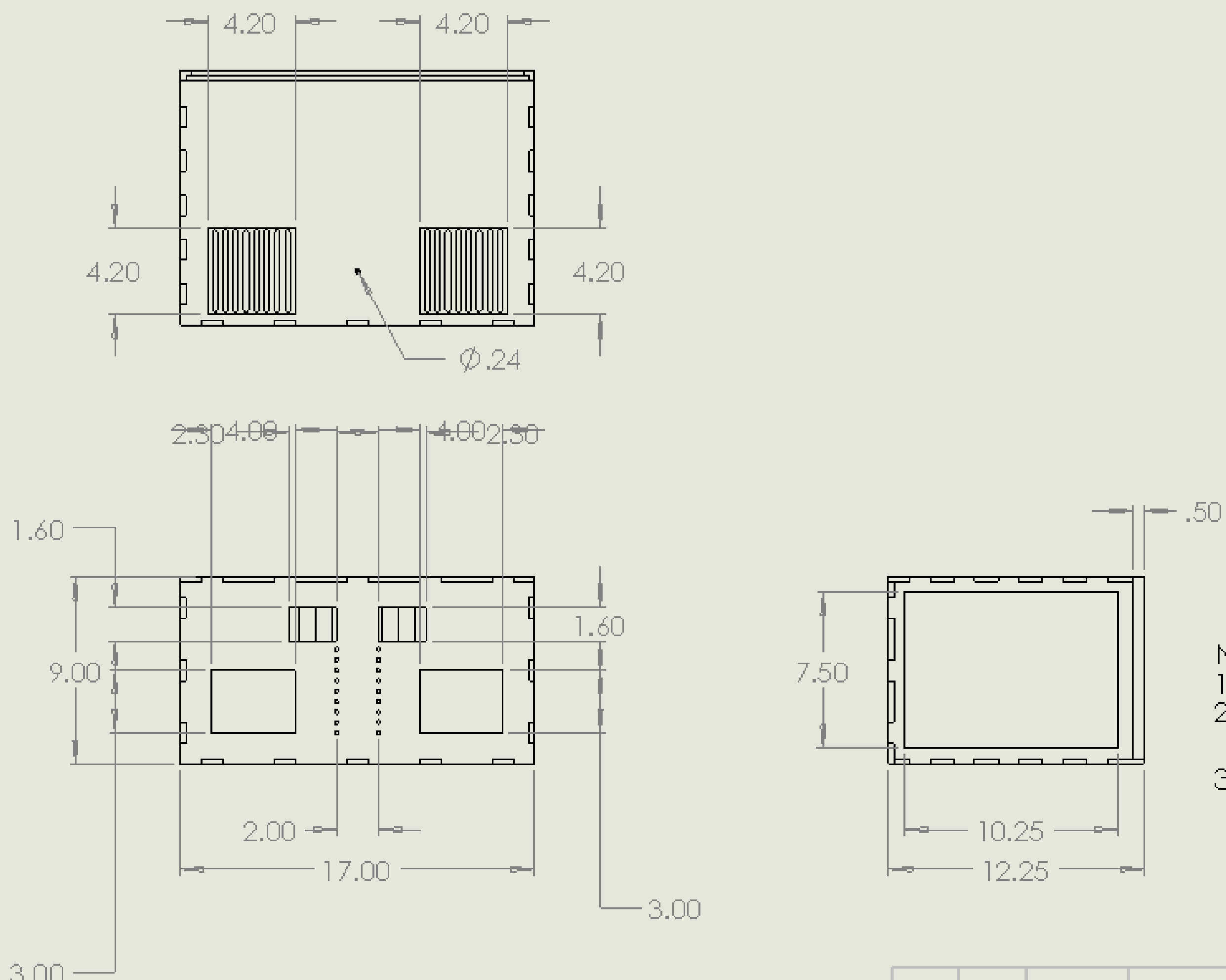
ITEM NO.	PART NAME	MATERIAL	QTY.
1	Top Panel	Acrylic	1
2	Top Fan Inserts	Acrylic	2
3	Back Panel	Acrylic	1
4	Front window	Acrylic	1
5	Side Insert	Acrylic	2
6	Side Panel	Acrylic	2
7	Front Panel	Acrylic	1
8	Bottom Panel	Acrylic	1
9	Back Panel Rail	Acrylic	2
10	Heating Pad	-	2
11	Aluminum Block	Aluminum	1
12	Metal Foam Block	Duocel® Aluminum Foam	1
13	LED	-	18
14	3 DIGIT LED Display	-	2
15	Fan	-	2
16	ArduinoMega	-	1
17	AC to DC Power Supply	-	1
18	Toggle Switch	-	1
19	Metal Plate Stand		2
20	Metal Stand Screws		8
21	M4 threaded insert		8

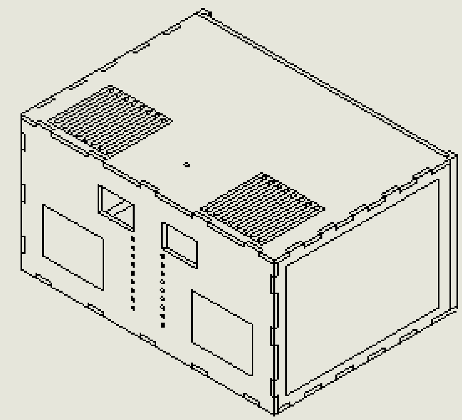
TITLE:
Thermal Conductivity Display Exploded View

SIZE B
DWG. NO. 1.0
REV
SCALE: 1:7

Acrylic Box Assembly Drawings



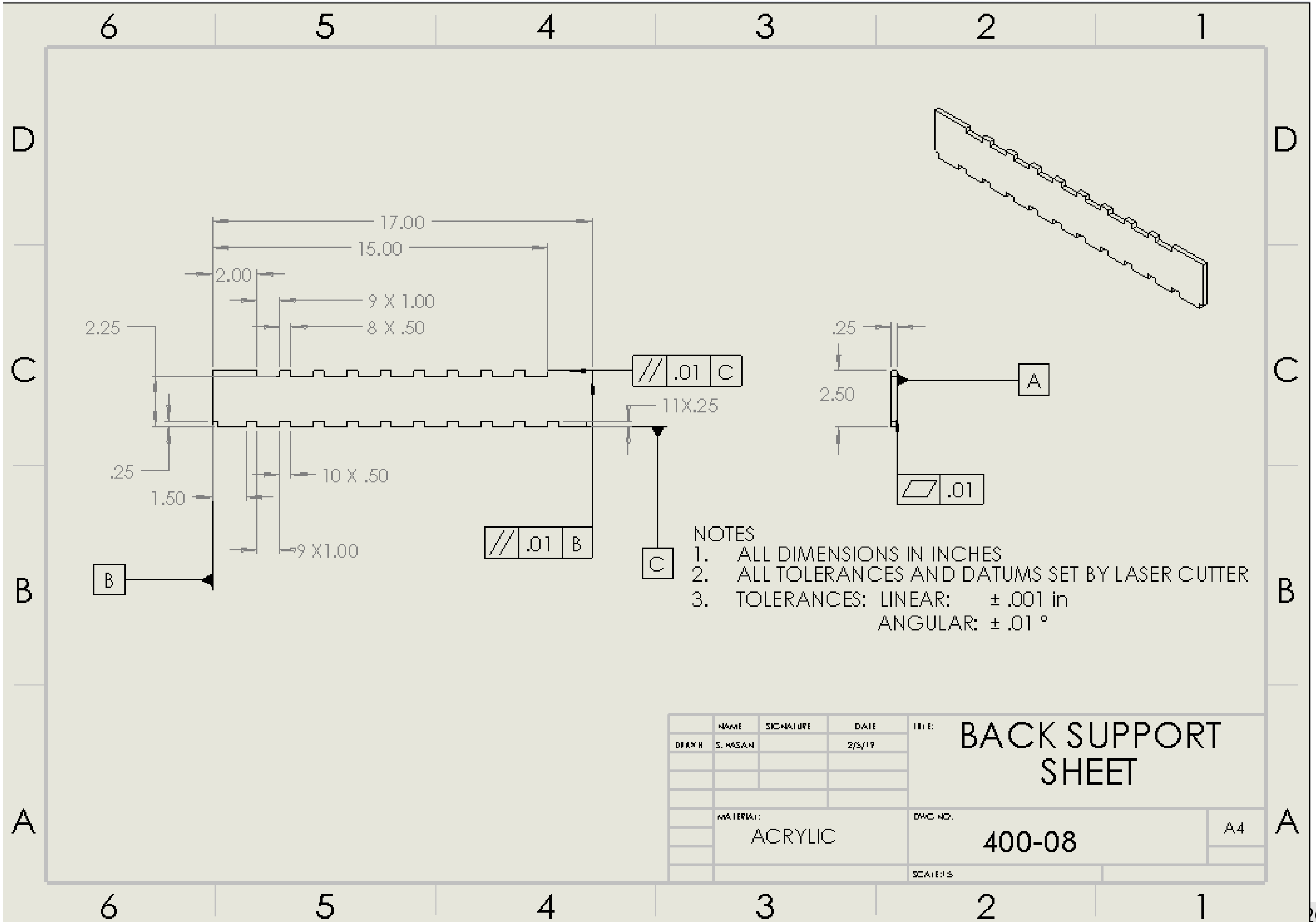


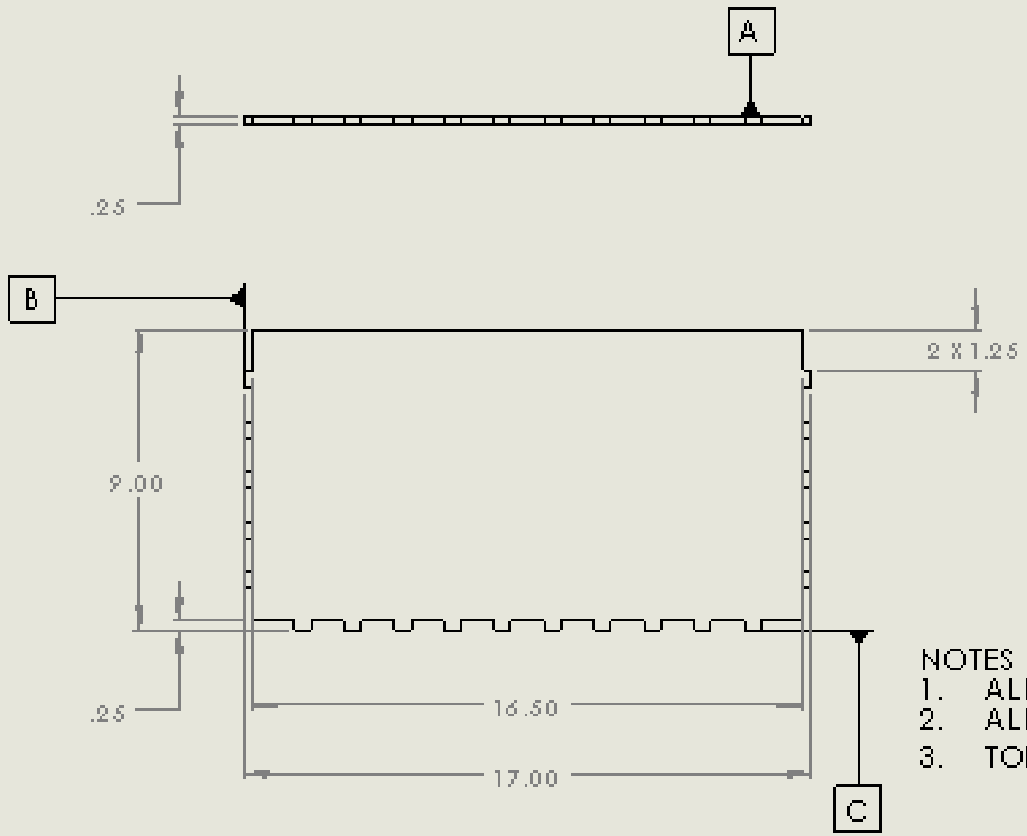


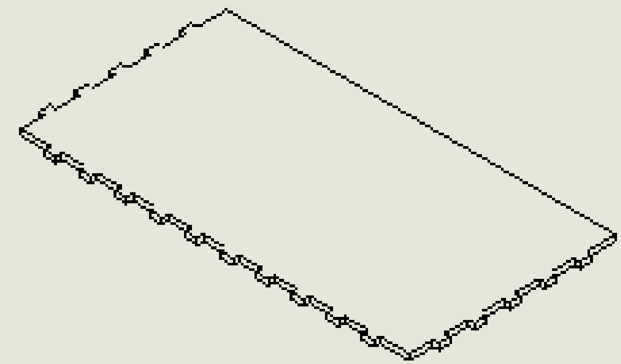
NOTES
1. ALL DIMENSIONS IN INCHES
2. ALL TOLERANCES AND DATUMS SET BY LASER CUTTER
3. TOLERANCES: LINEAR: ± .001 in
ANGULAR: ± .01 °

	NAME	SIGNATURE	DATE	TITLE:
DRAWN	S. HASAN		2/22/19	Acrylic Box Assembley
	MATERIAL: ACRYLIC			DWG NO. 2.0 — A4
				SCALE 1:8

Detailed Parts Drawings for Flow Resistance Display


17.00
15.00
2.00
9 X 1.00
8 X .50
2.25
.25
1.50
10 X .50
9 X1.00
11X.25
.01 C
.01 B
B
C
.25
2.50
A
.01
NOTES
1. ALL DIMENSIONS IN INCHES
2. ALL TOLERANCES AND DATUMS SET BY LASER CUTTER
3. TOLERANCES: LINEAR: ± .001 in
ANGULAR: ± .01 °
NAME
SIGNATURE
DATE
S. HASAN
TITLE:
BACK SUPPORT SHEET
MATERIAL:
ACRYLIC
DWG NO.
400-08
A4





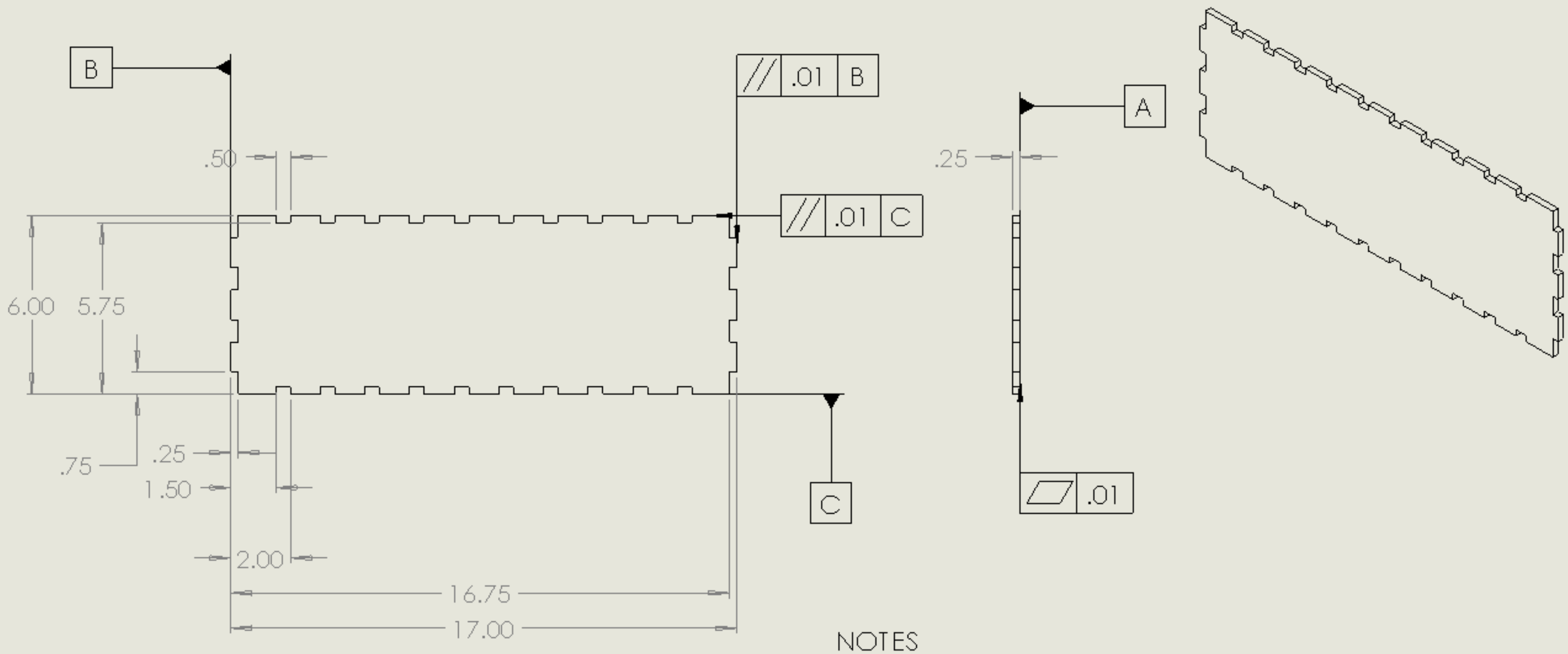
NOTES
1. ALL DIMENSIONS IN INCHES
2. ALL TOLERANCES AND DATUMS SET BY LASER CUTTER
3. TOLERANCES: LINEAR: ± .001 in
ANGULAR: ± .01 °

Bottom Acrylic Piece

Acrylic

400-02

A4



NOTES
1. ALL DIMENSIONS IN INCHES
2. ALL TOLERANCES AND DATUMS SET BY LASER CUTTER
3. TOLERANCES: LINEAR: ± .001 in
ANGULAR: ± .01 °

	NAME	SIGNATURE	DATE	TITLE:
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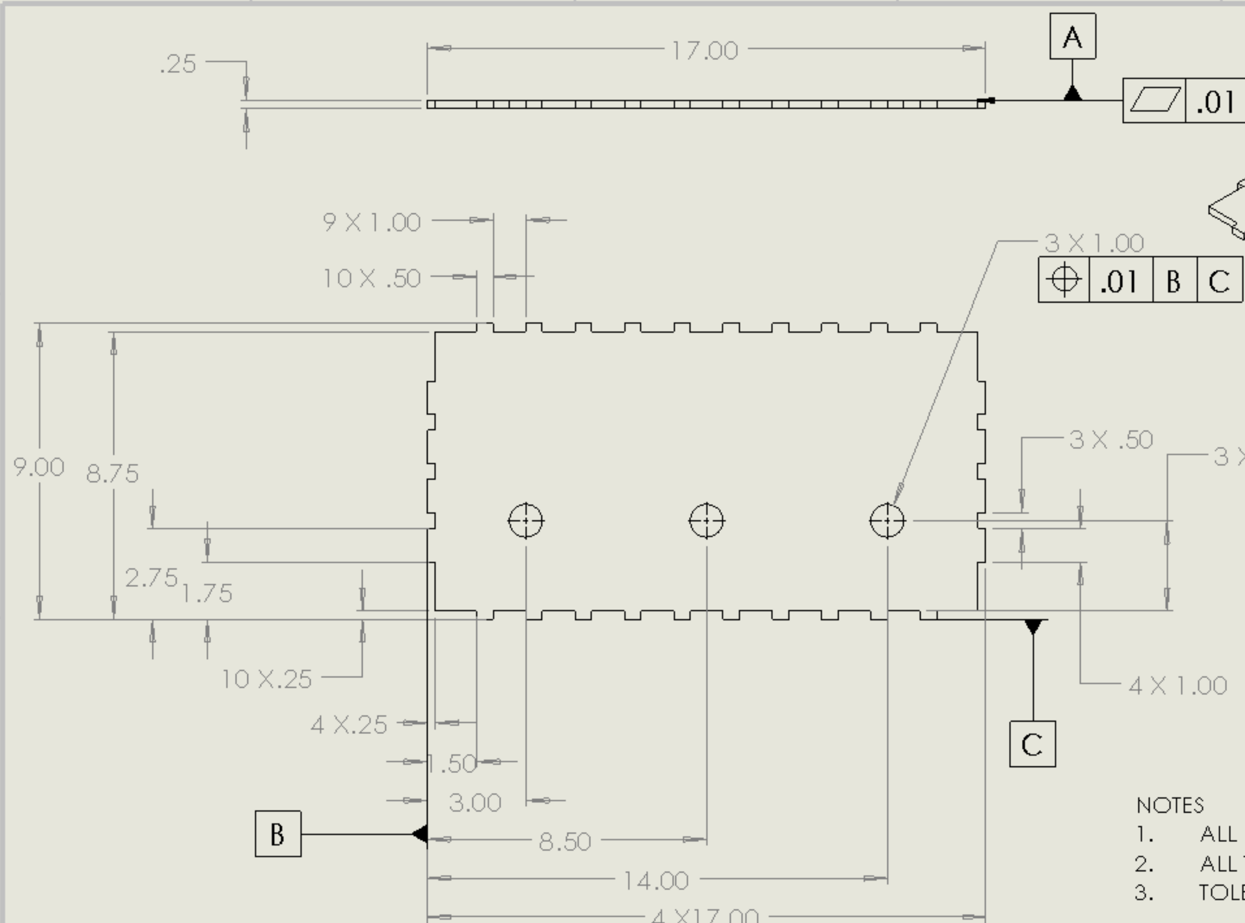
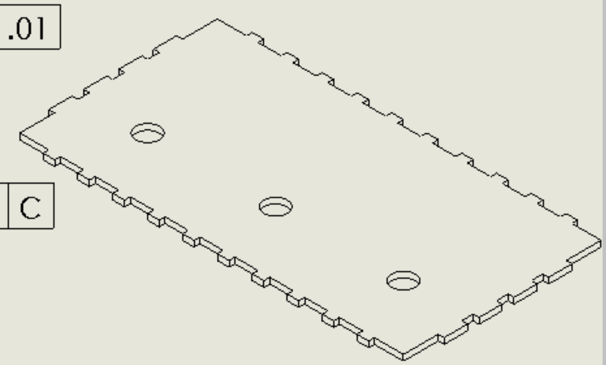
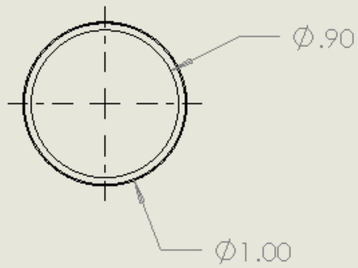
	MATERIAL: ACRYLIC			DWG NO. 400-03 A4
				SCALE:1:5

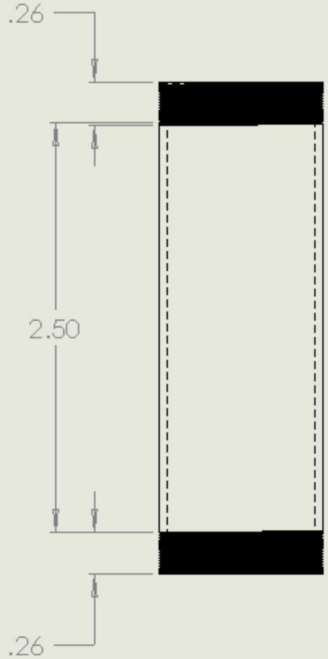


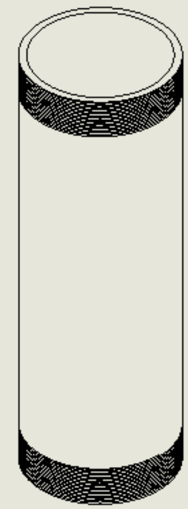


NOTES
1. ALL DIMENSIONS IN INCHES
2. ALL TOLERANCES AND DATUMS SET BY LASER CUTTER
3. TOLERANCES: LINEAR: ± .001 in
ANGULAR: ± .01 °

	NAME	SIGNATURE	DATE	TITLE:
DRAWN	S HASAN		2/3/19	Middle Sheet
	MATERIAL: ACRYLIC			DWG NO. 400-01 · A4
				SCALE:1:5

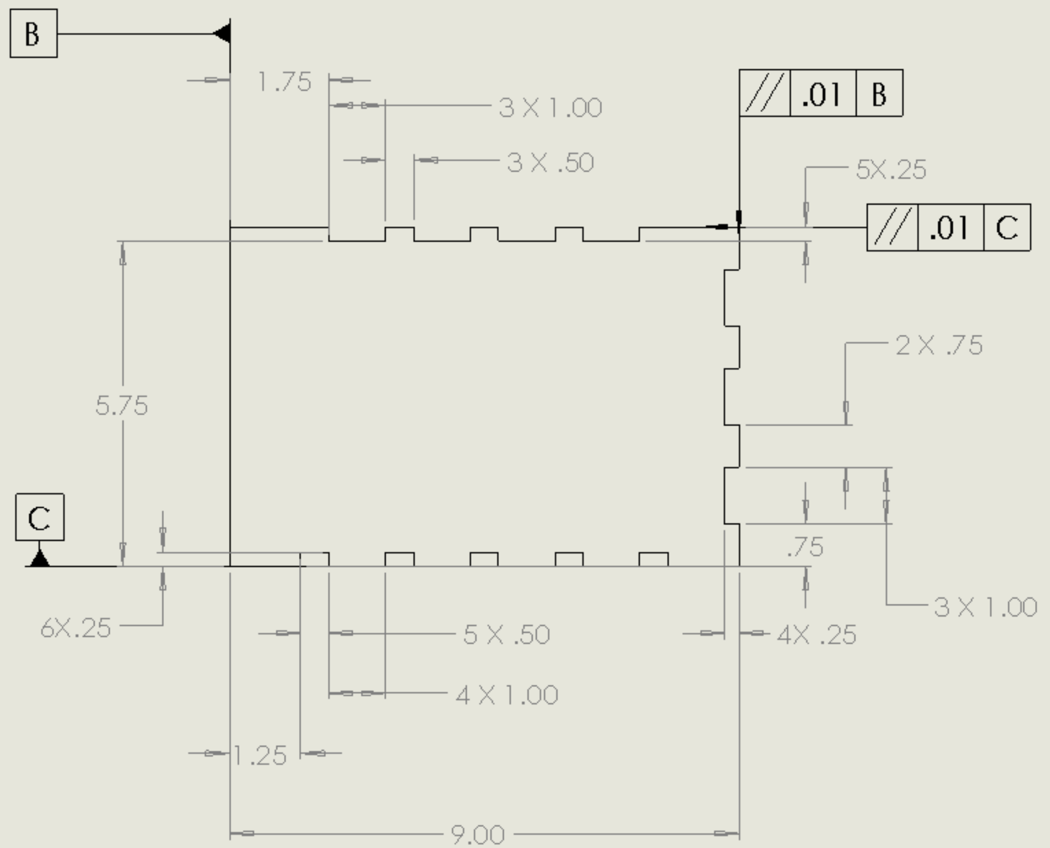


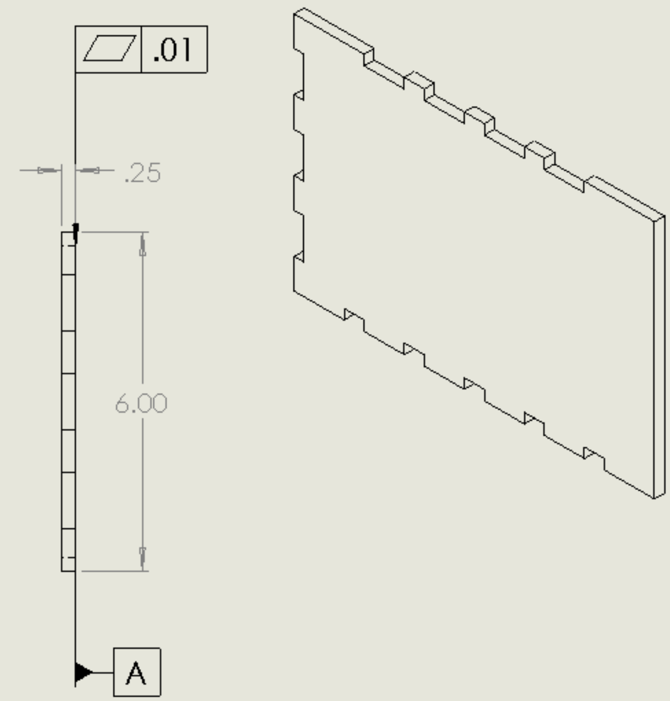




NOTE
1. REDRAWN SOURCED PART
2. TOLERANCES: LINEAR: ± .01 in
ANGULAR: ± .1 °

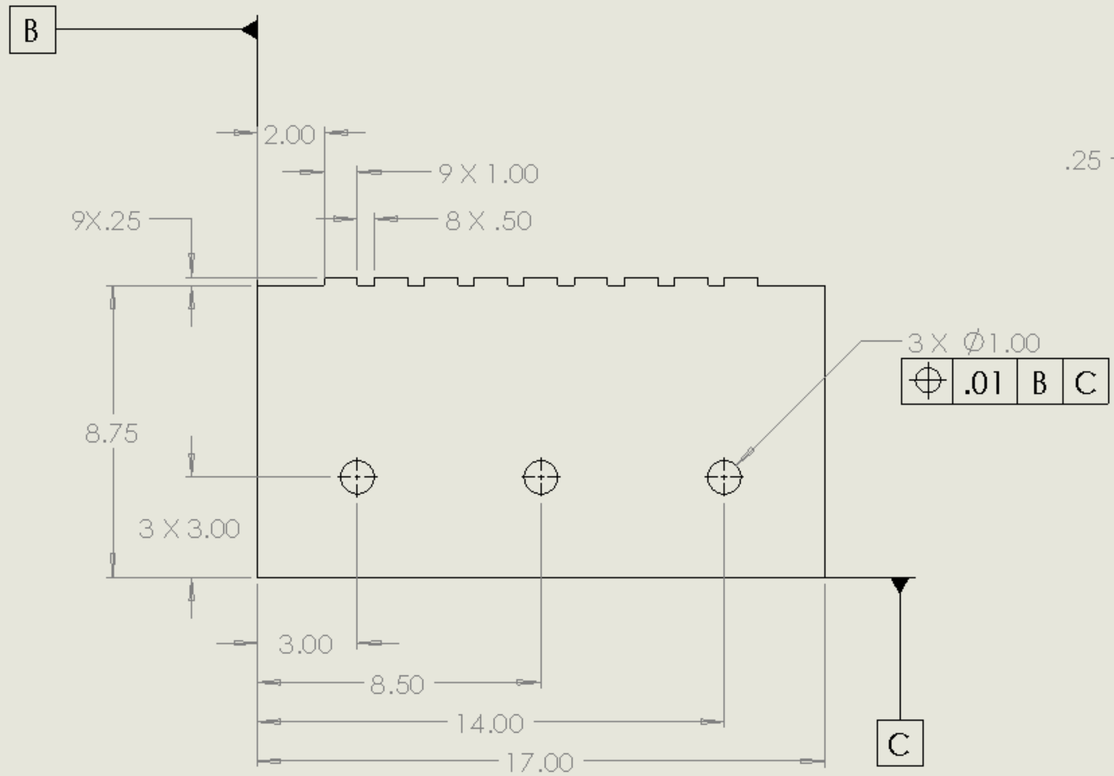
	NAME	SIGNATURE	DATE	TITLE:
DRAWN	S HASAN		2/3/19	PVC NIPPLE
	MATERIAL: PVC			DWG NO. 200-03 — A4
				SCALE:1:1

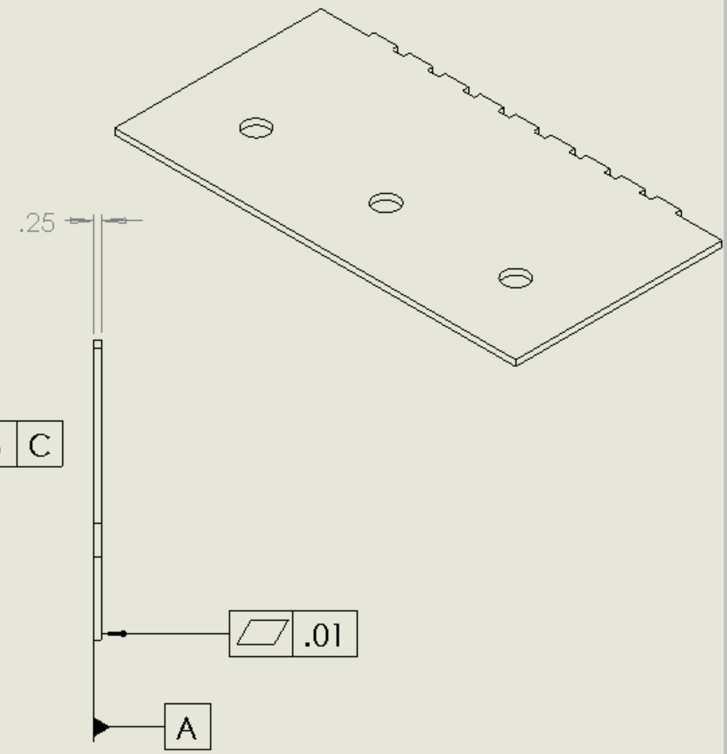




NOTES
1. ALL DIMENSIONS IN INCHES
2. ALL TOLERANCES AND DATUMS SET BY LASER CUTTER
3. TOLERANCES: LINEAR: ± .001 in
ANGULAR: ± .01 °

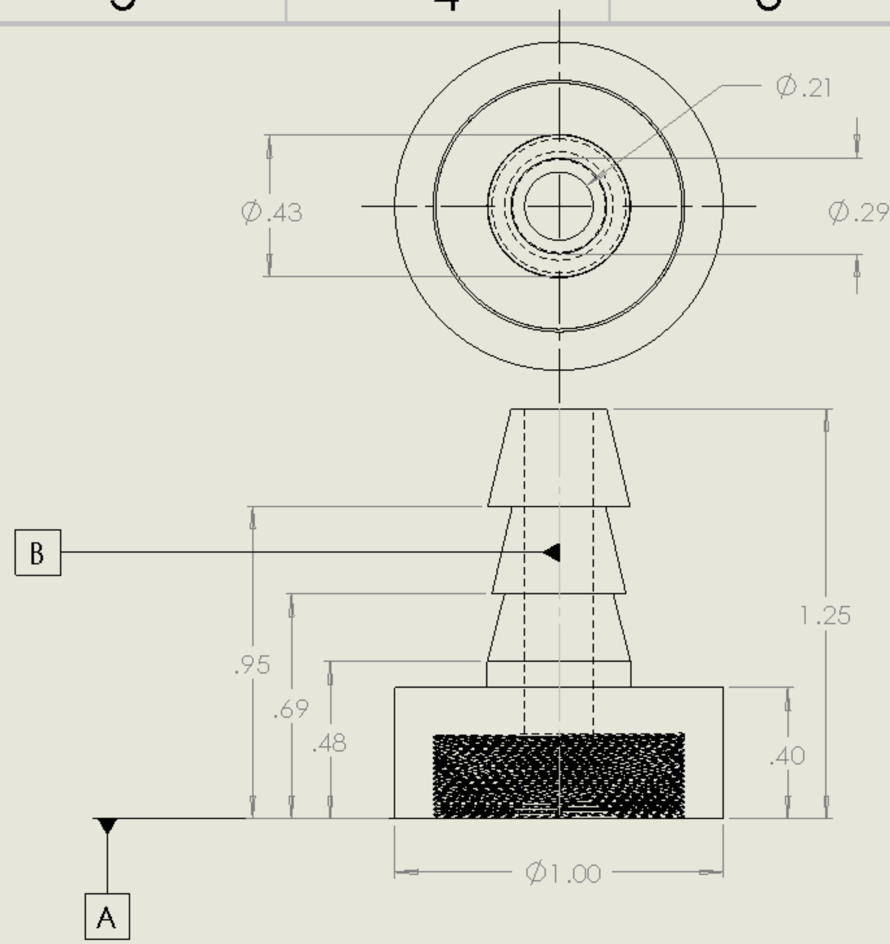
	NAME	SIGNATURE	DATE	TITLE: SIDE SHEET
DRAWN	S HASAN		2/3/19	
	MATERIAL: ACRYLIC			DWG NO. 400-09 A4
				SCALE:1:2

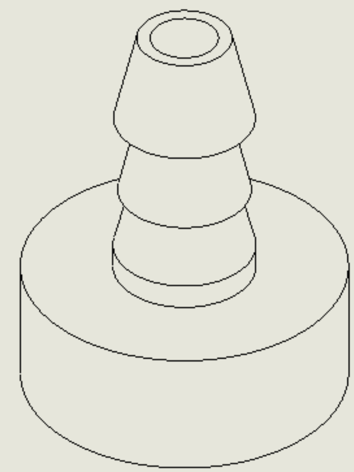




NOTES
1. ALL DIMENSIONS IN INCHES
2. ALL TOLERANCES AND DATUMS SET BY LASER CUTTER
3. TOLERANCES: LINEAR: ± .001 in
   ANGULAR: ± .01 °

	NAME	SIGNATURE	DATE	TITLE:
DRAWN	S HASAN		2/3/19	TOP SHEET
	MATERIAL: ACRYLIC			DWG NO. 400-04 — A4
				SCALE:1:5

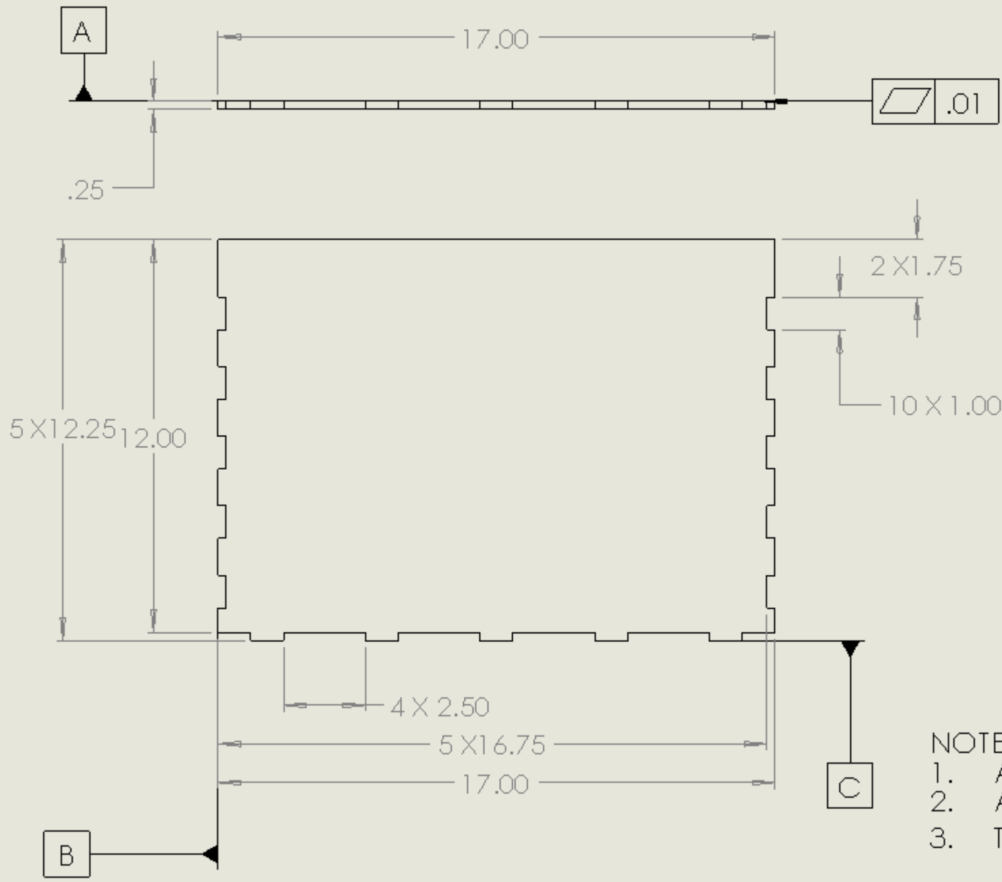


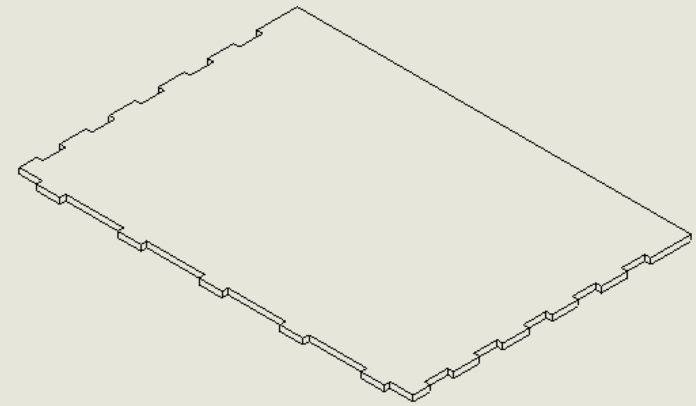


NOTE
1. REDRAWN SOURCED PART
2. TOLERANCES: LINEAR: ±.01 in
ANGULAR: ±.1 °

	NAME	SIGNATURE	DATE	TITLE:
DRAWN	S HASAN		2/3/19	TOP SHEET
	MATERIAL: ACRYLIC			DWG NO. 200-02
				SCALE:2:1
				A4

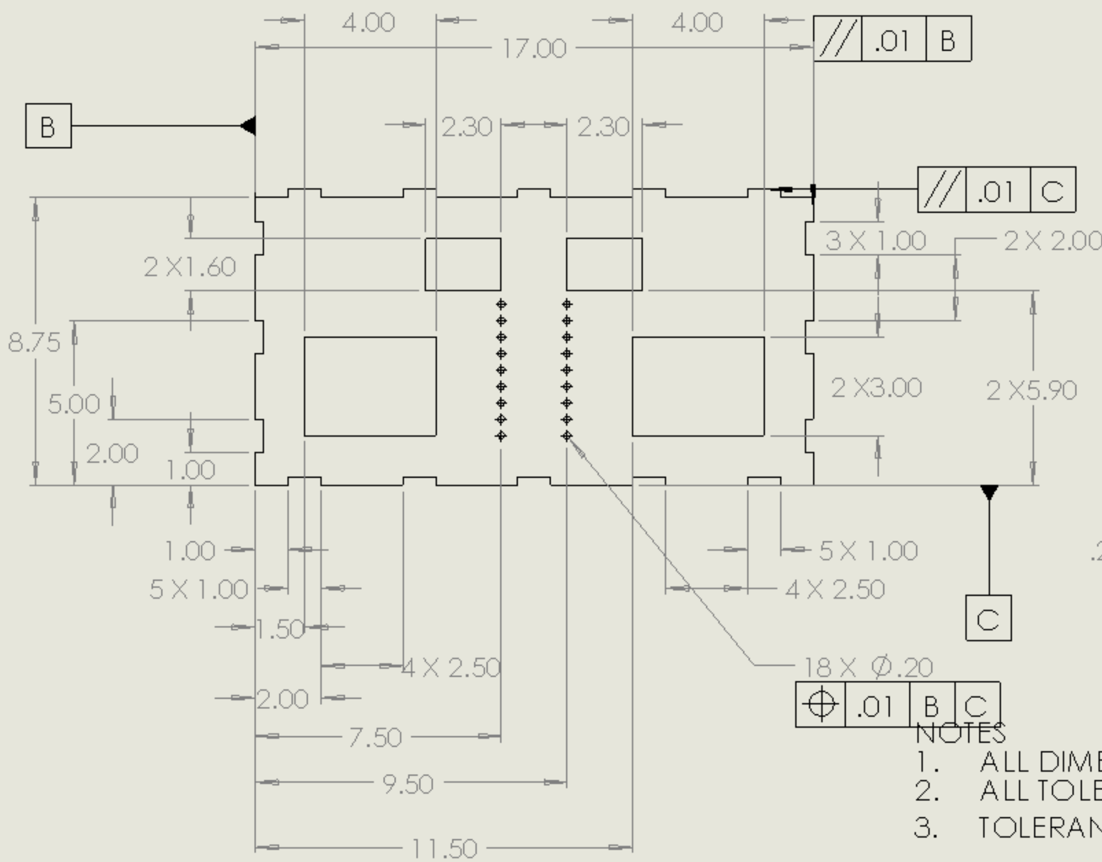
Detailed Parts Drawings for Thermal Display

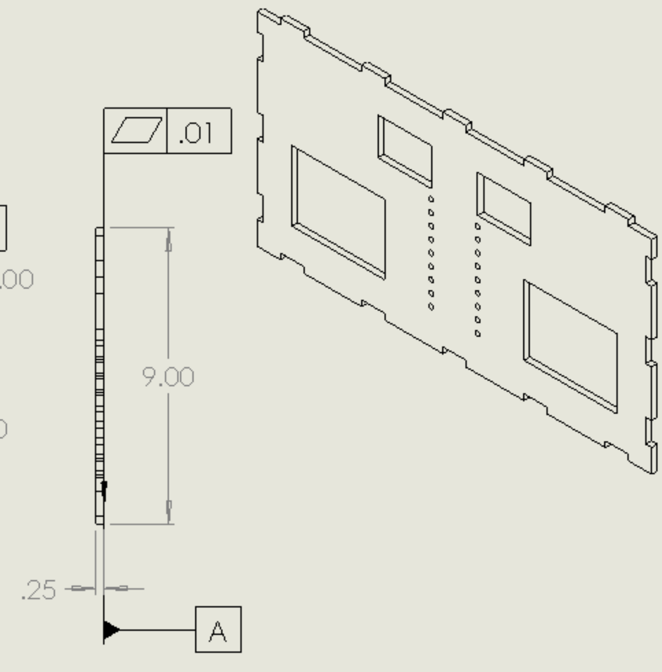




NOTES
1. ALL DIMENSIONS IN INCHES
2. ALL TOLERANCES AND DATUMS SET BY LASER CUTTER
3. TOLERANCES: LINEAR: ± .001 in
ANGULAR: ± .01 °

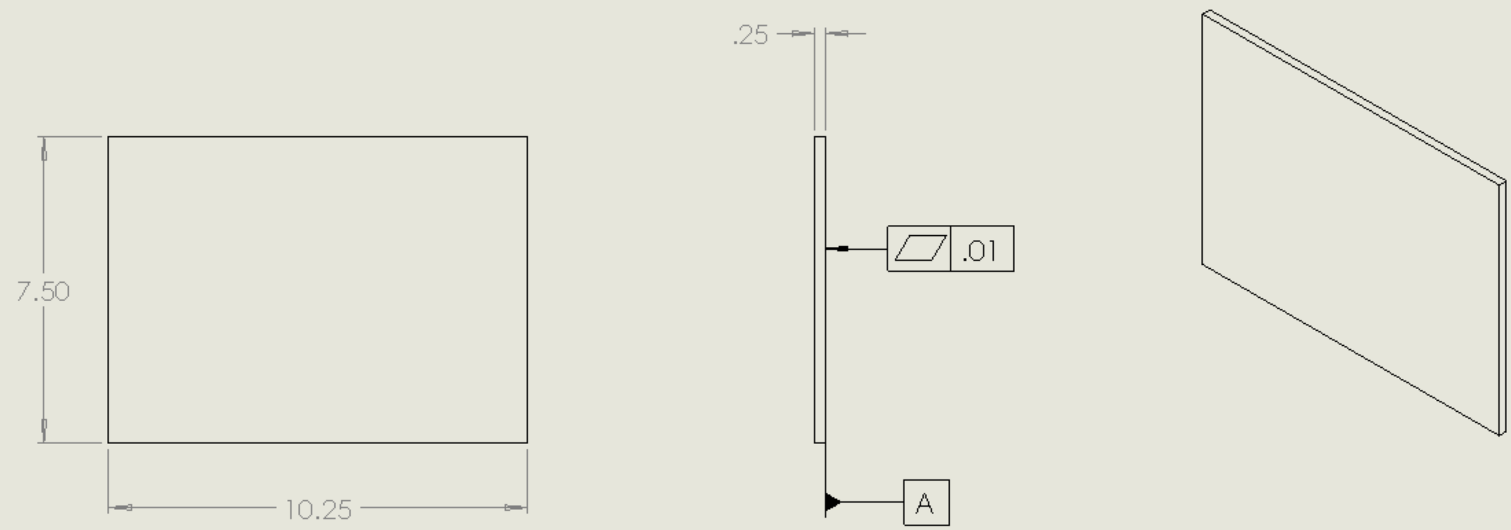
	NAME	SIGNATURE	DATE	TITLE:
DRAWN	S. HASAN		2/22/19	BOTTOM PANEL
	MATERIAL: ACRYLIC			DWG NO. 1.8 — A4
				SCALE 1:5





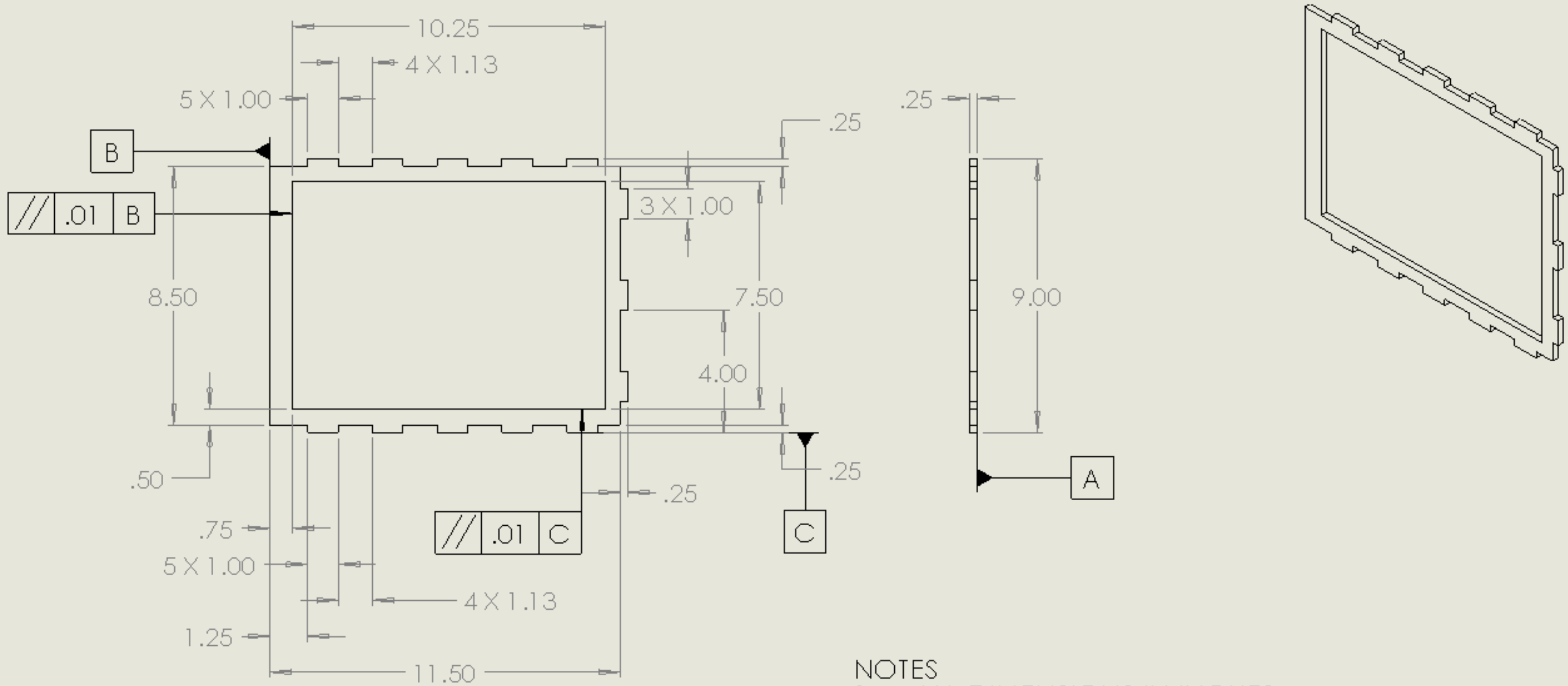
NOTES
1. ALL DIMENSIONS IN INCHES
2. ALL TOLERANCES AND DATUMS SET BY LASER CUTTER
3. TOLERANCES: LINEAR: ± .001 in
ANGULAR: ± .01 °

	NAME	SIGNATURE	DATE	TITLE: FRONT PANEL
DRAWN	S. HASAN		2/22/19	
	MATERIAL: ACRYLIC			DWG NO. 1- 07 — A4
				SCALE 1:5



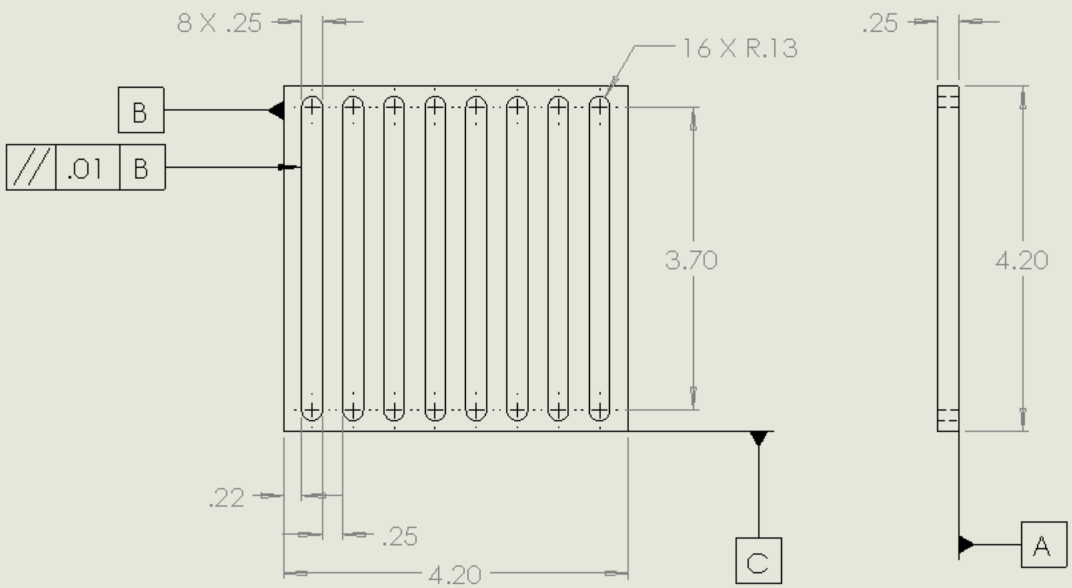
NOTES
1. ALL DIMENSIONS IN INCHES
2. ALL TOLERANCES AND DATUMS SET BY LASER CUTTER
3. TOLERANCES: LINEAR: ± .001 in
ANGULAR: ± .01 °

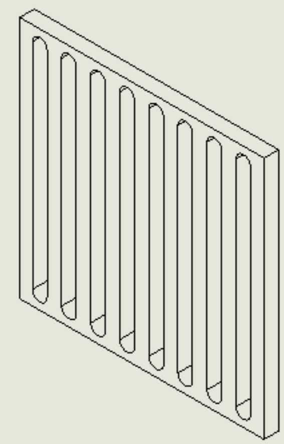
	NAME	SIGNATURE	DATE	TITLE:
DRAWN	S. HASAN		2/22/19	SIDE PANEL INSERT
	MATERIAL: ACRYLIC			DWG NO. 1- 05 — A4
				SCALE 1:4



NOTES
1. ALL DIMENSIONS IN INCHES
2. ALL TOLERANCES AND DATUMS SET BY LASER CUTTER
3. TOLERANCES: LINEAR: ± .001 in
ANGULAR: ± .01 °

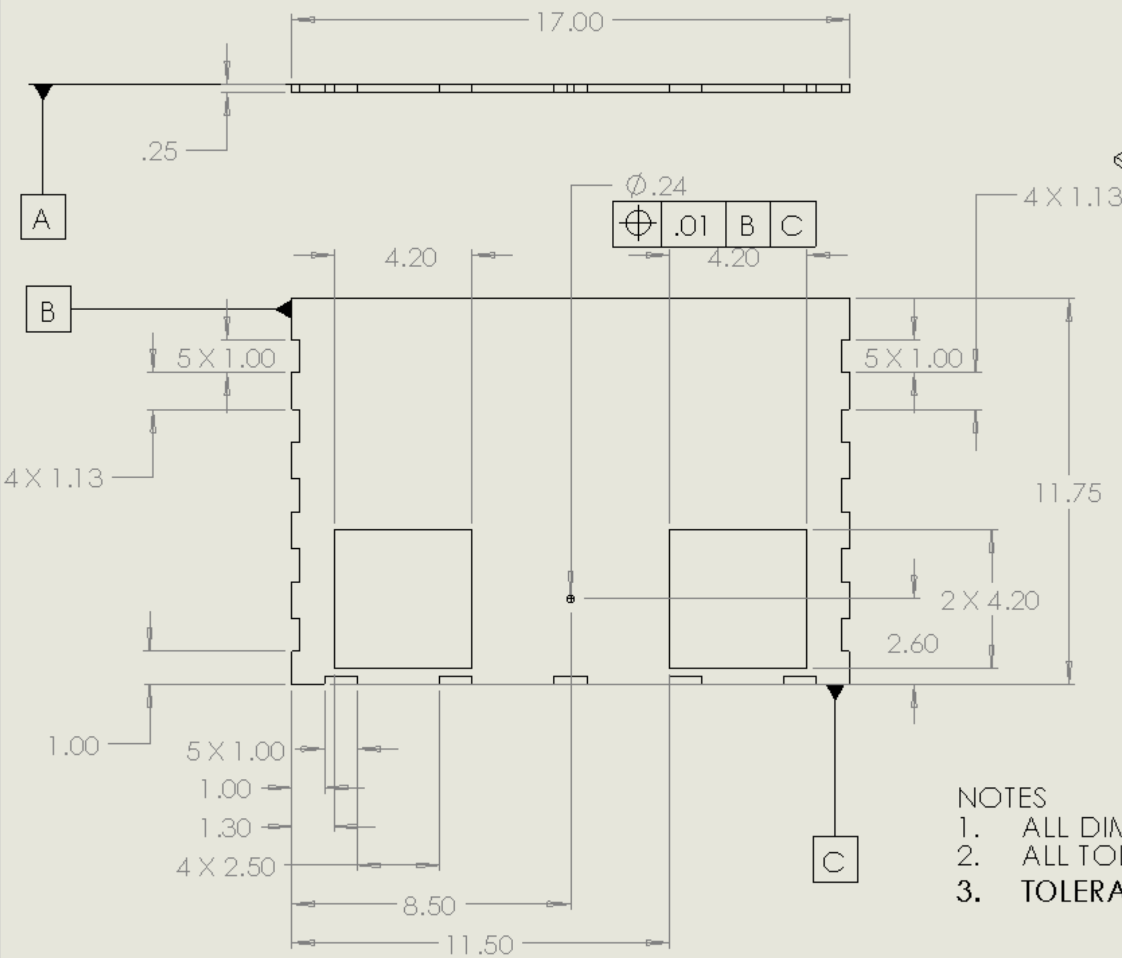
	NAME	SIGNATURE	DATE	TITLE: SIDE PANEL
DRAWN	S. HASAN		2/22/19	
MATERIAL: ACRYLIC				DWG NO. 1- 06
				A4
				SCALE 1:5

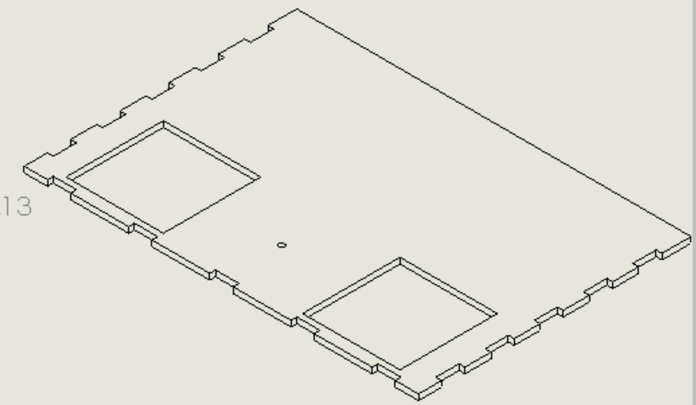




NOTES
1. ALL DIMENSIONS IN INCHES
2. ALL TOLERANCES AND DATUMS SET BY LASER CUTTER
3. TOLERANCES: LINEAR: ± .001 in
ANGULAR: ± .01 °

	NAME	SIGNATURE	DATE	TITLE:
DRAWN	S. HASAN		2/22/19	TOP PANEL INSERT
MATERIAL: ACRYLIC				DWG NO. 1- 02	A4
				SCALE 1:2





NOTES
1. ALL DIMENSIONS IN INCHES
2. ALL TOLERANCES AND DATUMS SET BY LASER CUTTER
3. TOLERANCES: LINEAR: ± .001 in
ANGULAR: ± .01 °

	NAME	SIGNATURE	DATE
DRAWN	S. HASAN		4/7/19

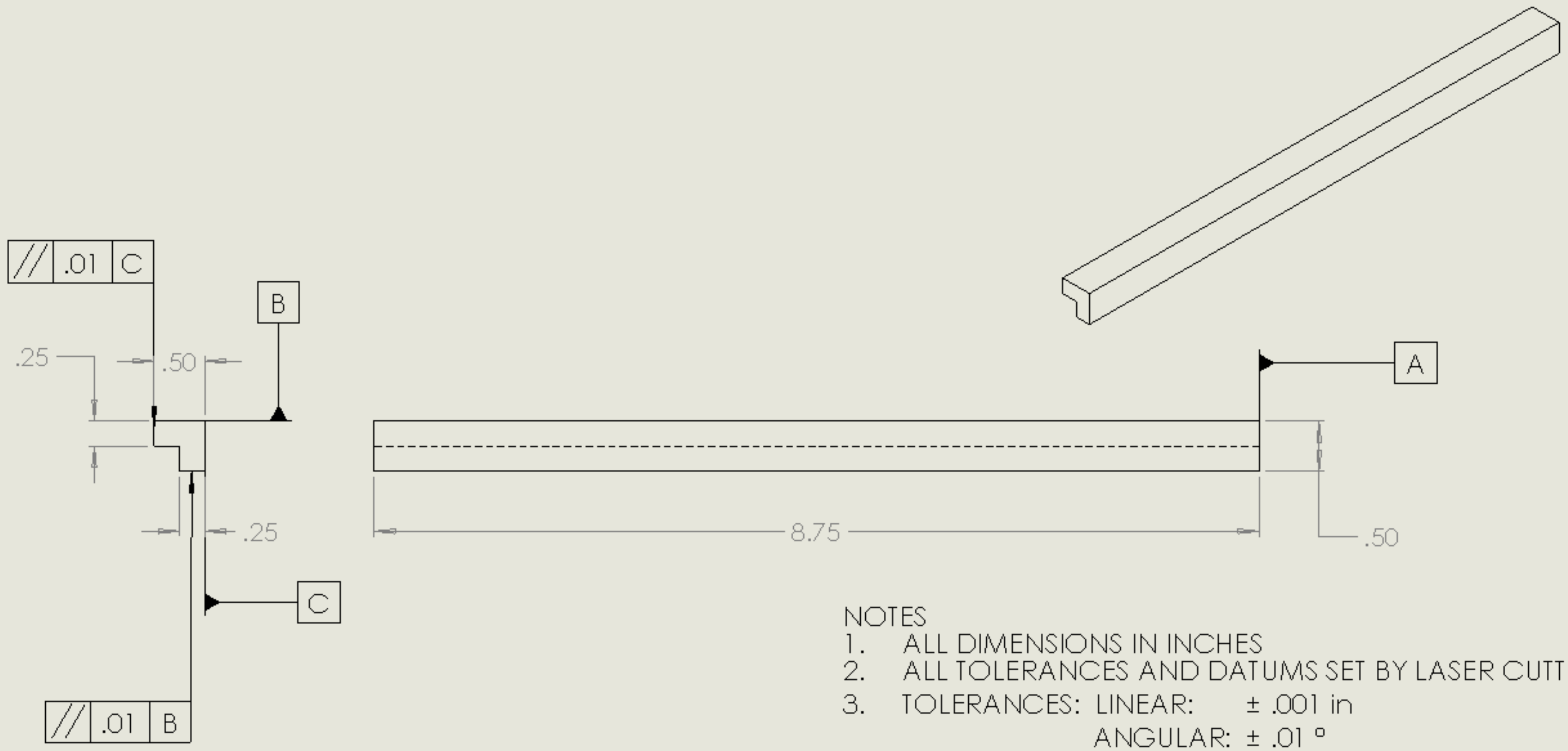
TITLE: TOP PANEL

MATERIAL: ACRYLIC

DWG NO. 1 - 01

A4

SCALE 1:5



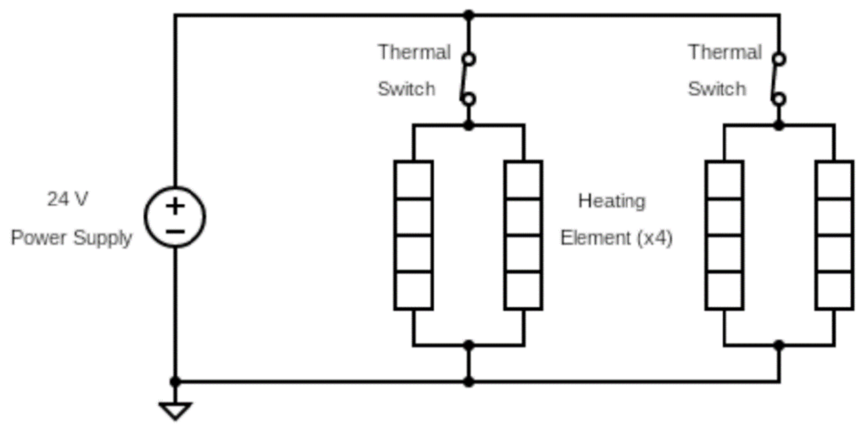
NOTES
1. ALL DIMENSIONS IN INCHES
2. ALL TOLERANCES AND DATUMS SET BY LASER CUTTER
3. TOLERANCES: LINEAR: ± .001 in
ANGULAR: ± .01 °

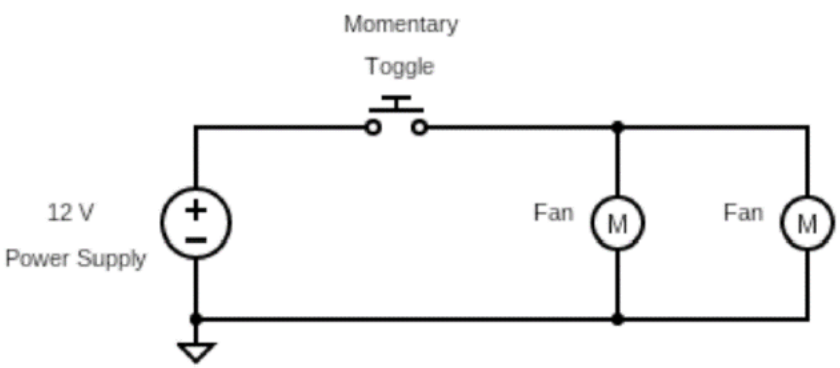
	NAME	SIGNATURE	DATE
DRAWN	S. HASAN		2/22/19

TITLE:	Back Panel Rails
MATERIAL:	ACRYLIC
DWG NO.	1- 09
	A4
SCALE 1:2	

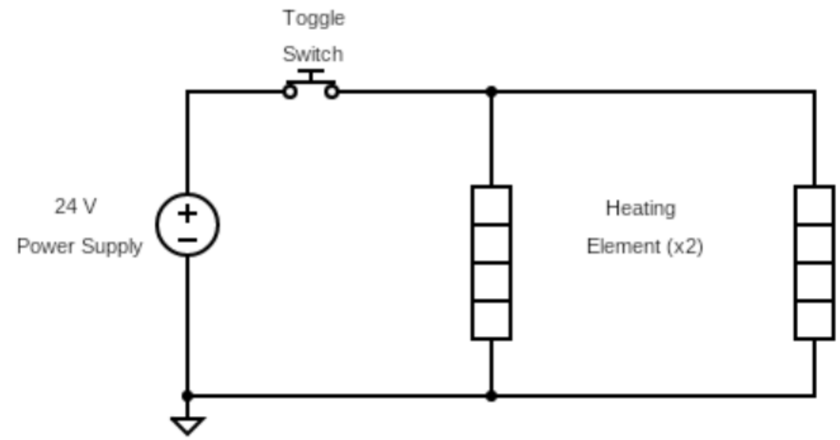
WIRING DIAGRAMS

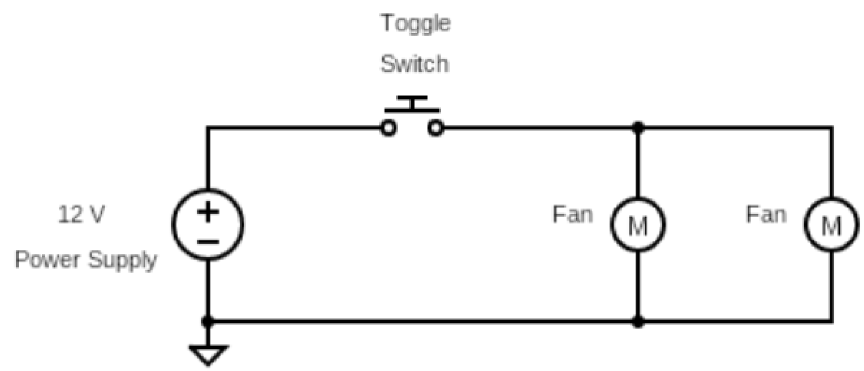
ORIGIONAL:

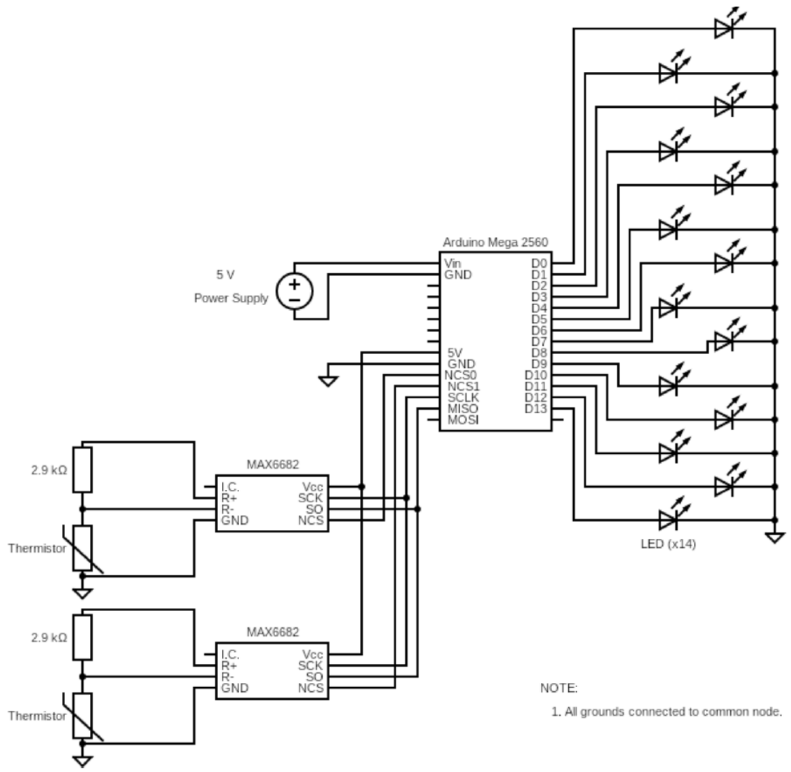


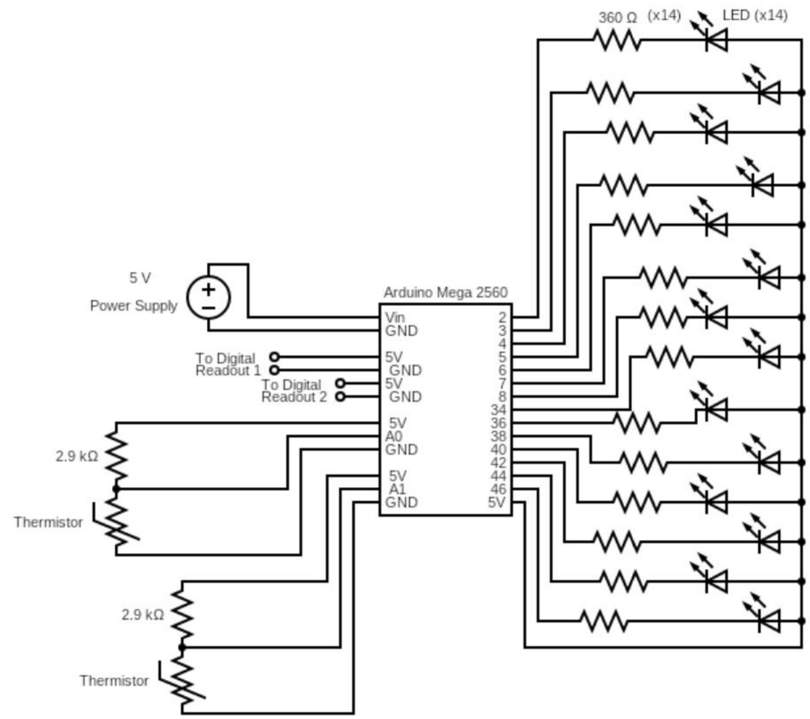


FINAL:






Arduino Mega 2560
5 V
Power Supply
Vin
GND
5V
GND
NCS0
NCS1
SCLK
MISO
MOSI
D0
D1
D2
D3
D4
D5
D6
D7
D8
D9
D10
D11
D12
D13
MAX6682
I.C.
R+
R-
GND
Vcc
SCK
SO
NCS
2.9 kΩ
Thermistor
MAX6682
2.9 kΩ
Thermistor
LED (x14)
NOTE:
1. All grounds connected to common node.


360 Ω (x14)
LED (x14)
5 V
Power Supply
Arduino Mega 2560
Vin
GND
To Digital
Readout 1
5V
GND
To Digital
Readout 2
5V
GND
5V
A0
GND
5V
A1
GND
2
3
4
5
6
7
8
34
36
38
40
42
44
46
5V
2.9 kΩ
Thermistor
2.9 kΩ
Thermistor

Appendix Y: Links to Purchased Parts Descriptions & Literature

Flow Control Display

Item	Product Description/Literature
Tubing	https://www.amazon.com/dp/B07G9VCFGS/?coliid=I28O0BGT5BXPZ&colid=2KWA66KIBS0FE&psc=0&ref_=lv_ov_lig_dp_it
Check Valve	https://www.amazon.com/dp/B07H68527Z/?coliid=I197NKJBOGORN9&colid=2KWA66KIBS0FE&psc=0&ref_=lv_ov_lig_dp_it
Splitter & release valve	https://www.amazon.com/dp/B00UNCB4GY/?coliid=I1Q5ZC903CWHDF&colid=2KWA66KIBS0FE&psc=0&ref_=lv_ov_lig_dp_it
Barb tube connectors	https://www.amazon.com/dp/B0064OJ1HE/?coliid=I2KATA42XG60AT&colid=2KWA66KIBS0FE&psc=0&ref_=lv_ov_lig_dp_it
Male to male converter	https://www.amazon.com/dp/B0015AOREO/?coliid=I2N2U2U43GLP0F&colid=2KWA66KIBS0FE&ref_=lv_ov_lig_dp_it&th=1
Acrylic Cylinders	https://www.amazon.com/dp/B0182IIPEO/?coliid=IMTZ2BWSQ7U88&colid=2KWA66KIBS0FE&psc=0&ref_=lv_ov_lig_dp_it
Adhesive	https://www.amazon.com/SCIGRIP-10315-Acrylic-Cement-Low-VOC/dp/B07ML4BRDY/ref=sr_1_3?ie=UTF8&qid=1546971474&sr=8-3&keywords=weldon+acrylic
Small Balloons	https://www.amazon.com/5-Latex-Red-Balloons-72ct/dp/B0016KZCX8/ref=sr_1_3?ie=UTF8&qid=1547138671&sr=8-3&keywords=5+inch+red+ballons
Large Balloons	https://www.amazon.com/Balloons-Premium-Helium-Quality-Red/dp/B071Y6Q58V/ref=sr_1_33?ie=UTF8&qid=1546969632&sr=8-33&keywords=red+balloons
Foot pump	https://www.amazon.com/dp/B000ODTYDC/?coliid=I1ROG57NRRBX3H&colid=2KWA66KIBS0FE&psc=0&ref_=lv_ov_lig_dp_it
Hand pump	https://www.amazon.com/Texsport-Double-Action-Hand-Mattress/dp/B000P9IRVK/ref=sr_1_21?ie=UTF8&qid=1547133984&sr=8-21&keywords=hand+air+pump
Red Acrylic Sheet	https://www.amazon.com/dp/B06XP1BN8W/ref=sxts_kp_bs_1?pf_rd_p=8778bc68-27e7-403f-8460de48b6e788fb&pd_rd_wg=36FuV&pf_rd_r=X4TJ7SCJJ1HGSNGFC89M&pd_rd_i=B06XP1BN8W&pd_rd_w=ZKP22&pd_rd_r=73af06c3-5173-4d42-ab6a-00be6391417c&ie=UTF8&qid=1547100313&sr=1&th=1
Black Acrylic Sheet	https://www.eplastics.com/ACRY20250-250PM24X48
Acrylic rod	https://www.eplastics.com/ACREXR0-500
PVC Nipple	https://www.usplastic.com/catalog/item.aspx?itemid=37311&catid=592%20

Thermal Display

Item	Product Description
Flexible Heater	https://www.amazon.com/dp/B07H4TKNFR/?coliid=I3R6DHMWKLXPMN&colid=2KWA66KIBS0FE&psc=0&ref_=lv_ov_lig_dp_it
Digial Thermocouple Readout	https://www.amazon.com/UCTRONICS-Centigrade-Temperature-Thermocouple-Protection/dp/B01IGUGO1E/ref=sr_1_49?keywords=Temperature+Meter+Gauge&qid=1549820371&s=gateway&sr=8-49
Aluminum Block	https://www.mcmaster.com/8975k242
Thermistor	media.digikey.com/pdf/Data%20Sheets/TEWA/TT08-10KC8-T105-1500.pdf
Resistors	http://www.vishay.com/docs/31018/cmfind.pdf
Arduino	https://store.arduino.cc/usa/mega-2560-r3
Jumbo LEDs	https://www.jameco.com/Jameco/Products/ProdDS/2152155.pdf
LEDS	https://www.jameco.com/Jameco/Products/ProdDS/790081.pdf
Fans	https://www.corsair.com/us/en/LED-Color/Fan-Size/Package-Quantity/ml-pro-led-config/p/CO-9050042-WW
Heat Shrink Tubing	https://www.amazon.com/560PCS-Heat-Shrink-Tubing-Eventronic/dp/B072PCQ2LW/ref=sr_1_6?ie=UTF8&qid=1550468957&sr=8-6&keywords=shrink+tubing
Button	https://www.adafruit.com/product/1190
Protoboard Shield	https://www.amazon.com/RobotDyn-Protoshield-Prototype-breadboard-Assembled/dp/B071JDRGGR/ref=sr_1_4?keywords=ARDUINO+MEGA+PROTO+SHIELD+REV3&qid=1549823860&s=gateway&sr=8-4
Wires	https://www.amazon.com/StrivedayTMFlexible-Silicone-Electric-electronic-electrics/dp/B01LH1FYR4/ref=sr_1_1?ie=UTF8&qid=1550466303&sr=8-1&keywords=Striveday%E2%84%A2Flexible+Silicone+Wire+18awg+Electric+wire+18+gauge+Coper+Hook+Up+Wire+300V+Cables+electronic+stranded+wire+cable+electrics+DIY+BOX-1
Pins	https://www.amazon.com/DEPEPE-2-54mm-Headers-Arduino-Prototype/dp/B074HVBTZ4/ref=sr_1_3?keywords=pin+headers+arduino&qid=1549820591&s=gateway&sr=8-3
Heat-Set Inserts	https://www.mcmaster.com/catalog/125/3421
Black Acrylic Sheet	https://www.eplastics.com/ACRY20250-250PM24X48
Clear Acrylic Sheet	https://www.eplastics.com/ACRYCLR0-250PM24X48
24V power supply	https://www.jameco.com/Jameco/catalogs/c181/P106.pdf
5 & 12V power supply	https://www.jameco.com/Jameco/catalogs/c181/P106.pdf

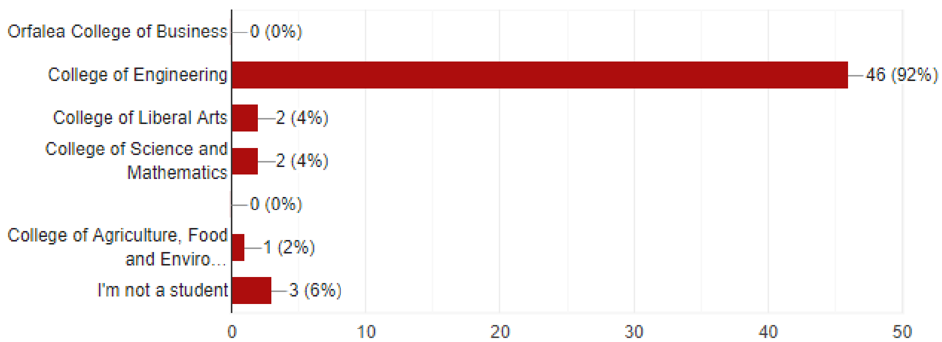
Thermal Display (Continued)

Item	Product Description
Power Cord	https://www.jameco.com/z/32V86S297-6-Foot-3-Conductor-SVT-Power-Cord-with-Pigtails_37997.html?CID=MERCH
Thermal Switch	https://www.bourns.com/docs/Product-Datasheets/AA.pdf
MAX6682 chip	https://datasheets.maximintegrated.com/en/ds/MAX6682.pdf
Max6682 breakout board	https://media.digikey.com/pdf/Data%20Sheets/Sparkfun%20PDFs/BOB-00497_Web.pdf
Thermal Paste	https://www.amazon.com/Noctua-NT-H1-Pro-Grade-Thermal-Compound/dp/B002CQU14A/ref=sr_1_2_sspa?ie=UTF8&qid=1550513201&sr=8-2-spons&keywords=thermal+paste&psc=1
Radiation Insulation	https://www.amazon.com/Thermo-Tec-13575-Adhesive-Aluminized-Barrier/dp/B00029KC2K/ref=sr_1_2?keywords=thermal+insulation+sheet&qid=1550439805&s=gateway&sr=8-2
Conductivity Insulation	https://www.amazon.com/Black-Resistant-Silicone-Rubber-Gasket/dp/B06WCZD1LZ/ref=sr_1_10?keywords=silicon+sheet&qid=1550952212&s=gateway&sr=8-10#feature-bullets-btf

Appendix Z: User Questionnaire and Results

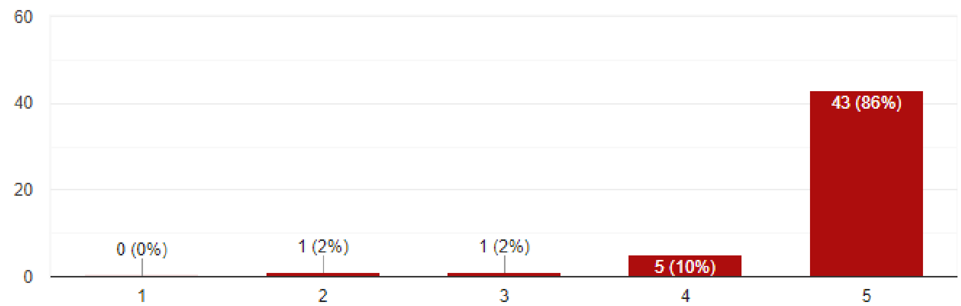
What college is your major in?

50 responses



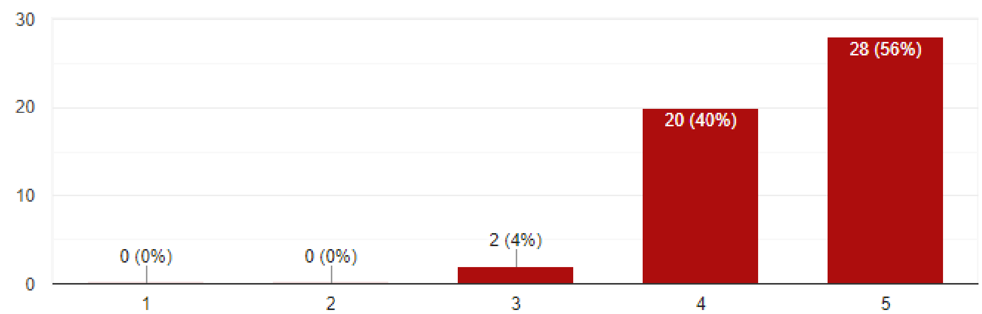
On a scale of 1-5, how easy is it to use this display?

50 responses



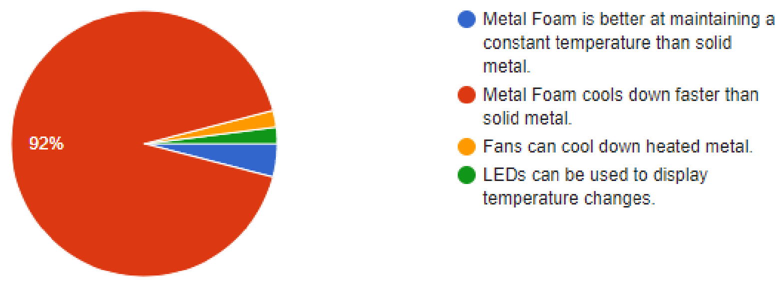
On a scale of 1-5, how eye-catching is this display?

50 responses



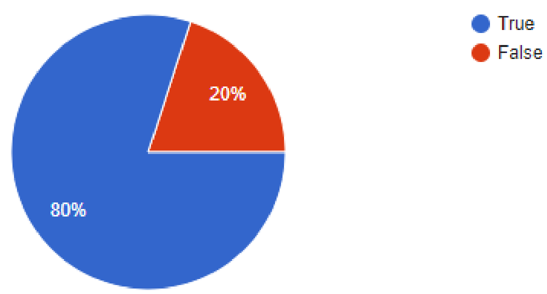
The purpose of this display is to show that...

50 responses



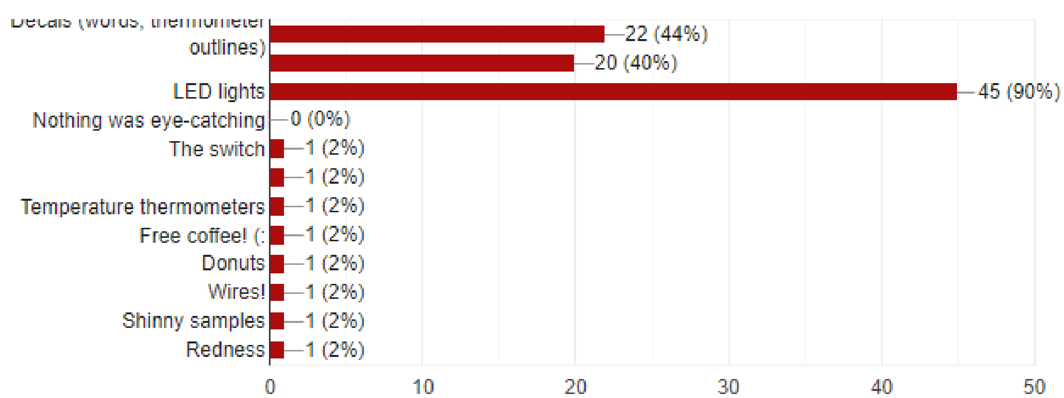
T/F: Metal foam can be used to cool a hot surface.

50 responses



Which aspects of this display were eye-catching?

50 responses



Appendix AA: Uncertainty Analysis Calculation

APPENDIX ___ : UNCERTAINTY ANALYSIS

DATA:

TEST	DATA (lbs)	PASS/FAIL
FLOW CONTROL DISPLAY	10.8 ± 0.1	—
THERMAL DISPLAY	14.6 ± 0.1	—
COMBINED, TOTAL	$25.4 \pm U_w$	PASS

ANALYSIS:

$$U_w = \sqrt{(Bias^2 + Precision^2 + Repeat.^2)}$$

Bias: NONE AVAIL. FROM MANUF.

Precision: $\pm 0.1 \times 2$

Repeat.: N/A

$$U_w = \sqrt{0.1^2 + 0.1^2}$$

$$= \sqrt{0.01 + 0.01}$$

$$= \sqrt{0.02}$$

$$U_w = 0.14$$

COMBINED WEIGHT:

25.4 ± 0.14 lbs

Appendix AB: User Manuals

Flow Control Display User Manual

Initial Warnings

Before using this display, the operator should familiarize themselves with the entire contents of this manual.

This display should not be left unattended when displayed. The attached pump could pose as a tripping hazard and/or the display may be misused, possibly resulting in injury.

Display Setup

1. Remove the Flow Control Display from the Pelican Case and set on flat, sturdy table. Ensure Display is set at least four inches in from the edge of the table to prevent falls.
2. Securely attach balloons to top of display at the appropriate locations as shown in Figure X.
3. Deploy the pump by running the pump and tubing under the table.

Ensure the tubing does not pose a tripping hazard. If needed, move the pump until it is completely clear of any and all foot traffic.

Display Operation

1. To begin use, make sure the manifold's valves leading to the metal foam and their balloons are fully open while the relief valve is fully closed.
2. Pump air into the system by operating the air pump and observe the resulting inflation of the balloons until all three balloons are full. Then stop operation of the air pump.
3. Once all balloons are full, open the relief valve to release the pressure in the system
4. Once all the excess air has left the system, the operator can repeat steps 1-3 to operate the display again.

Display Tear Down

1. Open all valves on the manifold so that all excess air has left the system.
2. Pick up the air pump and its tubing and detach from manifold.
3. Take off the balloons used and either keep for reuse or dispose of properly.
4. Place display inside Pelican Case as shown.

Display Troubleshooting

Potential Problem 1: Air pump is not supplying air to the manifold.

Suggested Course of Action:

1. Check that the air pump is on its “inflate” setting.
2. Check that any screw-ins or connections between the pump and the manifold are tight.
3. If the problem persists, use air leak fluid on any suspected portions of the tubing. If a tear or leak in the tubing has occurred, additional tubing may need to but cut and placed in the system.

Potential Problem 2: Balloons are not inflating.

Suggested Course of Action:

1. Check that the valves going to the balloon tubing/paths are fully open and that the relief valve is fully closed.
2. Check that the balloons are securely attached to the barbs on top of the display without obstruction.
3. Check that any screw-ins or connections between the manifold and the balloon barbs are tight.
4. If the problem persists, use air leak fluid on any suspected portions of the tubing. If a tear or leak in the tubing has occurred, additional tubing may need to but cut and placed in the system.

Potential Problem 3: Balloons are not deflating.

Suggested Course of Action:

1. Check that the valves going to the balloon tubing/paths are fully open and that the relief valve is also fully open.
2. Make sure that the air pump that was inflating the system is no longer operating or supplying pressure.
3. If the problem persists, detach the balloons completely and replace with new ones. One may also be able to use a “deflate” setting on the air pump in order to identify where the problem is located.

Thermal Conductivity Display User Manual

Initial Warnings

Before using this display, the operator should familiarize themselves with the entire contents of this manual.

This display should not be left unattended when plugged in to a power source. The device must be supervised at all times in case of emergency.

Display Setup

1. Remove the Thermal Display from the Pelican Case and set on flat, sturdy table.

Ensure display is set at least four inches in from the edge of the table to prevent falls.

2. Lift the back panel and pull out the power cord.
3. Plug the power cord into an appropriate outlet. An extension cord can be used if the outlet is too far away, but extension cords should not be used in series. If operating the display in a foreign country, an outlet adaptor will be required.

Ensure power cord is out of the way to prevent tripping.

4. Ensure metal blocks are placed on top of heating pads and enclosure ventilation is clear of obstructions.

Display Operation

1. The display will begin operating when the toggle switch is moved from the off position (in the middle) to the heating position (away from user).
2. Allow metal blocks to heat up for approximately five minutes.

If temperature exceeds 50°C, unplug the system and begin troubleshooting.

3. To activate the fans, toggle switch to the fan on position (towards the user). The display should show a temperature decrease for each metal block.
4. Flip the switch back to the off position to turn off the fans..

Display Tear Down

1. Deactivate the fans by flipping the switch back to the off position if they are active.
2. Unplug the power cord to turn off the system.
3. Wait until the blocks have cooled to a safe temperature, approximately 15 minutes.
4. Unplug the display from the outlet and wind cord up into small bundle.
5. Lift back panel and place power cord inside display for storage.
6. Place display inside Pelican Case as shown.

Display Troubleshooting

Potential Problem 1: Metal blocks are not heating up.

Suggested Course of Action:

1. Check that the power cord is firmly inserted into an outlet. If using an extension cord or adaptor, try plugging the display directly into the wall to ensure extension cord is not faulty.
2. Check to see that the power sources display green LED indicator lights are active to ensure they are working.
3. With the power off, check that the heating circuit connections have not been broken. If a wire has come loose, soldering may be required before display can be safely operated.

Potential Problem 2: Temperature LED display is not working.

Suggested Course of Action:

1. Check to see that the power source and Arduino green LED indicator lights are active to ensure they are working.
2. Check that the thermistors are securely placed into the metal blocks.
3. With the power off, check that the digital readout circuit connections have not been broken. If a wire has come loose, soldering may be required before display can be safely operated.
4. If some LED bulbs are operating as expected but others are not responding, the bulb(s) may be burnt out. Replacement LED bulbs must be inserted into the circuit.
5. Check that the linearization chip is not burned out using a multimeter to measure current. If the chip is not drawing current, it will need to be replaced.

Potential Problem 3: Temperature digital readout display is not working.

Suggested Course of Action:

1. Check that the thermocouple is securely placed into the metal blocks.
2. With the power off, check that the digital readout circuit connections have not been broken. If a wire has come loose, soldering may be required before display can be safely operated.

Potential Problem 4: Enclosure becoming hot to touch.

Suggested Course of Action:

1. Shut off the power to the heating circuit immediately.
2. Allow the enclosure to cool before inspecting the interior components.
3. Replace thermal switches. May require soldering.