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Environmental Stimulation Chamber for Nanosatellite Functional Testing

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Date: May 28, 2014

I HEREBY RECOMMEND THAT THE THESIS PREPARED
UNDER MY SUPERVISION BY

Taylor Donato, Joshua Summers, Nicholas Page and Brandon Wood

ENTITLED

Environmental Stimulation Chamber for Nanosatellite Functional Testing

BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF

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IN
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Dr. Nikola Djordjevic – Thesis Advisor

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Environmental Stimulation Chamber

for Nanosatellite Functional Testing

by

Taylor Donato, Nicholas Page, Joshua Summers and Brandon Wood

Submitted in Partial Fulfillment of the Requirements for the
Bachelor of Science Degree in
Mechanical Engineering in the School of Engineering

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Abstract

The goal of this project is to develop a nanosatellite thermal testing chamber for the Robotic Systems Laboratory at Santa Clara University. The nanosatellite industry has thrived in recent years and continues to grow at the level of universities and small businesses. To meet this demand, the team designed and built a testing bed capable of achieving environmental conditions adequate for testing nanosatellite hardware as a low-cost and low-maintenance alternative to more expensive and robust systems. Furthermore, the design can be fully manufactured and assembled at the university or small business level with inexpensive, sustainable, and commercially available components. The final product will save money and decrease energy consumption while fully realizing the thermal testing needs for nanosatellite communication hardware.

Acknowledgements

The team would like to thank our project advisors, Dr. Nik Djordjevic and Dr. Robert Marks. Throughout the project they provided us with invaluable guidance and resources that were essential to the success of the team. We thank them especially for the critique, enthusiasm, and devotion they provided that kept the team motivated and progressive. Without their support throughout the year this project would not have been possible.

We would also like to thank the faculty and student members of the Robotic Systems Laboratory at Santa Clara University. Their instruction and feedback at both early and late stages were key elements in design and completion of the project. Their provision of nanosatellite hardware and documentation was vital to development of the product. Particularly, we would like to thank Dr. Christopher Kitts for the extensive consultation he provided, without which the project would have been halted numerous times.

The team would also like to thank Don MacCubbin and Calvin Sellers for their insightful assistance throughout the machining process. Their patience and advice were critical to the manufacturing done throughout the project.

Table of Contents

List of Figures

List of Tables

Nomenclature

[atm]	Atmosphere
BoM	Bill of Materials
[°C]	Degrees Celsius
[cm]	Centimeters
FEA	Finite Element Analysis
[Hz]	Hertz
[kg]	Kilograms
LEO	Low Eart Orbit
[mA]	Milliamp
MATLAB	Matrix Laboratory
[mm]	Millimeter
[ms]	Millisecond
[mV]	Millivolt
NASA	National Aeronautics and Space Administration
O/OREOS	Organism/Organic Exposure to Orbital Stresses
P-POD	Poly Picosatellite Orbital Deployer
RSL	Robotic Systems Laboratory
SCU	Santa Clara University
U	10 x 10 x 10 [cm]
[V]	Volt
[W]	Watt
[W/m^2]	Watts per meter Squared
[W/mK]	Watts per meter Kelvin

Chapter 1: Introduction

1.1 Background

Since the emergence of the standardized CubeSat era beginning in 2000, there has been a substantial resurgence in nanosatellites. Nanosatellites offer a wide range of applications, including but not limited to telecommunications, earth observations, scientific research, biological experiments and military applications that can be developed at the academic level.[1] Large projects are often very complex by nature, leading to high costs and slow production times. Nanosatellites, in the academic setting offer the advantages of being low cost, having faster build times and providing an excellent opportunity for research with new and emerging technologies.[2]

Nanosatellites are small-scale satellites with a wet mass between 1 and 10 kilograms.[3] These satellites are popular low-cost platforms for academic and some government missions. In 1999, collaboration between California Polytechnic State University and Stanford University established a design standard for these satellites.[4] By developing a strict set of requirements for the nanosatellite platform this enabled designers and university programs to reduce cost and development time, increase accessibility to space, and sustain frequent launches. These satellites are designed around platforms of "U's", a unit of volume measuring 10x10x10 [cm] and typically range from 1U to a current 6U platform in development.[5]

The incorporation of COTS products has streamlined the production process. Take for example, the Flight-Proven 2.4GHz ISM Band COTS Communication System for Small Satellites: designed by Ignacio A. Mas and Christopher A. Kitts of the SCU Department of Mechanical Engineering RSL. Built on a 3 x 1U configuration, the purpose of this design was to "define and execute a method for inserting a COTS transceiver into a space flight system.[6] With successful COTS product integration, future satellites are continuing to increase the capacity of COTS products on nanosatellites. These products however require additional testing prior to being launched.

Twelve satellites are scheduled to launch in collaboration with NASA AMES Research Center over the next year. All of these products will undergo a space qualification testing process prior to launch. Because of this a low-cost environmental stimulation chamber capable of performing nanosatellite functional testing prior to space testing was invaluable. The chamber must allow for functional testing of communication hardware under slight environmental stimulation to practice mission objectives and protocol required for space flight.

1.2 Review of Field and Literature

Several companies already produce environmental chambers that perform thermal cycling, for example: Cincinnati Sub-Zero (CSZ) Incorporated, Temptronic Corporation and ESPEC North America. These companies manufacture bench top environmental chambers that operate in temperature ranges from about -70 degrees Celsius to 180 degrees Celsius. Typical internal components of a satellite experience temperature fluctuations of 0 degrees Celsius to 35 degrees Celsius, making the specifications for these products are beyond project requirements.

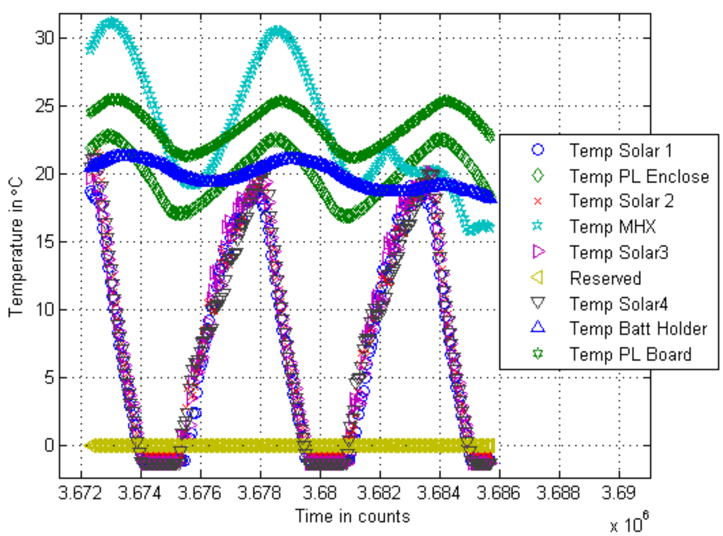

Figure 1-1: GeneSat-1 temperature profile

Requests for price quotes for similar size chambers have shown these chambers to be very expensive for a university level application. The Benchtop model from ESPEC has a temperature range of -20 degrees Celsius to 180 degrees Celsius.[7] With an internal volume of 1.5

cubic feet the system can heat or cool the environment at about 2 degrees C/min.[8] ESPEC quotes their Benchtop Temperature Chambers Model BTU-133 at a base price of $6,490.00.[9] That price quote does not include shipping costs, computer control interface or mobile carts for easily moving these heavy chambers. These additional costs can easily raise the overall price by a couple thousand dollars.

With the overall costs of university fabricated satellites being $2000 or less, the high cost of an industrial thermal chamber is high. The team researched the unique features of these field benchmark models in order to design a cost-effective solution to perform functional testing of nanosatellites. Computer software such as MATLAB, the Arduino platform and Microsoft Office Suite were the basis for the project design platform. All of these programs are easily accessible and do not require a steep learning curve, again emphasizing the ability for students at the university level to more easily design and test satellites.

1. 3 SCU Robotic Systems Laboratory Heritage

SCU has a rich history of success in launching and operating satellites. The RSL, located on the university campus, is the headquarters for mission operations. Students at both the undergraduate and graduate level routinely perform mission operations, ground segment engineering, and functional test services.[10]

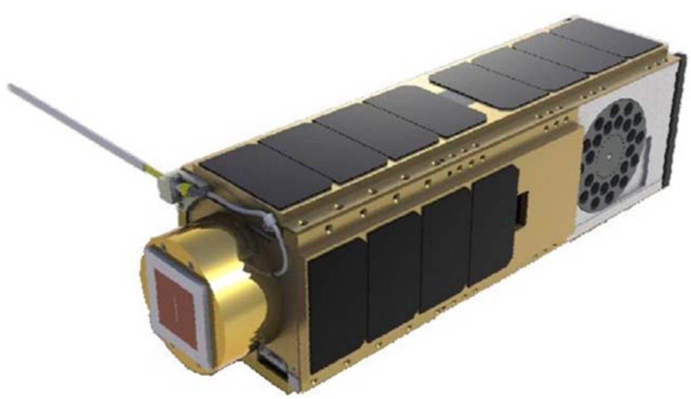

Figure 1-2: O/OREOS spacecraft launched November 2010

Satellite missions in which Santa Clara has participated include the Artemis Picosatellite, Sapphire Microsatellite, the GeneSat-1 nanosatellite, two FASTRAC nanosatellites, the NASA PharmaSat spacecraft and O/OREOS spacecraft shown above in Figure 1-2.[13]

1.4 Project Motivation

The RSL is a small part of a larger community that is driven to the advancement of nanosatellites as the new industry standard. Recent publications by companies such as SpaceWorks have examined the market demand for satellites in the 1kg to 50kg range. A significant rise in the area of scientific and technological research for small satellites has been recognized by the space community.

Next year, Santa Clara will be an integral part of 12 satellite launches, focusing on the communication hardware and software. The RSL continues to develop low-cost communication hardware but without extensive testing on their final products prior to delivering them to NASA. The goal of the project was to develop an environmental stimulation chamber for the purpose of performing functional satellite testing. The product provides employees of the RSL an additional tool to test their communication equipment.

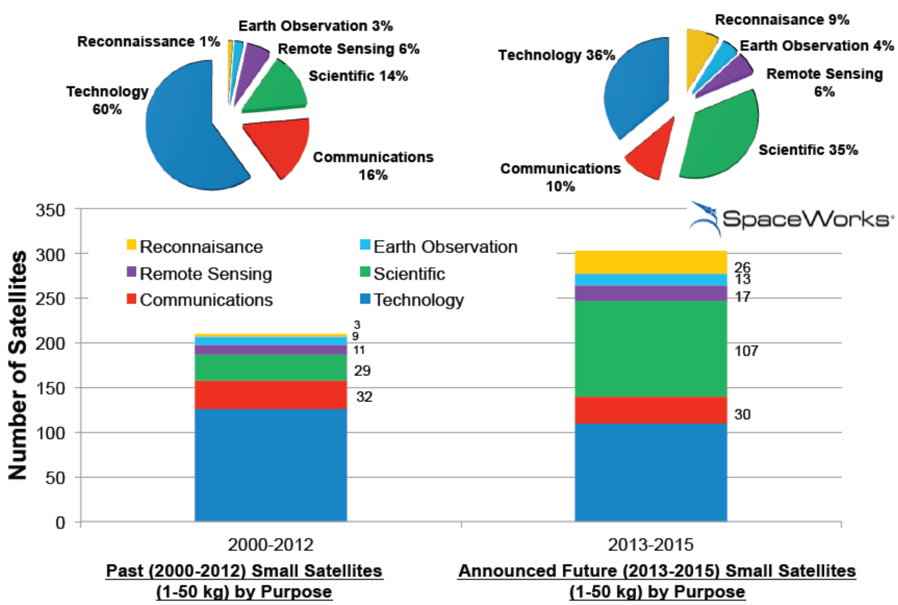

Figure 1-3: Nano/Microsatellite projections by sector for 2013-2015

1.5 Project Statement

The team objective is to design and fabricate an environmental stimulation chamber for use in performing functional testing of nanosatellites, specifically for the Santa Clara University Robotic Systems Laboratory.

Chapter 2: Systems Level Overview

The design team was challenged meet a variety of requirements from different sources. These requirements came from previous satellite mission data, internal RSL goals, and a customer needs survey.

2.1 Technical Requirements

Interviews with the employees of the RSL resulted in the following technical requirements:

1. Chamber shall provide a thermal testing range of 0 degrees Celsius to 40 degrees Celsius for the chamber air temperature.
2. Chamber shall be capable of performing a complete thermal cycle 0 degrees Celsius to 40 degrees Celsius and back to 0 within 90 minutes.
3. Chamber shall maintain a target chamber air temperature set by the user to within ±3 degrees for extended durations up to 12 hours.
4. Chamber shall be able to accommodate satellites ranging from 1U to 6U in size (Maximum of 2U by 3U configuration: 6000 cm^3).

Additional requirements that do not require verification testing include the following:

1. Chamber shall have a ½" cable pathway for internal to external cabling needed by the RSL without disrupting the testing environment.
2. Chamber shall be capable of being moved with a dolly by one person.
3. LCD display knob control of high and low temperatures as well a switch for set-point mode and cycle mode.

2.2 Subsystem Summary

The subsystems of the chamber are the thermal system and the controls system. The specifics of each subsystem are detailed further in the following chapters; however Figure 2-1 reflects the individual components of the major subsystems. In addition, Figure 2-2 provides an overall system architecture that includes the controls systems and its integration into the final design.

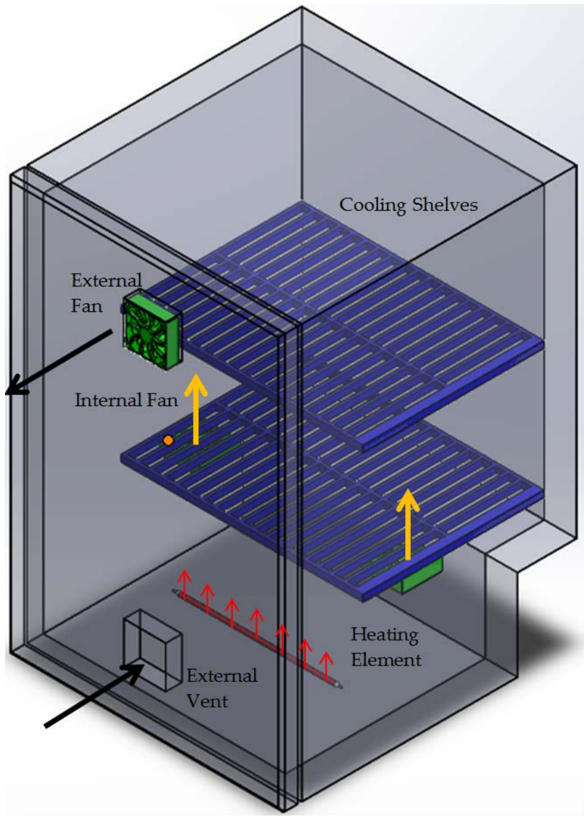

Figure 2-1: System Components Overview of Thermal Cycling Chamber

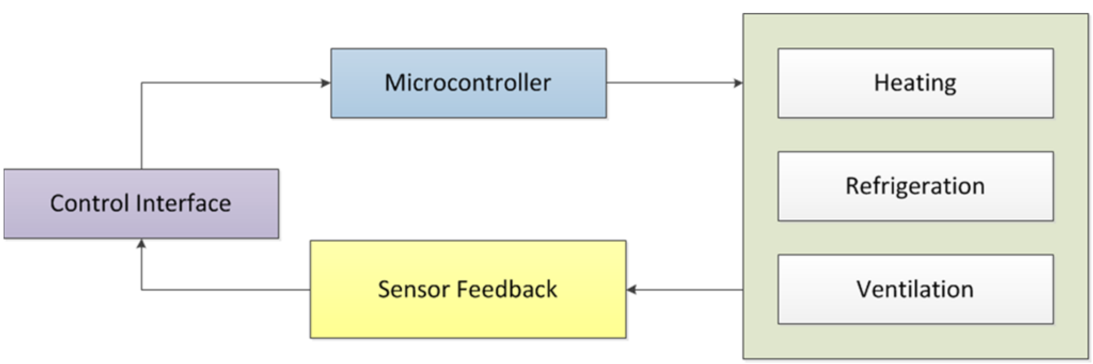

Figure 2-2: System Architecture of each individual subsystem

Chapter 3: Systems Engineering

3.1 Project Challenges and Constraints

Developing and launching a nanosatellite involves several major challenges, one of which is validation of functionality. Testing different subsystems individually and together is a process shared by all engineering programs, and is essential before considering launching a nanosatellite. The project design team needed to ensure comprehensive reliability of the product so that any functional testing would meet engineering standards such as those set by NASA. Before the product was built the RSL did not meet these standards with their thermal testing methods.

To provide reliable results the design team approached the project by specifying subsystems to address each of the requirements set by the RSL. Managing the interface of multiple subsystems is another process shared by most engineering projects, and is usually facilitated by a system engineering subteam. Because of the scale of this project the responsibilities to understand subsystem interaction was absorbed by all team members, rather than a specific subteam. These responsibilities include comprehension of technical knowledge in regard to the control and thermal subsystems, and how to mediate issues across both to ensure cohesion between components of the final assembly.

3.2 Project Organization

Two subsystems were designated for control and thermal aspects of the product, with three major phases of the project including design, manufacturing, and testing. A dedicated team member was appointed to lead each subsystem and project phase in order to optimize design and production. Additionally, a project leader was determined to be in charge of time management and scheduling to ensure deadlines were met for completion and documentation throughout the project. While individual team members were designated for each phase and subsystem, personal overlap frequently occurred as necessary for streamlining all project work.

The Control Subsystem team member handled the user interface and environmental control, including electrical wiring. The Thermal Subsystem team member handled research and design for heating, cooling, and ventilation of the product. The team member designated for managing the design phase was responsible for drawing and organizing components based on input from subsystem leaders, and mediating subsystem design requirements. The team member designated for managing the manufacturing phase was involved with fabrication and assembly of all system components, and finally, the team member designated to manage testing designed and executed system verification procedures.

Success of the project hinged on the ability of team members to focus on designated responsibilities while remaining conscious of the responsibilities of the team as a whole. To moderate project complexity the team met multiple times per week to assess progress and discuss any challenges that arose as early as possible.

3.3 Budgeting

Funding for the project was provided by SCU through the RSL. Monetary costs were estimated based on system requirements to form an initial expectation of the budget to be at most $600. This was achieved by the final design at $460. A complete project budget with a system breakdown of costs is provided in Appendix A.

3.4 Timeline

The project timeline is built around three primary stages: Research and Development, Manufacturing, and Systems Integration and Testing. The project leader organized task scheduling and personnel management through the use of the Gantt chart shown in Appendix B. Using this Gantt chart effectively reduced delays in design and manufacturing and facilitated continuous development of the co-dependent subsystems.

3.5 Design Process

To complete the project as efficiently as possible the thermal and control subsystems were often developed simultaneously. This was not always the case, because aspects of one subsystem occasionally depended on completion of aspects of the other. This was especially prevalent in the manufacturing stage, where subsystems were interfaced and integrated into the chamber assembly. Particularly, debugging and refining the control system was only possible after the thermal system was ready to be integrated into the chamber assembly, which was the most time consuming stage of the project. Conversely, research and development for both subsystems needed to be done at the same time so that their designs did not conflict. Approaching the design phase this way facilitated a more cohesive joining of the subsystems once they were physically manufactured.

Chapter 4: Conceptual Design

To address the need for a low-cost product, a used mini-freezer was selected as the platform for design. A pre-owned unit provided both an affordable price and an integrated cooling system, assuming it passed initial testing to demonstrate that it could meet project requirements. Once a suitable mini-freezer platform was selected, the design process continued by modifying that unit to incorporate other subsystems. Figure 4-1 shows the Sanyo HF-5015 unit that was ultimately chosen. The internal capacity of the Sanyo HF-5015 is 5 cubic feet, with two shelves made of copper cooling tubes and metal grates to protect them. These shelves allow testing of two nanosatellites simultaneously.

Figure 4-1: Sanyo HF-5015 Freezer Unit with 5 cubic foot internal capacity

At this point in design the major concern was temperature control. This issue includes being able to physically achieve the user's desired temperature range and controlling how the product reaches that temperature. A ventilation system using computer fans to circulate air was proposed to enhance heating and cooling, and to facilitate a greater rate of heat transfer to the internal environment and hardware being tested. This feature was to be included as a section of the thermal subsystem. The following chapters describe the research, analysis and design processes for the thermal and control subsystems, highlighting key design details that were incorporated into the final product.

Chapter 5: Thermal Subsystem

5.1 Satellite Thermal Background

Previous nanosatellite temperature profile data provided by individual component sensors while in orbit suggests a fairly standard operating temperature. Figure 5-1 depicts the temperature profile for the Microhard MHX transceiver; noted as the top curve. The maximum temperature ranged from just below 0°C to just below 35°C for all nanosatellite components.

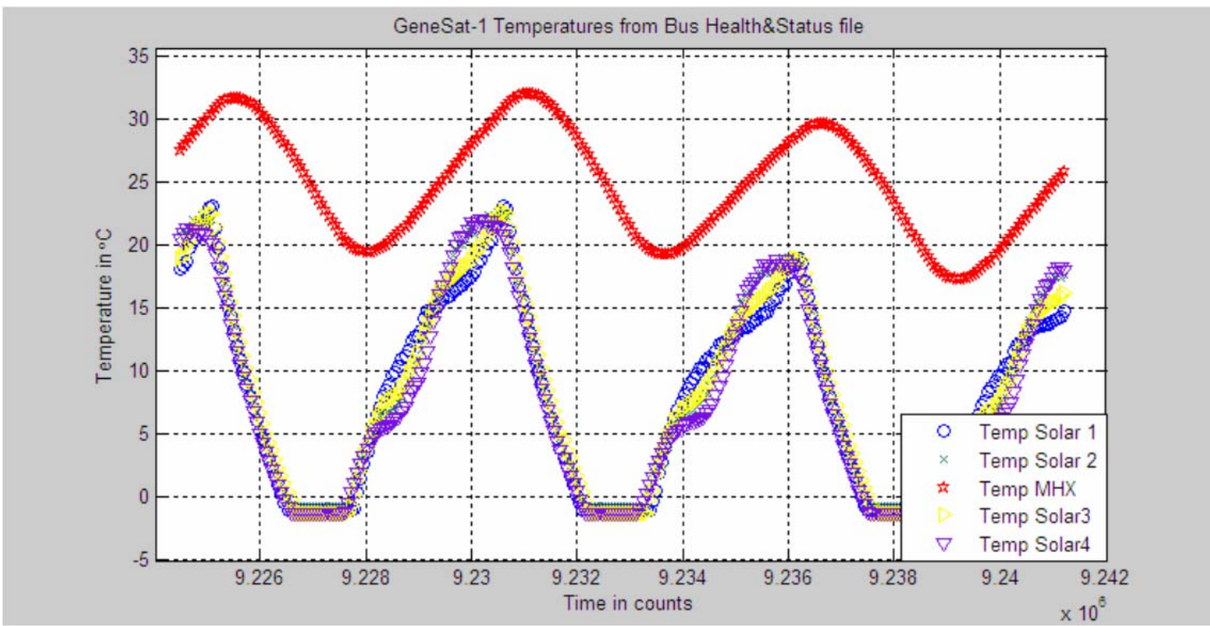

Figure 5-1: Temperature profile from GeneSat-1 Biological Microsatellite in 2006

5.2 Requirements

The thermal requirements are shown in Chapter 2 as requirements 1-3. The desired operating temperature range was 0°C to 40°C. These values are based on data showing that most of the internal components of a nanosatellite remain in this range for the duration of on-orbit missions, represented in figure 5-1. The accuracy of the operating temperature needed to be within ±3 degrees of the user input for up to 12 hours of testing in steady-state conditions. Thermal cycling was designed to meet the requirement that the chamber be capable of temperature variability comparable to orbital conditions for the housed communication hardware. One full thermal cycle of the chamber is characterized by cooling the air from 40°C to

0°C, and then heating from 0°C back to 40°C. The converse, heating from 0°C to 40°C and cooling back to 0°C, is also a full thermal cycle. Partial thermal cycles are also possible via custom high and low temperatures input by the user (i.e. 30°C and 15°C). The RSL required a full thermal cycle be achievable in 90 minutes with 45 dedicated to cooling and 45 dedicated to heating—a timeframe reflective of the actual thermal conditions hardware is subject to on-orbit, as shown in figure 5-1.

5.3 Modes of Heat Transfer

5.3.1 Conduction

There are two modes of heat transfer that heavily influence temperature of the air and nanosatellites in the chamber: convective and conductive. Conductive heat transfer is the transfer of energy at the atomic level from the hotter particles to the cooler particles in a fluid or solid. One way to quantify this energy transfer or temperature gradient is through a rate equation called Fourier's Law. Fourier's Law depicts that the heat flux, q_x'' (W/m^2), is inversely related to the conductive heat transfer, k (W/m*K), coefficient and the heat transfer rate, or temperature change, ΔT or dT (K), in one direction, dx (m), as shown in Equation 5.1 below.

$$q_x'' = -k\frac{dT}{dx} \tag{5.1}$$

This heat transfer rate equation can be simplified further for one-dimensional, steady-state conditions as shown in Equation 5.2 below.

$$q_x'' = -k\frac{T_2 - T_1}{L} \tag{5.2}$$

In this equation L represents the length of, or distance between, two points in a fluid or solid, and T_1 and T_2 represent the temperatures at two points of a fluid or solid on the x-axis plane. Conduction will be one of the main heat transfer factors between the nanosatellite exterior and the electronics at the nanosatellites core.

5.3.2 Convection

Convection is the heat transfer through the circulation of heated parts of a fluid and the thermal diffusion of an object to that fluid. Besides material properties, the factors that influence convective heat transfer are flow situation, speed of the fluid, and the size of the object that the fluid is in contact with. The rate equation for convective heat transfer is that heat flux, q'' (W/m^2), equals the convective heat transfer coefficient, h (W/m^2*K) times the temperature difference between the object surface, T_s, and the fluid temperature, T_∞, as shown in Equation 5.3 below.

$$q'' = h(T_s - T_\infty) \qquad (5.3)$$

The convective heat transfer coefficient is influenced by a number of variables such as Nusselt number, *Nu*, and Reynolds number, *Re*. Nusselt number is the ratio of convective heat transfer coefficient, h (W/m^2*K), and the conductive heat transfer coefficient, k (W/m*K), of the fluid flow multiplied by the characteristic length, L_c (m), as shown in Equation 5.4 below.

$$Nu_L = \frac{hL_c}{k} \qquad (5.4)$$

The characteristic length varies with the object's geometry that is undergoing the heat transfer. Nusselt number is dependent on Reynolds number is equal to the inertial force of the fluid divided by the fluid's viscous force as shown in Equation 5.5 below.

$$Re_L = \frac{\rho u L_c}{\mu} \qquad (5.5)$$

The fluid's inertial force is a product of the fluid's density ρ (kg/m^3), speed u (m/s), dynamic viscosity μ (kg/m*s), and the characteristic length of the object undergoing the heat transfer if it is external flow, or can be the hydraulic diameter of the duct, D_h, if it is internal flow. Also, Reynolds number determines if the flow is either laminar or turbulent, and the critical Reynolds number that separates laminar from turbulent is $Re_{c,r} = 2300$. There is a certain relationship between the Nusselt number and Reynolds number that is dependent on the flow situation, such as a flow over a horizontal plate or flow over a horizontal cylinder. For laminar flow over a horizontal plate, the Nusselt number is equal to the product of Reynolds number and the fluid's Prandtl number *Pr*, which is the ratio of kinematic viscosity and thermal diffusivity and can be found in thermal property tables, as shown in Equation 5.6 below.

$$Nu_L = 0.332Re_x^{1/2}Pr^{1/3} \tag{5.6}$$

Overall, the Nusselt number equations follow a similar format of the product of Reynolds and Prandtl number, and the only factor that changes with the flow situations is the coefficient and the exponents of the Reynolds and Prandtl number. But these relationships and equations of Reynolds number are only used for a fluid in motion. If the fluid is just standing still, then it is called natural convection and uses Rayleigh number *Ra*, which is the buoyancy flow of a fluid. The Rayleigh number is equal to the product of Grashof number, *Gr*, and Prandtl number as shown in Equation 5.7 below.

$$\mathrm{Ra_L} = \mathrm{Gr_L Pr} = \frac{\mathrm{g\beta L_c^3(T_s\text{-}T_\infty)}}{\mathrm{v^2}}\mathrm{Pr} \tag{5.7}$$

In this equation, g (m/s^2) represents gravitational acceleration, β (K^{-1}) is the fluid's expansion coefficient, T_s and T_∞ represent the surface and fluid temperature, and v (m^2/s) represents the fluid's kinematic viscosity. The relationship between Nusselt number and Rayleigh number depend on the object and its orientation with respect to the fluid. For natural convection, the Nusselt number is equivalent to the product of the Rayleigh and Prandtl number as shown in Equation 5.8 below which is for natural convection of a vertical plate.

$$Nu_L = \{0.825 + \frac{0.387Ra_L^{\frac{1}{6}}}{\left[1+\left(\frac{0.492}{\mathrm{Pr}}\right)^{\frac{9}{16}}\right]^{\frac{8}{27}}}\}^2 \tag{5.8}$$

The Nusselt number relation to Rayleigh and Prandtl number follow a similar equation format, but the exponents and coefficients vary with the object's geometry and heat transfer orientation to the object.

5.4 Design Options

For cooling both the built-in refrigeration cycle and thermoelectric pads were considered. Thermoelectric pads were also considered as a heat source in comparison to a conventional heating element. The following gives a brief description of each system option before making trade-off analyses.

5.4.1 Refrigeration Cycle

The vapor-compression cycle is common to many refrigerators. The vapor-compression cycle as depicted in figure 5-2b has four main components: the compressor, condenser, expansion valve and evaporator. Through the use of a refrigerant hot air can be extracted from a confined space to cool it down. The cycle, as shown in figure 5-2a, begins with refrigerant entering the compressor as a saturated vapor. Here it compressed to a high pressure, result in a higher temperature. Leaving the compressor, the superheated vapor enters the condenser where heat is extracted by the ambient cooling air passing over the coils. Next is the expansion valve, where a significant drop in pressure and temperature occurs. The resulting liquid and vapor mixture is now at a lower temperature than the enclosed space to be refrigerated. As the mixture passes through the evaporator, hot air passes over the cool refrigerant, thereby extracting heat from the confined space and consequently cooling it. The process repeats itself as the vapor exiting the evaporator is cycled into the compressor.

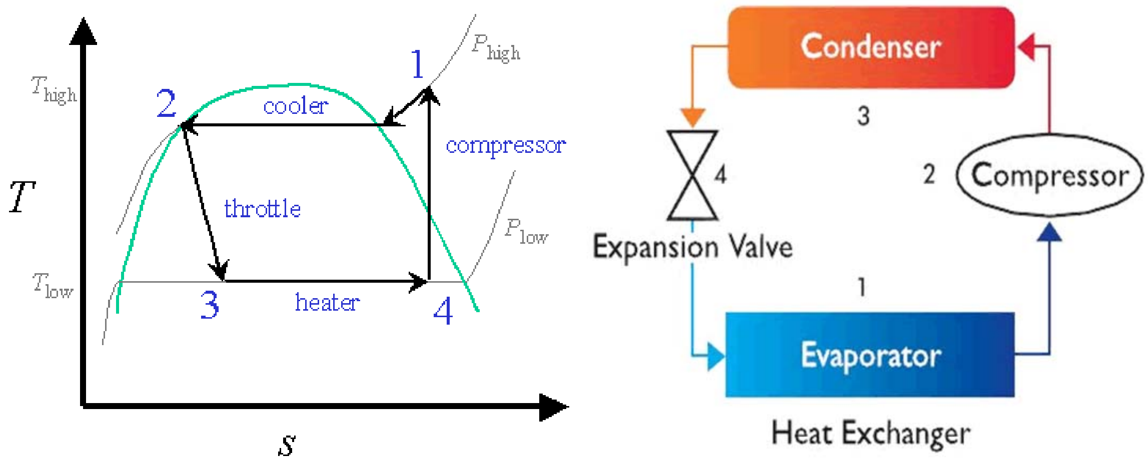

Figure 5-2: (a) Vapor-Compression Cycle (b) Refrigeration Cycle architecture

5.4.2 Thermoelectric Pads

Thermoelectric technology uses the principal of the Peltier effect – passing electric current through dissimilar conductive materials. As figure 5-3 illustrates, electrons pass through these dissimilar materials to create a temperature differential where one side becomes hot and the other becomes cold. For cooling, a simple reverse in polarity will switch the temperature extremes on each side of the pad. Adequate heat sink design would help increase efficiency and effectiveness of the system.

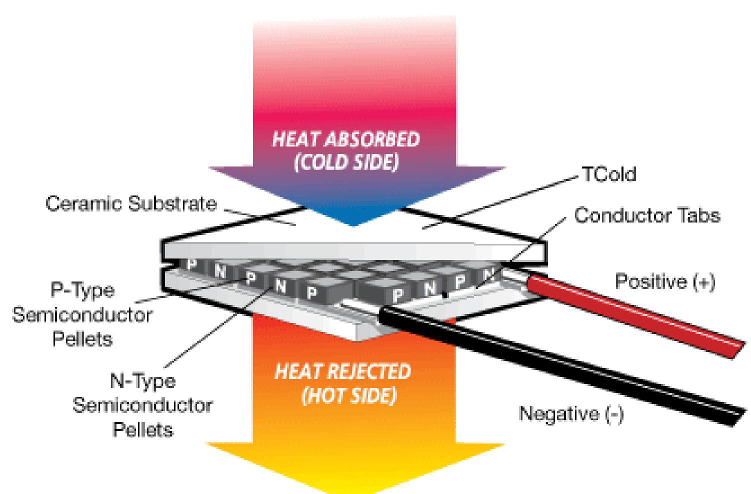

Figure 5-3: Thermoelectric Heating Pad with description of design

5.4.3 Heating Element

Utilizing the same heat source as a toaster oven or kitchen oven, this technology incorporates a resistant yet conductive material that heats up as current passes through it. The most common material used for heating elements is a nickel-chromium alloy referred to as Nichrome. A variable power supply would be incorporated to control the current passing through the wire, as the temperature is a function of current.

5.5 Trade-Off Analysis

Trade-off analysis was developed to compare each option for heating and cooling. The comparison parameters, organized in Table 5-1, were response time, effectiveness, accuracy, additional costs, size and maintenance.

Table 5-1: Trade-off analysis of heating and cooling system options.

	Heating Element	Thermoelectric Heating Pads	Heat Lamp Matrix	Refrigeration Cycle	Thermoelectric Cooling Pads
Response Time	✓				✓
Effectiveness	✓			✓	
Control Accuracy		✓	✓	✓	
Fabrication	✓				✓
Wiring Set-Up	✓			✓	
Compact Size	✓	✓			✓
Maintenance	✓			✓	

The built-in refrigeration cycle was selected for its maintenance, effectiveness, and controllability characteristics. Even though thermoelectric cooling pads are smaller, the refrigeration cycle is built into the chamber structure so it doesn’t occupy additional space.

For the heating system a heating element was selected for its ease of fabrication, response time, maintenance requirements, compact size, heat generation and minimal additional cost for implementation compared to thermoelectric heating pads. The quantitative trade-off analysis in table 5-2 compares the 300W heating element and the 60W thermoelectric pad.

Table 5-2: Quantitative trade-off analysis between the 300W heating element and five 60W thermoelectric.

Variable	300W Heating Element	60W Thermoelectric Pads
System Cost	$20.00	$62.50
Size	diameter - 1/4" length - 12"	1.58" x 1.58" x 0.141"
Temperature Limit	200 °C	180 °C
Response Time	240 seconds	60 seconds
Additional Requirements	Mounting System	Heat Sinks, Fans

In order for a thermoelectric pad system to match the power of a heating element, five pads would be necessary and make it more expensive than the heating element.

5.6 Refrigeration Cycle Analysis

For the cooling system, a mini-freezer called the Sanyo HF-5015 was purchased, depicted in figure 4-1. This mini-freezer has a voltage and current rating of 120 volts and 1.1 amperes and an interior volume of 5 cubic feet. When the mini-freezer arrived, initial testing was performed on its cooling capabilities. The testing was performed with a thermocouple placed at the center of the mini-freezer's interior volume taking temperature measurements every 3 to 4 minutes. The mini-freezer was able to cool the internal environment from 14°C to 0°C in less than 900 seconds as shown in Figure 5-4 below.

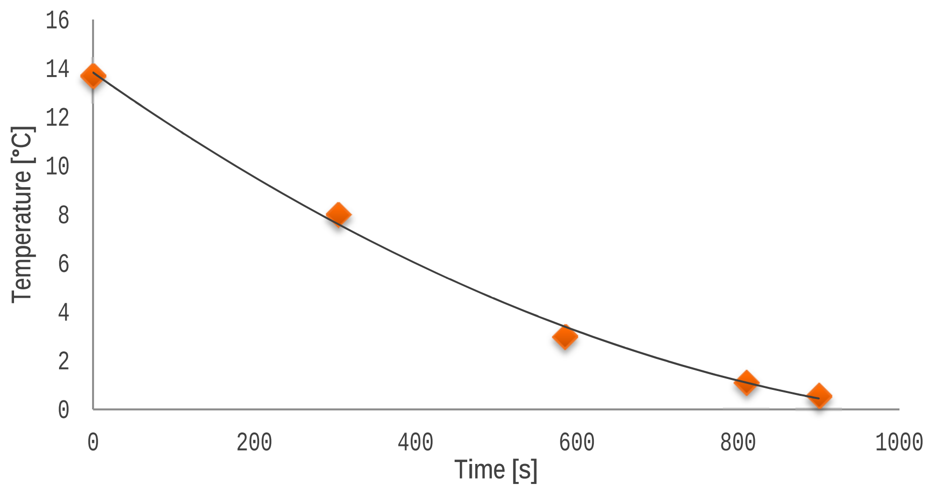

Figure 5-4: Graphical representation of the cooling capability of the mini-freezer

The mini-freezer was kept on overnight to determine the minimum temperature achievable by the built-in cooling system to be -22°C. These tests verified that this mini-freezer could fulfill the cold temperature range of the system requirements set for the product. Uniform cooling in the mini-freezer is facilitated by the two shelves with copper tubing spaced evenly towards the top and bottom separating the interior volume

5.7 Heating Element Design

During design the team had to choose the appropriate heating element that could fit in the mini-freezer interior and would provide enough power to heat the air in the chamber. Calculations were performed to find the energy needed to heat the interior volume from 0°C to 40°C. The power needed to heat air in 10 minutes was around 19.62 Watts, but these calculations did not include the heat loss through the mini-freezer walls and shelves. To incorporate this margin of error and heat losses, a 300-Watt heating element with a length of 12 inches and diameter of 0.25 inches was selected, which was small enough to fit at the bottom of the mini-freezer chamber and powerful enough to heat the interior volume adequately. Considering the heating element has a current running through it, an insulating material or grounding method would be needed for its installation for safety purposes. The heating element was made of Nichrome and an ideal electrical insulator chosen for the heating element was Teflon because its melting point is around 327°C and has great dielectric properties.

5.8 Ventilation System Design

A ventilation system assists the heating and cooling process by cycling out air as is pertinent to the input temperature. During cooling the ventilation system cycles hot air out of the chamber to quickly remove heat until the interior temperature matches room temperature. When heating, the ventilation system cycles heat into the chamber and removes cold air until the interior reaches room temperature. In both cases when the interior reaches room temperature the vents are closed and air is blocked from leaking out and working against the thermal system. This concept is detailed in table 5-3 below.

Table 5-3: Thermal cycling cases for implementation of the ventilation system

Case	$T_{ambient}$[°C]	Refrigeration	300W Element	Shelf Fans	Door Fan/Vents
A	0 to 20	Off	On	On	On/Open
B	20 to 40	Off	On	On	Off/Closed
C	40 to 20	On	Off	On	On/Open
D	20 to 0	On	Off	On	Off/Closed

The air flow speed has a linear relationship with the Reynolds number *Re*, or the non-dimensional flow velocity, which is a major factor in the calculation of the Nusselt number *Nu*. If the flow is between parallel vertical plates, over a horizontal cylinder, or over a horizontal plate determines the relationship between the Nusselt and Reynolds Number. The Nusselt number has a direct proportional relationship with the convective heat transfer coefficient, meaning that the airflow speed is directly proportional to the convective heat transfer coefficient. The difference between natural and forced convective of a horizontal plate is less than 0.8 W/m^2*K in terms of the convective heat transfer coefficient, *h*, as shown in Table 5-4 below. These calculations were made using a horizontal plate with a characteristic length of 0.1016 meters, used air properties at 20°C, and assumed a temperature difference of 20°C between the plate surface and the air.

Table 5-4: Heat transfer coefficient in horizontal plate situations of natural and forced convection

	Natural Convection	Forced Convection
u (m/s)	0	0.896
Pr	0.713	0.713
Ra_L/Re_L	2204118	6024.725
Nu_L	20.807	23.022
k_{fluid} (W/mK)	0.0257	0.0257
h (W/m^2K)	5.263	5.823

5.10 Passive Dehumidifying System

During the initial tests of the mini-freezer, condensation was forming on the top shelf after a 45-minute long test. This was an obvious problem considering the electrical wiring inside the chamber as well as the hardware that was to be tested in it. Humidity has been partially addressed by the ventilation system which cycles air through the chamber, but only to a certain extent. This led to the implementation of a passive dehumidifying system using Drierite desiccants from Santa Clara University's Materials Lab. Desiccants are polymer crystals that absorb up to 25% of their own weight in water. To test how effect they would be, tests were conducted with a 500 mL beaker, boiling water and suspending the Drierite in the steam. During these tests desiccants were weighed before and after 20 minutes of suspension in the steam to show a 5 to 10 percent increase from water absorption. This series of tests was just experimental to determine that Drierite was a viable solution. Appropriate instruments and sensors for humidity testing in the chamber were not available to the team, so this was the only way to address the condensation issue in the scope of this project. To implement the desiccant into the chamber, mesh bags were made out of screen to hold any necessary amount of Drierite and could be custom-fit to the appropriate areas of the chamber.

5.11 Predictive Thermal Tool

A predictive thermal tool using MATLAB to calculate the temperatures of air inside the chamber was developed for use by the RSL to accompany nanosatellite testing. The code accounted for multiple factors including the heating element surface, mini-freezer walls, the nanosatellite's exterior and core, air entering and exiting through the ducts when inputting the size of the nanosatellite, and the temperature range desired for the thermal cycle testing. The setup of the thermal tool utilized a thermal resistance diagram to represent the energy balance between the heating element, mini-freezer walls, environmental air, inlet duct, nanosatellite exterior, outlet duct and the nanosatellite core as shown in Figure 5-5 below, and further detailed in Table 5-5.

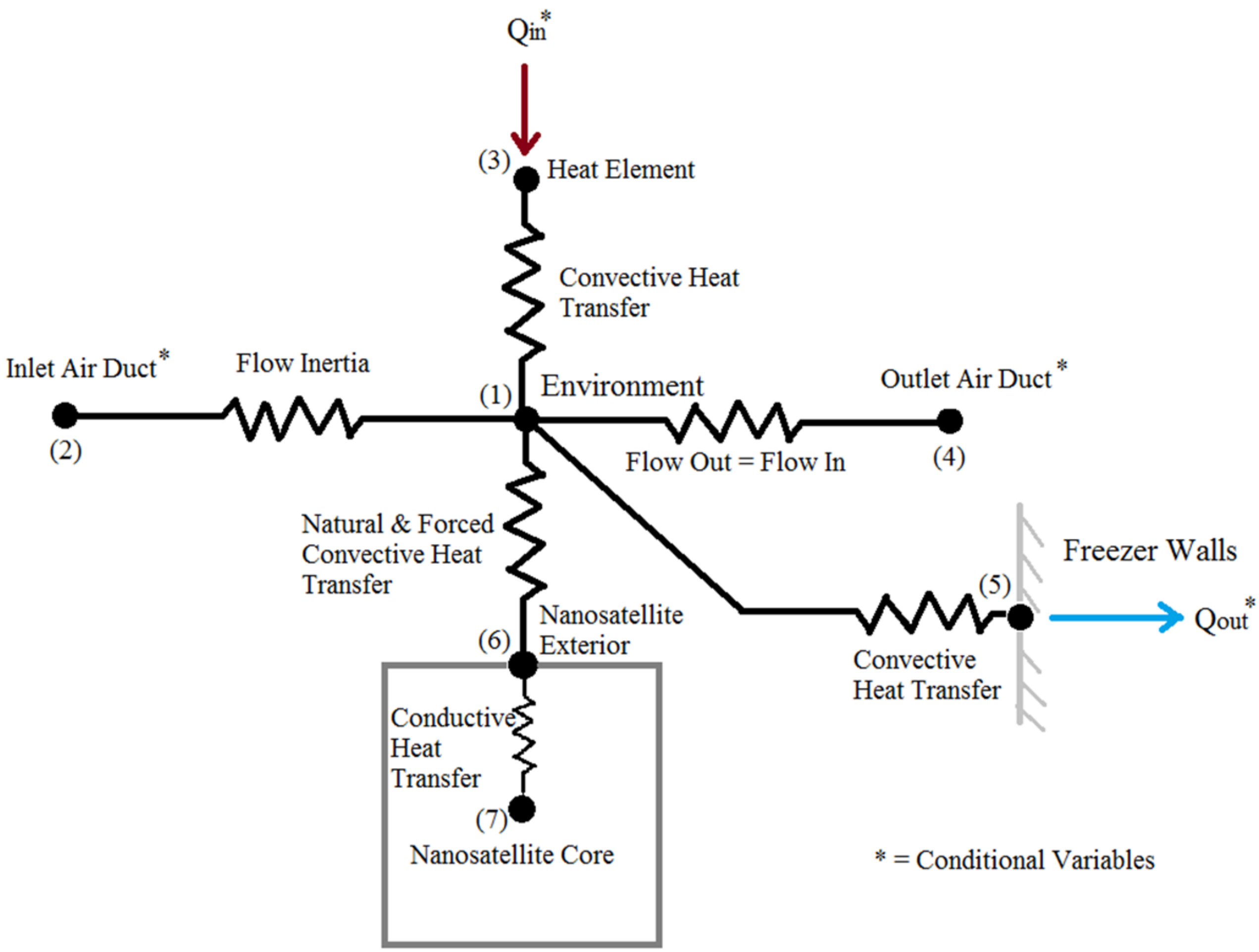

Figure 5-5: Thermal Resistance Diagram of energy balance between the heating element, inlet duct, outlet duct, environmental air, mini-freezer walls, nanosatellite exterior and core

Table 5-5: List of the nodes corresponding to their representation in the test chamber

Node	Description	Material/Fluid
1	Ambient Air	Air
2	Inlet Air Flow w/o Fan	Air at Room Temperature
3	Heat Element	Nichrome
4	Outlet Air Flow w/Fan	Air
5	Mini-Freezer Walls	ABS Plastic
6	Nanosatellite Surface	4041-Aluminum
7	Nanosatellite core	Molded Plastics

The nodes represent the temperature of each of the components within the test chamber. A thermal resistor represents the modes of heat transfer between the two components. Depending on the mode of heat transfer, the thermal resistance value, $R_{t,cond}$ and $R_{t,conv}$, will be proportional to the conductive or convective heat transfer coefficient times the area normal to the heat transfer as shown in Equations 5.9 and 5.10 below.

$$R_{t,cond} = \frac{L}{kA} \tag{5.9}$$

$$R_{t,conv} = \frac{1}{hA} \tag{5.10}$$

For either the conductive or convective thermal resistance, it is the relation of the temperature difference between the surfaces, $\boldsymbol{T_s}$, or the surrounding fluid, $\boldsymbol{T}_\infty$. The heat transfer special cases between each of the nodes along with the equations representing their relations are shown in table 5-6 and 5-7.

Table 5-6: Thermal resistor characteristics and equations between all the thermal components

Resistors	Nodes	Mode (Rad/Cond/Conv)	Special Case	Resistance Equation
R12	1, 2	Natural Convection	Induced Flow from Outlet Duct Fan	$R_{12} = \frac{1}{\dot{m} * \rho_{air} * C_{p,air}}$
R13	1, 3	Convection and Radiation	1.) Convection between Air and Heat Element Surface 2.) Cross Flow	$R_{13} = \frac{1}{\overline{h}_3 * A_{s,heater}}$
R14	1, 4	Flow Inertia	Flow In = Flow Out	$T_1 = T_4$
R15	1, 5	Convection	1.) Uniform Heat Flux to Air thru Freezer Shelves 2.) Natural Convection	$R_{15} = \frac{1}{h_5 * A_{wall}}$
R16	1,6	Convection	1.) Natural or Forced Convection 2.) Internal Flow of a Noncircular Tube	$R_{16} = \frac{1}{h_6 * A_{C,duct}}$
R67	1,7	Conduction	Conduction thru the aluminum walls to nanosatellite core	$R_{67} = \frac{L}{k_{Al} * A_c}$

Table 5-7: Additional parameters and equations affecting for the thermal resistors

Resistors	Additional Equations
R12	None
R13	$\overline{h}_3 = \frac{Nu_{D,3} * k_{air}}{2 * r_{HE}}$ $Nu_{D,3} = 0.75 * Re_{D,3}^{0.4} * Pr^{0.37} * (\frac{Pr}{Pr_s})^{0.25}$
R14	None
R15	$h_5 = \frac{Nu_{L,5} * k_{air}}{L_c}$ $Nu_{L,5} = [0.825 + \left(\frac{0.387 * Ra_5^{\frac{1}{6}}}{(1 + (\frac{0.492}{Pr})^{\frac{9}{16}})^{\frac{8}{27}}} \right)]^2$
R16	$h_6 = \frac{Nu_{L,6} * k_{air}}{L_c}$ Natural: $Nu_{L,6} = 0.54 * (Ra_6^{\frac{1}{3}})$ Forced: $Nu_{L,6} = 4.44 - \left[\frac{4.0 - (\frac{b}{a})}{1} \right] * (4.44 - 3.96)$
R67	None

5.12 Work Summary

The analysis and calculations were performed using Microsoft Excel and MATLAB Source Code for the thermal subsystem. Constant thermal properties of air at either 0°C, 20°C or 40°C depending on the thermal cycling situation were used for the calculations. The materials used for the analysis of the mini-freezer walls and the heating element were acrylonitrile butadiene styrene (ABS) plastic and nichrome respectively, and constant thermal properties were assumed during calculations.

Chapter 6: Controls Subsystem

6.1 Summary and Purpose

This subsystem controls the environmental temperature within the test chamber by managing the built-in refrigeration cycle, a 300W heating element, two CPU fans, and two motor-powered ventilation doors. An on-off control system, also known as a bang-bang or hysteresis controller, was used much like a traditional HVAC system. Feedback from five LM35 temperature sensors was used to ensure even heating was obtained and to provide an average temperature to the Arduino Mega 2560 microcontroller to determine whether further heating or cooling was necessary to achieve the desired temperature.

6.2 System Architecture

The subsystem architecture is composed of four primary components; the plant, feedback loop, controller, and actuators, and is shown in figure 6-1 below. The plant is the environment of the test chamber. The LM35 temperature sensors provide feedback to the microcontroller for real-time temperature in the environment. The microcontroller code was developed in the Arduino IDE and determines how the system reacts to the temperature feedback. Finally, the microcontroller sends commands to the refrigeration cycle, the heater, the fans, and motors depending on the state of the system. The user has the ability to choose whether the system performs thermal cycles or whether the system maintains a single temperature for a prolonged period of time. The three states in automation mode include cooling, heating, and off.

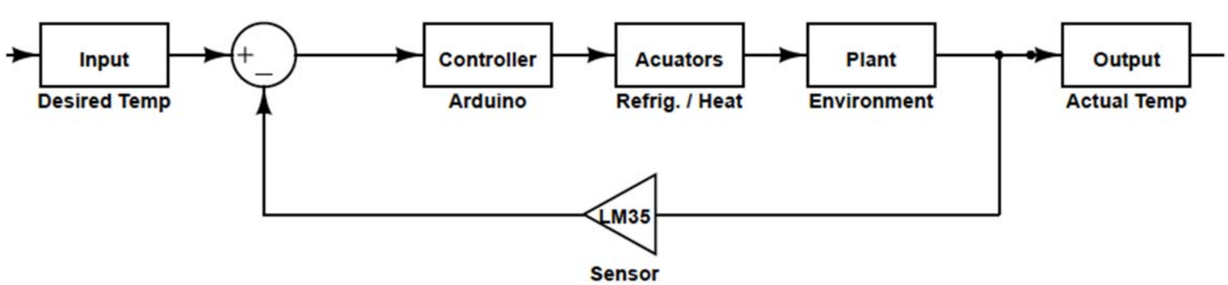

Figure 6-1: Thermal Control System Architecture

The user has the ability to set a number of testing variables such as the desired temperatures for heating and cooling, the number of cycles desired, and cycle duration. These variables are chosen via control knobs and variables set within the program. The desired temperatures, actual temperature, and cycle number values are displayed on the LCD readout. The user may also set the cycle duration time, the number of cycles desired, and the current room temperature within the program.

6.3 Control System Design

The control system was developed to allow the user to both set a maintained temperature and to be autonomous which allows testing without having to manually switch between heating and cooling. This was accomplished by incorporating a switch and also by using a finite state machine that determined if the system should be heating or cooling based on time and temperature feedback. When the timer reaches the desired cycle time, the system will switch states.

The thermal chamber contains equipment with different voltage requirements. The refrigeration system and 300W heating element are powered by alternating current, the fans and motors are powered by 12V direct current, and all remaining components are powered by 5V direct current. The 12V was acquired by using an AC/DC converter that was modified from a laptop charger and the 5V was acquired from the 12V DC/DC converter by using a step down buck converter. Figure 6-2 details the power schematic including these components.

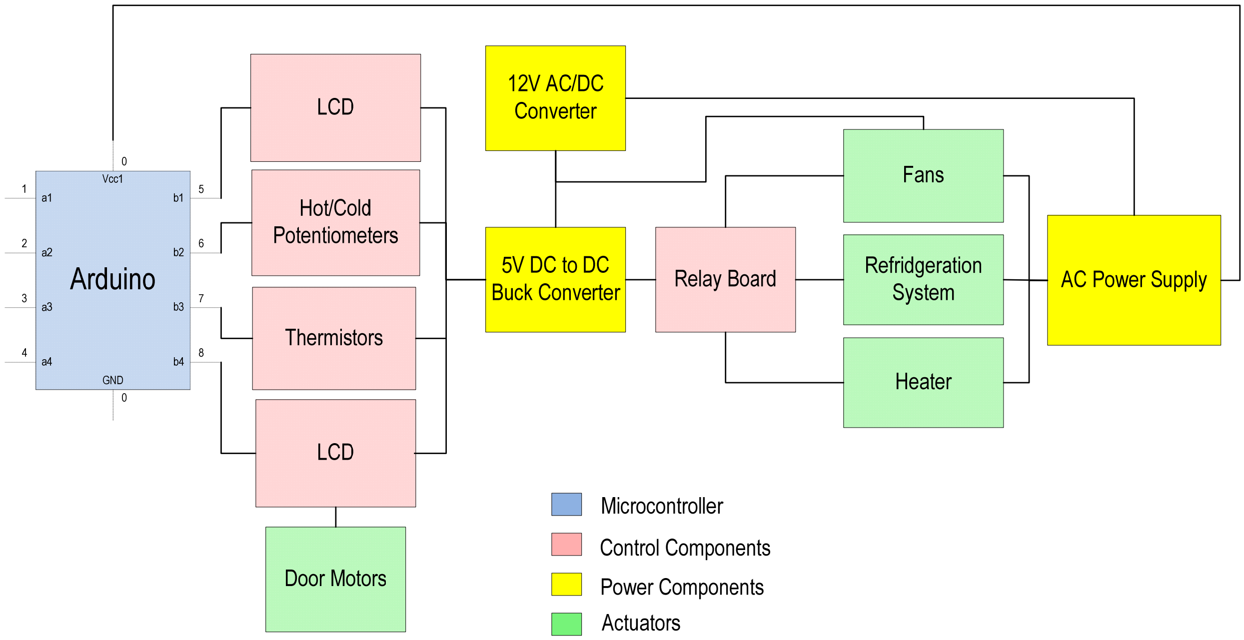

Figure 6-2: Electronic Power Schematic

The refrigeration system, heating element, fans, and motors are turned on and off using a relay that is controlled by the Arduino. The Arduino processes the average temperature given by the LM 35 sensors and turns on the actuators accordingly.

Due to noise in the temperature signals, filtering was necessary for accurate readings. Low-pass filtering was used to remove the noise and was calculated using Equation 6.1, where f_c is the cut-off frequency, R is resistor value, and C is the capacitor value. A resistor with a value of 10kΩ and a capacitor with a value of 220μF were chosen to achieve a cut-off frequency of 0.7 Hz.

$$f_c = \frac{1}{2\pi RC} \tag{6.1}$$

After incorporating passive low pass filters, steady signals were achieved and allowed the system to perform as desired.

Chapter 7: Manufacturing and Assembly

The majority of manufacturing was centered on integrating the ventilation system into the chamber door, and safely implementing the 300W heating element without compromising the existing refrigeration system and mini-freezer structure. Less intensive manufacturing processes include the passive dehumidification system and housing the electrical wiring.

7.1 Chamber Door

The mini-freezer door had a built in plastic shelving piece that was eventually replaced by a retrofitted galvanized steel plate shown in figure 7-1 below.

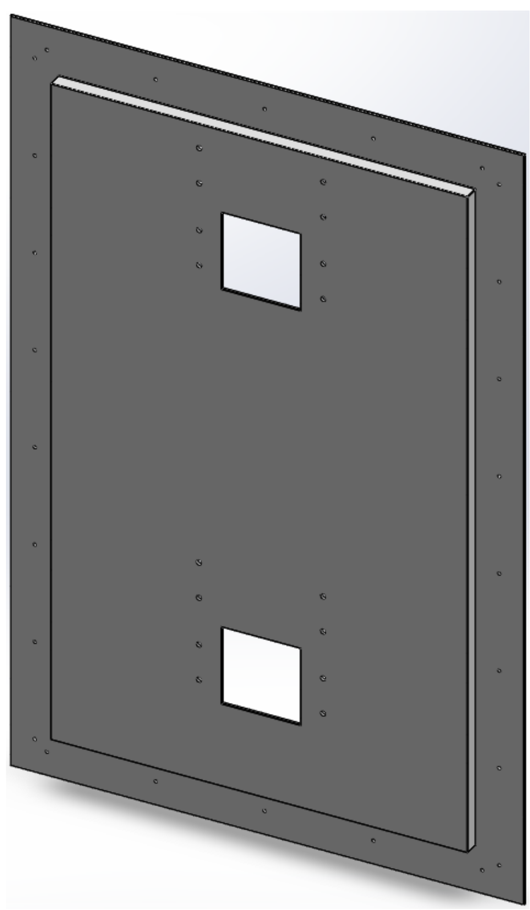

Figure 7-1: Interior Galvanized Panel mounted to door for ventilation system

The steel plate was fabricated to account for the raised layer of rigid polyurethane insulation in the door. This was done by using the same galvanized sheet metal to create z-brackets around the outside of the door plate, which were attached using aluminum rivets. The steel plate was retrofitted to the door through the z-bracket border using the original screw holes where the plastic shelving piece was originally attached. All sheet metal components were fabricated in the machine shop at SCU.

The original door seal was formed by a plastic lining fitted around the outer edge of the plastic shelving piece. The galvanized steel plate was sized such that this same plastic lining could be used. Doing so simplified the manufacturing process and simultaneously accounted for the system requirement that wiring be run from the interior to exterior without compromising the thermal environment—the plastic seal was flexible enough to allow all electrical wiring a direct pathway through the door while still remaining airtight.

7.2 Ventilation System

To manufacture the ventilation system the door plate needed numerous modifications. Two holes needed to be cut out through the entire door for the air ducts, and mounting holes needed to be drilled for the vent doors and motor system. The duct holes were limited as to how high and low on the door they could be placed without interfering with the rack and pinion mechanism selected to operate the two ventilation doors. The duct and vent door sizes were based on the size of the CPU fan used to cycle air through the chamber, which was 3.625 by 3.625 inches. To attach the fans and vent grills to the door a sheet metal piece shown in figure 7-2 was fabricated. This same concept was design and built for mounting the motors to the door with various bracket pieces shown in Appendix F.

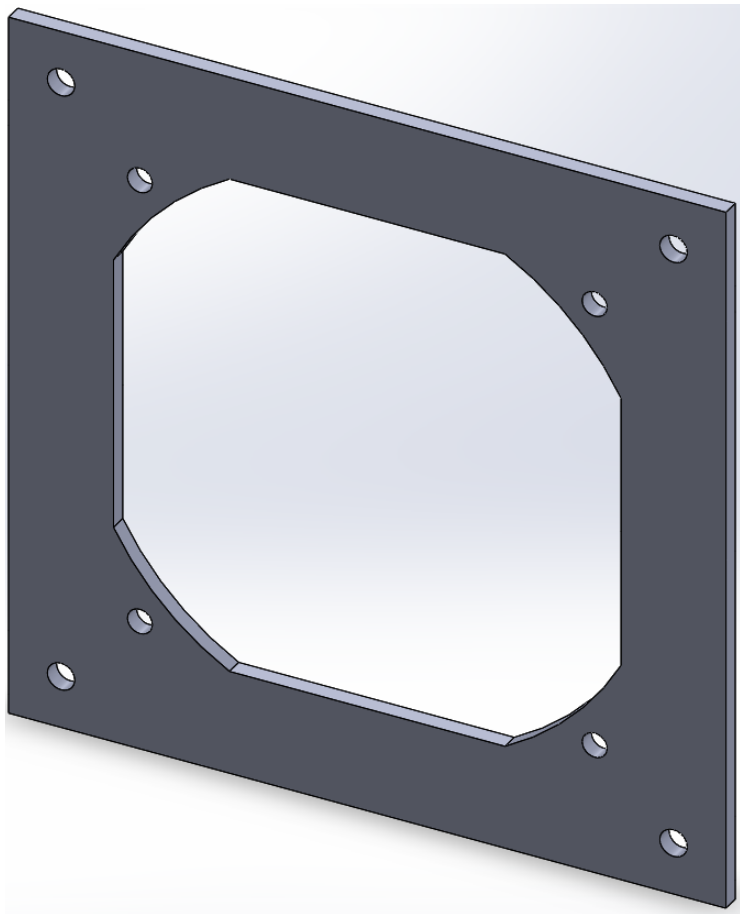

Figure 7-2: CPU Exterior Fan Mounting Bracket

The rack and pinion pieces were purchased online rather than made in the machine shop to maintain precise tolerances at low labor and monetary cost. The economic aspect of manufacturing is detailed further in chapter 9. To operate this mechanism a customized Delrin hub shown in figure 7-3 was fabricated using a lathe, such that the pinion could be press-fit to the motor. The rack was secured to the door via machine screws and holes were drilled through the side of the rack, shown in Appendix F drawing of the modified rack gear. The last components of the ventilation system assembled were the two shelf fans, which were attached to the copper tubing built-in to the chamber via plastic tube clamps.

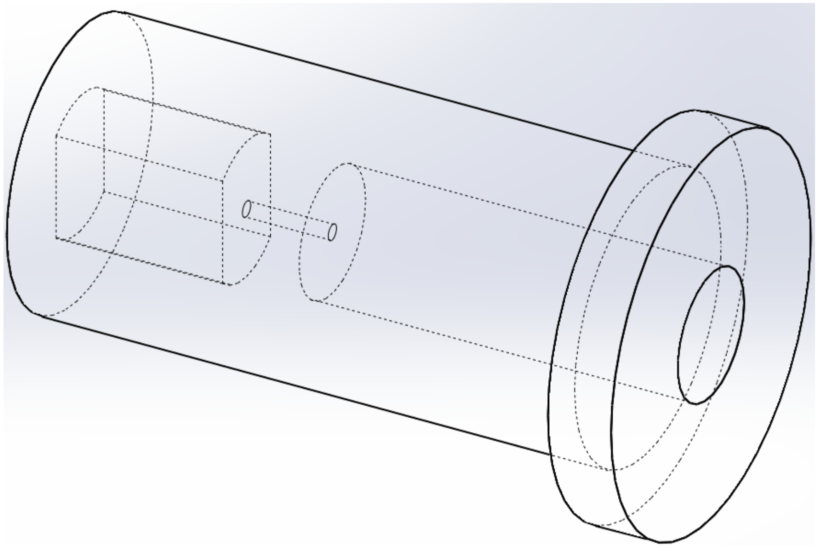

Figure 7-3: Machined Delrin hub adapter for pinion gear and motor shaft

7.3 Heating Element

The heating element was mounted to a galvanized sheet metal tray shown in figure 7-4. This part was fitted to the width of the chamber, but not secured directly to the floor, such that it could slide back and forth to reposition the heating element if desired by the user or be removed completely for maintenance purposes.

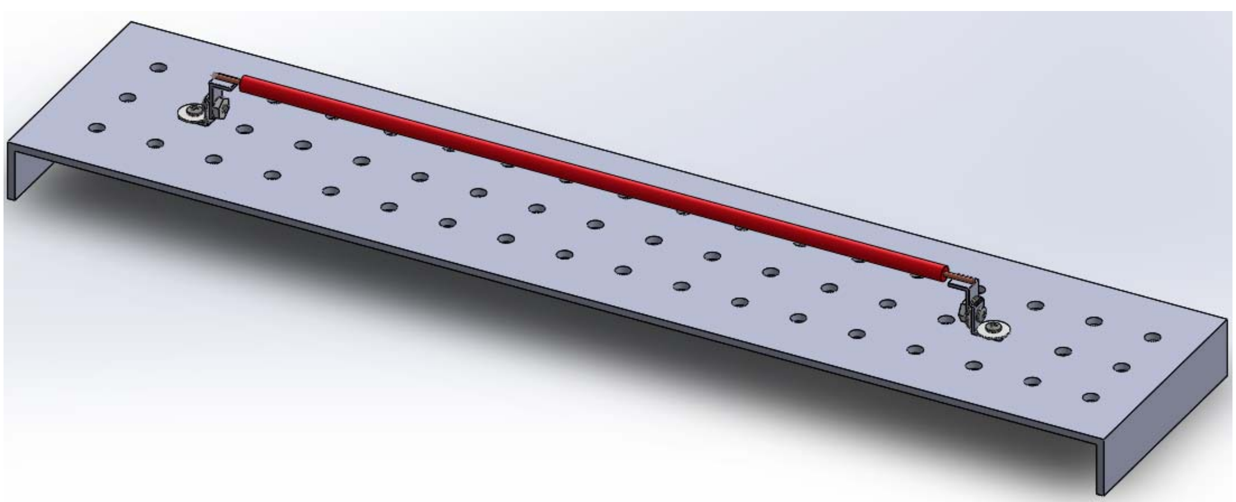

Figure 7-4: Heating Element adjustable tray with assembled 300W heating element shown

Holes with a diameter of 0.25 inches were added to the part using a power drill in a 1x1 inch lattice to facilitate better air circulation around the heating element. The Teflon insulating washers were cut with the same shear press used to cut the galvanized steel.

Once attached, wiring for the heating element was routed through holes in the mount plate for aesthetic appeal and protection from direct exposure to the heating element at close proximity. These wires were grouped with the thermistor power and feedback wiring, routed behind the steel door plate, and out of the chamber through a hole drilled in the top z-bracket to minimize the amount of exposed wiring in the chamber.

Chapter 8: System Requirements Verification Testing and Results

8.1 Purpose and Methodology

The two main objectives for system verification and testing were to one, demonstrate that the chamber successfully met system requirements, and two, provide comprehensive performance capabilities to the RSL for varying thermal conditions. The chamber was constructed to house and test a multitude of hardware ranging from individual communications components to multiple fully assembled nanosatellites at once, so testing protocol was designed to document operational performance throughout this range. Testing procedures were based in simply recording system behavior while operating with different items in the chamber, and providing the results to the RSL to help them optimize their own usage of the chamber once the project was complete.

While not all tests have been completed, data analysis thus far demonstrates that the chamber is capable of meeting all technical requirements. Testing up to this point has been done with an empty chamber, but will eventually include results for various items representing a range of operational scenarios. Each requirement will be verified for operation with the following items in the chamber: exposed communications hardware, one 3U nanosatellite, and one 6U (or two 3U) nanosatellites. Exposed hardware is to consist of a complete set of nanosatellite communication hardware without the housing of a fully assembled nanosatellite.

8.1 Requirements Verification Matrix

A verification testing matrix was developed in order to ensure system requirements were satisfied. The matrix, shown in Table 8-1, identifies the four technical requirements for the project. The verification method involved one or more of the following: Analysis (A), Experimentation (E) and Measurement (M). The following sections describe in greater detail the testing process and results of each testing method.

Table 8-1: Requirements Verification Matrix for each technical requirement,

Item #	Description	Verification Method	Pass/Fail	Numeric Value	Notes/Comments
1	Achieve 0°C and 40°C	A/E	Pass	-2°C to 46°C	Chamber can sustain temperatures from -20°C to 80°C.
2	90 min. cycle between 0°C and 40°C	E	Pass	60 min.	This was verified without ventilation, which will improve performance further.
3	±3°C for up to 12 hrs	E	To Be Determined	±3°C for 2 hrs.	Manually recording data at 1 minute intervals, no full test was completed at this point.
4	Hold 1U – 6U satellite sizes	M	Pass	5 cu. ft.	Can hold 2 6U configurations (each 10 cm x 20 cm x 30 cm) with 20% additional room in each direction

8.2 Temperature Range and Cycle Testing

Testing protocol was designed to verify the range and cycle requirements simultaneously by measuring the chamber performance when set to cycle between 0°C and 40°C. Of the 90 minutes required for the thermal cycle, 45 minutes were designated each for cooling and heating. After heating the chamber to at least 40°C, the cooling cycle was turned on and temperature was recorded every minute until the chamber achieved 0°C. At this point refrigeration was turned off, and heating was turned on until the chamber reheated to 40°C. With an empty chamber and no ventilation the temperature response was faster than necessary to meet the 90 minute requirement. In the 45 minutes designated to cooling, the chamber cooled from 46°C to -2°C. The temperature response is shown in figure 8-1.

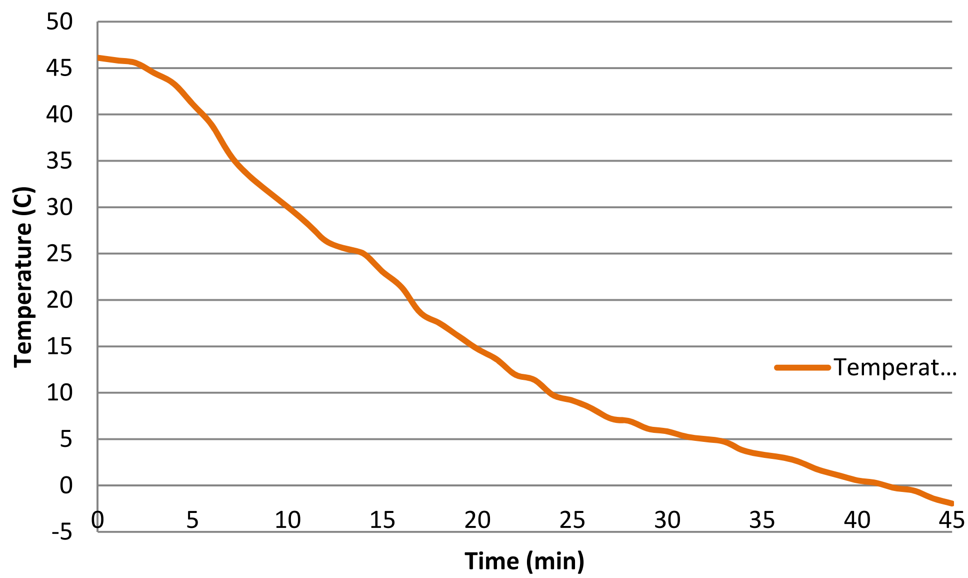

Figure 8-1: Cooling from 46°C to -2°C in under 45 minutes

In the 45 minutes dedicated to heating, the chamber heated from -2°C to 41°C in 15 minutes. This is shown in figure 8-2. Together the times for heating and cooling indicate a full cycle between 0°C and 40°C takes less than 60 minutes.

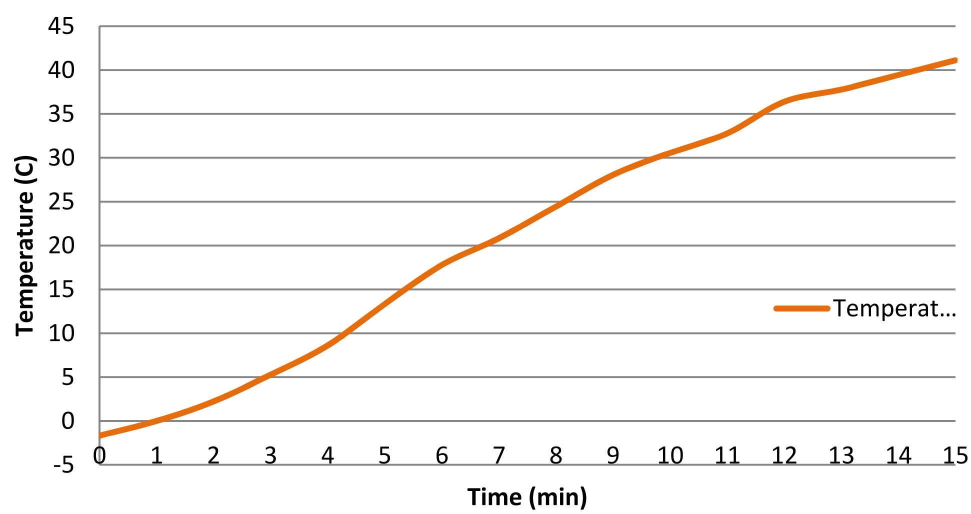

Figure 8-2: Heating from -2C to 41C in under 15 minutes

It is important to note that this testing was done without utilizing the ventilation system. Ventilation is expected to further decrease the time taken for heating and cooling throughout the full temperature range, which will compensate for the thermal load of the items placed in the chamber during future testing. This is demonstrated theoretically by the thermal predictive tool referenced in the thermal subsystem chapter.

8.3 Endurance and Accuracy

Endurance refers to the requirement of operating for up to 12 hours, and accuracy refers to maintaining temperatures within three degrees of the user input. Verification for these two requirements will also be done simultaneously. Currently, no 12 hour test has been run. A data retrieval system has yet to be implemented into the control system, making it impractical to run long tests with manual recording of temperature every minute.

For cooling, the chamber will be set to 0 degrees Celsius and temperature readings will be recorded every minute for a full 12 hour test. This process will be repeated at 20°C and 40°C to demonstrate accuracy and endurance throughout the operational temperature range, with the full range of materials in the chamber. Although a full endurance test was not run at this time, the team maintains full confidence that it will perform for far longer than 12 hours. The mini-freezer refrigeration system was designed to run continuously for multiple years, while all the materials used in design are rated for multiple years of use.

8.4 Future Testing

There is still much work to be done to complete the comprehensive testing protocol designed. So far the functionality has been verified with an empty chamber and all technical requirements tested vastly exceed expectations as predicted. The endurance and accuracy testing has not been performed because the control system did not fully implement the Stamplot data retrieval program. It was not practical to run a full 12 hour test with manual data retrieval, but with Stamplot this testing will be completed. In the future the tests that have been run with an empty chamber will be repeated with the described items. These results will be documented and provided to the RSL to give them a reference from which to base expectations on during their own testing procedures.

Chapter 9: Business Plan and Cost Analysis

9.1 Introduction/Background

Although NASA currently regulates the majority of nanosatellite launches, the transition to a market of commercial developers like Space-X is creating more opportunities for investors in the industry. Technological advancements have allowed the private sector more access to nanosatellite development through the use of off-the-shelf products. As a result of this growth, the demand for functional testing has increased at the university and start-up business level.

To address this demand at Santa Clara University the team developed a thermal cycling chamber for initial testing of internal hardware. A limited number of thermal chambers are already available on the market as detailed in chapter 1, however, the cost of these products are in the $4000 to $7000 range. Furthermore, these options often provide a much wider range of testing features than is necessary in the university setting, specifically in the case of the RSL. With a university budget these options are frequently unaffordable, creating demand for a more cost-effective method of thermally testing nanosatellite hardware.

9.2 Goals and objectives

The primary goal of the team is to provide a reliable low-cost tool for initial thermal testing of nanosatellites. Before the product was developed, students in the RSL performed hardware testing at room temperature. To run those tests in varying thermal conditions they had to constantly move equipment from a hot environment, such as a conventional oven, to a cold environment, such as a freezer compartment. This practice is inefficient and unreliable from an engineering standpoint because it is difficult to control the environment precisely, and is subject to many uncontrollable variables. Although the product was specifically designed to meet the needs of the RSL at SCU, minimal modifications, if any, make it useful to other universities and businesses as well.

9.3 Product Description

The platform of the chamber is marketable in terms of accessibility due to the use of off-the-shelf products wherever possible. This approach enables minimal modifications to design in order to accommodate varying requirements across the market.

The chamber can fully cycle through a range of 0°C to 40°C in under 90 minutes. In addition, the chamber will maintain set temperatures for durations of up to 12 hours with an accuracy of ±3°C and even heating throughout the chamber in steady-state conditions. The size of the chamber allows for a range of equipment to be tested, from individual hardware components to a 6U CubeSat platform, while also being relatively lightweight and portable.

The design of the chamber uses the integrated cooling system of a reused mini freezer unit. The heat source is an affordable 300W conventional heating element secured to a movable tray in the chamber. The ventilation system and controls interface are constructed almost entirely from commercially available components that are customizable depending on the need of the customer, none of which cost more than $45. A few small parts were made using power tools and a standard lathe, out of low-cost materials including galvanized steel sheet metal, acrylic, and delrin plastic.

9.4 Cost Analysis

In total the product cost is about $460. This does not include costs for labor and overcompensation during the design and manufacturing stages of the project. For the purposes of this project labor is assumed to be free, however this may change depending on how the product is reproduced. Including the cost of spare parts and materials brings the total to about $618.

It is important to note that many parts used in the final assembly can be purchased at a wide range of prices. The mini-freezer platform was purchased as a lightly used system for a small fraction of the original cost of a brand new unit. Furthermore, cost of materials and machining varies greatly depending on location and resources. Most materials were purchased locally which reduced costs by avoiding shipping fees or the effects of a limited market that drives up prices in less accessible locales. The specific costs of individual components are listed in Appendix A.

9.5 Financial Outlook

Success of the product in terms of marketability is centralized on demand from customers at the university and small business level. This demand varies depending on individual programs that may desire different system requirements than those of the RSL. In the case of temperature range, accuracy, and power, this variance can be addressed by substituting a more appropriately sized heating element for the 300W part used in the product. If more space is needed in the chamber, a larger mini-freezer can be used as the design platform. At this point the product marketability is directed toward the conceptual design more so than a replicable system, namely, a low-cost thermal cycling chamber does not entail the same exact product for every customer.

Currently there are no competitive products that offer the same service for a similar cost. The closest comparable products are higher performance devices at much higher costs, built to suit the needs of a wider range of customers. For customers that don't need this range, the only option is to manufacture a device in-house. The product design used in this project can be manufactured and assembled in as little as a few days, making buildability a minor concern. Ultimately the objective of the project was to eliminate the need for purchasing commercially available services, so while the product is marketable in terms of demand it is less-so in terms of how easy it would be for a customer to make the product themselves. Considering that purchasing a prefabricated model of the product could increase costs for a customer compared to building one themselves, it would still be significantly cheaper than purchasing the more expensive devices highlighted in chapter 1. In the case of a customer without the means of replicating the product in-house, buying a prefabricated model is the best and only option.

Chapter 10: Engineering Standards and Realistic Constraints

10.1 Brief Description of Project and Areas of Impact

The goal of this project has been to design and build an environmental stimulation chamber for nanosatellite functional testing. The demand for this product comes from the Robotic Systems Laboratory (RSL) at Santa Clara University. The nanosatellite industry has become more prevalent in recent years, and the engineering behind it is often done at the university level. The final product will enable the RSL to run customized in-house testing, saving time and money in the process. Providing this chamber to the customer will have environmental and societal impacts in various stages of the project, starting in the design phase. During the design phase the major concerns are environmental impact and manufacturability, which remains a concern in the manufacturing phase. Sustainability, economic impact, and social impact are considered throughout the manufacturing and post-assembly phases as well.

10.2 Impact Area Background Information and Details

Environmental constraints were prevalent during the design process. Once the chamber is assembled and operating, it produces no harmful byproducts or environmentally dangerous side effects. The primary areas in which the team is concerned with environmental impact is selection of materials and power consumption. Because the functionality of the chamber is relatively simple, there are many different materials that fulfill design requirements and will result in less power consumption than the previous testing methods used by the RSL. While monetary cost is a prio-989rity, the team has been continually mindful of the environmental cost of the materials used. If a more expensive option included more eco-friendly features, the team chose this option over a cheaper one as long as it did not exceed budget limitations rather than saving money in the production process.

Manufacturability was a major concern in the building process, but not as much for future work or reproduction. From the start, production of the chamber was intended to be a one-time event, resulting in one chamber for private use in the RSL. Mass-production was not considered.

During the design phase manufacturability was one of the deciding factors in the selection of multiple components. In the instance of the heating system, a 300W heating element was selected over thermoelectric pads because it would be easier to implement into the mini-freezer. Manufacturability was a concern as far back as making the decision to use the built-in refrigeration system rather than build a chamber from the ground up. From a manufacturing standpoint, using the mini-freezer made the building phase much simpler and focused.

The economics of the product were an essential design consideration and influence. At the request of the customer, the RSL needed a low-cost thermal cycling chamber that could stimulate the surrounding environment. The initial prospective budget was estimated to be around $600. From there, the team did research on the market availability of thermal cycling chambers that met or exceeded the design requirements of this project. The team was able to find three products currently on the market, however, these products were outside the budget of $600. The first product, ESPEC BTU-133 has an operating temperature range of -20C to 180C. The baseline cost of this particular model is $6,490. The second comparable product was the Cincinnati Sub-Zero MicroClimate MCB-1.2 Bench top, with a temperature range of -30C to 190C. The base price for the Cincinnati model was around $4,500. The last comparable product on the market was the inTESTthermal THERMOCHAMBER with a temperature range of -65C to 200C which far exceeds the system requirements needed. The team produced a system that was far more cost effective and tailored to the needs of the RSL.

The sustainability of a product and its materials is directly related to both its environmental and economic impact. Selecting components and materials that are low-maintenance and long-lasting has been important to us considering the desired lifetime of the final product, but it is also important to select materials that do not harm the environment via byproducts in either fabrication or operation. Sustainability was prioritized over material cost if it meant saving customers money in the long run.

While the product will not directly influence a wide audience, it is a useful tool for the RSL that bolsters a larger social impact. Ideally the test chamber will help the RSL work faster and produce better results in their work with nanosatellites. Nanosatellites offer a wide range of applications, including but not limited to telecommunications, earth observations, scientific research, biological experiments, military applications that can be developed at the academic level. Large projects are often very complex by nature, leading to high costs and slow production times. Nanosatellites in the academic setting offer lower costs and faster build times, and are an excellent opportunity for research with new and emerging technologies.

10.3 Product Use

Since the product will be used privately by the RSL, the scope of influence is limited. Social and economic impacts directly affect the RSL, which includes around 5 to 10 students and faculty each year. The immediate effects of operating the chamber will be minimal, but the ability it provides is powerful. By producing more reliable testing data in a less costly process, the RSL will make progress more efficiently in any endeavors related to the satellites they test. In this sense, the scope of influence of this project is very large.

10.4 Documented Quantitative Results

One feature of the project that is related to environmental and economic impact is power consumption. Table 10-1 shows the expected energy consumption of the product compared to one method used by the RSL in the past, in which they used a conventional oven and refrigerator.

Table 10-1: Power Consumption of One Nanosatellite Functional Test

	Testing Method	Wattage (W)	Test Duration (hours)	Power Consumption (kWh)
Previous Testing Method	Conventional Oven	3000	3	9
	Refrigerator (2010 model)	800	3.75	3
Testing with our Product	Chamber Heating Element	300	3	0.9
	Mini-Freezer Unit	132	3.75	0.495

Expected savings are around 10kWh per test, decreasing power consumption by around 83%. The RSL may run numerous tests per day throughout the year, ultimately saving money for the university as well.

10.5 Summary

Throughout this project, little to no negative societal or environmental impact was maintained as an active design and manufacturing constraint. The physical components of the product are among the most sustainable and eco-friendly materials obtainable within the alotted budget and timeframe. Manufacturability and economic impact were major driving forces in the design and building process that led us to producing a chamber that meets system requirements at a much more affordable level than previous options for the RSL. It is difficult to quantify these impacts in all aspects, but the product demonstrably saves money in both production and operation. As the nanosatellite industry continues to grow, this project has provided a tool to help the RSL continue to progress alongside it.

Chapter 11: Conclusion

11.1 Summary

The objective of this project was to develop a thermal cycling stimulation chamber capable of performing functional testing of nanosatellites. The project made use of many commercial off-the-shelf products assembled together. Now that the product is complete, students of the RSL will be capable of testing communication hardware that is under development. The platform for the chamber is easily manufactured making future modifications and additions very manageable.

The major subsystems of the chamber are the thermal and control subsystems. The thermal subsystem consists of a single 300W heating element, an integrated refrigeration system capable of achieving -22°C, and a CPU-fan-driven ventilation system. The control subsystem is capable of operating the chamber under two distinct modes of either set-point temperature or thermal cycling. It is designed around an Arduino Mega Microcontroller through which all knobs, switches and displays are integrated. The Arduino is a very open-ended platform making it ideal future modifications and additions by the RSL or future senior design teams.

To ensure all requirements were met the team developed a system requirements verification matrix alongside a comprehensive testing protocol specific to each requirement. The tests verified that the chamber could reach the full range of 0°C to 40°C, fully cycling back and forth between those extremes in under 90 minutes. The team is confident that the chamber will hold a specified temperature within 3°C of the user input value for up to 12 hours. This is based both on observations of the chamber in operation, and expectations of the materials used. This feature will be tested as part of future work.

Results of testing the temperature range and cycle duration yielded promising results. The cooling system was able to cool 45°C degrees in 45 minutes, while the heating element increased the temperature 40°C in just 15 minutes. The total cycle duration desired by the RSL takes less than 60 minutes, which is an improvement of over 30% on the design they desired.

11.2 Lessons Learned

As a whole, the team learned many lessons centralized on time management and communication. These two key components of any engineering project were the cause of the majority of setbacks throughout the project. Related issues were mainly localized to systems engineering. Integrating the various subsystems proved to be a far more complicated task than any team members foresaw, and it was both educational and stressful to overcome these adversities. One manifestation of this was the frequent complications in completing the control subsystem programming to function with the assembled hardware. While the program operated as it was intended on a computer interface, unforeseen complications arose when the hardware behaved unexpectedly. Dealing with these kinds of issues often took longer than it did to create the program itself, but in the end proved to be factors that united the team in overcoming them.

11.3 Future Work

Aside from completing all necessary testing, there is much potential for future work on the project. The current dehumidification system is of a passive design and needs to be replaced regularly. This could be improved upon by implementing an automated system with more engineering work towards optimization. Additionally, there is structural room to add signal attenuation and power simulation subsystems that could help the RSL test communication hardware further. The current design team had a limited knowledge of programming so the current control system could be expanded upon significantly. One example of this is adding temperature control to simulate thermal shock conditions for testing. Altogether this team was able to design a system that exceeded expectations of the RSL, but there is certainly potential to improve upon the final product.

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Appendix A: Project Budget

Itemized Purchases for Enviromental Stimulation Chamber from Taylor Donato								
Purchase Date	Business Name	Item Description	Quanity	Cost/Unit	Total Item Cost	Shipping & Handling	Tax	Total Cost
17-Mar-14	Amazon	CanaKit UK1122 Dual Bi-Directional Motor Driver	1	$ 20.00	$ 20.00	$ 6.29	$ -	$ 26.29
18-Mar-14	Rockler	Mini Drawer Slides 7-3/16	1	$ 10.49	$ 10.49	$ 7.99	$ 1.62	$ 20.10
18-Mar-14	Pololu Corporation	Solarbotics GM2 224:1 Gear Motor Offset Shaft	2	$ 5.95	$ 11.90			
		Solarbotics GMB28 Gear Motor Bracket	2	$ 1.49	$ 2.98			
					$ 14.88	$ 5.95	$ -	$ 20.83
18-Mar-14	McMaster-Carr	Steel 20 Deg Pressure Angle Spur Gear	1	$ 21.04	$ 21.04			
		Steel 20 Deg Pressure Angle Spur Gear Rack	1	$ 19.30	$ 19.30			
					$ 40.34	$ 5.86	$ 3.53	$ 49.73
31-Mar-14	Home Depot	1' x 1' Weldable Sheet Metal	1	$ 7.24	$ 7.24			
		Milwaukee 5/32"' Black Oxide Bit	1	$ 2.17	$ 2.17			
		Washer Flat SAE SS #6	1	$ 1.18	$ 1.18			
		Machine Screw #6-32x1"	1	$ 1.18	$ 1.18			
		Machine Screw #6-32x3/4"	1	$ 1.18	$ 1.18			
		Machine Screw #6-32x1/2"	1	$ 1.18	$ 1.18			
					$ 14.13	$ -	$ 1.24	$ 15.37
1-Apr-14	Home Depot	Machine Screw Nut #10-32	1	$ 1.18	$ 1.18			
		Machine Screw Round Head SS #10-32x1/2"	1	$ 1.18	$ 1.18			
		Dewalt 1/16" Split Point Drill Bit	1	$ 2.97	$ 2.97			
					$ 5.33	$ -	$ 0.47	$ 5.80
2-Apr-14	Anchor Electronics	CPU Fan	1	$ 6.95	$ 6.95			
		20 Gauge Wire	2	$ 1.00	$ 2.00			
		7" Jumper Wire 10 pk.	1	$ 6.00	$ 6.00			
					$ 14.95	$ -	$ 1.31	$ 16.26
9-Apr-14	McMaster-Carr	Steel 20 Deg Pressure Angle Spur Gear	1	$ 21.04	$ 21.04	$ 5.46	$ 1.84	$ 28.34
12-Apr-14	Rockler	Mini Drawer Slides 7-3/16	1	$ 10.49	$ 10.49	$ 7.99	$ 1.62	$ 20.10
14-Apr-14	Home Depot	Milwaukee 5/32" Black Oxide Bit	1	$ 2.17	$ 2.17			
		Machine Screw #10-32x1/2"	2	$ 1.18	$ 2.36			
		Machine Screw #6-32x1-1/2"	1	$ 1.18	$ 1.18			
					$ 5.71		$ 0.50	$ 6.21
17-Apr-14	Home Depot	3 Pc. Nail Setter Kit	1	$ 5.97	$ 5.97			
		3 in.x3 in. Angle Bracket	2	$ 2.57	$ 5.14			
		Milwaukee 11/64" Drill Bit	1	$ 2.27	$ 2.27			
		Machine Screw #8-32x1/2"	2	$ 1.18	$ 2.36			
		Machine Screw Nut #8-32	2	$ 1.18	$ 2.36			
		Machine Screw #4-40	1	$ 1.18	$ 1.18			
		Storaway Organizer	1	$ 3.97	$ 3.97			
					$ 23.25		$ 2.03	$ 25.28
28-Apr-14	Home Depot	Machine Screw #8-32x1-1/2"	1	$ 1.18	$ 1.18			
		Machine Screw Nut #8-32	1	$ 1.18	$ 1.18			
		Machine Screw #10-24x1/2"	1	$ 1.18	$ 1.18			
					$ 3.54		$ 0.31	$ 3.85
29-Apr-14	Anchor Electronics	CPU Fans	3	$ 6.95	$ 20.85			
		Miscellaneous #22 Gauge Wire	5	$ 1.00	$ 5.00			
					$ 25.85		$ 2.26	$ 28.11
2-May-14	Anchor Electronics	Box of Heat Shrink	1	$ 9.98	$ 9.98			
		3m 3 ft. White heat Shrink	2	$ 0.90	$ 1.80			
		Wire Clamps	1	$ 1.34	$ 1.34			
					$ 13.12		$ 1.15	$ 14.27
2-May-14	Home Depot	4" Cable Tie	1	$ 2.38	$ 2.38			
		Machine Screw Nut #8-32	2	$ 1.18	$ 2.36			
		1-Hole Cable Clamps	1	$ 1.28	$ 1.28			
		Cabinet Screw #8-32x1-1/2"	1	$ 1.98	$ 1.98			
					$ 8.00		$ 0.70	$ 8.70
							TOTAL	$ 134.86
							TOTAL	$ 289.24

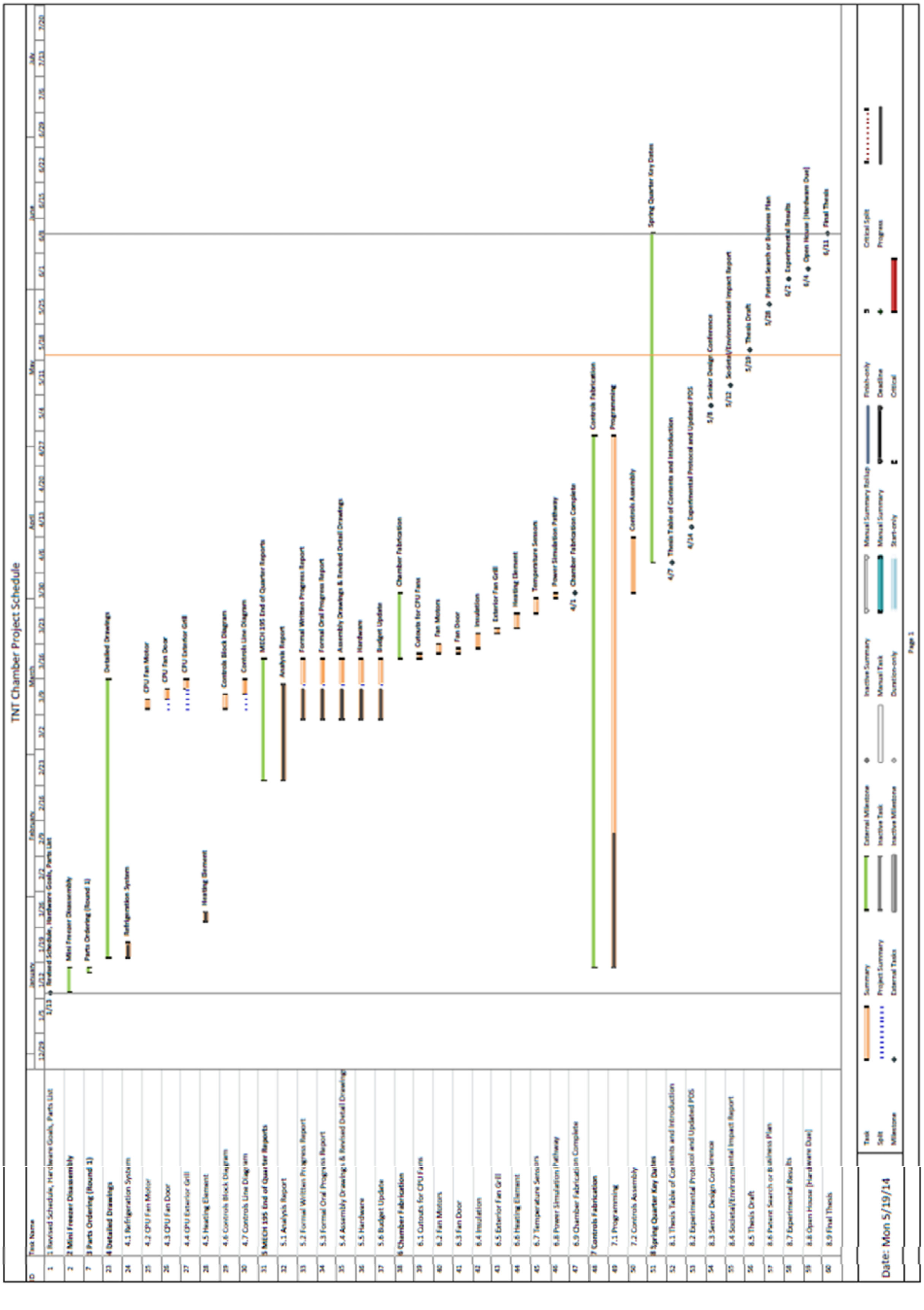
Itemized Purchases for Environmental Stimulation Chamvber from Brandon Wood

Purchase Date	Business Name	Item Description	Quantity	Cost/Unit	Total Item Cost	Shipping&Handling	Tax	Total Cost
10/13/2013	Craigslist	Freezer Unit	1	$ 30.00	$ 30.00			
					$ 30.00			$ 30.00
1/18/2014	Anchor Electronics	Heat Shrink	4	$ 0.88	$ 3.52			
		AC/DC Adapter	1	$ 7.95	$ 7.95			
		20 guage wire	2	$ 1.00	$ 2.00			
		10k Potentiometer	2	$ 0.95	$ 1.90			
		breadboard	1	$ 14.95	$ 14.95			
		wire stripper	1	$ 7.07	$ 7.07			
		LM 35 Thermistor	10	$ 1.15	$ 11.50			
		10k Potentiometer	2	$ 0.95	$ 1.90			
		knobs	2	$ 0.81	$ 1.62			
		100k potentiometer	3	$ 1.36	$ 4.08			
					$ 56.49		$ 4.94	$ 61.43
2/7/2014	Amazon	Jumper Wires	1	$ 6.45	$ 6.45			
		Soldering Iron	1	$ 13.99	$ 13.99			
		20 Ga Wire	1	$ 6.90	$ 6.90			
		Parallax LCD	1	$ 29.99	$ 29.99			
					$ 57.33			$ 57.33
2/17/2014	Amazon	Arduino Mega	1	$ 28.00	$ 28.00			
					$ 28.00			$ 28.00
2/19/2014	Amazon	Cable Ties	1	$ 6.03	$ 6.03			
					$ 6.03			$ 6.03
2/20/2014	Amazon	8 ch. Relay Board	1	$ 19.58	$ 19.58			
					$ 19.58			$ 19.58
3/3/2014	Amazon	Jumper Wires	1	$ 7.70	$ 7.70			
					$ 7.70			$ 7.70
4/10/2014	Amazon	Wall Adapter	1	$ 5.19	$ 5.19			
					$ 5.19			$ 5.19
4/10/2014	Anchor Electronics	#14 Wire	45	$ 0.125	$ 5.63			
		Rosin Flux	1	$ 8.95	$ 8.95			
					$ 14.58		$ 1.29	$ 15.87
4/27/2014	Amazon	DC-DC Buck	1	$ 10.95	$ 10.95			
					$ 10.95			$ 10.95
4/27/2014	Anchor Electronics	220µF Caps	5	$ 0.23	$ 1.15			
		10K Ω Resistors	1	$ 0.35	$ 0.35			
		20Gg. Wire	18	$ 1.00	$ 18.00			
					$ 19.50		$ 1.71	$ 21.21
4/29/2014	Lowe's	Electrical Tape	1	$ 3.98	$ 3.98			
		4-40 Screws	2	$ 1.24	$ 2.48			
		Clear Tape	1	$ 4.98	$ 4.98			
		Extenstion Cord	1	$ 13.97	$ 13.97			
		Power Strip	1	$ 7.98	$ 7.98			
					$ 33.39		$ 2.92	$ 36.31
4/29/2014	Home Depot	Junction Box	1	$ 22.64	$ 22.64			
		Strain Relief	3	$ 1.52	$ 4.56			
					$ 27.20		$ 2.38	$ 29.58
								$ 329.18

Appendix B: Project Timeline

TNT Chamber Project Schedule.mpp

ID	Task Name	Finish	Start	Duration	Predecessors
1	Revised Schedule, Hardware Goals, Parts List	Mon 1/13/14	Mon 1/13/14	0 days	
2	**Mini Freezer Disassembly**	**Fri 1/17/14**	**Mon 1/13/14**	**5 days**	
7	**Parts Ordering (Round 1)**	**Fri 1/17/14**	**Fri 1/17/14**	**1 day**	
23	**Detailed Drawings**	**Sat 3/15/14**	**Mon 1/20/14**	**48 days**	**6**
24	Refrigeration System	Wed 1/22/14	Mon 1/20/14	3 days	
25	CPU Fan Motor	Tue 3/11/14	Mon 3/10/14	2 days	24
26	CPU Fan Door	Thu 3/13/14	Mon 3/10/14	2 days	25
27	CPU Exterior Grill	Sat 3/15/14	Mon 3/10/14	2 days	26
28	Heating Element	Tue 1/28/14	Mon 1/27/14	2 days	
29	Controls Block Diagram	Wed 3/12/14	Mon 3/10/14	3 days	
30	Controls Line Diagram	Sat 3/15/14	Mon 3/10/14	3 days	29
31	**MECH 195 End of Quarter Reports**	**Wed 3/19/14**	**Mon 2/24/14**	**21 days**	
32	Analysis Report	Fri 3/14/14	Mon 2/24/14	17 days	6
33	Formal Written Progress Report	Wed 3/19/14	Sat 3/8/14	9 days	32
34	Formal Oral Progress Report	Wed 3/19/14	Sat 3/8/14	9 days	32
35	Assembly Drawings & Revised Detail Drawings	Wed 3/19/14	Sat 3/8/14	9 days	32
36	Hardware	Wed 3/19/14	Sat 3/8/14	9 days	32
37	Budget Update	Wed 3/19/14	Sat 3/8/14	9 days	32
38	**Chamber Fabrication**	**Tue 4/1/14**	**Thu 3/20/14**	**11 days**	
39	Cutouts for CPU Fans	Thu 3/20/14	Thu 3/20/14	1 day	35
40	Fan Motors	Sat 3/22/14	Fri 3/21/14	2 days	39
41	Fan Door	Fri 3/21/14	Fri 3/21/14	1 day	39
42	Insulation	Mon 3/24/14	Sat 3/22/14	2 days	41
43	Exterior Fan Grill	Tue 3/25/14	Tue 3/25/14	1 day	42
44	Heating Element	Fri 3/28/14	Wed 3/26/14	3 days	43
45	Temperature Sensors	Mon 3/31/14	Sat 3/29/14	2 days	44
46	Power Simulation Pathway	Tue 4/1/14	Tue 4/1/14	1 day	45
47	Chamber Fabrication Complete	Tue 4/1/14	Tue 4/1/14	0 days	46
48	**Controls Fabrication**	**Fri 5/2/14**	**Sat 1/18/14**	**90 days**	**7**
49	Programming	Fri 5/2/14	Sat 1/18/14	90 days	7
50	Controls Assembly	Sat 4/12/14	Wed 4/2/14	10 days	47
51	**Spring Quarter Key Dates**	**Wed 6/11/14**	**Mon 4/7/14**	**56 days**	
52	Thesis Table of Contents and Introduction	Mon 4/7/14	Mon 4/7/14	0 days	
53	Experimental Protocol and Updated PDS	Mon 4/14/14	Mon 4/14/14	0 days	
54	Senior Design Conference	Thu 5/8/14	Thu 5/8/14	0 days	
55	Societal/Environmental Impact Report	Mon 5/12/14	Mon 5/12/14	0 days	
56	Thesis Draft	Mon 5/19/14	Mon 5/19/14	0 days	
57	Patent Search or Business Plan	Wed 5/28/14	Wed 5/28/14	0 days	
58	Experimental Results	Mon 6/2/14	Mon 6/2/14	0 days	
59	Open House [Hardware Due]	Wed 6/4/14	Wed 6/4/14	0 days	
60	Final Thesis	Wed 6/11/14	Wed 6/11/14	0 days	


TNT Chamber Project Schedule
Date: Mon 5/19/14

Appendix C: Thermal Calculations

Air Volume (ft^3)	8
Air Volume (m^3)	0.226535
Heat Element Volume (m^3)	9.65278E-06
Heat Element Surface Area (m2)	0.00608049
Characteristic Length (m)	0.0015875
Mass of Air (kg)	0.292909755
Energy (J) required to heat Air from 0 to 40 C	11774.97215
Time (sec)	**Power required to Heat Air (W)**
600	19.62
900	13.08

Appendix D: Safety Precautions and Instruction Manual

In order to maintain safety, a number of steps are necessary to run or modify this test chamber.

1) Work in pairs when running or modifying the system.
2) Ensure that the AC plug is not connected to the wall when performing maintenance or dealing with electronic components.
3) When turned on, ensure that the relay cover is on.
4) After the system is powered on, do not touch or attempt to modify electronic components.
5) In case of an emergency, unplug all components.

Instruction Manual

1) Place satellite inside testing chamber
2) Power on Arduino and electronics.
3) To record data, plug the Arduino into the computer via USB and open Stamplot to record chamber temperatures.
4) The user has 20 seconds from when the Arduino is powered up to choose settings such as manual or automation and to set the desired temperatures. If using manual mode, use the right knob to set the desired temperature.
5) The system will turn on appropriate systems to reach desired temperatures.
6) Initially the code is set up to run 4 cycles at 45 minutes each. This includes cooling, heating, cooling, and then heating. If these parameters need to be changed, the user must change variables “numCycles” and “cycleTime” in the Arduino Program.

Appendix E: System Code in Arduino IDE

```
//TNT Chamber Code
//Created by Brandon Wood
//June 4, 2014 Revision
#include <SoftwareSerial.h>

//Temperature Variables
float temp1, temp2, temp3, temp4, temp5, avgTemp;          // Converted temperature values
int tempPin1 = A0;                              // Temperature Sensor 1
int tempPin2 = A1;                              // Temperature Sensor 2
int tempPin3 = A2;                              // Temperature Sensor 3
int tempPin4 = A3;                              // Temperature Sensor 4
int tempPin5 = A4;                              // Temperature Sensor 5
int readcTemp, readhTemp, cTemp, hTemp;                   // User Input Knobs
int memTemp = 0;                                // Hysteresis Flag

//Timer Variables
unsigned long previousMillis, currentMillis, startMillis;
unsigned long elapsedTime = 0;
unsigned long cycleTime = 45;                        // Enter time for each cycle in minutes
unsigned long interval = cycleTime*60*1000;               // Length of time between cycles in
milliseconds

//Cycle Variables
int numCycles = 4;                              // Set number of cycles for testing
int cycleCounter = 1;
int roomTemp = 25;                              // Set room temperature
int setupDelay = 20000;                         // Set setup delay before program runs

//Motor Driver variables
int in1 = 23;
int in2 = 25;
int in3 = 27;
int in4 = 29;
int ena = 31;
int enb = 33;
int y = 0;                               // Open Doors Flag
int z = 0;                               // Close Doors Flag

//Emergency Stop
int emergencyStop = 0;                          // Emergency Stop Interrupt Flag
```

```
//FINITE STATE MACHINE STATES
enum state{cool, heat, off};
volatile state currentState = cool;                 // Automation Begins with Cooling

void setup() {
  //Computer Serial Port
  Serial.begin(9600);
  //LCD Serial Port
  Serial2.begin(9600);
  //Relay Pins
  pinMode(22, OUTPUT);                              // Cooling relay pin
  pinMode(24, OUTPUT);                              // Heating relay pin
  pinMode(26, OUTPUT);                              // Fans relay pin
  digitalWrite(22, HIGH);
  digitalWrite(24, HIGH);
  digitalWrite(26, HIGH);
  //Motor Controller Pins
  //pinMode(23, OUTPUT);
  //pinMode(25, OUTPUT);
  //pinMode(27, OUTPUT);
  //pinMode(29, OUTPUT);
  //pinMode(31, OUTPUT);
  //pinMode(33, OUTPUT);
  //User Interface Pins
  pinMode(2, INPUT);
  pinMode(20, INPUT);
  attachInterrupt(3, stopSystem, FALLING);          //Emergency Stop PushButton on Pin 20
  delay(setupDelay);
}

void loop() {
  //Emergency Stop
  if (emergencyStop == 1){
    digitalWrite(22, HIGH);
    digitalWrite(24, HIGH);
    digitalWrite(26, HIGH);
    Serial2.write("Stopped");
    Serial2.write(13);
    Serial2.write("Reset Test");
  }
  //Setpoint Mode
  if (digitalRead(2) == 0){
    displayTemp2();
```

```
  if (avgTemp < hTemp && avgTemp < hTemp - 2){                    // Below hysteresis
    digitalWrite(22, HIGH);
    digitalWrite(24, LOW);
    memTemp = 0;
  }
  if (avgTemp > hTemp && avgTemp > hTemp + 2){                    // Above hysteresis
    digitalWrite(24, HIGH);
    digitalWrite(22, LOW);
    memTemp = 0;
  }
  if (avgTemp <= hTemp + 0.5 && avgTemp >= hTemp - 0.5){                              // At
desired temperature
    digitalWrite(22, HIGH);
    digitalWrite(24, HIGH);
    digitalWrite(26, HIGH);
    memTemp = 1;
  }
  if (avgTemp < hTemp && avgTemp > hTemp - 2 && memTemp == 2){      // Turns both
systems off
    digitalWrite(22, HIGH);
    digitalWrite(24, HIGH);
  }
  if (avgTemp > hTemp && avgTemp < hTemp + 2 && memTemp == 1){       // Turns both
systems off
    digitalWrite(22, HIGH);
    digitalWrite(24, HIGH);
  }
}
 //Automation Mode
 if (digitalRead(2) == 1){
 startMillis = millis();
 switch (currentState) {
  case cool:
    digitalWrite(24, HIGH);
    displayTemp();
    Serial.println("cooling");
    if (cycleCounter > numCycles) {
      currentState = off;
    }
    if (elapsedTime >= interval) {
      elapsedTime = 0;
      y = 0;
      z = 0;
```

```
   digitalWrite(22, HIGH);
   //delay(400);
   digitalWrite(24, LOW);
   currentState = heat;
   cycleCounter = cycleCounter + 1;
}
if (avgTemp >= cTemp && avgTemp >= roomTemp){
   digitalWrite(22, LOW);
  /*if (y == 0) {
    displayTemp();
    digitalWrite(26, LOW);
    openDoors();
    delay(500);
    stopDoors();
    y = 1;
  }*/
  digitalWrite(26, LOW);
}
if (avgTemp >=cTemp && avgTemp < roomTemp){
  digitalWrite(22, LOW);
  displayTemp();
  /*if (z == 0) {
    digitalWrite(26, HIGH);
    closeDoors();
    delay(500);
    stopDoors();
    z = 1;
  }*/
  digitalWrite(26, HIGH);
}
 if (avgTemp < cTemp){
   digitalWrite(22, HIGH);
   digitalWrite(26, HIGH);
   delay(30000);
}
if (avgTemp < hTemp && avgTemp < cTemp - 3){                // Below hysteresis
  digitalWrite(22, HIGH);
  digitalWrite(24, LOW);
  memTemp = 0;
}
if (avgTemp > cTemp && avgTemp > cTemp + 3){                // Above hysteresis
  digitalWrite(24, HIGH);
  digitalWrite(22, LOW);
```

```
      memTemp = 0;
    }
    if (avgTemp == cTemp){                                          // At desired temperature
      digitalWrite(22, HIGH);
      digitalWrite(24, HIGH);
      digitalWrite(26, HIGH);
      memTemp = 1;
    }
    if (avgTemp < cTemp && avgTemp > cTemp - 3 && memTemp == 1){       // Turns both
systems off
      digitalWrite(22, HIGH);
      digitalWrite(24, HIGH);
    }
    if (avgTemp > cTemp && avgTemp < cTemp + 3 && memTemp == 1){        // Turns both
systems off
      digitalWrite(22, HIGH);
      digitalWrite(24, HIGH);
    }
     //Serial.println(elapsedTime);
     currentMillis = millis();
     elapsedTime += (currentMillis - startMillis);
     Serial.println(elapsedTime);
     break;
   case heat:
    digitalWrite(22, HIGH);
    displayTemp();
    Serial.println("heating");
    if (cycleCounter > numCycles) {
      currentState = off;
    }
    if (elapsedTime >= interval) {
      elapsedTime = 0;
      y = 0;
      z = 0;
      digitalWrite(24, HIGH);
      //delay(400);
      digitalWrite(22, LOW);
      currentState = cool;
      cycleCounter = cycleCounter + 1;
    }
    if (avgTemp <= hTemp && avgTemp <= roomTemp){
      digitalWrite(24, LOW);
      /*if (y == 0) {
```

```
        digitalWrite(26, LOW);
        openDoors();
        delay(1000);
        stopDoors();
        y = 1;
      }*/
      digitalWrite(26, LOW);
    }
    if (avgTemp <= hTemp && avgTemp > roomTemp){
      digitalWrite(24, LOW);
      /*if (z == 0) {
        digitalWrite(26, HIGH);
        closeDoors();
        delay(1000);
        stopDoors();
        z = 1;
      }*/
      digitalWrite(26, HIGH);
    }
     if (avgTemp > hTemp-3){
       digitalWrite(24, HIGH);
       digitalWrite(26, HIGH);
    }
     currentMillis = millis();
     elapsedTime += (currentMillis - startMillis);
     Serial.println(elapsedTime);
     break;
   case off:
    Serial.println("off");
    displayTemp();
    digitalWrite(22, HIGH);
    digitalWrite(24, HIGH);
    digitalWrite(26, HIGH);
     break;
  }
  }
}
void displayTemp(){
  Serial2.write(17);          //turn on LCD backlight
  temp1 = analogRead(tempPin1);
  delay(10);
  temp1 = analogRead(tempPin1);
  //temp1 = temp1 * 0.48828125;
```

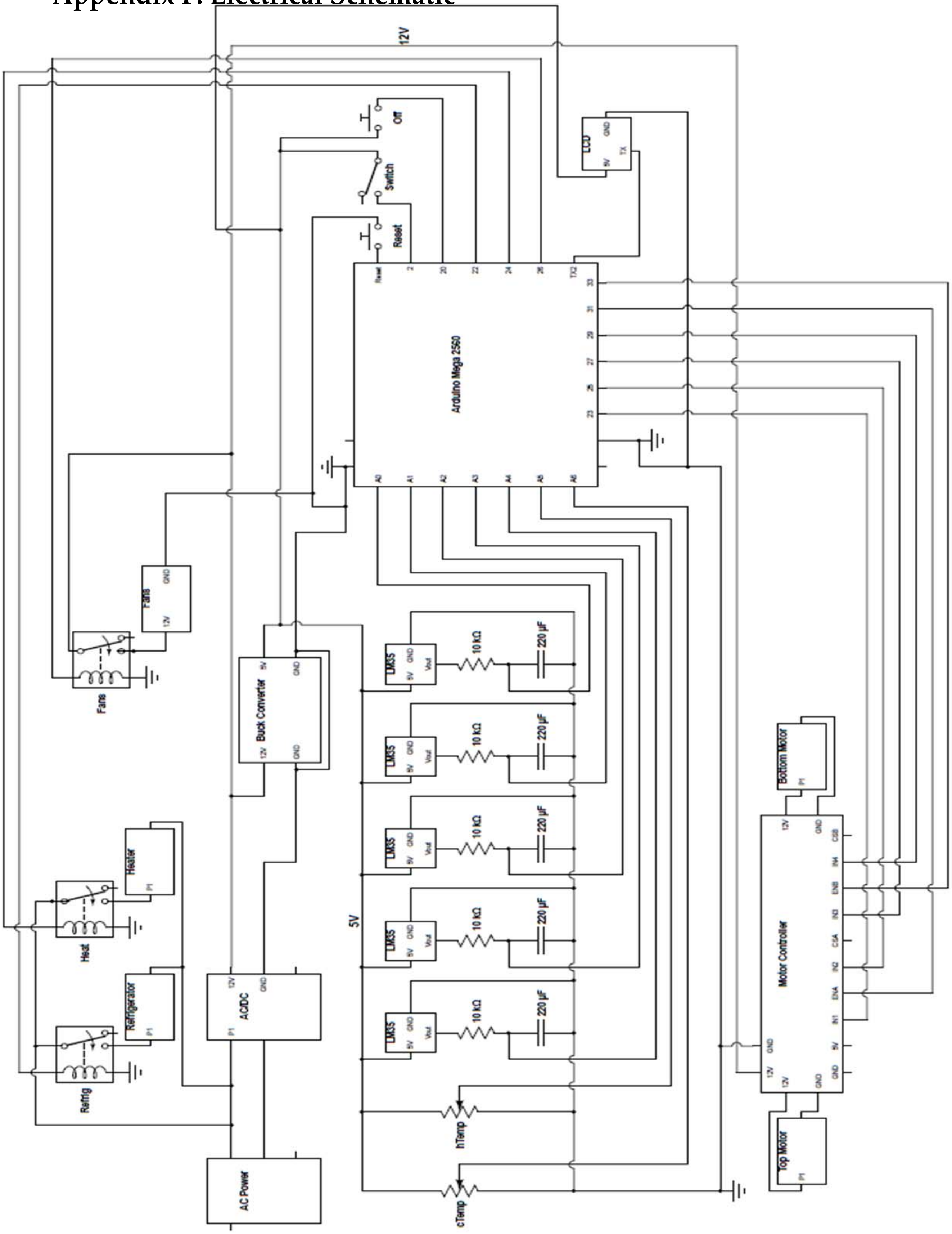
```
delay(10);
temp2 = analogRead(tempPin2);
delay(10);
temp2 = analogRead(tempPin2);
//temp2 = temp2 * 0.48828125;
delay(10);
temp3 = analogRead(tempPin3);
delay(10);
temp3 = analogRead(tempPin3);
//temp3 = temp3 * 0.48828125;
delay(10);
temp4 = analogRead(tempPin4);
delay(10);
temp4 = analogRead(tempPin4);
delay(10);
//temp4 = temp4 * 0.48828125;
temp5 = analogRead(tempPin5);
delay(10);
temp5 = analogRead(tempPin5);
delay(10);
//temp5 = temp5 * 0.48828125;
avgTemp = ((temp1 + temp2 + temp3 + temp4 + temp5)*.48828125)/5;
readcTemp = analogRead(A5);
delay(10);
readcTemp = analogRead(A5);
delay(10);
readhTemp = analogRead(A6);
delay(10);
readhTemp = analogRead(A6);
delay(10);
cTemp = map(readcTemp, 0, 1023, -20, 25);
hTemp = map(readhTemp, 0, 1023, 15, 60);
delay(10);
/*Serial.println(temp1);
Serial.println(temp2);
Serial.println(temp3);
Serial.println(temp4);
Serial.println(temp5); */
Serial2.write(12);          //clear
Serial2.write(22);          //removes curser and blink
Serial2.write("Temp:");
Serial2.print(avgTemp);
Serial2.write("  ");
```

```
 Serial2.print(cycleCounter);
 Serial2.write(13);              //start a new line
 Serial2.write("Low:");
 Serial2.print(cTemp);
 Serial2.print("   ");
 Serial2.write("High:");
 Serial2.print(hTemp);
 Serial.println(avgTemp);
 delay(200);
}

void displayTemp2(){
 Serial2.write(17);           //turn on LCD backlight
 temp1 = analogRead(tempPin1);
 delay(10);
 temp1 = analogRead(tempPin1);
 //temp1 = temp1 * 0.48828125;
 delay(10);
 temp2 = analogRead(tempPin2);
 delay(10);
 temp2 = analogRead(tempPin2);
 //temp2 = temp2 * 0.48828125;
 delay(10);
 temp3 = analogRead(tempPin3);
 delay(10);
 temp3 = analogRead(tempPin3);
 //temp3 = temp3 * 0.48828125;
 delay(10);
 temp4 = analogRead(tempPin4);
 delay(10);
 temp4 = analogRead(tempPin4);
 delay(10);
 //temp4 = temp4 * 0.48828125;
 temp5 = analogRead(tempPin5);
 delay(10);
 temp5 = analogRead(tempPin5);
 delay(10);
 //temp5 = temp5 * 0.48828125;
 avgTemp = ((temp1 + temp2 + temp3 + temp4 + temp5)*.48828125)/5;
 readcTemp = analogRead(A5);
 delay(10);
 readcTemp = analogRead(A5);
 delay(10);
```

```
  readhTemp = analogRead(A6);
  delay(10);
  readhTemp = analogRead(A6);
  delay(10);
  cTemp = map(readcTemp, 0, 1023, -20, 20);
  hTemp = map(readhTemp, 0, 1023, -20, 90);
  delay(10);
  /*Serial.println(temp1);
  Serial.println(temp2);
  Serial.println(temp3);
  Serial.println(temp4);
  Serial.println(temp5); */
  Serial2.write(12);              //clear
  Serial2.write(22);               //removes curser and blink
  Serial2.write("Temp:");
  Serial2.print(avgTemp);
  Serial2.write("  ");
  Serial2.print(cycleCounter);
  Serial2.write(13);              //start a new line
  //Serial2.write("Low:");
  //Serial2.print(cTemp);
  //Serial2.print("   ");
  Serial2.write("SetTemp:");
  Serial2.print(hTemp);
  Serial.print(avgTemp);
  delay(200);
}

//Emergency Stop
void stopSystem()
{
  digitalWrite(22, HIGH);
  digitalWrite(24, HIGH);
  digitalWrite(26, HIGH);
  emergencyStop = 1;
}
//Close Doors
void closeDoors()
 {
   digitalWrite(ena, LOW);
   digitalWrite(enb, LOW);
   digitalWrite(in1, HIGH);
   digitalWrite(in3, HIGH);
```

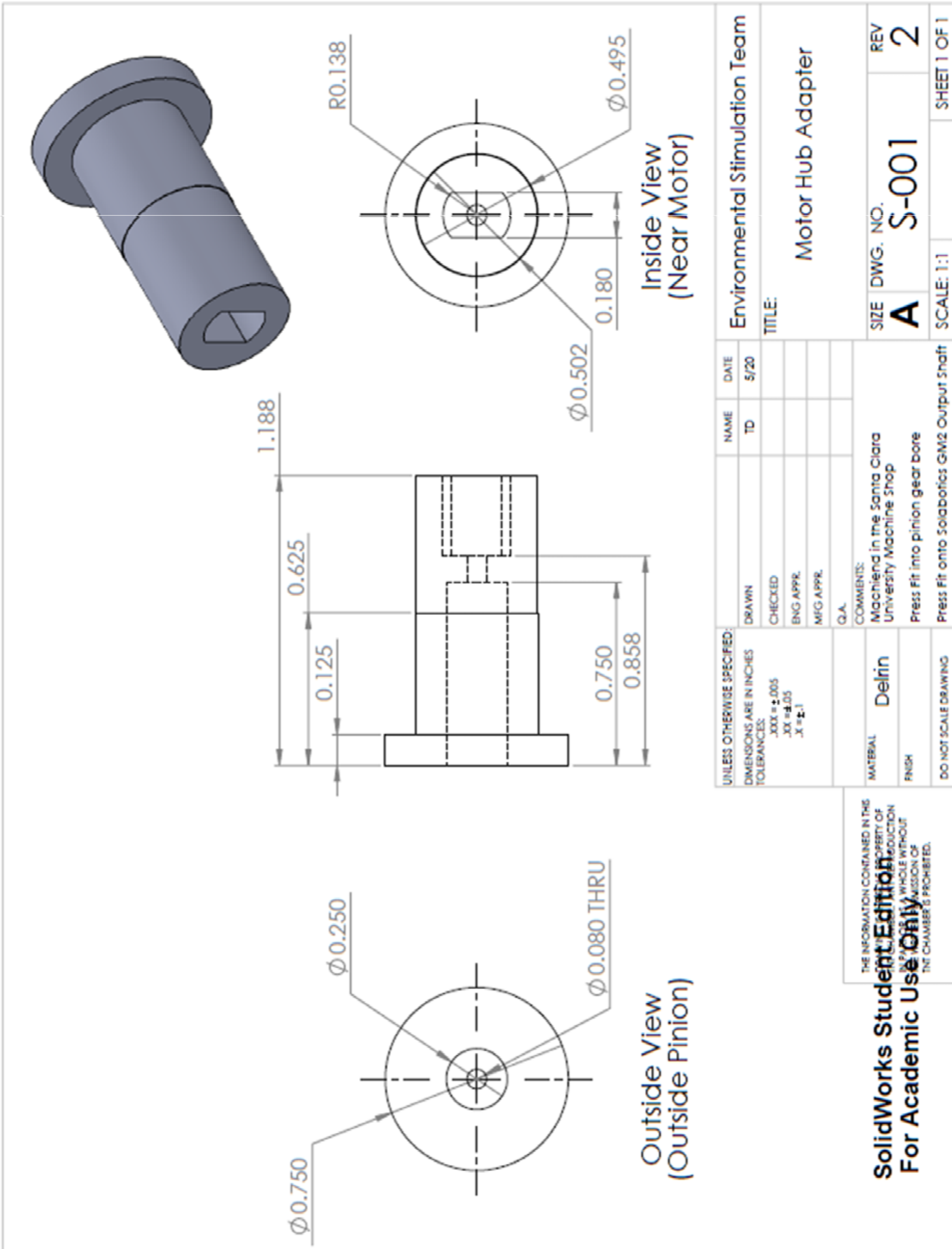
```
  digitalWrite(in2, LOW);
  digitalWrite(in4, LOW);
  digitalWrite(ena, HIGH);
  digitalWrite(enb, HIGH);
 }

 //Open Doors
void openDoors()
 {
 digitalWrite(ena, LOW);
 digitalWrite(enb, LOW);
 digitalWrite(in1, LOW);
 digitalWrite(in3, LOW);
 digitalWrite(in2, HIGH);
 digitalWrite(in4, HIGH);
 digitalWrite(ena, HIGH);
 digitalWrite(enb, HIGH);
 }

//Stop Doors
void stopDoors()
 {
 digitalWrite(ena, LOW);
 digitalWrite(enb, LOW);
 digitalWrite(in1, HIGH);
 digitalWrite(in3, HIGH);
 digitalWrite(in2, HIGH);
 digitalWrite(in4, HIGH);
 digitalWrite(ena, HIGH);
 digitalWrite(enb, HIGH);
 }
```

Appendix F: Electrical Schematic



Appendix G: Detailed Part and Assembly Drawings

Contents


Outside View
(Outside Pinion)
Ø0.750
Ø0.250
Ø0.080 THRU
1.188
0.625
0.125
0.750
0.858
Inside View
(Near Motor)
R0.138
Ø0.495
Ø0.502
0.180
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
.XXX = ±.005
.XX = ±.05
.X = ±.1
MATERIAL
Delrin
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
TD
5/20
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Machiend in the Santa Clara University Machine Shop
Press Fit into pinion gear bore
Press Fit onto Solabotics GM2 Output Shaft
Environmental Stimulation Team
TITLE:
Motor Hub Adapter
SIZE
A
DWG. NO.
S-001
REV
2
SCALE: 1:1
SHEET 1 OF 1
SolidWorks Student Edition.
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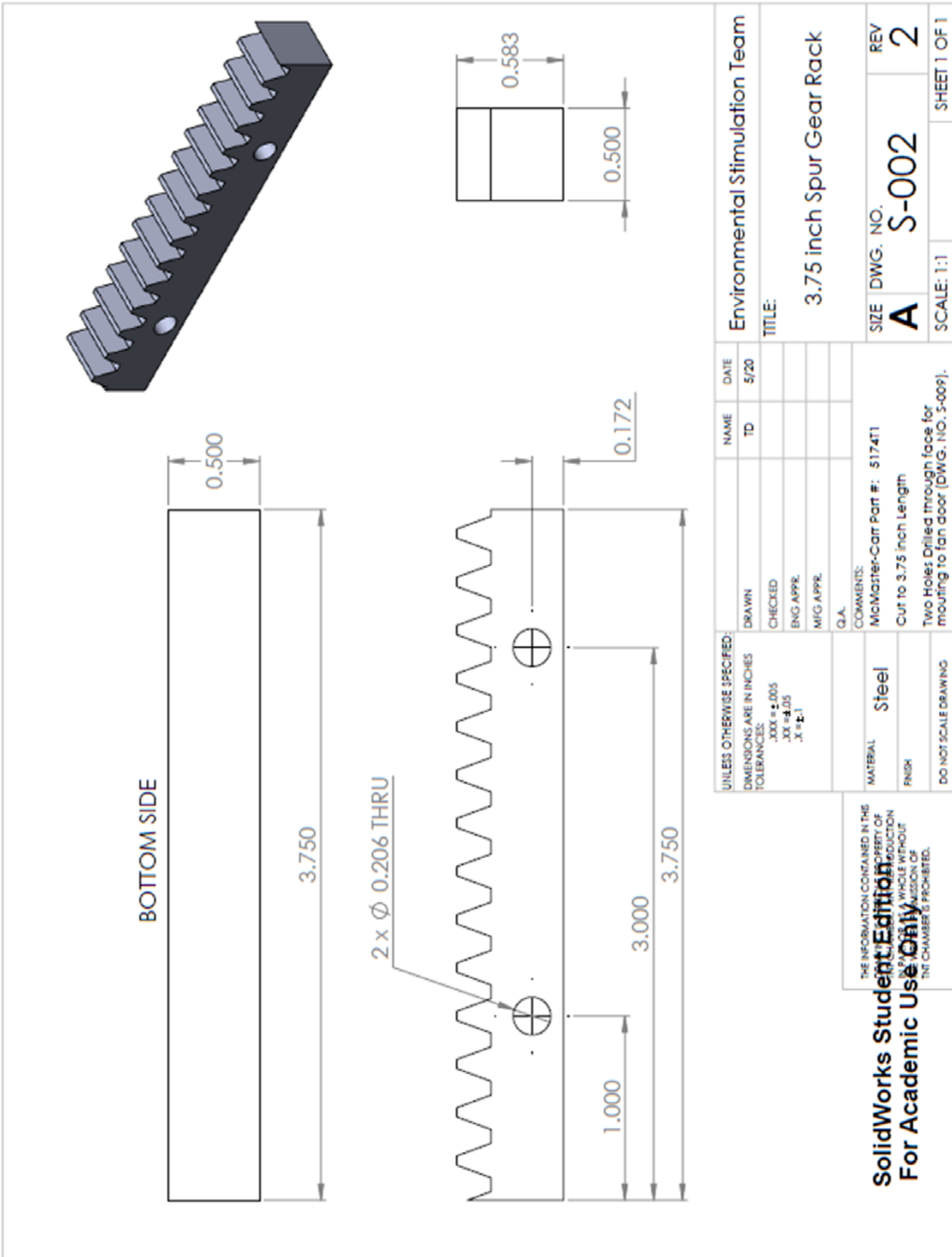
BOTTOM SIDE
0.500
3.750
2 x Ø 0.206 THRU
3.000
1.000
3.750
0.172
0.583
0.500
Environmental Stimulation Team
TITLE:
3.75 inch Spur Gear Rack
SIZE
A
DWG. NO.
S-002
REV
2
SCALE: 1:1
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
NAME
DATE
DRAWN
TD
5/20
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
McMaster-Carr Part #: 5174T1
Cut to 3.75 inch Length
Two Holes Drilled through face for mouting to fan door (DWG. NO. S-009).
MATERIAL
Steel
FINISH
DO NOT SCALE DRAWING
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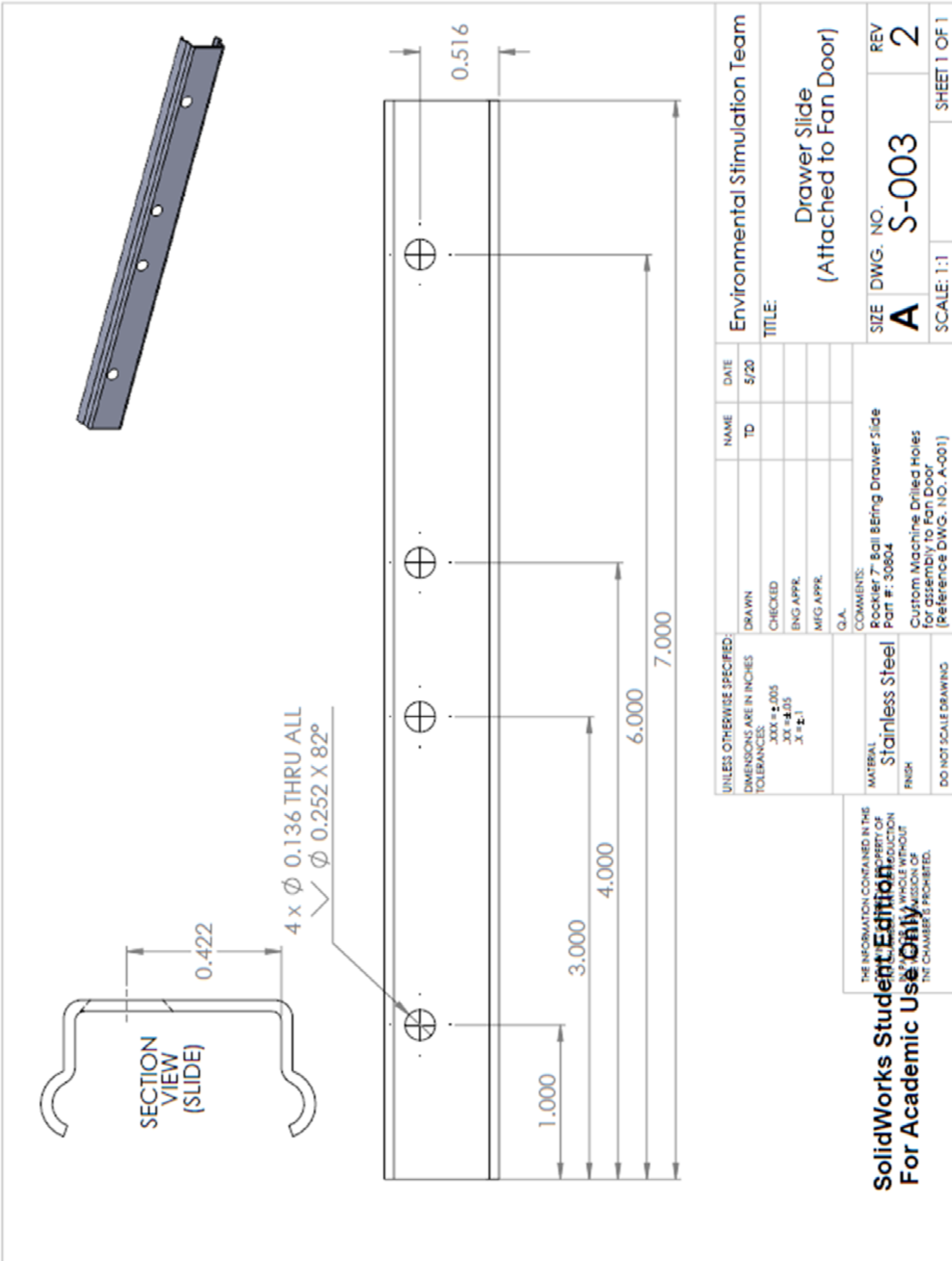
SECTION VIEW (SLIDE)
0.422
0.516
4 x Ø 0.136 THRU ALL
Ø 0.252 X 82°
1.000
3.000
4.000
6.000
7.000
Environmental Stimulation Team
TITLE:
Drawer Slide (Attached to Fan Door)
SIZE A
DWG. NO. S-003
REV 2
SCALE: 1:1
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
.XXX = ±.005
.XX = ±.05
.X = ±.1
NAME
DATE
DRAWN
TD
5/20
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Rockler 7" Ball BEring Drawer Slide Part #: 30804
Custom Machine Drilled Holes for assembly to Fan Door (Reference DWG. NO. A-001)
MATERIAL
Stainless Steel
FINISH
DO NOT SCALE DRAWING
SolidWorks Student Edition.
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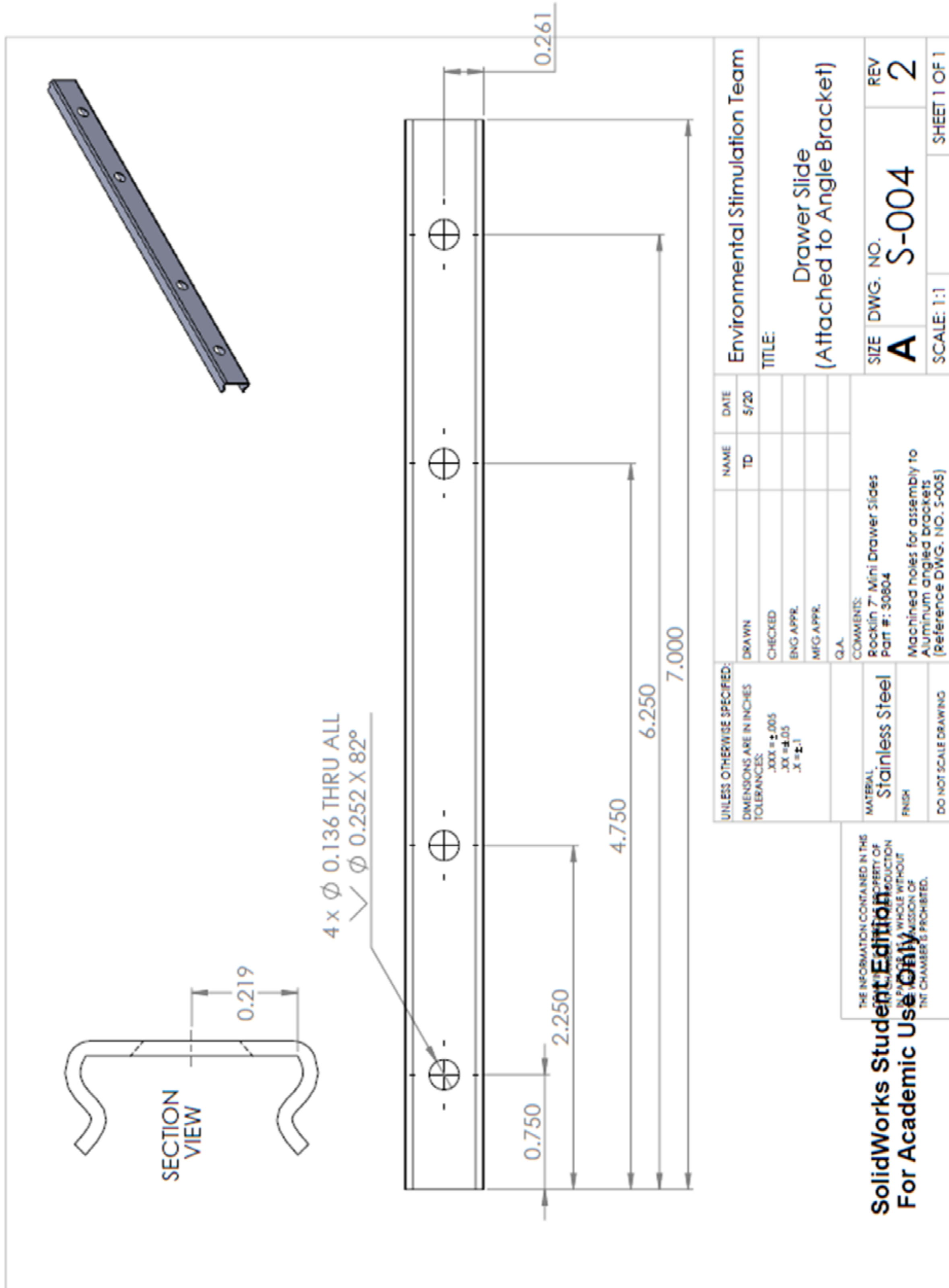
1
2
3
4
5


SECTION VIEW
0.219
4 x Ø 0.136 THRU ALL
⌵ Ø 0.252 X 82°
0.261
0.750
2.250
4.750
6.250
7.000
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
.XXX = ±.005
.XX = ±.05
.X = ±.1
MATERIAL
Stainless Steel
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
TD
5/20
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Rocklin 7" Mini Drawer Slides
Part #: 30804
Machined holes for assembly to Aluminum angled brackets (Reference DWG. NO. S-005)
Environmental Stimulation Team
TITLE:
Drawer Slide
(Attached to Angle Bracket)
SIZE
A
DWG. NO.
S-004
REV
2
SCALE: 1:1
SHEET 1 OF 1
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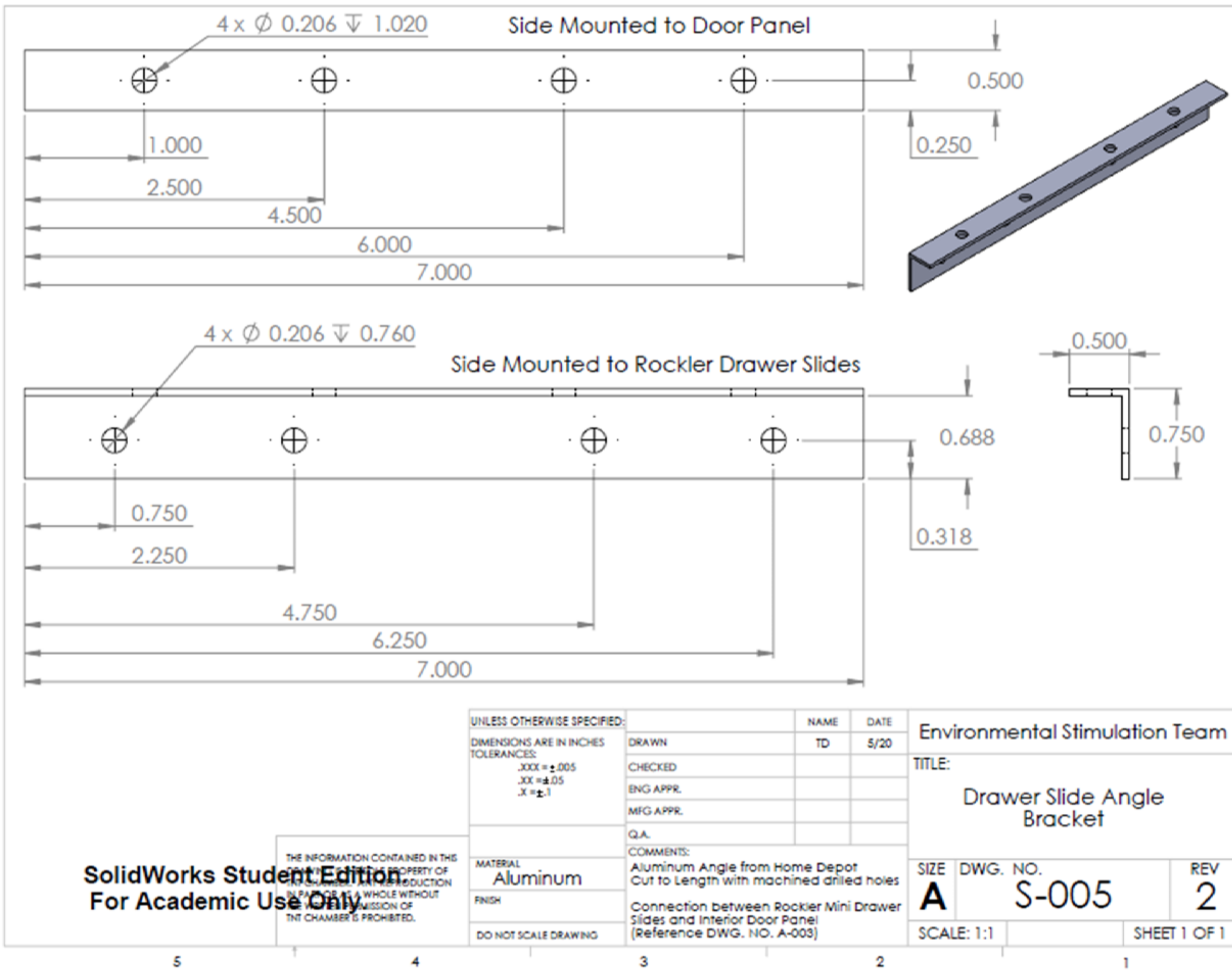

Side Mounted to Door Panel
4 x Ø 0.206 ↧ 1.020
1.000
2.500
4.500
6.000
7.000
0.500
0.250
Side Mounted to Rockler Drawer Slides
4 x Ø 0.206 ↧ 0.760
0.750
2.250
4.750
6.250
7.000
0.688
0.318
0.500
0.750
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
.XXX = ±.005
.XX = ±.05
.X = ±.1
NAME
DATE
DRAWN
TD
5/20
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Aluminum Angle from Home Depot
Cut to Length with machined drilled holes
Connection between Rockler Mini Drawer Slides and Interior Door Panel (Reference DWG. NO. A-003)
MATERIAL
Aluminum
FINISH
DO NOT SCALE DRAWING
Environmental Stimulation Team
TITLE:
Drawer Slide Angle Bracket
SIZE
A
DWG. NO.
S-005
REV
2
SCALE: 1:1
SHEET 1 OF 1
SolidWorks Student Edition.
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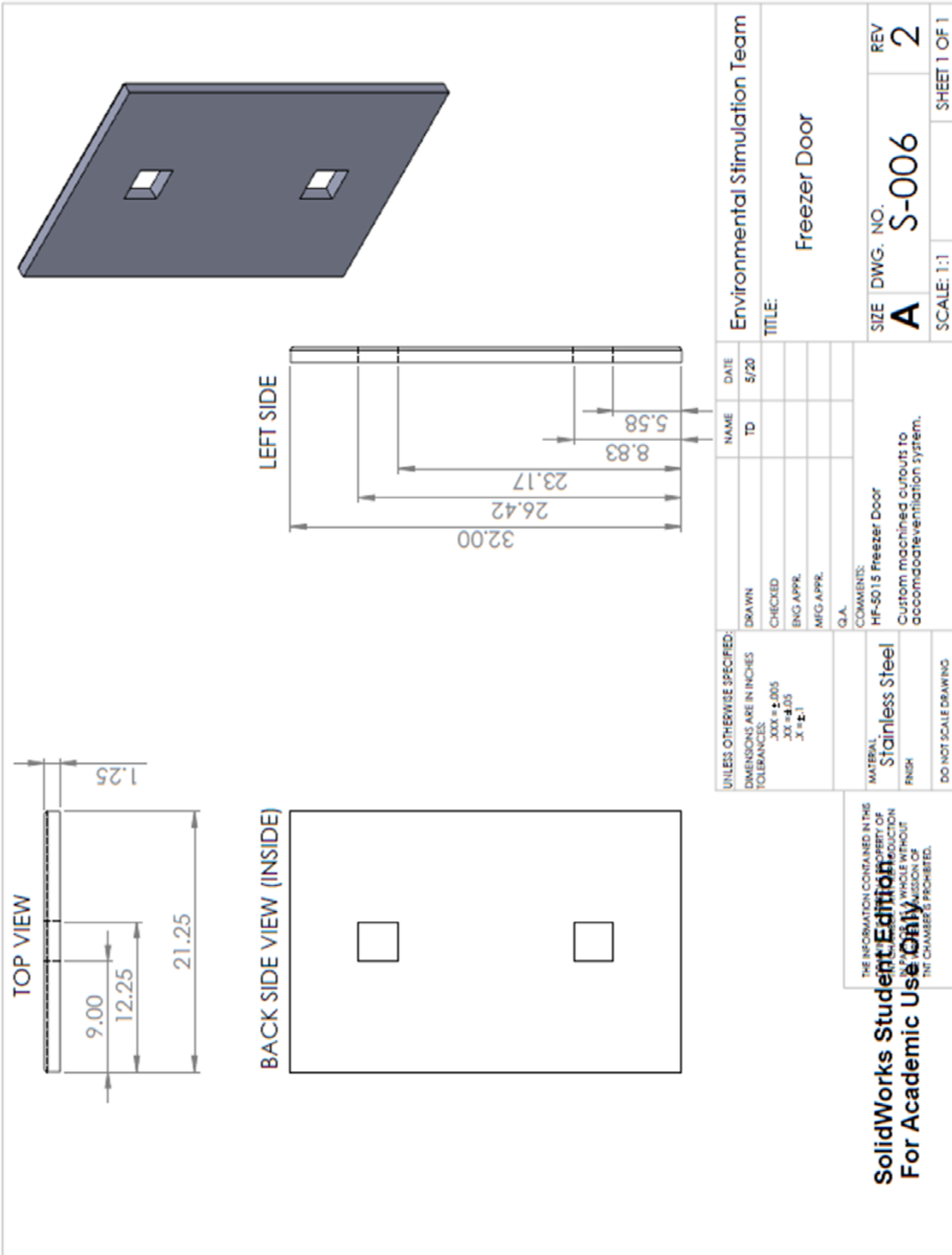
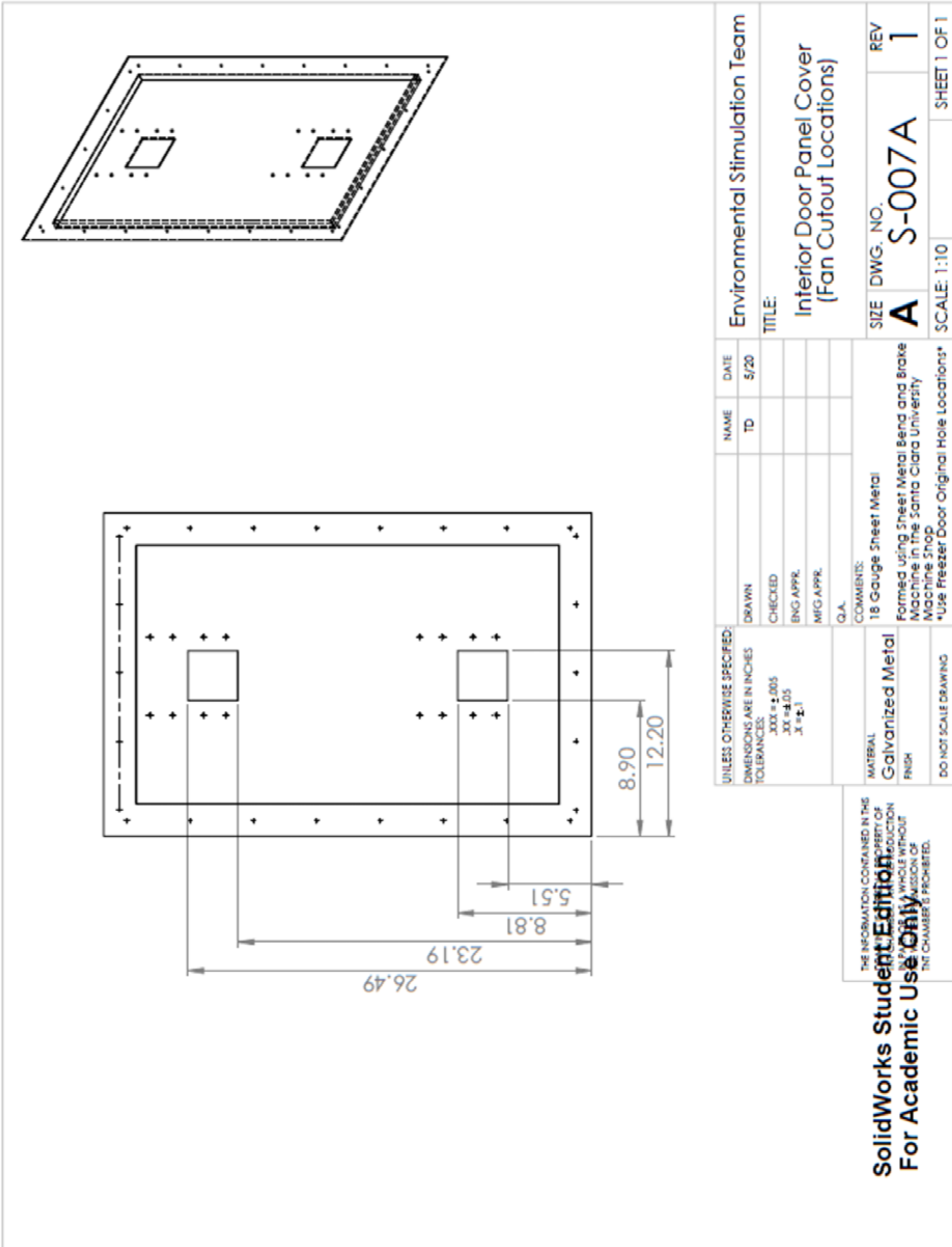
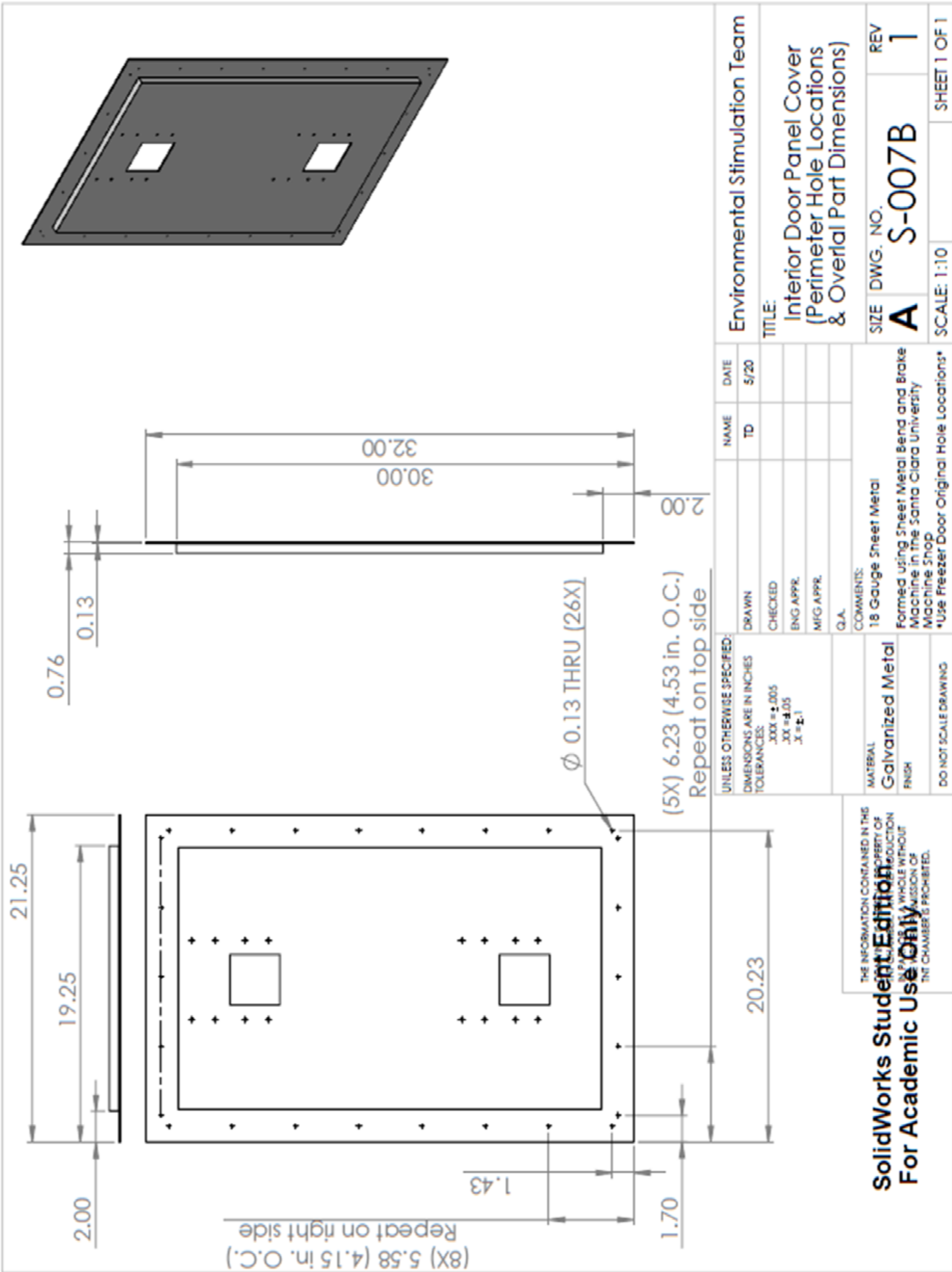
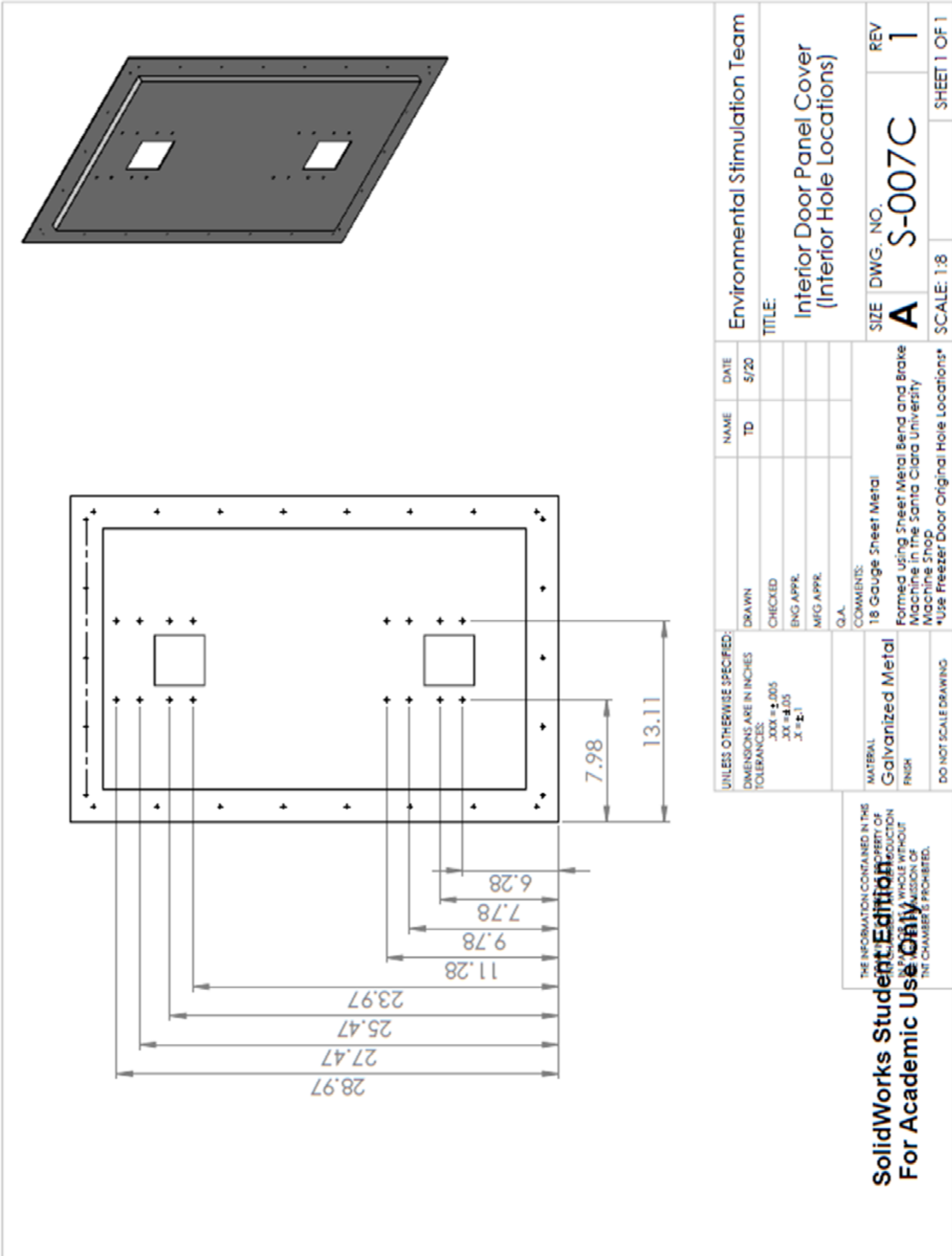
5
4
3
2
1


TOP VIEW
BACK SIDE VIEW (INSIDE)
LEFT SIDE
1.25
9.00
12.25
21.25
32.00
26.42
23.17
8.83
5.58
Environmental Stimulation Team
TITLE:
Freezer Door
SIZE A
DWG. NO. S-006
REV 2
SCALE: 1:1
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
MATERIAL
Stainless Steel
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
TD
5/20
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
HF-5015 Freezer Door
Custom machined cutouts to accomodoate ventilation system.
SolidWorks Student Edition.
For Academic Use Only.

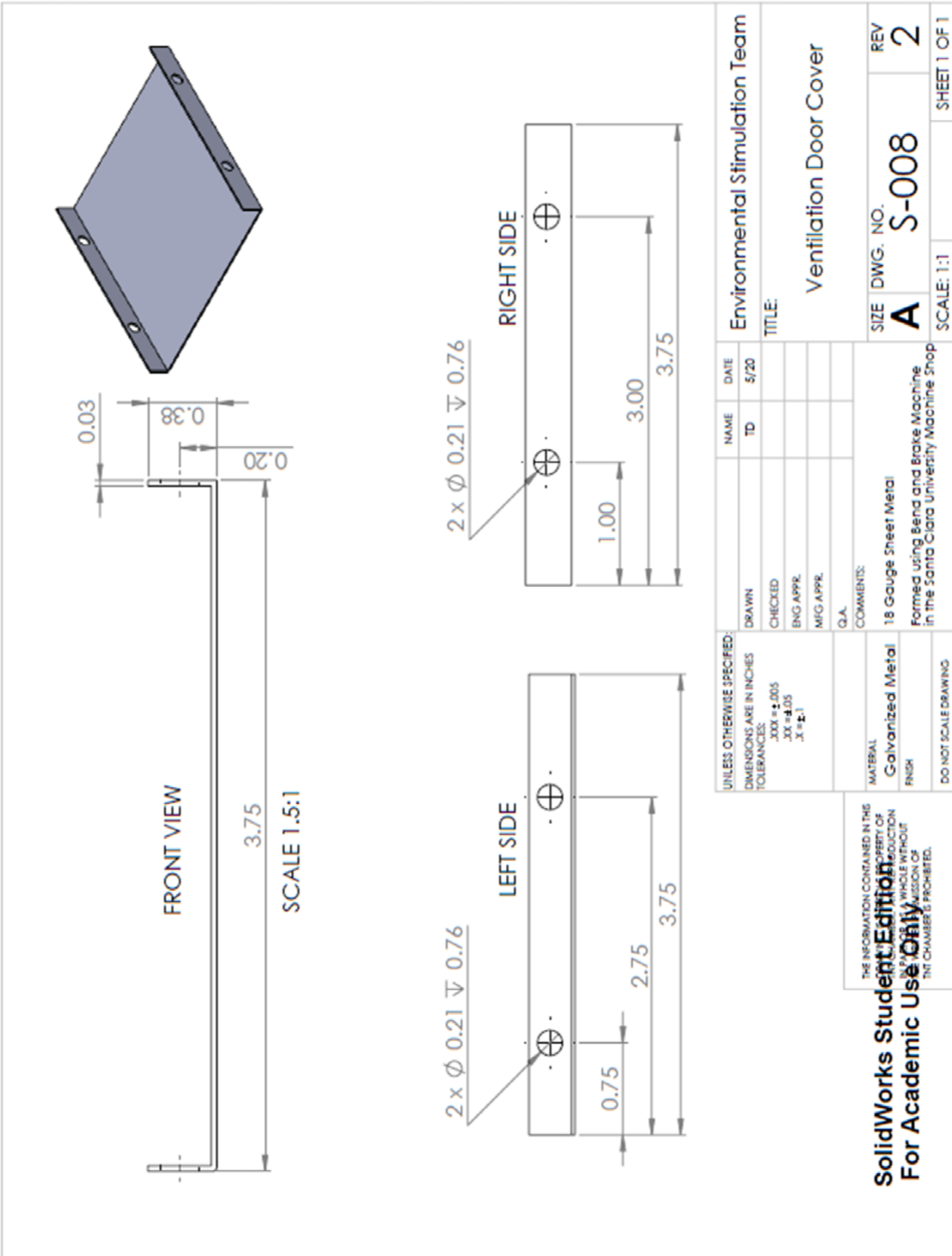

Environmental Stimulation Team
TITLE:
Interior Door Panel Cover (Fan Cutout Locations)
SIZE A
DWG. NO. S-007A
REV 1
SCALE: 1:10
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
NAME
DATE
DRAWN
TD
5/20
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
18 Gauge Sheet Metal
Formed using Sheet Metal Bend and Brake Machine in the Santa Clara University Machine Shop
Use Freezer Door Original Hole Locations
MATERIAL
Galvanized Metal
FINISH
DO NOT SCALE DRAWING
SolidWorks Student Edition.
For Academic Use Only.
8.90
12.20
5.51
8.81
23.19
26.49



Environmental Stimulation Team
TITLE:
Interior Door Panel Cover
(Perimeter Hole Locations
& Overlal Part Dimensions)
SIZE
A
DWG. NO.
S-007B
REV
1
SCALE: 1:10
SHEET 1 OF 1
NAME
DATE
DRAWN
TD
5/20
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
18 Gauge Sheet Metal
Formed using Sheet Metal Bend and Brake Machine in the Santa Clara University Machine Shop
Use Freezer Door Original Hole Locations
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
.XXX = ±.005
.XX = ±.05
.X = ±.1
MATERIAL
Galvanized Metal
FINISH
DO NOT SCALE DRAWING
SolidWorks Student Edition.
For Academic Use Only.
32.00
30.00
2.00
0.76
0.13
⌀ 0.13 THRU (26X)
(5X) 6.23 (4.53 in. O.C.)
Repeat on top side
21.25
19.25
20.23
2.00
1.43
1.70
(8X) 5.58 (4.15 in. O.C.)
Repeat on right side



Environmental Stimulation Team
TITLE:
Interior Door Panel Cover
(Interior Hole Locations)
SIZE A
DWG. NO. S-007C
REV 1
SCALE: 1:8
SHEET 1 OF 1
NAME DATE
DRAWN TD 5/20
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
18 Gauge Sheet Metal
Formed using Sheet Metal Bend and Brake Machine in the Santa Clara University Machine Shop
Use Freezer Door Original Hole Locations
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
.XXX = ±.005
.XX = ±.05
.X = ±.1
MATERIAL
Galvanized Metal
FINISH
DO NOT SCALE DRAWING
SolidWorks Student Edition.
For Academic Use Only.
7.98
13.11
6.28
7.78
9.78
11.28
23.97
25.47
27.47
28.97


FRONT VIEW
SCALE 1.5:1
3.75
0.03
0.38
0.20
LEFT SIDE
2 x Ø 0.21 ↧ 0.76
0.75
2.75
3.75
RIGHT SIDE
2 x Ø 0.21 ↧ 0.76
1.00
3.00
3.75
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
.XXX = ±.005
.XX = ±.05
.X = ±.1
MATERIAL
Galvanized Metal
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
TD
5/20
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
18 Gauge Sheet Metal
Formed using Bend and Brake Machine in the Santa Clara University Machine Shop
Environmental Stimulation Team
TITLE:
Ventilation Door Cover
SIZE
A
DWG. NO.
S-008
REV
2
SCALE: 1:1
SHEET 1 OF 1
SolidWorks Student Edition.
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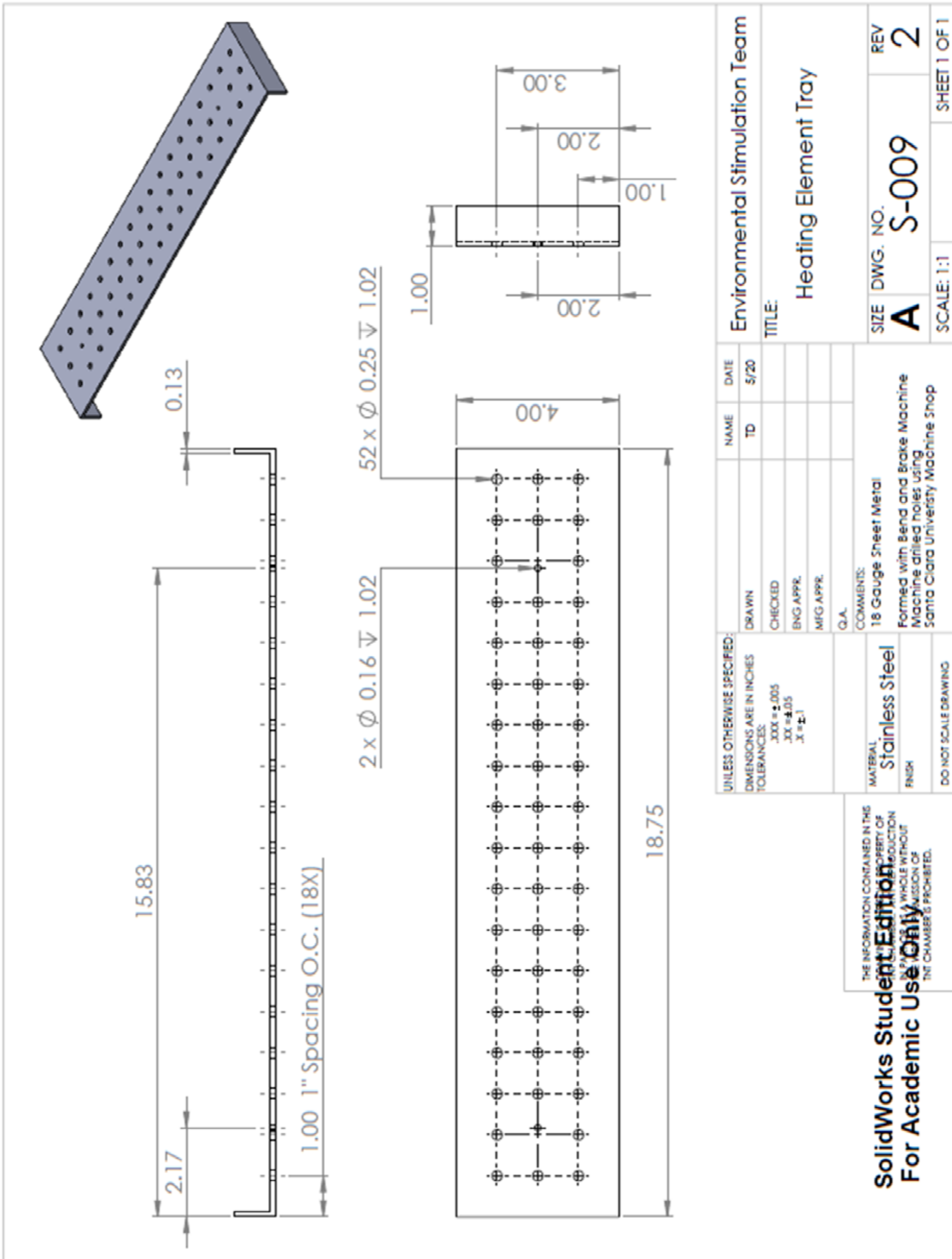
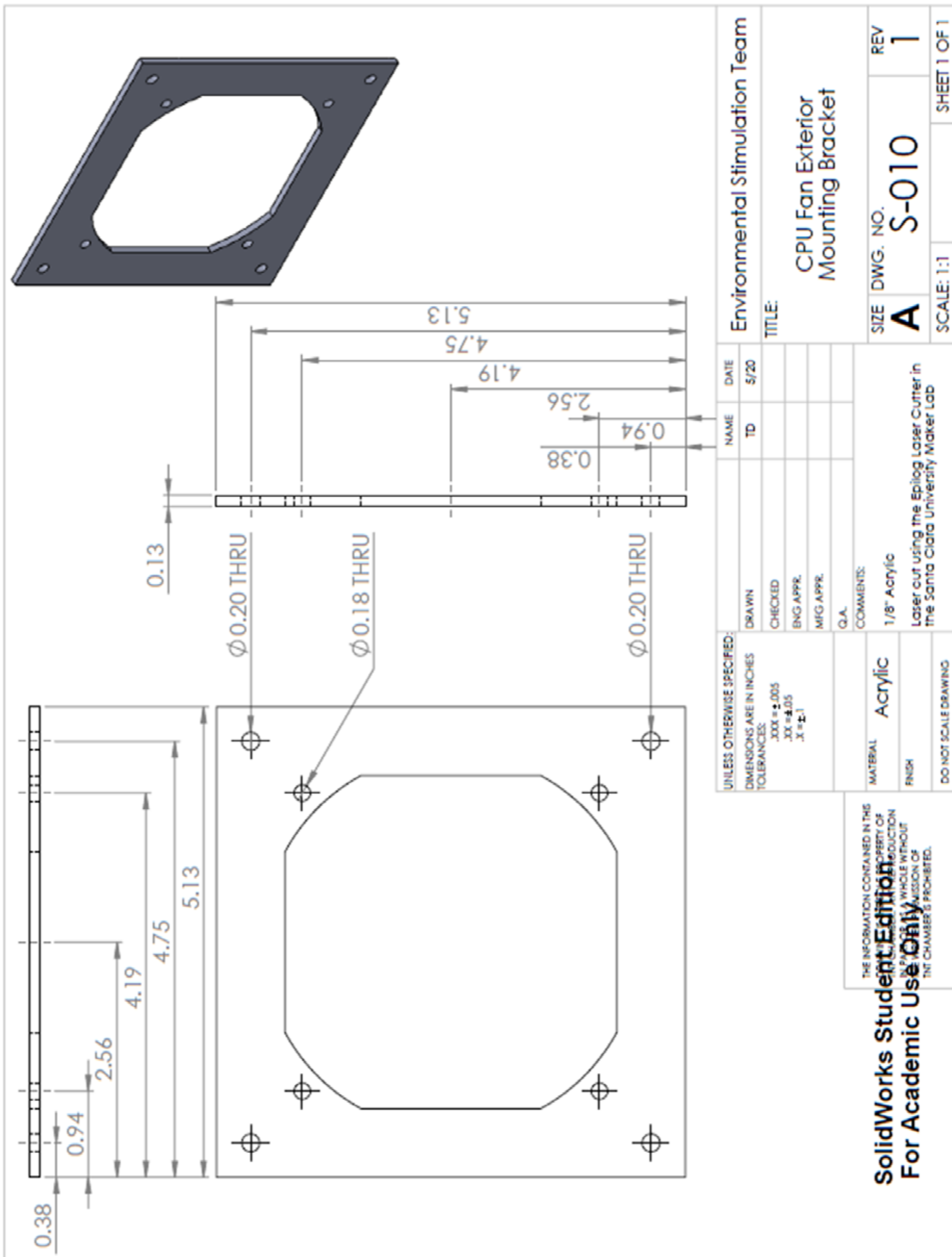
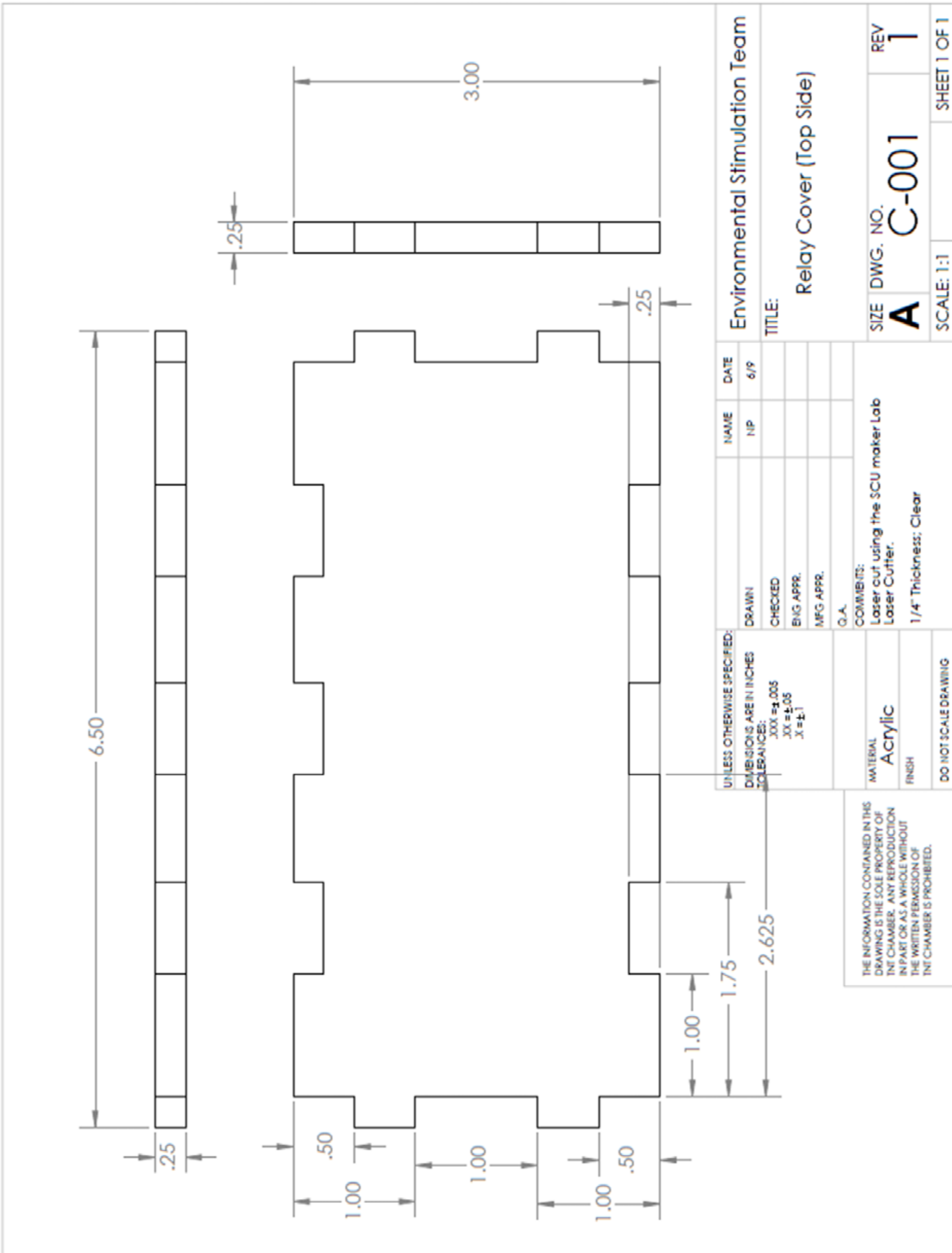
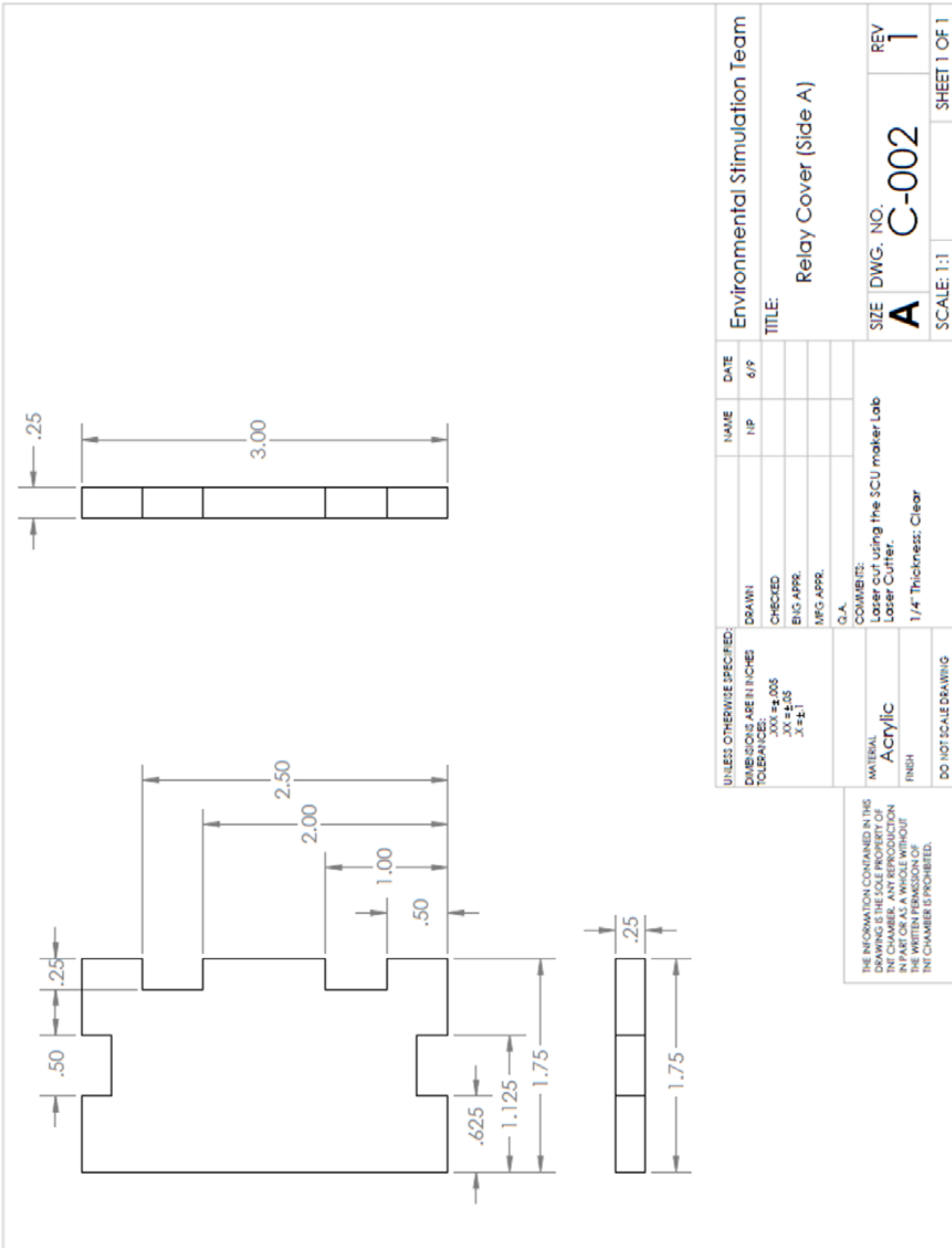

Environmental Stimulation Team
TITLE:
Heating Element Tray
SIZE A
DWG. NO. S-009
REV 2
SCALE: 1:1
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
.XXX = ±.005
.XX = ±.05
.X = ±.1
MATERIAL
Stainless Steel
FINISH
DO NOT SCALE DRAWING
NAME DATE
DRAWN TD 5/20
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
18 Gauge Sheet Metal
Formed with Bend and Brake Machine
Machine drilled holes using
Santa Clara University Machine Shop
SolidWorks Student Edition.
For Academic Use Only.
15.83
2.17
0.13
1.00
1" Spacing O.C. (18X)
52 x Ø 0.25 ↧ 1.02
2 x Ø 0.16 ↧ 1.02
4.00
18.75
1.00
3.00
2.00
1.00
2.00

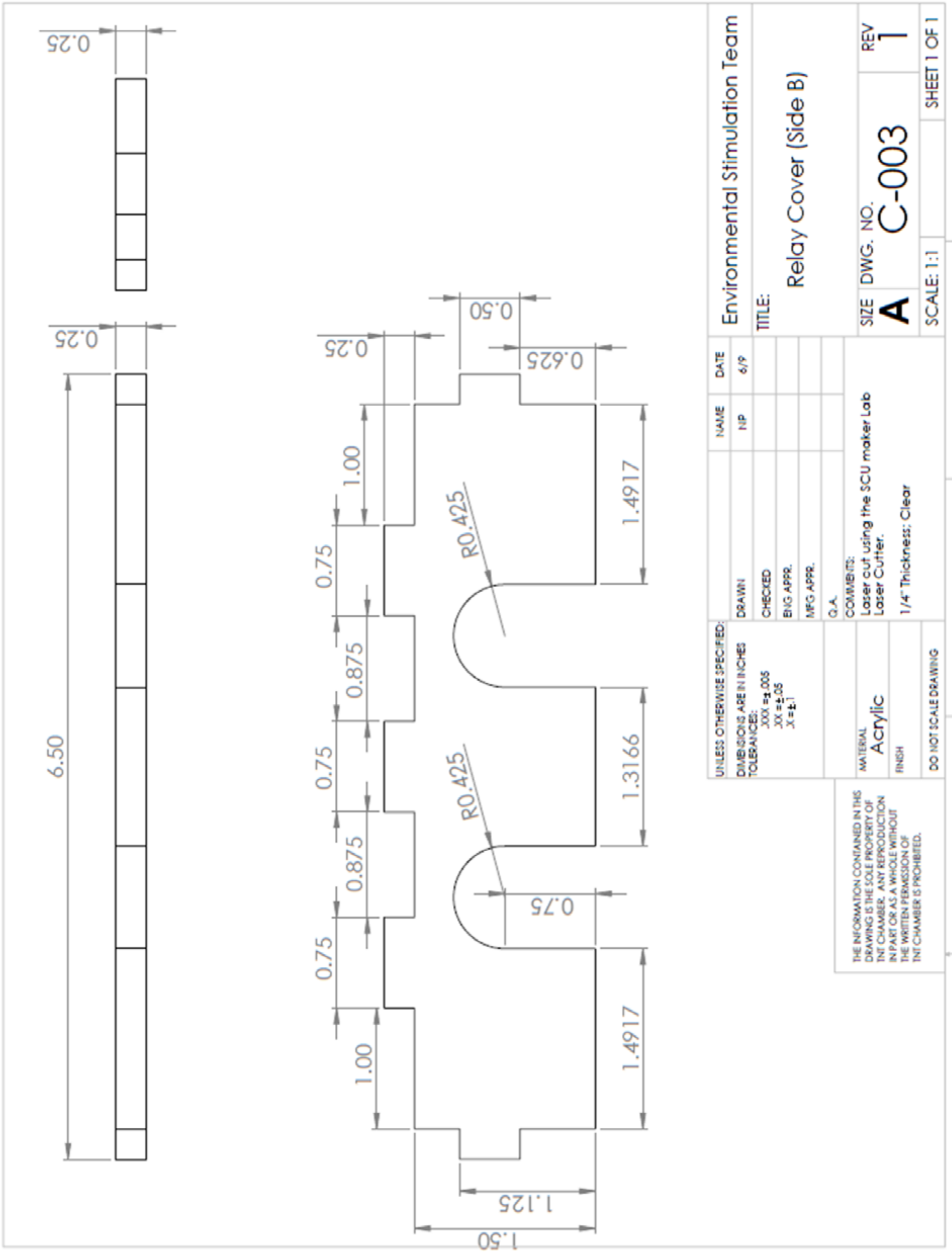

Environmental Stimulation Team
TITLE:
CPU Fan Exterior Mounting Bracket
SIZE A
DWG. NO. S-010
REV 1
SCALE: 1:1
SHEET 1 OF 1
NAME
DATE
DRAWN TD 5/20
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
1/8" Acrylic
Laser cut using the Epilog Laser Cutter in the Santa Clara University Maker Lab
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
.XXX = ±.005
.XX = ±.05
.X = ±.1
MATERIAL Acrylic
FINISH
DO NOT SCALE DRAWING
SolidWorks Student Edition.
For Academic Use Only.
Ø0.20 THRU
Ø0.18 THRU
Ø0.20 THRU
0.13
0.38
0.94
2.56
4.19
4.75
5.13



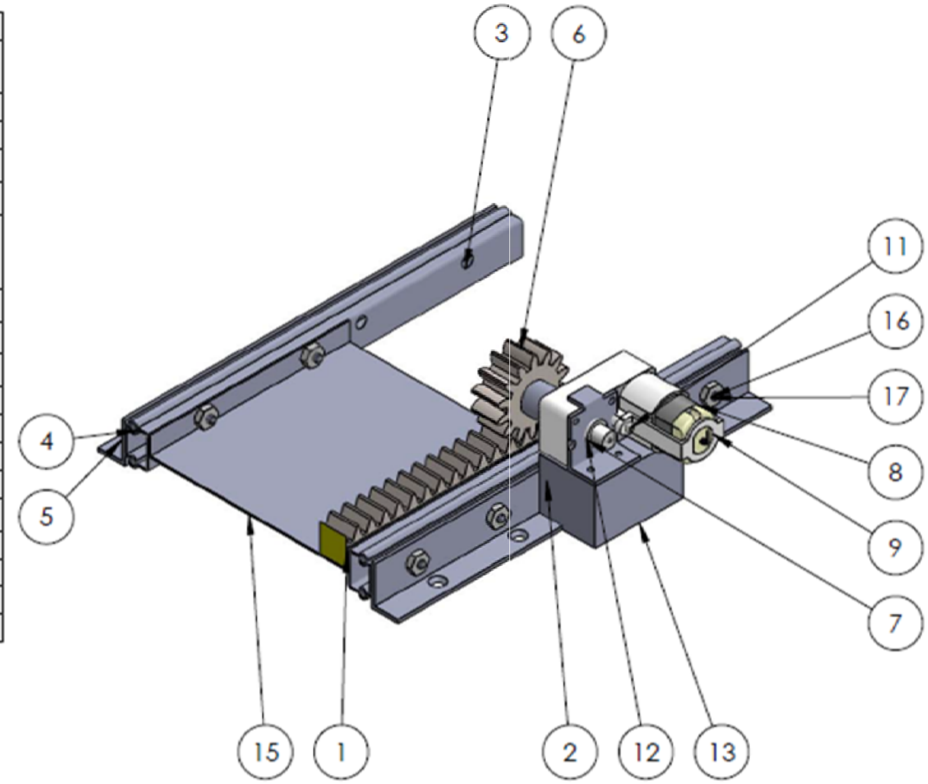
Environmental Stimulation Team
TITLE:
Relay Cover (Top Side)
SIZE A
DWG. NO. C-001
REV 1
SCALE: 1:1
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
.XXX = ±.005
.XX = ±.05
.X = ±.1
NAME
DATE
DRAWN NP 6/9
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Laser cut using the SCU maker Lab Laser Cutter.
1/4" Thickness; Clear
MATERIAL
Acrylic
FINISH
DO NOT SCALE DRAWING
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF TNT CHAMBER. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF TNT CHAMBER IS PROHIBITED.
3.00
.25
6.50
2.625
1.75
1.00
.50



Environmental Stimulation Team
TITLE:
Relay Cover (Side A)
SIZE
A
DWG. NO.
C-002
REV
1
SCALE: 1:1
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
NAME
DATE
DRAWN
NP
6/9
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Laser cut using the SCU maker Lab Laser Cutter.
1/4" Thickness; Clear
MATERIAL
Acrylic
FINISH
DO NOT SCALE DRAWING
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF TNT CHAMBER. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF TNT CHAMBER IS PROHIBITED.
.25
3.00
2.50
2.00
1.00
.50
.25
.50
.625
1.125
1.75
.25
1.75


Environmental Stimulation Team
TITLE:
Relay Cover (Side B)
SIZE A
DWG. NO. C-003
REV 1
SCALE: 1:1
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
.XXX =±.005
.XX =±.05
.X =±.1
MATERIAL
Acrylic
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
NP
6/9
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Laser cut using the SCU maker Lab Laser Cutter.
1/4" Thickness; Clear
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF TNT CHAMBER. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF TNT CHAMBER IS PROHIBITED.
0.25
6.50
0.25
0.50
0.625
0.25
1.00
0.75
0.875
0.75
0.875
0.75
1.00
R0.425
R0.425
1.4917
1.3166
1.4917
0.75
1.125
1.50
1
2
3
4
5

ITEM NO.	PART NUMBER	QTY.
1	Inch - Rack-spur - rectangular 12DP 20PA 0.5FW .5PH 4.5L---SAll	1
2	Drawer Slide Cabinet Side	2
3	Drawer Slide Drawer Side	2
4	Drawer Slide Ball Bearing	4
5	Drawer Mounting Angle Bracket	2
6	Inch - Spur gear 12DP 14T 20PA 0.5FW --- S14N3.0H2.0L0.03125N	1
7	gm2	1
8	RM3-regular motor	1
9	GMstrap1	1
10	screw_head1	2
11	screw_head2	2
12	GM2 Bracket	1
13	Motor mount Block	1
14	Hub Assembly	1
15	CPU fan	1
16	91771A124	10
17	90480A006	12
18	91771A129	2



UNLESS OTHERWISE SPECIFIED:		NAME	DATE
	DRAWN	TD	03/19
	CHECKED		
	ENG APPR.		
	MFG APPR.		
	Q.A.		
MATERIAL	COMMENTS:		
FINISH			
DO NOT SCALE DRAWING			

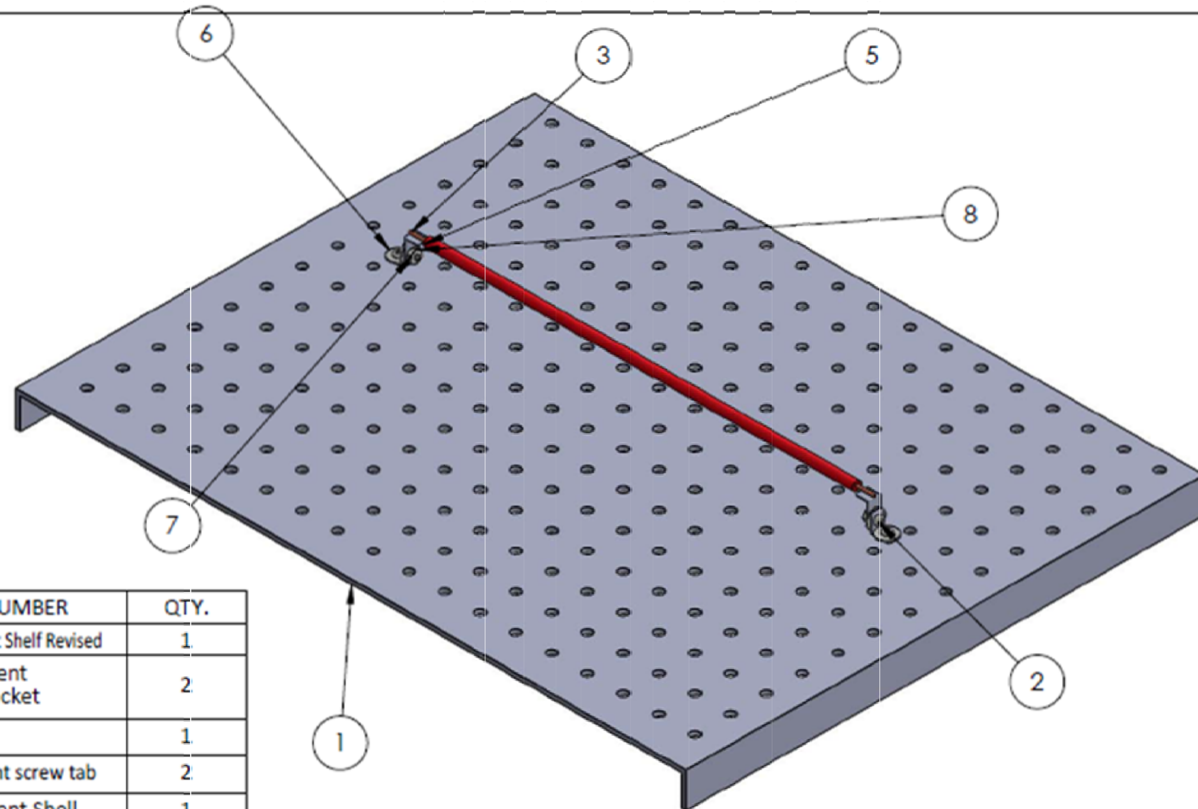
TNT Chamber

TITLE:

Motor and Fan Assembly

SIZE	DWG. NO.	REV
A	A-001	1
SCALE 1: 3		SHEET 1 OF 1

5 4 3 2 1



ITEM NO.	PART NUMBER	QTY.
1	Bottom Desiccant Shelf Revised	1
2	Heating Element Mounting Bracket	2
3	Copper Wire	1
4	Heating Element screw tab	2
5	Heating Element Shell	1
6	94610A225	4
7	91772A125	4
8	90480A006	4

UNLESS OTHERWISE SPECIFIED:

	NAME	DATE
DRAWN	TD	03/19
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

MATERIAL

FINISH

DO NOT SCALE DRAWING

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TNT Chamber

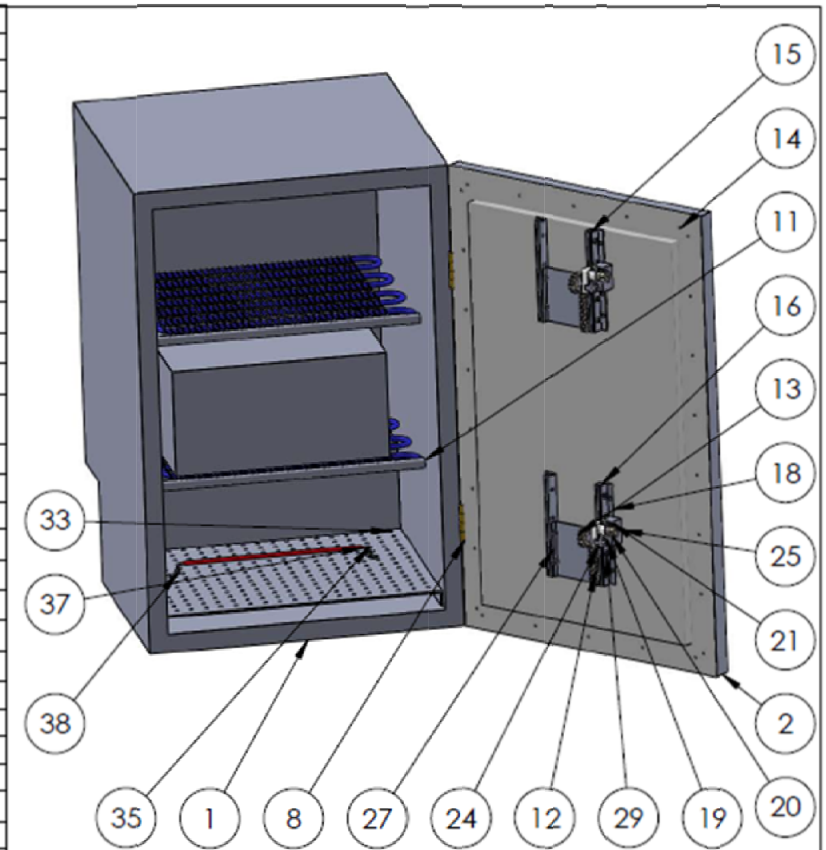
TITLE: Heating Element Assembly

SIZE A | DWG. NO. A-002 | REV 1

SCALE: 1:10 | WEIGHT: | SHEET 1 OF 1

5 4 3 2 1

ITEM NO.	PART NUMBER	QTY.
1	Freezer Unit no cutouts	1
2	Fridge Door	1
3	Max Satellite Size Block	1
4	Piping shelve	3
5	Piping connector 985 radius	2
6	0.75 radius piping corner	2
7	straight 20 in pipe	1
8	Door Hinge	4
9	Hinge_01_Pin	2
10	Fridge shelf grate	6
11	Shelf Front protector	3
12	Inch - Rack-spur - rectangular 12DP 20PA 0.5FW .5PH 4.5L---SAll	2
13	Inch - Spur gear 12DP 14T 20PA 0.5FW --- S14N3.0H2.0L0.03125N	2
14	10 Gauge Standard Steel Inside Door Panel	1
15	Drawer Slide Cabinet Side	4
16	Drawer Slide Drawer Side	4
17	Drawer Slide Ball Bearing	8
18	Drawer Mounting Angle Bracket	4
19	gm2	2
20	RM3-regular motor	2
21	GMstrap1	2
22	screw_head1	4
23	screw_head2	4
24	GM2 Bracket	2
25	Motor mount Block	2
26	Hub Assembly	2
27	CPU fan	2
28	91771A124	20
29	90480A006	28
30	91771A129	4
31	CPU Fan Model	1
32	CPU Fan Mounting Plate	1
33	Bottom Desiccant Shelf Revised	1
34	Heating Element Mounting Bracket	2
35	Copper Wire	1
36	Heating Element screw tab	2
37	Heating Element Shell	1
38	94610A225	4
~~39~~	~~91772A125~~	~~4~~



	NAME	DATE
DRAWN	TD	03/19
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

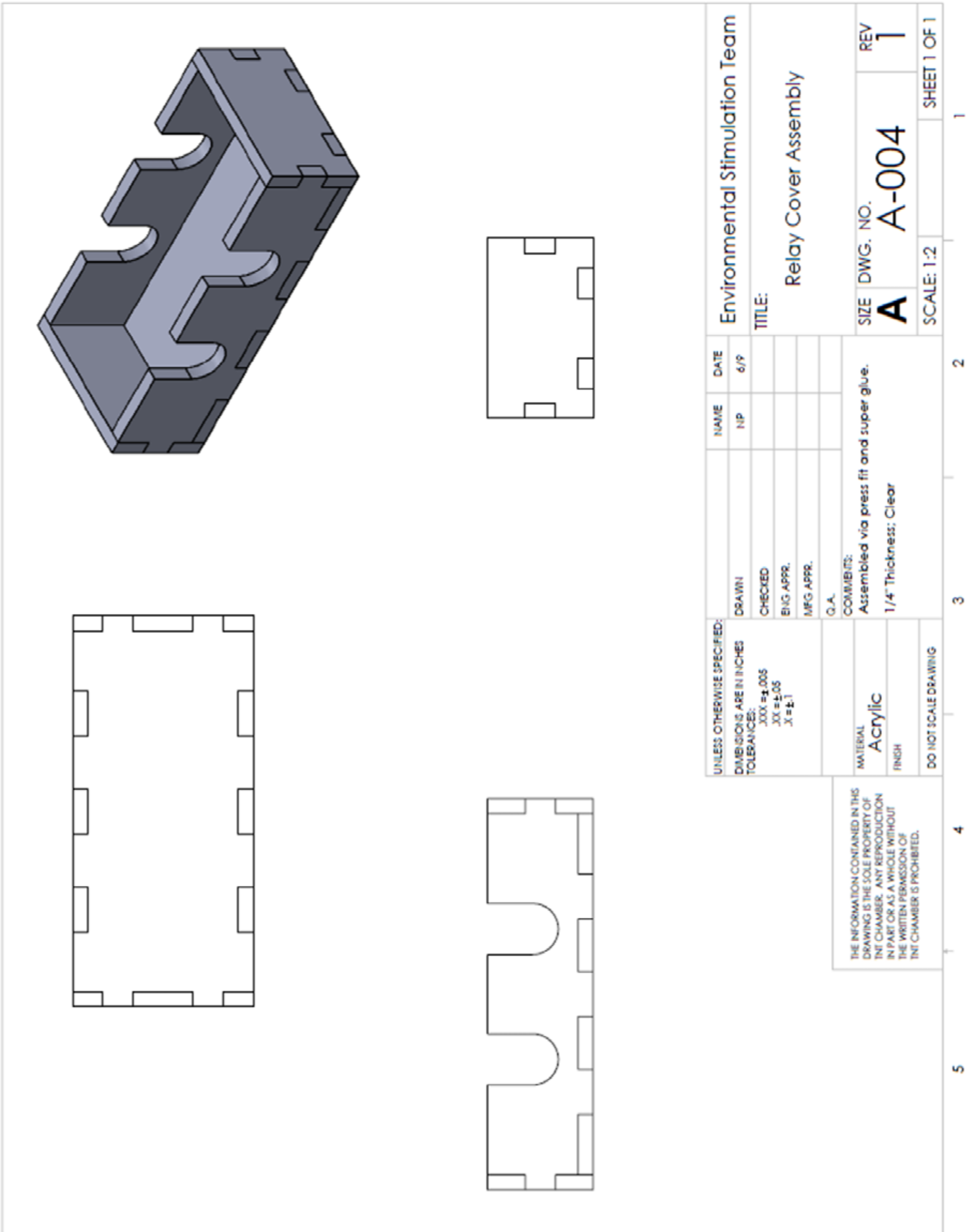
TNT Chamber

TITLE: Complete Assembly

SIZE A | DWG. NO. A-003 | REV 1

SCALE: 1:20 | SHEET 1 OF 1

5 4 3 2 1


Environmental Stimulation Team
TITLE:
Relay Cover Assembly
SIZE A
DWG. NO. A-004
REV 1
SCALE: 1:2
SHEET 1 OF 1
NAME DATE
DRAWN NP 6/9
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Assembled via press fit and super glue.
1/4" Thickness; Clear
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
.XXX = ±.005
.XX = ±.05
.X = ±.1
MATERIAL
Acrylic
FINISH
DO NOT SCALE DRAWING
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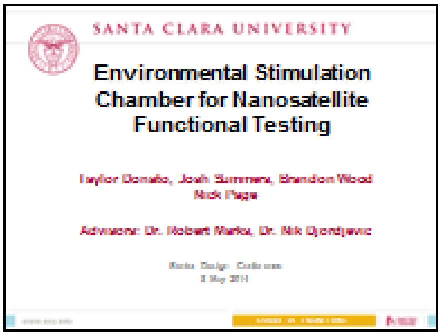
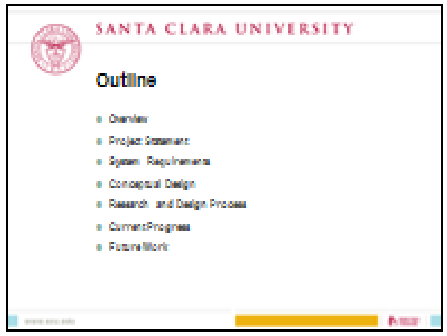
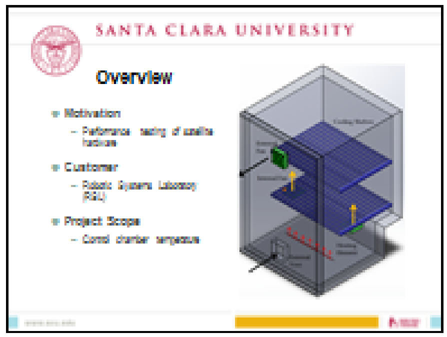
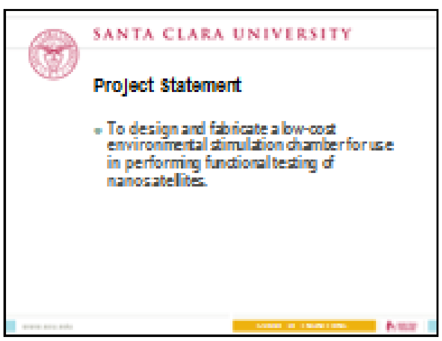
1
2
3
4
5

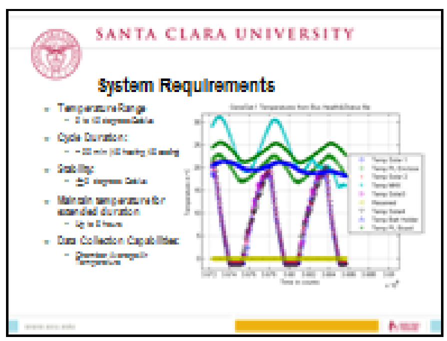
Appendix H: Senior Design Conference PowerPoint Presentation



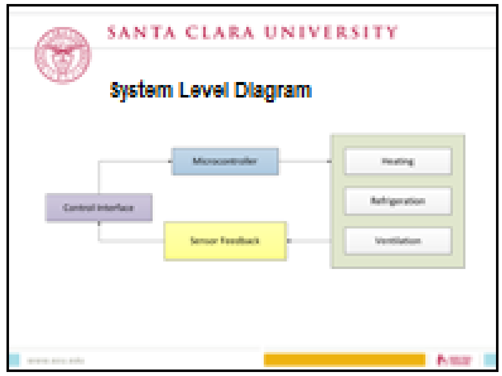


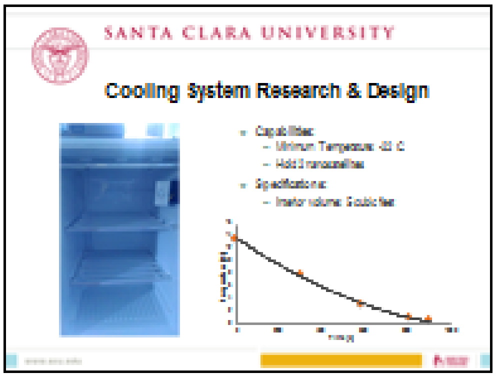


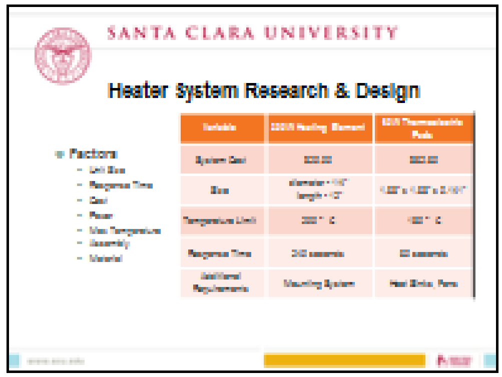


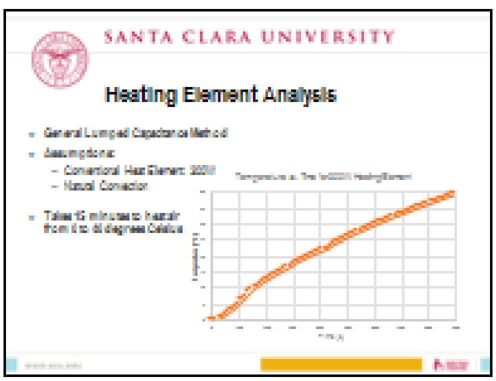


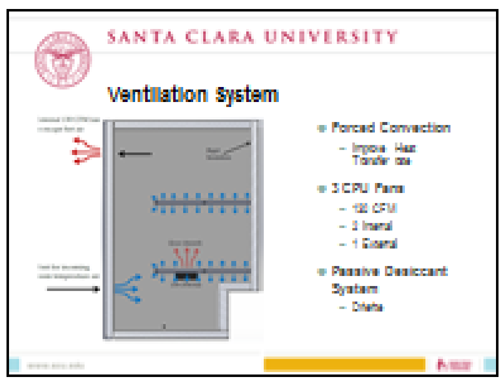

SANTA CLARA UNIVERSITY
Conceptual Design
Mini-Freezer as baseline
– Adequate internal volume
– Integrated cooling system
Make modifications as necessary
– Heating system
– Controls interface

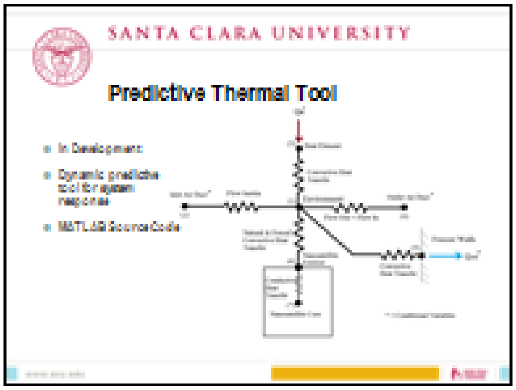

SANTA CLARA UNIVERSITY
System Level Diagram
Microcontroller
Control Interface
Sensor Feedback
Heating
Refrigeration
Ventilation


SANTA CLARA UNIVERSITY
Cooling System Research & Design
Capabilities:
Specifications:

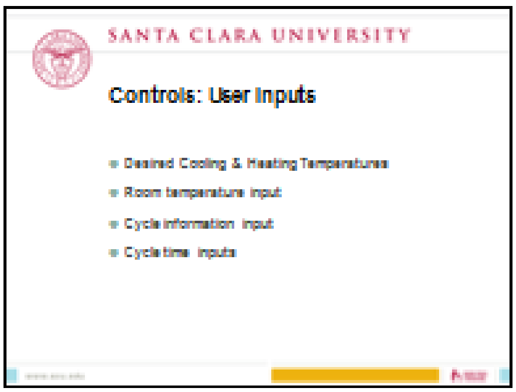

SANTA CLARA UNIVERSITY
Heater System Research & Design
Factors

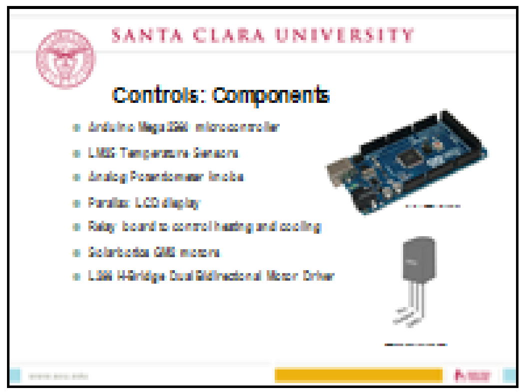

SANTA CLARA UNIVERSITY
Heating Element Analysis
General Lumped Capacitance Method
Assumptions:

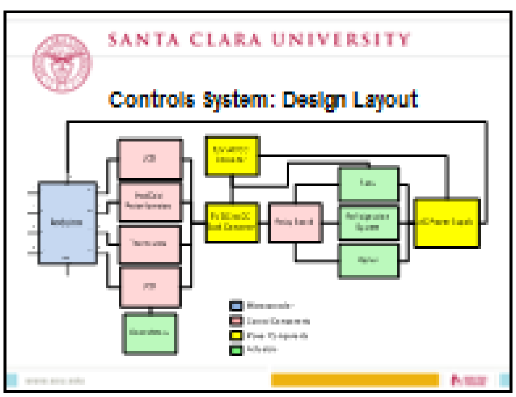

SANTA CLARA UNIVERSITY
Ventilation System
Forced Convection
3 CPU Fans
– 1 External
Passive Desiccant System


SANTA CLARA UNIVERSITY
Predictive Thermal Tool
In Development
Dynamic predictive tool for system responses
MATLAB Source Code


SANTA CLARA UNIVERSITY
Controls: Capabilities
Knob temperature control with corresponding LCD temperature display
Set specific temperature cycling for 90-minute tests
Program plots the temperature distribution inside the chamber versus time using StampPlot
Controlling CPU Fan-Ventilation System during thermal cycling

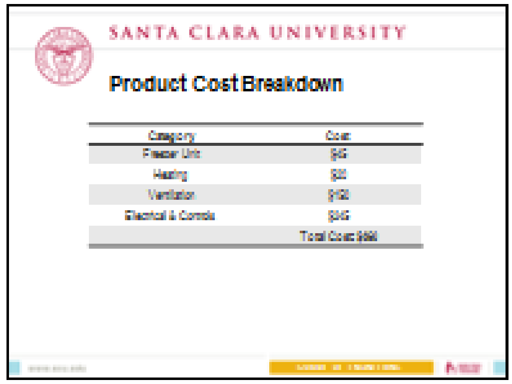

SANTA CLARA UNIVERSITY
Controls: User Inputs
Desired Cooling & Heating Temperatures
Room temperature input
Cycle information input
Cycle time inputs

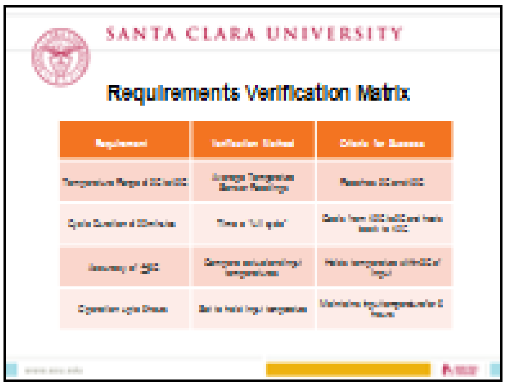

SANTA CLARA UNIVERSITY
Controls: Components
Arduino Mega 2560 microcontroller
LM35 Temperature Sensors
Analog Potentiometer knobs
Parallax LCD display
Relay board to control heating and cooling
Solarbotics GM8 motors
L298 H-Bridge Dual Bidirectional Motor Driver

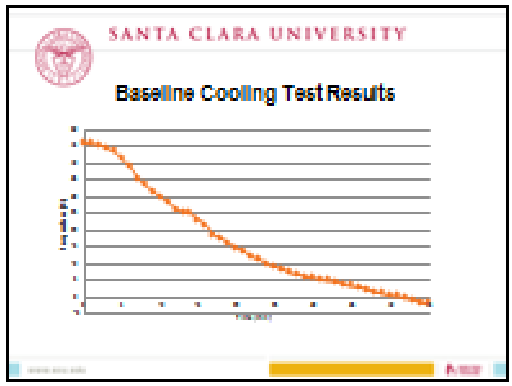

SANTA CLARA UNIVERSITY
Controls System: Design Layout

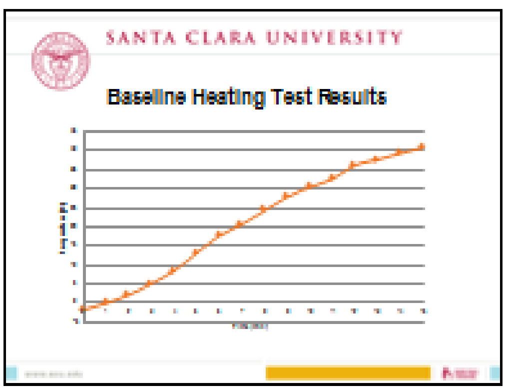

SANTA CLARA UNIVERSITY
Final Assembly


SANTA CLARA UNIVERSITY
Final Assembly


SANTA CLARA UNIVERSITY
Product Cost Breakdown


SANTA CLARA UNIVERSITY
Requirements Verification Matrix


SANTA CLARA UNIVERSITY
Baseline Cooling Test Results

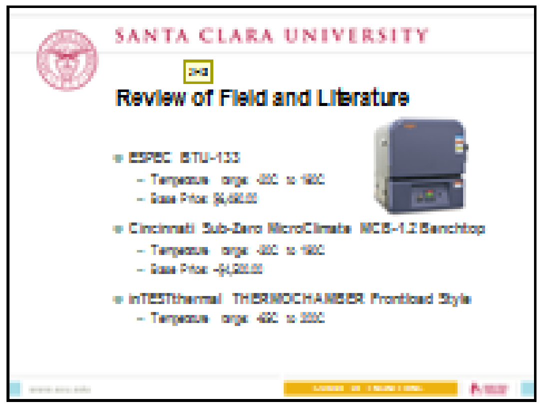

SANTA CLARA UNIVERSITY
Baseline Heating Test Results


SANTA CLARA UNIVERSITY
Conclusion


SANTA CLARA UNIVERSITY
Acknowledgements


SANTA CLARA UNIVERSITY
Questions?


SANTA CLARA UNIVERSITY
Timeline


SANTA CLARA UNIVERSITY
Review of Field and Literature
ESPEC BTU-133
Cincinnati Sub-Zero MicroClimate MCB-1.2 Benchtop
inTESTthermal THERMOCHAMBER Frontload Style

Appendix J: Predictive Thermal Tool

Predictive Thermal Tool MATLAB Code:
airtemp.m:

```
%Predictive Thermal Tool
function [envtemp] =
airtemp(T1initial,T1final,nslength,nswidth,nsheight,roomtemp,HEtime)
%make sure the dimensions of the nanosatellite are entered in meters
deltaT = (T1final - T1initial);
%HEtime is the amount of time that the heat element has been ON at the
%start of the thermal cycling or set temperature range

%NODE 1 Properties: Environmental Air
    %all air properties are dependent on temperature, must enter manually for
now
if T1initial >= 273
    if T1initial < 293 %Air thermal properties at 0 C
        rhoAir = 1.293; %density of air in kg/m3
        CpAir = 1005; %specific heat capacity of air in J/kg*K
        PrAir = 0.715; %Prandtl Number of air unitless
        viscKAir = 13.30*10^(-6); %Kinematic viscosity of air
        betaAir = 3.67*10^(-3); %Expansion coefficient Beta of air
        kAir = 0.0243; %conductive heat transfer coefficient of air
    elseif T1intial > 293 %air thermal properties at 20C
        rhoAir = 1.205; %density of air in kg/m3
        CpAir = 1005; %specific heat capacity of air in J/kg*K
        PrAir = 0.713; %Prandtl Number of air unitless
        viscKAir = 15.11*10^(-6); %Kinematic viscosity of air
        betaAir = 3.43*10^(-3); %Expansion coefficient Beta of air
        kAir = 0.0257; %conductive heat transfer coefficient of air
    else
    rhoAir = 1.205; %density of air in kg/m3
    CpAir = 1005; %specific heat capacity of air in J/kg*K
    PrAir = 0.713; %Prandtl Number of air unitless
    viscKAir = 15.11*10^(-6); %Kinematic viscosity of air
    betaAir = 3.43*10^(-3); %Expansion coefficient Beta of air
    kAir = 0.0257; %conductive heat transfer coefficient of air
    end
else
    rhoAir = 1.205; %density of air in kg/m3
    CpAir = 1005; %specific heat capacity of air in J/kg*K
    PrAir = 0.713; %Prandtl Number of air unitless
    viscKAir = 15.11*10^(-6); %Kinematic viscosity of air
    betaAir = 3.43*10^(-3); %Expansion coefficient Beta of air
    kAir = 0.0257; %conductive heat transfer coefficient of air
end
    rhoPlastic = 66/0.0624; %density of ABS plastic in kg/m3
    rhoAlum = 2700; %density of aluminum in kg/m3
    kAlum = 205; %conductive heat transfer coefficient for Aluminum
    kPlastic = 0.144; %conductive heat transfer coefficient for ABS plastic
```

```
%NODE 2 Properties: Inlet Air Vent w/induced airflow from CPU fan
    fanspd = 0.005979;
%CPU fan speed converted to m^3/s from 130 CFM and with Fan radius of 0.04604
meters
    %R12 = 1/(fanspd*rhoAir*CpAir);
    %fanspd in meters per second divide the cross sectional area of the fan
to fanspd

%NODE 3 Properties: Heat Element
    %possibly check page 22 for relationship between time and temperature of
heat element heat generation
    HElength = 12*0.0254;
    HEradius = (0.25*0.0254)/2;
    HESArea = 2*pi*HEradius*HElength + 2*pi*(HEradius^2);
%heat element surface area w/ length of 12in. and diameter of 1/4 in.
    HEVol = pi*(HEradius^2)*HElength;
%heat element volume w/ length of 12in. and diameter of 1/4 in.
    ReD3 = (fanspd*(2*HEradius))/viscKAir;
%Reynolds number for the cross flow over the heat element and is usually
between 1-40; found it to be around 2.8546
    C = 0.75;
%values for C,m,n are from page 458 of Fundamentals of Heat and Mass Transfer
by Bergman
    m = 0.4;
    n = 0.37;
%considering Pr never exceeds 1 for Air from temps -150 to 400 degrees C
    PrS = 0.685;
%max surface temp of heat element is around 203 degrees C so Prs equals 0.68
    NuD3 = C*(ReD3^m)*(PrAir^(n))*((PrAir/PrS)^(1/4));
%equation 7.53, page 458
    hbar3 = (NuD3*kAir)/(2*HEradius);
    %%qin = 300/HEVol; %heat element heat load in Watts; max heat element
heat temp is 203.333 degrees Celsius

    if T1final-T1initial > 0
        if HEtime < 320 %units are in seconds
            HEtemp = 0.635*HEtime + T1initial;
        elseif HEtime >= 320
            HEtemp = 476.666;
        end
    elseif T1final-T1initial < 0
        HEtemp = T1initial;
    end

%NODE 4 Properties: Outlet Air Vent w/Fan
    %Temp at node 4 equals temp at node 1
    %The CPU Fan is in the outlet air vent

%NODE 5 Properties: Mini-freezer wall temperature
    %%qout = 132; %freezer heat sink cooling ability
    xlen = 0.48895; %length of freezer wall
    ylen = 0.59373; %width of freezer wall
    x2len = 0.36354; % x2len and y2len accounting for the change in width of
the wall that is close to the floor of the mini-freezer
    y2len = 0.15875;
    zlen = (1/8)*0.0254; %thickness of freezer wall
```

```
    xxlen = 0.36354; %length of the freezer floor
    yylen = 0.47466; %width of the freezer floor
    xxxlen = 0.48895; %length of freezer ceiling
    yyylen = 0.47466; %width of freezer ceiling
    wallArea = (xlen*ylen)+(x2len*y2len)+(xxlen*yylen)+(xxxlen*yyylen);
%area of freezer walls, treated as flow over vertical walls
    LCx = xlen/2;
%LCx, LCy, LCz, LCx2, LCy2, LCxx, LCyy, LCxxx, LCyyy are the characteristic
lengths of the freezer wall
    LCy = ylen/2;
    LCz = zlen/2;
    LCx2 = x2len/2;
    LCy2 = y2len/2;
    LCxx = xxlen/2;
    LCyy = yylen/2;
    LCxxx = xxxlen/2;
    LCyyy = yyylen/2;
    Gr5 = ((LCz^3)*9.81*deltaT*betaAir)/(viscKAir^2); %Grashoff's number for
Node 6
    Ra5 = Gr5*PrAir; %Rayleigh number for convection between 1 and 5
    Nu5 = (0.825 + ((0.387*(Ra5^(1/6)))/((1 +
((0.492/PrAir)^(9/16)))^(8/27))))^2;
%Natural Convection between air and freezer interior walls (vertical plate)
    h5 = (Nu5*kAir)/LCz;

%NODE 6 Properties: Exterior of nanosatellite
            %make sure to use all side walls, top, and sides
            %thickness is in terms of the sheet metal thickness that makes up
the exterior of the nanosatellite
        %nslength = ; %length of nanosatellite
        %nswidth = ; %width of nanosatellite

        %nsheight = ; %height of nanosatellite
    %Natural Convection at NODE 6
    nsthick = (1/16)*0.0254; %thickness of nanosatellite exterior sixteenth
of an inch
    nsLCl = nslength/2; %nsLCl, nsLCw, nsLCt, nsLCh are the characteristic
lengths of the nanosatellite walls
    nsLCw = nswidth/2;
    nsLCt = nsthick/2;
    nsLCh = nsheight/2;
    nsareawl = nswidth*nslength; %area with width and length of nanosatellite
    nsareawh = nswidth*nsheight; %area with width and height of nanosatellite
    nsarealh = nslength*nsheight; %area with length and height of
nanosatellite
    nsSurfArea = nsarealh;
    %nsSurfArea = (2*nsareawl) + (2*nsareawh) + (2*nsarealh); %surface area
of nanosatellite
    nsVolume = nslength*nswidth*nsheight; %volume of nanosatellite
    Gr6 = ((nsLCt^3)*9.81*deltaT*betaAir)/(viscKAir^2); %Grashoff's number
for Node 6
    Ra6 = Gr6*PrAir; %Rayleigh number for convection between 1 and 6
if Ra6 <= 10^7
    Nu6free = 0.54*(Ra6^(1/4)); %Nusselt number for natrual convection
elseif Ra6 > 10^7
    Nu6free = 0.15*(Ra6^(1/3));
```

```
end
    %Forced Convection at NODE 6
    a = (xxlen/2)-(nswidth/2); %the space between the nanosatellie and the
freezer wall
    b = xlen; %space between the nanosatellite and the freezer wall, the
width of the cross section -> parallel to the wall;
    %b/a equals 3.477 --> with uniform surface temperature ----> Table 8.1
page 553
    if b/a <= 8.0
        if b/a > 4.0 %between b/a equaling 8.0 and 4.0
            fReDh6 = 82 - (((8.0-(b/a))/4)*(82-73));
            Nu6force = 5.60-(((8.0-(b/a))/4)*(5.60-4.44)); %Nusselt number
for forced convection
        elseif b/a <= 4.0
            if b/a >= 2.0
                if b/a < 3.0 %between b/a equaling 3.0 and 2.0
                    fReDh6 = 69 - (((3.0-(b/a))/1)*(69-62));
                    Nu6force = 3.96-(((3.0-(b/a))/1)*(3.96-3.39)); %Nusselt
number for forced convection
                elseif b/a >= 3.0 %between b/a equaling 4.0 and 3.0
                    fReDh6 = 73 - (((4.0-(b/a))/1)*(73-69));
                    Nu6force = 4.44-(((4.0-(b/a))/1)*(4.44-3.96)); %Nusselt
number for forced convection
                end
            end
        end
    end
    AcDuct = b*a; %Cross sectional area between the nanosatellite and the
freezer door
    PDuct = 2*(b+a); %wetted perimeter of the duct
    Dh6 = (4*AcDuct)/PDuct; %Hydraulic diamter of duct forced convection
along satellite from fans
    Re6 = (fanspd*Dh6)/viscKAir; %Reynolds number for the forced convection
between 1 and 6
    f6 = fReDh6/Re6; %friction factor
if T1final-T1initial > 0
    if T1initial < roomtemp
        Nu6 = Nu6force; %Forced and Free Convection of nanosatellite exterior
        h6 = (Nu6*kAir)/nsLCl; %convective heat transfer coefficient between
nodes 1 and 6
    elseif T1initial >= roomtemp
        Nu6 = Nu6free;
        h6 = (Nu6*kAir)/nsLCl;
    end
elseif T1final-T1initial < 0
    if T1initial > roomtemp
        Nu6 = Nu6force; %Forced and Free Convection of nanosatellite exterior
        h6 = (Nu6*kAir)/nsLCl; %convective heat transfer coefficient between
nodes 1 and 6
    elseif T1initial < roomtemp
        Nu6 = Nu6free;
        h6 = (Nu6*kAir)/nsLCl;
    end
end

%NODE 7 Properties: Core of nanosatellite
```

```
    %conductive heat transfer coefficient of the nanosatellite in W/m*K,
material is aluminum sheet metal
    %R67 is equal to L/(nsK*A) with A equaling the plane area that is normal
to the direction of the heat transfer

if T1final-T1initial > 0 %thermal cycling range components
    Qdotin = 300; %heating element ON
    Qdotout = 0;
elseif T1final-T1initial < 0 %mini-freezer refrigeration cycle ON
    Qdotin = 0;
    Qdotout = 132;  %place heat transfer from Refrigerator going from 40 to 0
C
end

if T1final-T1initial > 0
    if T1initial < roomtemp
        R12 = 1/(fanspd*rhoAir*CpAir);
        R14 = 1/(fanspd*rhoAir*CpAir); %or make it equal to 0
    elseif T1initial > roomtemp
        R12 = 0;
        R14 = 0;
    end
elseif T1final-T1initial < 0
    if T1initial > roomtemp
        R12 = 1/(fanspd*rhoAir*CpAir);
        R14 = 1/(fanspd*rhoAir*CpAir); %or make it equal to 0
    elseif T1initial < roomtemp
        R12 = 0;
        R14 = 0;
    end
end

     R13 = 1/(hbar3*HESArea);
    R15 = 1/(h5*wallArea);
    R16 = 1/(h6*AcDuct);
    R67 = nsthick/2*(kAlum*nsSurfArea);

    tempmatrix = [(-1/R13) (1/R13) 0 0 0; (-
((1/R13)+(1/R12)+(1/R16)+(1/R15))) (1/R13) (1/R15) (1/R16) 0; (1/R16) 0 0 (-
((1/R16)+(1/R67))) (1/R67); (1/R15) 0 (-1/R15) 0 0; 0 1 0 0 0];
    %tempmatrix = [(-1/R13) (1/R13) 0 0 0; (-
((1/R13)+(1/R12)+(1/R16)+(1/R15))) (1/R13) (1/R15) (1/R16) 0; (1/R16) 0 0 (-
((1/R16)+(1/R67))) (1/R67); (1/R15) 0 (-1/R15) 0 0; 0 1 0 0 0];
    %tempmatrix is the system of equations for steady-state setup for freezer
heat element setup
    %Qvector = [Qdotin;0;0;Qdotout;0;roomtemp;476];
    Qvector = [-Qdotin;-(20/R12);0;-Qdotout;HEtemp];
    Tresults = tempmatrix\Qvector; %Tresults equal to [T1;T3;T5;T6:T7]
    envtemp = Tresults(1);
    %Above is the base algorithim of the energy balance between all the
thermal
%components and a transient can be  built upon each of the temperature
%nodes from this system of equations listed in tempmatrix, if you set the
%correct boudary conditions.

end
```