Red Feather Solar Furnace

Preliminary Proposal

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DISCLAIMER

EXECUTIVE SUMMARY

The NAU Capstone team is partnered with Red Feather to design a solar furnace. Red Feather is a non-profit organization that helps the Native American people with their housing needs on the reservation. The Native American people used to receive coal from a power plant, but it was recently shut down. In addition, coal is known to cause respiratory illnesses. The NAU Capstone team was tasked with designing a sustainable and lasting solution to their heating problems. A solar furnace was chosen due to these reasons.

Multiple customer needs and engineering requirements were considered in designing the solar furnace. The final design was developed from a decision matrix and refined using both engineering computations, as well as a comprehensive analysis of the failure modes of the device. System heat loss, fan optimization, and solar technology were researched to better understand what materials and what configuration would be best for the solar furnace. Some of the materials of the final design include aluminum, a plywood base, a corrugated sheet, plexiglass, and more. A corrugated sheet will be used for the heat fins. Plexiglass will be used for the low cost and durability of the solar furnace. Wood will be used due to the cost and strength of the material. Only basic power tools will be needed to construct the solar furnace. Red Feather will be able to replicate the solar furnace to distribute to those on the Native American Reservation. The current cost of the solar furnace with testing is $477.71. The cost of the solar furnace not including the testing cost is about $439.73.

Testing and building of the final design are scheduled for semester 2.

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1 BACKGROUND

1.1 Introduction

The team is partnered with Red Feather, a non-profit organization, to create a heating solution for the Native American people on the reservation. Red Feather is a non-profit organization that develops sustainable solutions for the housing needs of the Navajo and Hopi Tribes such as repairing and renovating homes for the members of the Native American community. They also organize professionals, volunteers, and materials to address the needs of the Native American community.

The Native American people used to receive coal from a coal power plant to heat their homes, the Navajo Generating Station. The coal plant closed in November of 2019 making heating homes more expensive. In addition, burning coal increases respiratory health risks. Other forms of heat such as space heaters are not practical due to the risk of fires. Solar heaters are a good option for being renewable and inexpensive long term [1].

1.2 Project Description

Following is the original project description provided by the sponsor.

> Red Feather Development Group, a non-profit in Flagstaff, works with the Navajo and Hopi Tribes to develop and implement sustainable solutions to their housing needs. Currently, the majority of these two Nations use coal and or wood to heat their homes during the extremely cold winters. Wood and coal smoke is one of the leading contributors to the higher respiratory disease rates on American Indian Reservations (5 times higher). With the pending closure of a coal-fired electricity plant and the mine that supplies it, coal is expected to become very scarce over the next couple years. It is expected that the majority of households using primarily coal to heat their homes will switch to wood, since it can be burned in the same stove, and historically has been reasonably abundant. Tribal officials expect this increase demand for wood will strain local woodlands and rapidly create a similar scarcity for both fuels. The remaining fuel choices are electricity and propane, as only a very limited number of families have access to Natural Gas. Propane has a number of risks, including CO poisoning and risk of explosion, as well as being cost prohibitive for most families. Electricity is not available for thousands of Navajo and Hopi families, and when it is available, space heaters are the most common appliance used for heating. Not only are space heaters the most expensive way to heat a home but they are the number one cause of home fire deaths in the United States [1].
>
> This capstone project will task a team of students to research and develop sustainable and lasting solutions to the different heating problems on the reservations. This is the second year NAU ME capstone has partnered with Red Feather and this year's team may work off of the results of last year to create a more economical solution to the last solution. This project will begin as an analytical project where the team's final deliverables are in-depth theoretical models of the proposed solutions, thoroughly backed by analyses. However, there is a strong potential to procure extra sponsorship during the semester to provide resources for prototyping and testing. Red Feather may also provide additional solar furnaces for the team

to do a comparative study on the Return-On- Investment (ROI) of the currently marketed products versus the team's solution [1].

2 REQUIREMENTS

2.1 Customer Requirements (CRs)

The customer requirements are listed below.

- Low cost
- Heat a home
- Store heat
- Durable
- Low weight
- Easy to build

The team met with the client who is a leader at Red Feather to gather customer needs and find more about the conditions on the reservations. The solar furnace must have a low cost, able to heat an entire home, and scalable for different size homes. The homes on the reservations range from 200 square feet to about 1500 square feet. In addition, the solar furnace must be able to be built with standard power tools and welding equipment so that volunteers or residents would be able to manufacture it. It also must have a low weight so that it could be installed by two people or less. The solar furnace must also be durable so that it can last a long time. It must have a low noise level, be wall or roof mountable, and have a heat storage capability.

2.2 Engineering Requirements (ERs)

Table 1: Engineering Requirements

Technical Requirement	Technical Requirement Goal
Cost	$350
Heat Generation	1500 W
Heat Capacity	2 hours
Weight	45 kg
Durability	20 years
Noise Level	40 dBa
Install Time	3 hours

Based on the customer needs, engineering requirements were made. Red Feather currently pays $750 for their solar furnaces. From speaking with the client, the goal cost would be $350 so the solar furnaces would be affordable to a larger amount of people. The heat generation would be 1500 W because that is what is needed to comfortably heat a home and is also comparable to what space heaters produce. The heat capacity would be 2 hours because the home will continue to stay warm for a while after the solar has been shut off. The weight of the solar furnace would be 45 kg so that it could be installable by only one or two people. The durability of the solar furnace would be 20 years because it is important for the consumers to have a return on investment. The noise level would be under 40 dBa so it would not interfere with the consumers lives such as not allowing them to sleep. The install time would be under 3 hours so that it would take less people and resources to install the solar furnace.

2.3 Functional Decomposition

The team made a black box model and functional model to analyze the different signal, materials, and energy in a solar furnace system. The functional model shows the different subfunctions of the system.

2.3.1 Black Box Model

The black box model is shown in figure 1. This shows the inputs and outputs of various data to heat a home. This helps the team visualize the project because it breaks down the different materials, energy, and signals to better understand a solar furnace.

Material in	Cold air	Heat Home	Heated air	Material out
Energy in	Solar Energy		Energy Transfer as heat	Energy out
Signal in	Setting thermostat		Change in temperature in home	Signal out

Figure 1: Black Box Model

2.3.2 Functional Model/Work-Process Diagram/Hierarchical Task Analysis

The functional models help break down subfunctions of a device and the different energy flows. The function model is shown below in figure 2 for a device with a solar furnace, solar panel, fan, and battery system.

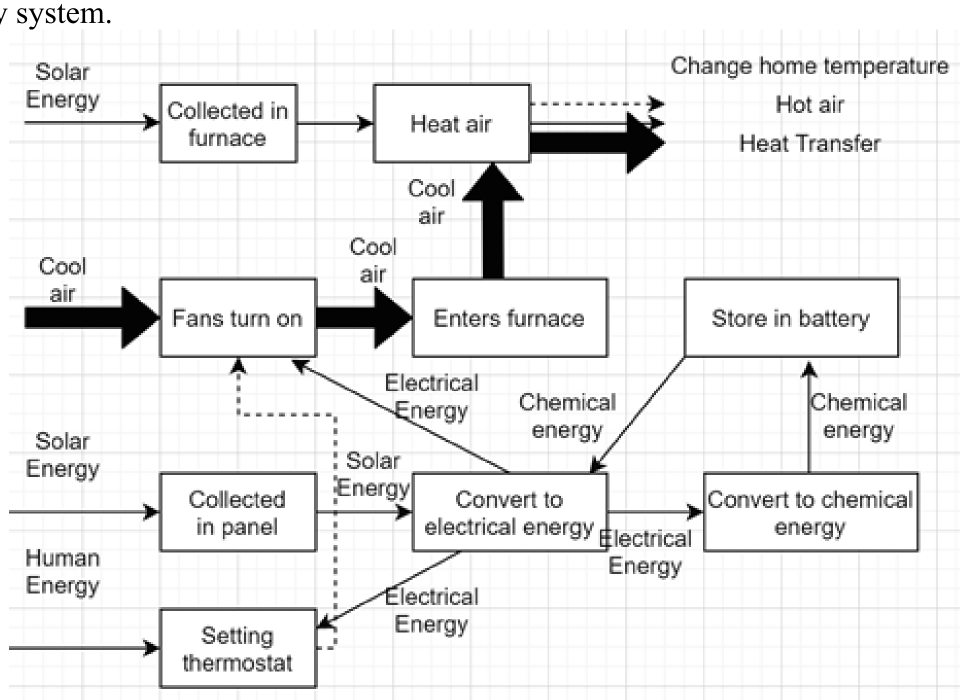

Figure 2: Functional Flow Diagram of Solar Furnace, Solar Panel, Fan, and Battery System

2.4 House of Quality (HoQ)

After generating the engineering requirements and customer needs for the Solar Furnace project, the team placed them into a house of quality, HoQ, that established their rank of importance. The HoQ is shown in figure 3.

	Technical Requirements						
1	Cost						
2	Heat generation	9					
3	Heat Capacity	9	3				
4	Weight	9	9	9			
5	Durability	9	9	9	9		
6	Noise level	9	3	1	1	1	
7	Install Time	9	1	3	9	1	1

Legend	
A	Your Solar Home
B	SolarArctica
C	Previous Capstone Team

	Customer Needs	Customer Weights	Cost	Heat generation	Heat Capacity	Weight	Durability	Noise level	Install Time	1 Poor	2	3 Acceptable	4	5 Excellent
1	Low cost	5	9	9	9	9	9	9	9		A	B	C	
2	Heat a home	5	9	9	9	1	3	1	3			BC	A	
3	Low noise	4	9	3	1	1	1	9	1		AC	B		
4	Store Heat	3	9	3	9	9	3	1	3	ABC				
5	Durable	4	9	3	3	3	9	1	3		C		AB	
6	Low weight	5	9	9	9	9	9	1	9		B	C		A
7	Easy to build	4	9	1	3	9	9	1	9		A	C	B	
	Technical Requirement Units		$	W	hr	kg	Year	dBa	hr					
	Technical Requirement Targets		$350	1500	2	45	20	40	3					
	Absolute Technical Importance		270	172	190	174	190	102	166					
	Relative Technical Importance		1	5	2	4	3	7	6					
	Reference Number		1	2	3	4	5	6	7					

(Customer Opinion Survey: columns 1 Poor – 5 Excellent)

Figure 3: House of Quality

In the HoQ the customer needs were first correlated to the engineering requirements as shown in the center of the figure. These correlations were then multiplied against the customer weight for their respective category and added for each engineering requirement to determine the Absolute Technical importance. The rankings of these numbers were determined and then ranked to find the Relative Technical Importance. The Relative Technical Importance shows the team which engineering requirements are the most important to focus on to best meet the customer needs of the project. The most important engineering requirement was the cost of the Furnace as price reduction is the primary goal of the project. The next is the heat capacity of the design which tells the team the furnace must still be able to produce enough heat compared to commercial options despite a reduced price. The third most important engineering requirement is durability. This is important for the design as commercial solar furnaces are long lasting and require little to no maintenance. To be competitive the team's prototype must accomplish the same goals. From the HoQ the team was able to infer that other engineering requirements such as install time and noise level are less important to the success of the design. They will still be considered when

making decisions but will not be the primary deciding factor.
In the HoQ the team also benchmarked two commercial options by Your Solar Home and Arctica Solar as well as the design of the previous Red Feather Capstone team. This benchmarking is shown on the right of the HoQ.
The reference number for testing the engineering requirements in section 3 is shown in the row on the figure.

2.5 Standards, Codes, and Regulations

Due to the novel nature of the project there are few standards that the project must adhere to. The team found no standards or codes related to solar air furnaces in general but were able to find some general standards that apply to commercial solar panels and solar applications. These standards will be used as references and guides for the project, but the client has made it clear that there are no requirements for standards to be followed as the device is to be built and used by Red Feather Themselves and will be adapted for each application as necessary. Table 2 shows a list of the standards the team is using while designing and building the solar furnace

Table 2: Standards of Practice as Applied to this Project

Standard Number or Code	**Title of Standard**	**How it applies to Project**
ASTM Y14.5	Dimensioning and Tolerancing	CAD drawings will adhere to standard to ensure readability and consistency
ISO/ TC 180 /SC 4	Solar Systems - Thermal performance, reliability and durability	Ensure panels are made from lasting materials and are effective at producing energy. Some of the wiring specifications can be used regarding the photovoltaic panel setup.
ISO/ TC 180/SC 1	Solar Systems- Climate- Measurement and Data	Ensures the accurate data measurements are taken including wind, solar intensity, and air temperatures.

The team used the ASTM Y14.5 standard [2] to tolerance and dimension the CAD drawings provided in this report. This will ensure that the model is fully dimensioned and could be easily constructed by anyone with the drawings.

ISO TC 180/SC 4 [3] is a standard for solar systems to be used in commercial production. It specifies efficiencies, durability, and wiring procedures for solar energy sources. There is much detail as to how photovoltaic panels should be installed and wired which will apply to the small photovoltaic panel used to run the fan in the system.

ISO TC 180/SC 1 [4]is a standard for solar systems regarding how climate data is measured. It specifies tolerances for temperature measurements to be used with solar systems as well as how wind and solar intensity affect energy output.

3 Testing Procedures (TPs)

Multiple testing procedures will be used to test how the design meets various engineering requirements such as heat output and noise level. Some materials used include an anemometer, an Arduino board, and thermocouples. These tests will show the system is reliable.

3.1 Testing Procedure 1: Cost

3.1.1 Testing procedure 1: Objective

The objective is to meet the engineering requirement of being under $350.

3.1.2 Testing procedure 1: Resourced Required

The resources required will be an excel spreadsheet to keep track of all the expenses. Expenses include materials for the solar furnace such as the wood and plexiglass while other expenses may include testing materials.

3.1.3 Testing Procedure 1: Schedule

Cost will be kept track of the entire length of the project. The estimated material cost is around $400 which is close to the engineering requirement goal of $350.

3.2 Testing Procedure 2: Heat Generation

3.2.1 Testing procedure 1: Objective

The engineering requirement of continuing to keep a room warm for two hours after the solar furnace has been on will be tested. This will be determined using a room thermometer and recording the temperature for two hours. The temperature should not drop too much after the solar furnace has been turned off.

3.2.2 Testing procedure 1: Resourced Required

A thermostat or room thermometer will be needed to measure the temperature in the room after a given amount of time. A room thermometer should be available for free in the thermal fluids lab or one could be purchased on amazon for $8.99. [5]

3.2.3 Testing Procedure 1: Schedule

This will take place on October 27, 2020 during the same day heat output is also tested.

3.3 Testing Procedure 3: Heat Output

This procedure this will test the engineering requirement of heat generation of at least 1500 Watts. This will be accomplished using tools such as thermocouples and an Arduino board. An

3.3.1 Testing Procedure 3: Objective

The test is to see the heat output of the solar furnace and if it reaches 1500 Watts. Thermocouples will be placed on the inside and outside of the solar furnace. An anemometer will measure the mass flow rate of the air. An Arduino board will be attached to the thermocouples to send data onto a laptop. The following equation will be used to find the heat output. The heat output is shown in the following equation where Q is the heat output, Mc is the specific heat capacity, T_2 is the final temperature, and T_1 is the ambient temperature. $Q=mc(T_2-T_1)$ [6]

3.3.2 Testing Procedure 3: Resources Required

The resources testing is shown in Table 3. The testing will be conducted in an outdoor sunny location. Excel software is needed to read the data. All team members will be present when testing. The thermocouples will be attached to the Arduino board. An anemometer measures the flow rate. A pyranometer measures solar irradiance. The total cost of the testing materials would be about $154.20.

Table 3: Testing Materials

Part	Number	Price	Subtotal	Source
Arduino	1	$20.50	$20.50	https://www.amazon.com/
Thermocouples	3	$8.74	$26.22	https://www.amazon.com/
Anemometer	1	$25.49	$25.49	https://www.amazon.com/
Handheld Digital Pyranometer	1	$81.99	$81.99	https://www.amazon.com/
	Solar Furnace Testing Total		$154.20	

3.3.3 Testing Procedure 3: Schedule

[Provide a breakdown of how long the test will take, when it will likely be run, and how it fits into your second semester schedule. Also describe anything that must be completed before this test can be run.]

The test should take 1-2 days to complete. Multiple other tasks such as more individual analyses, testing of benchmarked products, self-learning, and prototype building must be completed before testing procedure 1. The final product is the major deliverable that must be completed before the testing and is therefore why testing the final product is not scheduled until October 27, 2020.

Table 4: Testing Procedure 3

Task	Start	Finish
Testing Final Product: Procedure 1	10/27/20	10/28/20
Order all necessary materials for testing ...	10/27/20	10/27/20
Set up testing apparatus for testing proc...	10/28/20	10/28/20
Conduct Testing Procedure 1	10/28/20	10/28/20

The following portion of the Gantt chart shows a visual representation of how long each task should take in order of table 4 above. The top number indicate the testing will take place the 27th through the 29th of October.

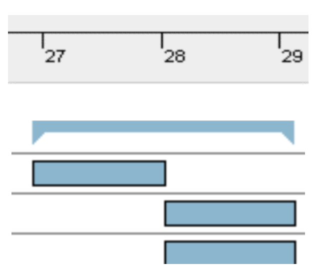

Figure 4: Testing Procedure 1 Gannt Chart

3.4 Testing Procedure 4: Weight

3.4.1.1 Testing procedure 4: Objective

The objective is to measure the weight of the solar furnace. The targeted engineering requirement is 45 kg.

3.4.1.2 Testing procedure 4: Resourced Required

The resources required for testing the weight of the solar furnace is a scale. A scale should be available in the thermal fluid's lab. If there is not scale present, then a scale could be purchased for $27.79 from amazon. This test will take place indoors will all team members present. [7]

3.4.2 Testing Procedure 4: Schedule

The testing procedure will take place October 26-29, 2020. This testing procedure is expected to take less than 10 minutes.

3.5 Testing Procedure 5: Durability

3.5.1 Testing procedure 1: Objective

The objective is to test the durability of the solar furnace. The engineering requirement analyzed is lasting 20 years. This is can be predicted by analyzing the materials used.

3.5.2 Testing procedure 1: Resourced Required

The strength of the materials will be researched to find out how much force it would take to break each material.

3.5.3 Testing Procedure 1: Schedule

The individual analysis will have the team members research the strength of the different materials. This is expected to take place starting on September 14, 2020 and end October 1, 2020.

Table 5. Durability Analysis

Individual Anlaysis 2	9/14/20	10/1/20
Research Individual Topic	9/14/20	10/1/20
Research Individual Topic	9/14/20	10/1/20
Research Individual Topic	9/14/20	10/1/20

3.6 Testing Procedure 6: Noise Level

3.6.1 Testing Procedure 6: Objective

The engineering requirement of being less than 40 decibels will be tested. The sound level will be tested with a decibel meter.

3.6.2 Testing Procedure 6: Resources Required

A decibel meter will be used to measure the total sound from the solar furnace. A decibel meter is $18.97 from amazon [8]. Testing will take place in an outdoor sunny location with all three team members present.

3.6.3 Testing Procedure 6: Schedule

The final product and other deliverables must be completed before testing the noise level. Testing procedure 2 is scheduled to take place October 29, 2020.

Table 6. Noise level Analysis

Testing Procedure 2: Noise Level	10/29/20	10/30/20
Order necessary equipment for Procedu...	10/29/20	10/29/20
Set up testing apparatus	10/30/20	10/30/20
Use decibel reader to conduct testing pr...	10/30/20	10/30/20

The following Gannt chart shows a physical representation of how long each task should take in order of table 6 shown above. The top number indicate the 29th and 30th of October.

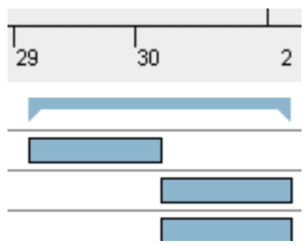

Figure 5: Testing Procedure 2 Gannt Chart

3.7 *Testing Procedure 7: Install Time*

3.7.1 Testing procedure 7: Objective

The install time of being under 3 hours will be tested by estimating the time people would need to put the solar furnace together.

3.7.2 Testing procedure 7: Resourced Required

The resources required will be an instruction manual so that someone else would be able to put the solar furnace together.

3.7.3 Testing Procedure 7: Schedule

This engineering requirement is a lower priority engineering requirement but will be tested in time permits. This test will take place in November after the heat output and noise level tests have been completed.

In conclusion, the engineering requirement of being under $350 will be analyzed by keeping track of the materials needed to build the solar furnace. The heat capacity will be analyzed by examining the heat 2 hours after the solar furnace has been shut off. The weight will be analyzed by 2 people being able to lift the solar furnace. The durability can be analyzed by predicting whether the solar furnace will last 20 years. The install time can be analyzed by determining whether 2 people can put the solar furnace together in 3 hours.

4 Risk Analysis and Mitigation

The solar furnace is a relatively basic device, and thus there are few areas of failure to be considered. The only component that could fail, in terms of safety, is the bracket attaching the furnace to the wall. Even then, the only way it would be a safety issue is if the bracket fails during installation or while someone is standing under the device. In terms of functionality, there a few ways that the device could fail, ranging from the screws to the fan. All modes of failure \addressed in the FMEA table seen in Appendix A (table A.1). Any failure mode with an RPN over 100 has a recommended action. The remainder of this section goes into more detail on each of the failure modes addressed in the FMEA.

4.1 Critical Failures

4.1.1 Potential Critical Failure 1: Mounting Bracket Damage/Failure

There are a couple ways the mounting bracket could fail however it is a simple design and correct construction and implementation should avoid either of these failures. The first way the bracket could fail is if the mating of the two pieces becomes misaligned (possible due to inclement weather). The mating will be vertically locked into place due to its design. To avoid horizontal misalignment a flat steel bracket will be attached using wood screws on the left and right side of the bracket once the two pieces are together. The other way that the bracket could fail is if one of the mating "hooks" breaks off. This should not be an issue because the bracket will be made from 2x4 planks which have a high tensile strength. Even if a "hook" were to break, there are multiple "hooks" per bracket and the device will not fall. This is a good reason to check the brackets somewhat regularly.

4.1.2 Potential Critical Failure 2: DC Fan Failure

The DC electric fan is what brings the heated air into the home. If this fan were to fail, the device would not function correctly. There is not much that can be done regarding simple part failure, this is determined by the quality of the fan from the manufacturer. The fan is within the device (not exposed to weather) so the only detrimental factor is heat. The fan that will be used will be heat resistant which should reduce unforeseen failures.

4.1.3 Potential Critical Failure 3: Solar Panel Damage/Failure

If the solar panel that powers the fan were to fail, the issue would be the same as that of a DC fan failure. Like the DC fan, general failure will be determined by the quality provided from the manufacturer. One other possible failure is if the solar panel were to be shattered. This could be due to vandalism, hail, wildlife, or a range of other causes. Solar panels are meant to be outdoors, so again this is up to the manufacturer. The solar panel should also be checked regularly for damage.

4.1.4 Potential Critical Failure 4: Thermostatic Controller

The thermostatic controller is what will tell the fan to turn on, basically initiating a switch between the solar panel and fan. If this part fails, the fan will either not start, or will start at the incorrect temperature. Again, general failure is up to the manufacturer however there are a few things that can be done to preemptively address failure. The thermostat will be within the device (not exposed to weather) so the only detrimental factor is heat. The fan that will be used will be heat resistant which should reduce unforeseen failures. Also, all thermostats will be calibrated against a control temperature prior to installation to ensure temperature readings are accurate.

4.1.5 Potential Critical Failure 4: Wiring

The solar panel, thermostatic controller and the DC fan will be connected by wires. The connection could be interrupted due to possible wiring issues. The wiring will be double checked when installed, and high-quality wiring materials will be utilized. This should eliminate any preventable wiring issues.

4.1.6 Potential Critical Failure 5: Attachment Screws/Adhesives Failure

In order to attach the components together during construction, it is necessary to use screws or adhesives of some kind. Adhesives are usually temperature resistant but can still fail under excessive heat. Wood screws are reliable but if they strip out, they can come undone. To keep the device from falling apart, both wood screws and silicone adhesives will be used to construct the device. The wood screws will be standardized throughout the device, as well as an installation technique for said screws. A high temperature adhesive will be used to increase the strength of component mating.

4.1.7 Potential Critical Failure 6: Paint Coating Deterioration

Under extreme heat, especially cycled heat, some types of paint will deteriorate. This will reduce heat absorption and could lead to paint shavings or fumes going into the home, which is dangerous. To keep this from happening, the current plan is to use a heat resistant paint and apply multiple coats. If this however is still a problem in testing, components may be powder coated.

4.1.8 Potential Critical Failure 7: Plexiglass Damage

The last possible point of failure is the plexiglass sheet on the front of the furnace. Plexiglass is shatterproof and is a very strong polymer, but that does not mean it is impossible to break. Like the solar panel, the sheet could be broken by vandalism, weather, or wildlife. Previously, the idea of multiple panes was pondered to make replacement cheaper and easier. This however would significantly increase the complexity of construction so a single sheet will most likely be used. If there are issues with the single sheet during construction or testing however, the plexiglass sheet will be broken up into multiple pieces.

4.2 Risks and Trade-offs Analysis

The main trade off due to mitigating risk is an increase in price and weight. Increasing the strength of the materials such as the brackets and plexiglass is achieved by increasing the amount of material or using a stronger material which increases price and weight of the device. To mitigate electrical risks with the solar panel, thermostat, and wiring, higher quality materials can be used. The only tradeoff is increased price for better parts. For mitigation of pain coating, adhesives, and screws, higher quality materials can be used as well which increases price. Ultimately the team's goal was to balance material quality vs price as best they could so that they will be able to be confident in their device while remaining in the price range desired by the client.

5 DESIGN SELECTED – First Semester

The team first selected their final design using a decision matrix and Pugh chart that are shown in appendix C. To validate the design the team conducted analyses on different components of the device. These analyses not only conceptually proved the devices feasibility, but also better informed their design decisions going forward.

5.1 Design Description

The final design was developed from the decision matrix and refined using both engineering computations, as well as a comprehensive analysis of the failure modes of the device. Outlined in this section is the engineering analysis as well as models of the final design itself.

5.1.1 Individual Analysis: System Heat Loss

Understanding the heat loss out of the boundaries of the system is an important part in evaluating the concepts that were selected. Three different casing options were analyzed: simple wood casing, wood and metal casing, and wood with an air gap casing. These design options scored the highest on the decision matrix. Images of each casing design can be seen below in figure 6.

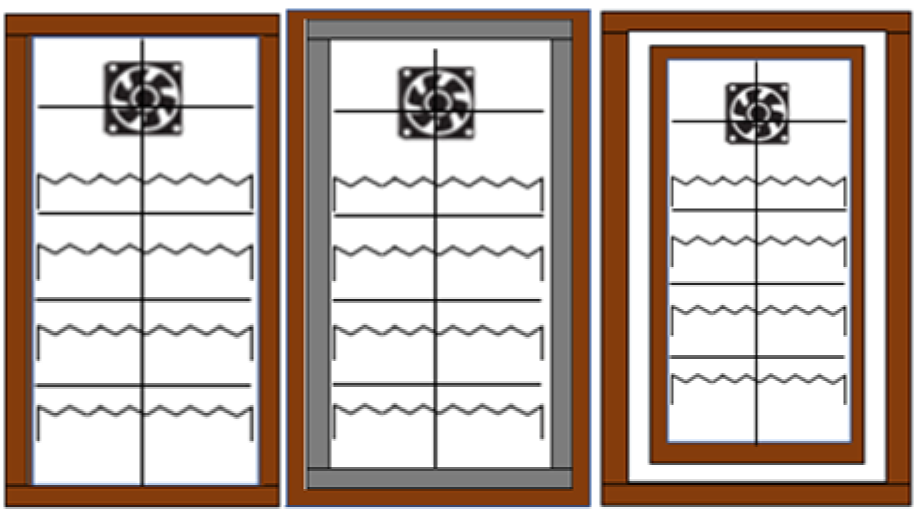

Figure 6: Casing design options

A thermal resistive network was created for each of these casing options and the heat loss across the boundaries was evaluated at a temperature difference of 50°C. The heat transfer, q is defined by equation 1 below. In that equation, ΔT is the temperature system across the boundaries, and R_{th} is the sum of the thermal resistances. There are two types of thermal resistances, one for conductive heat transfer (equation 2) and one for convective heat transfer (equation 3). In conductive heat transfer, L is the length/thickness of the wall, k is the thermal conductivity, and A is the cross-sectional area of the wall. In convective heat transfer, h is the heat transfer coefficient, and A is the cross-sectional area of the wall.

$$q = \frac{\Delta T}{\sum R_{Th}}$$ Equation 1 [6]

$$R_{conduction} = \frac{L}{kA}$$ Equation 2 [6]

$$R_{convection} = \frac{1}{hA}$$ Equation 3 [6]

In order to evaluate the equations above, it is necessary to obtain the thermal conductivities of wood, steel and air. The thermal conductivities of wood, steel, and air are 0.048 W/mK, 54 W/mK, and .025 W/mK respectively [9]. The computed heat loss values for each casing design can be seen below in table 7. The work that resulted for these values can be found in Appendix C (figures D.1, D.2 and D.3).

Table 7: Heat loss values

Case Design	Heat Loss (W)
Simple wood casing	34.01
Wood/Steel hybrid casing	33.99
Wood with air gap casing	27.95

There is a heat loss difference of approximately 6W between the simple wood casing, and the design with an air gap. The steel layer did very little to reduce heat loss. Since 1W = 3.4 BTU/hr and the device has a theoretical output of 22000BTU/day, this loss is negligible compared to the complexity associated with the construction of an air gap.

5.1.2 Individual Analysis: Fan Optimization

Some assumptions will be made to simplify the calculations for the fan sizing. First, the heat production will be considered uniform across the inside of the solar furnace. Second, the heat produced will be considered constant. Finally, the interior of the home and ambient conditions outside it will be considered constant. This analysis only details the optimal air flow rate through the solar furnace and not heating efficiency or sizing as it relates to the home. Third, an outside temperature of 30 degrees Fahrenheit will be used to calculate the heating energy needed for the home. This is not the lowest daytime temperature in Flagstaff but would allow the solar furnace to be the main heating source during the day for most of the year. Last, the current commercial solar furnace used by Red Feather will be used as a baseline for heat production capability as the team's goal is to meet the same production capability as it.

To find the flow rate for the furnace, the heat production and therefore difference in temperature from inlet to outlet must be considered. Most solar furnaces aim for a temperature increase of between 50 and 60-degrees Fahrenheit [10]. This is not because of efficiency, but what owners feel satisfied with. Air that is 50 degrees hotter than ambient feels hot to the touch and resembles the output of a space heater. Essentially it reassures the owner that the system is working. [10]. For this analysis the temperature difference will be 50 degrees Fahrenheit or about 28 degrees C or K. At these temperatures, the SOLARSHEAT 1500 GS outputs about 20,400 BTU/day to heat 750 square feet [11]. The model is about 3.5 ft by 7.2 ft to make about 25 square feet.

Equation 4 can be used to find heat rate where: $\dot{Q}$ is the heat rate
$\dot{m}$ is the mass flow rate
Cp is the specific heat of air
ΔT is the difference in inlet and outlet temp

$$\dot{Q} = \dot{m}\ Cp\ \Delta T \quad \text{Equation 4 [6]}$$

Equation 1 can be rearranged to solve for the mass flow rate as shown in equation 5.

$$\dot{m} = \frac{\dot{Q}}{Cp\,\Delta T} \text{ Equation 5 [6]}$$

The flow rate can then be found using equation 6. Where: Q is the flow rate
ρ is density

$$Q = \frac{\dot{m}}{\rho} \text{ Equation 6 [6]}$$

The current prototype for the team is expected to be about 4 ft by 8 ft for 32 square feet (1.28 the size of the SOLARSHEAT). With the assumption that the team has met the SOLARSHEAT'S capability this would generate 26,112 BTU/day. Assuming 12 hours of sunlight per day:

Then using equation 2 the mass flow rate can be calculated as 0.058 kg/s. And equation 3 can be used to find the flow rate to be 0.0477 m^3/s which is about 101 ft^3/min. These numbers are like those of found commercial models which should allow for and ideal flow rate of heat through the system. The fan does not need to be perfectly rated for 101 cubic feet per minute as a slightly faster flow rate will still conduct the same heat energy into the home, just at lower temperature.

5.1.3 Individual Analysis: Solar Technology

There are many ways for people to obtain power such as burning fossil fuels and wind power. Solar energy is a great way for people to power their homes due to the carbon-free and renewable energy produced. Photovoltaic cells convert radiation from the sun into electricity. [12] Radiation is defined as energy transfer through electromagnetic waves. [13] The heat must be absorbed through an absorber material such as aluminum covered with a Kynar layer which produces a solar absorbance of 91.5%. [14]

Solar power allows people who live off the electricity grid to have power. For people who live on the power grid, the excess energy flows back into the power grid. Photovoltaic cells are made of semi-conducting material such as silicon and establish an electric field. Phosphorous is also added to the silicon for more electrons to add more negative charge. The element boron is added to the bottom layer of a solar panel to create more positive charge. This configuration is the main way that solar panels conduct electricity. In addition, conductive plates made from metal collect the electrons to move them through the wires.

Solar thermal power plants generate electricity like photovoltaic panels. Concentrating solar thermal technology is used by solar power plants. Solar power plants produce a much larger scale of energy. The power plants use the solar power to heat a fluid which then produces steam that produces electricity. [12] In solar thermal technology, energy from the sun is used to heat an engine, which then powers a generator that makes electricity. [15] Solar thermal energy is different from photovoltaic because solar thermal involves heating a fluid while photovoltaic directly changes the sun's energy to electricity. The advantage of using solar thermal energy versus photovoltaic energy is that storage of energy is possible. The heat is stored in a working fluid. The advantage of photovoltaic energy is that it is simpler for small scale houses, easier to manufacture, and is much cheaper. The team's main goal is to heat a home as shown in the black box diagram. After analyzing both solar thermal and photovoltaic, it was feasible to go with

photovoltaic and not store any heat. Photovoltaic would be the cheaper and more realistic option [15].
It is also important to consider how heat is produced and lost in a typical home. This includes analyzing the heat in situations such as how many people are in the home and their activities that make them produce more heat. According to Egan, in his work of "Concepts of Thermal Comfort", walking upstairs produces 4400 Btu/H of body heat versus only 300 Btu/H of body heat while sleeping. A more thorough analysis will give the team a better idea of how much power the solar furnace would have to produce to comfortably heat a home.[16]

5.2 Implementation Plan

Going forward with the completed CAD model and bill of materials the team will construct a full-size prototype of the design. During the construction process the team will create detailed instructions on how to best construct the device to ensure optimal performance for Red Feather. After the creation of the prototype is will be tested as described in section 3 to ensure that it meets all customer needs and engineering requirements.

5.2.1 Bill of Materials

The main resources outside of the Bill of Materials in table 8 are basic power tools. Red Feather will do all manufacturing in house to reduce cost. Due to the varying need and scale of production, vendors chosen are mainly hardware stores like Home Depot, Lowes, and Harbor Freight, and online stores such as Amazon. Bulk purchasing from suppliers remains an option for Red Feather to investigate should their production rate ever increase. Due to selecting readily available materials, there is much leftover material after creating an individual solar furnace. Reusing these leftovers would decrease production costs for building multiple units.

Table 8: Bill of Materials

Part	Qty	Price	Subtotal	Source
2"x4"x10' Pressure Treated Wood	3	$11.77	$35.31	https://www.lowes.com/p
2'x4' Plexiglass	4	$28.58	$114.32	https://www.lowes.com/p
2'x12' Galvalume Roofing Panel	2	$26.98	$53.96	https://www.lowes.com/p
Fan	1	$26.05	$26.05	https://www.boatid.com/a
Aluminum Plates	5	$21.98	$109.90	https://www.homedepot.c
Solar Panel	1	$64.99	$64.99	https://harborfreight.com/
Ducting 4" x 12'	1	$18.77	$18.77	https://www.homedepot.c
Heat resistant Caulk	1	$12.99	$12.99	https://www.homedepot.c
Wood screws 50pk	1	$3.44	$3.44	https://www.walmart.com
Arduino	1	$20.50	$20.50	https://www.amazon.com
Thermocouples	2	$8.74	$17.48	https://www.amazon.com
	Solar Furnace Total		$477.71	

5.2.2 CAD Model

The team's current CAD model shown in figures 7 and 8 will be used to create the prototype to be tested. All dimensions are accurate to the full-scale model and reflected in the Bill of Materials. The CAD model will be used to create the initial set of instructions to create the solar furnace, which the team can amend as they create the full-scale prototype. The exploded view of the model, as well as a simple BOM explaining the components from the exploded view, can be seen below in figures 7 and 8 This dimensioned model can be found in Appendix B (figure B.1) and is dimensioned in millimeters. Each of the part drawings for this assembly be found in Appendix B as well (Figures B.2 through B.10).

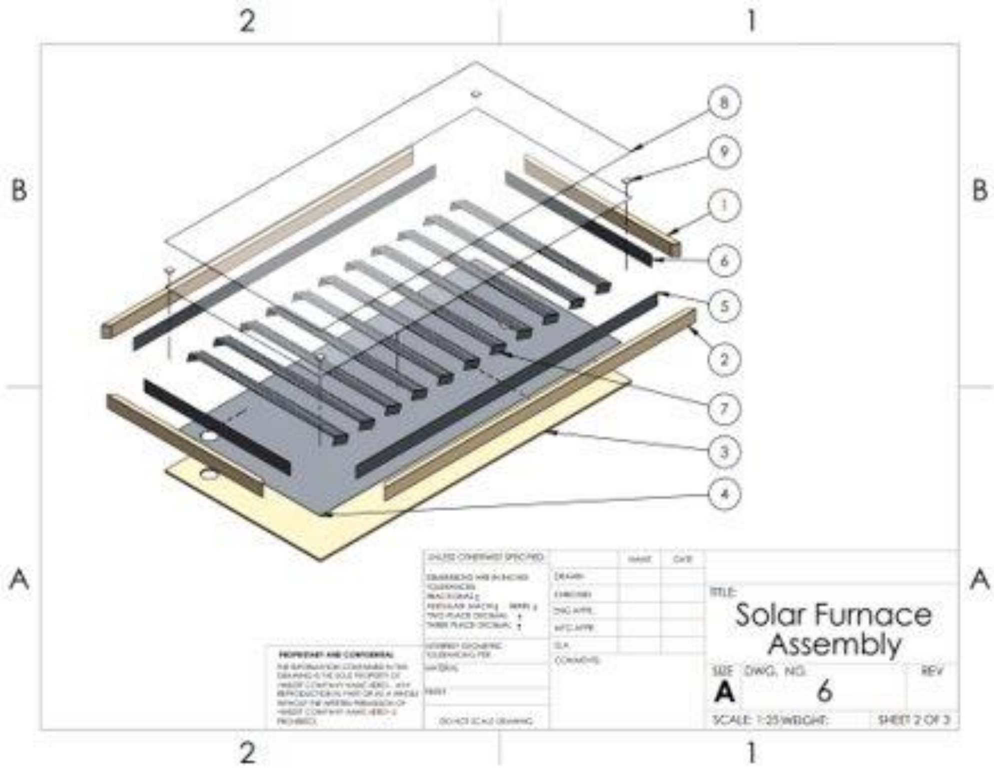

Figure 7: Exploded View of CAD Model

Figure 8: Assembly View of CAD Model

5.2.3 Implementation Schedule

The schedule for the rest of the project is as follows
The schedule and Gannt chart for semester 1 is shown in appendix E. The second semester schedule is shown in table 9. The first task is to start testing the NAU Capstone of 2018-2019 Solar Furnace and any of the other benchmarked solar furnaces. Research analysis will be conducted to test the strength of the materials in the solar furnace or any other research that needs to be further investigated. The Gannt chart shows how long each task should take in corresponding order from table 9. The final product is expected to be completed October 19, 2020. The final CAD package and final report will be completed before December 10, 2020.

Table 9: Semester 2 Schedule

Name	Begin date	End date
Testing of NAU Capstone 2018-2019 and other solar p...	8/24/20	9/11/20
Post mortem(Reflection of first semester)	8/24/20	9/1/20
Self-Learning	8/31/20	9/8/20
Start Building Prototype	8/31/20	9/18/20
Individual Anlaysis 2	9/14/20	10/1/20
Research Individual Topic	9/14/20	10/1/20
Research Individual Topic	9/14/20	10/1/20
Research Individual Topic	9/14/20	10/1/20
Start Building Final Project	9/21/20	10/19/20
Testing Final Product: Procedure 1	10/27/20	10/28/20
Order all necessary materials for testing procedur...	10/27/20	10/27/20
Set up testing apparatus for testing procedure 1	10/28/20	10/28/20
Conduct Testing Procedure 1	10/28/20	10/28/20
Testing Procedure 2: Noise Level	10/29/20	10/30/20
Order necessary equipment for Procedure 2	10/29/20	10/29/20
Set up testing apparatus	10/30/20	10/30/20
Use decibel reader to conduct testing procedure 2	10/30/20	10/30/20
Final Report	11/27/20	12/10/20
CAD package	11/27/20	12/10/20

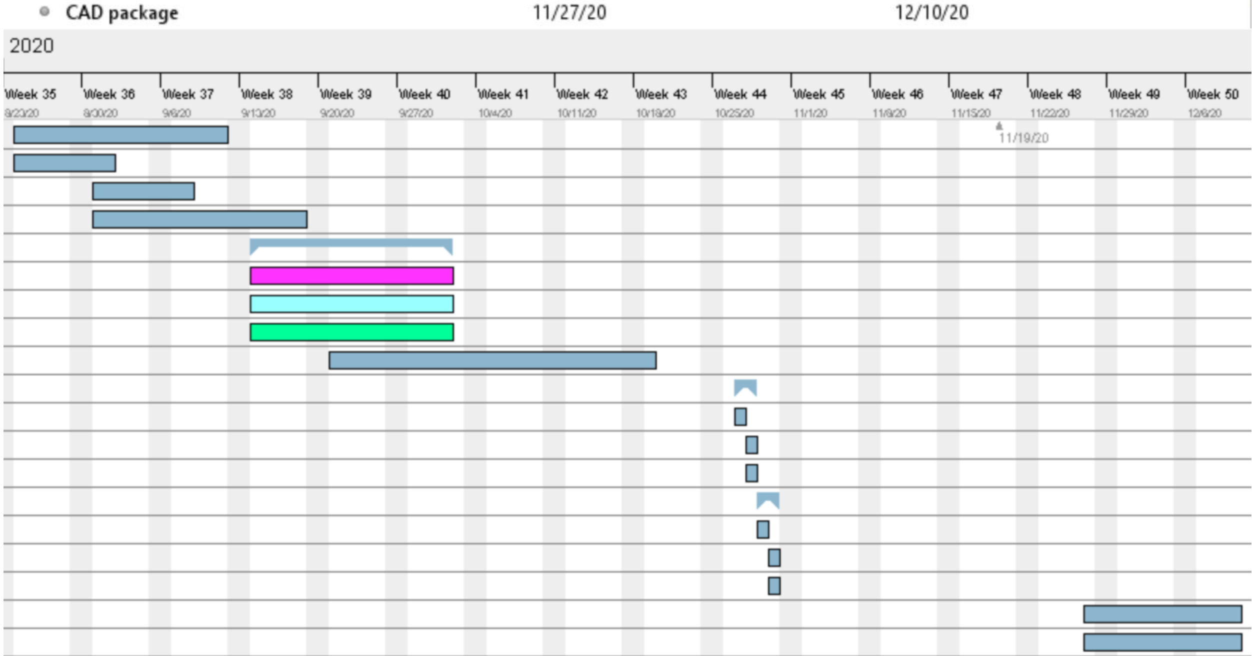

Figure 9: Semester 2 Gannt Chart

6 CONCLUSIONS

Through iteration and the utilization of design techniques learned in a multitude of engineering courses, Team Red Feather has settled on a final design for a renewable, and affordable, solar furnace. This report has outlined the design of this furnace as well as each step taken to arrive at this design. The next steps for this project will be the actual construction of the model and the testing of said model against current industry leading designs. Through creation of the prototype, a detailed construction manual will be developed further. Construction will also help to shape the design to make it as manufacturable as possible. Testing will refine the design to make it truly usable device, and comparable to models from manufacturers such as Arctica Solar and Your Solar Homes. This device, a continuation of the design from a previous capstone team, should result in an affordable, mass producible, solar furnace that will greatly improve the heating capabilities of some of the less fortunate residents of the Navajo Nation.

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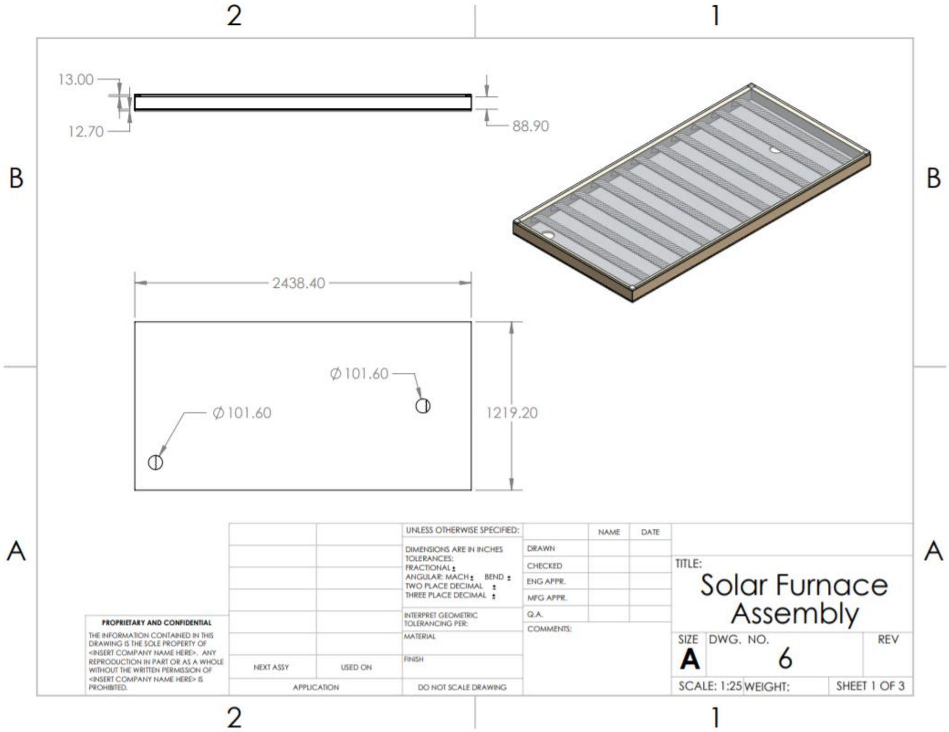
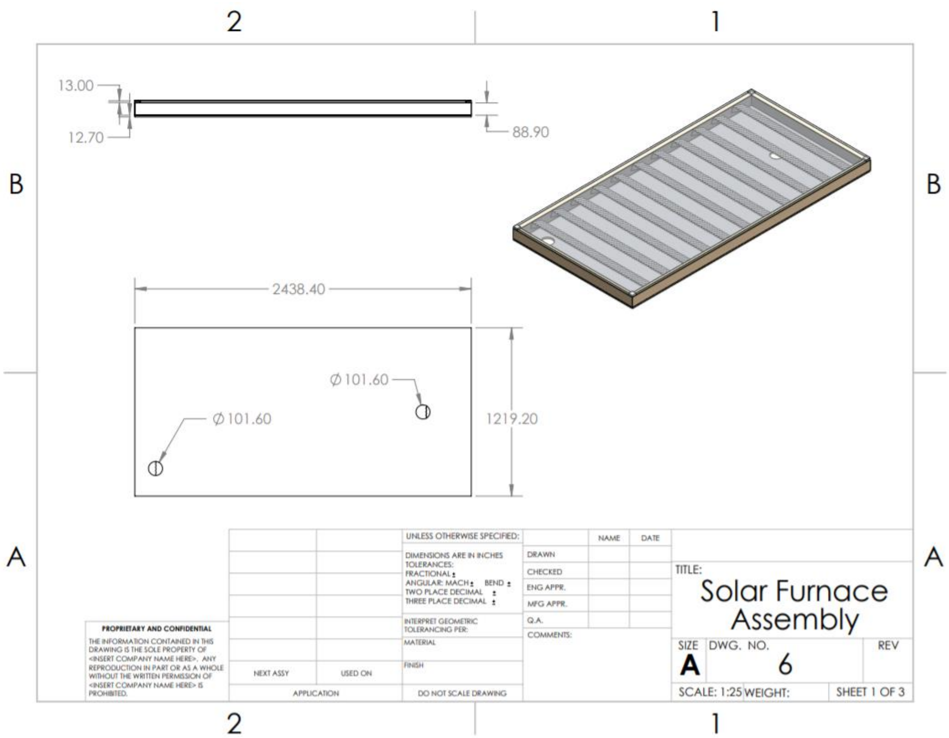
8 APPENDICES

8.1 Appendix A: FMEA

Part	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Causes and Mechanisms of Failure	Occurance (O)	Current Design Controls Test	Detection (D)	RPN	Recommended Action
Mounting Bracket	Misalignment	Detachment from mounting surface; furnace breaks from fall; injury to someone in the viscinity.	8	Inclement weather; wildlife interference; vandalism.	2	Extra flat plate brackets.	6	96	Check bracket once per month.
	Hook breakage	Detachment from mounting surface; furnace breaks from fall; injury to someone in the viscinity.	8	Inclement weather; wildlife interference; stress due to weight of system; vandalism.	2	multiple hooks per bracket	6	96	Check bracket once per month.
DC Fan	General failure	Lack of air flow; overheating of system; reduced temperature in the home.	7	Manufacturer error.	2	Hot air coming out of vents.	6	84	Check fan once per month. Check that hot air is coming out of vents each day.
	Heat damage	Lack of air flow; overheating of system; reduced temperature in the home.	7	cyclical stress from use.	3	Hot air coming out of vents.	6	126	Check fan once per month. Check that hot air is coming out of vents each day.
Solar Panel	General Failure	Lack of power to system; lack of air flow; overheating of system; reduced temperature in the home.	7	Manufacturer error.	2	Hot air coming out of vents.	6	84	Inspect solar panel once per month. Check that hot air is coming out of vents each day.
	Shattering	shattered glass on the ground below the furnace; lack of power to system; lack of air flow; overheating of system; reduced temperature in the home.	7	Inclement weather; wildlife interference; vandalism.	2	Hot air coming out of vents.	6	84	Inspect solar panel once per month. Check that hot air is coming out of vents each day.
Thermostatic Controller	General failure	Lack of air flow; overheating of system; reduced temperature in the home.	7	Manufacturer error.	2	Analog thermometer. Hot air coming out of vents.	6	84	Check the analog thermometer once per month. Check that hot air is coming out of vents each day.
	Heat damage	Lack of air flow; overheating of system; reduced temperature in the home.	7	cyclical stress from use.	3	Analog thermometer. Hot air coming out of vents.	6	126	Check the analog thermometer once per month. Check that hot air is coming out of vents each day.
	Calibration error	Air flow at the incorrect temperature; overheating of the system; reduced temperature in the home	7	Manufacturer error; calibration mistake during pre-install testing.	3	Analog thermometer. Hot air coming out of vents.	6	126	Check the analog thermometer once per month. Check that hot air is coming out of vents each day.
Wiring	General failure	Lack of air flow; overheating of system; reduced temperature in the home.	7	Manufacturer error.	2	Hot air coming out of vents.	6	84	Have second person double check wiring.
	Installation error	Lack of air flow; overheating of system; reduced temperature in the home.	7	Improper installation technique; not double checking work.	3	Hot air coming out of vents.	6	126	Have second person double check wiring.
	Heat damage	Lack of air flow; overheating of system; reduced temperature in the home.	7	Cyclical stress from use.	3	Hot air coming out of vents.	6	126	Have second person double check wiring.
Wood Screws	Breakage	Detachment from mounting surface; furnace breaks from fall; detachment of components from whole system; breakage of component from fall; injury to someone in the viscinity.	6	Manufacturer error; incorrect installation; incorrect screw sizing.	1	Standardized installation mehtod. Strength test of chosen screws. Use of adhesive.	6	36	None
	Hole strippage	Detachment from mounting surface; furnace breaks from fall; detachment of components from whole system; breakage of component from fall; injury to someone in the viscinity.	6	Incorrect installation (too large of pre-drilled hole); incorrect screw sizing.	2	Standardized installation mehtod. Use of adhesive.	6	72	None
Silicon Adhesive	Heat Damage	detachment of components from whole system; breakage of component from fall; injury to someone in the viscinity.	5	Cyclical stress from use.	3	Standardized quantity for application. Use of screws.	7	105	Test cyclical response to heat.
	Quanity misestimate	detachment of components from whole system; breakage of component from fall; injury to someone in the viscinity.	5	Incorrect application of adhesive.	2	Standardized quantity for application. Use of screws.	7	70	None
Paint coating	Heat damage	Reduced heat generation; paint residue entering the home causing health risks.	7	cyclical stress from use; incorrect paint type.	2	Heat resisitant paint. Multiple layers	7	98	Test cyclical response to heat. Switch to powder coating if needed.
	Light damage	Reduced heat generation; paint residue entering the home causing health risks.	7	cyclical stress from use; incorrect paint type.	1	UV resisitant paint. Multiple layers	7	49	Test cyclical response to light. Switch to powder coating if needed.
Plexiglass damage	Shattering	Increased risk of damage to interior components; lack of heat generation; injury to somone in the visicnity of falling plexiglass pieces.	7	Inclement weather; wildlife interference; vandalism.	1	Thick guage plexiglass. Multiple panes.	5	35	Strength test against rocks/hail/beebees.

8.2 Appendix B: CAD Drawings





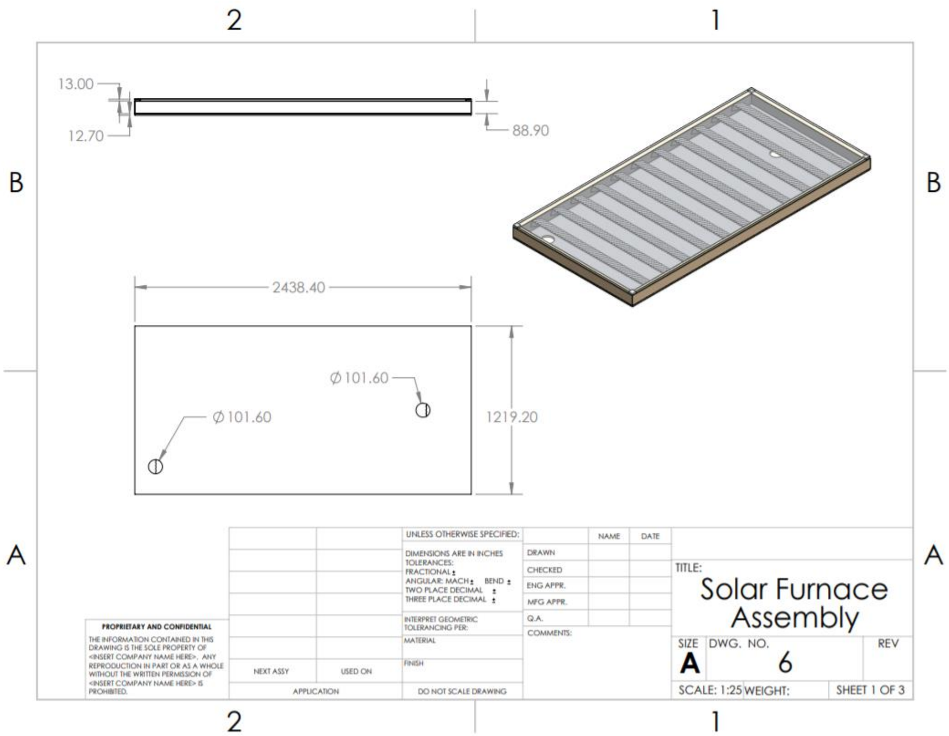
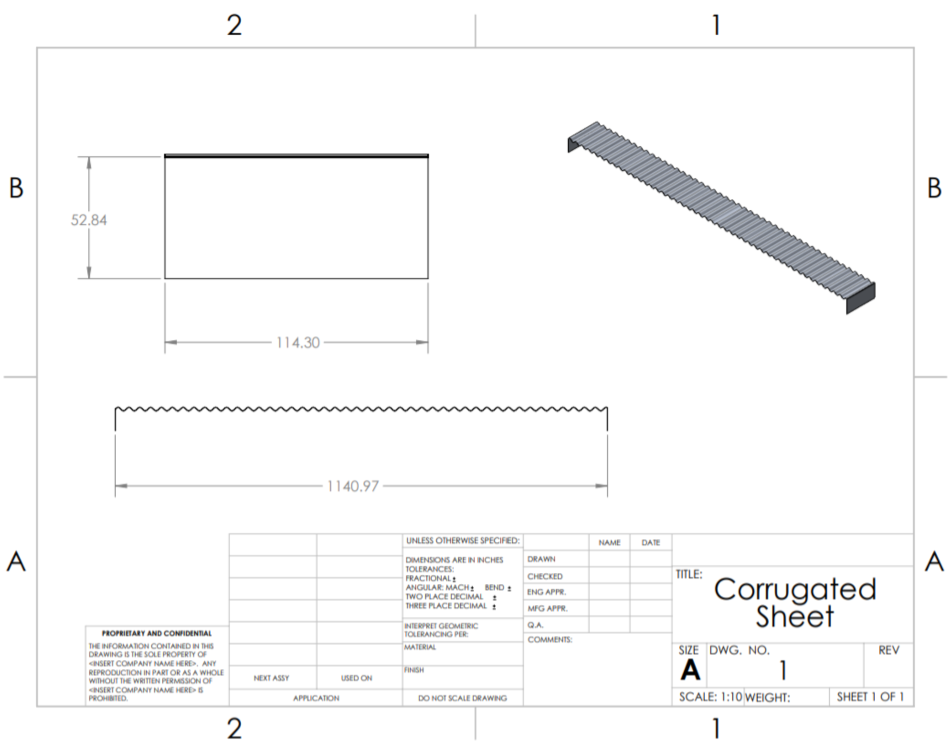


Figure B.1: Solar Furnace Assembly



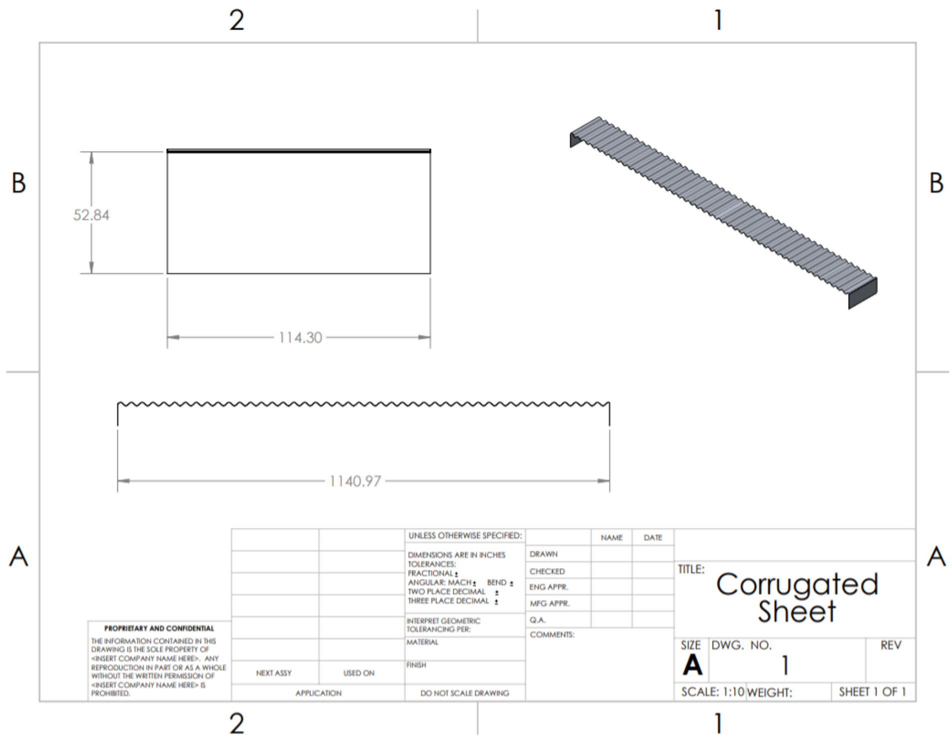
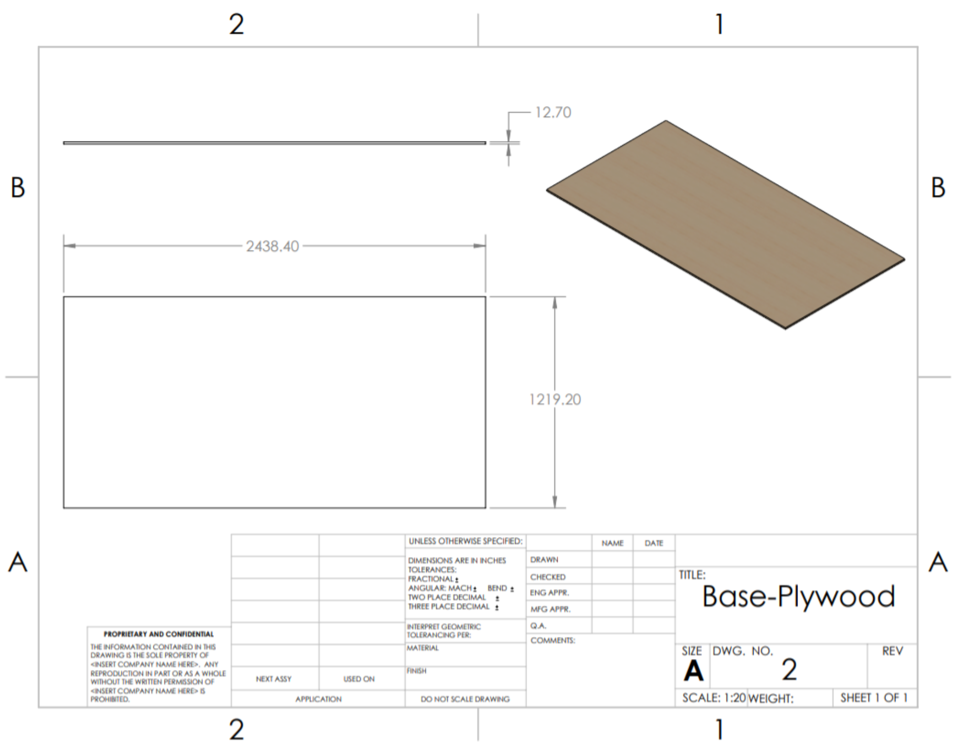


Figure B.2: Corrugated Sheet



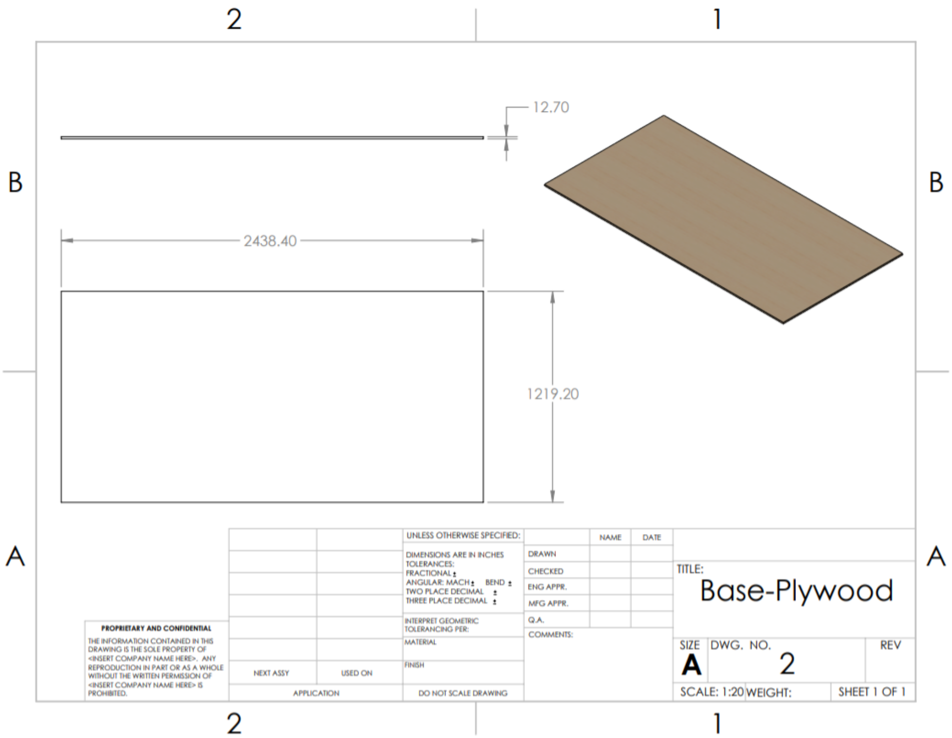
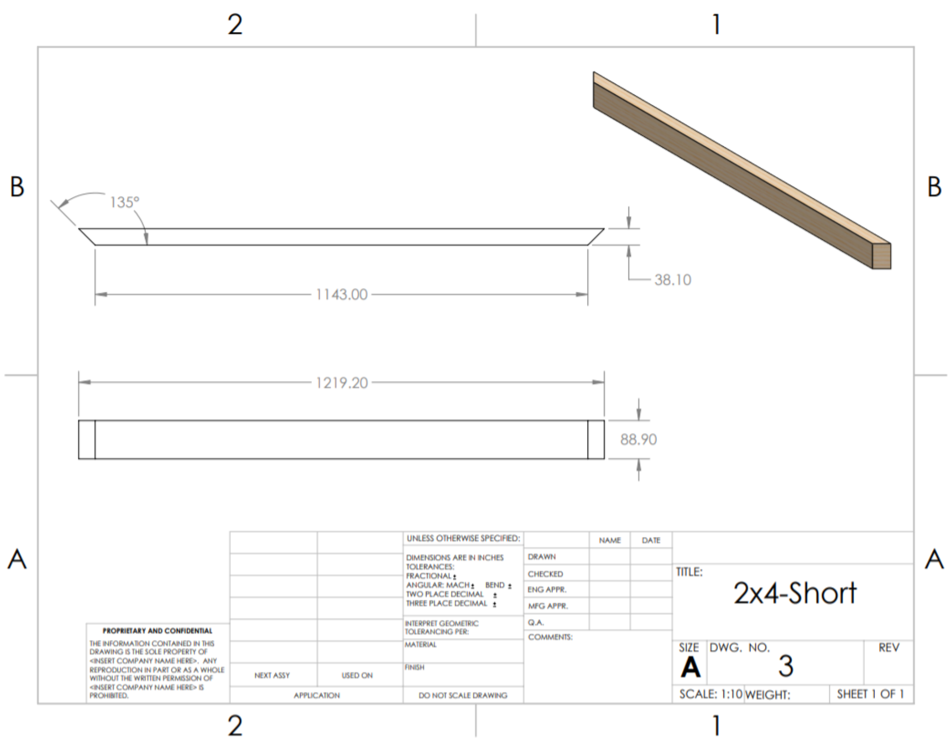


Figure B.3: Plywood base



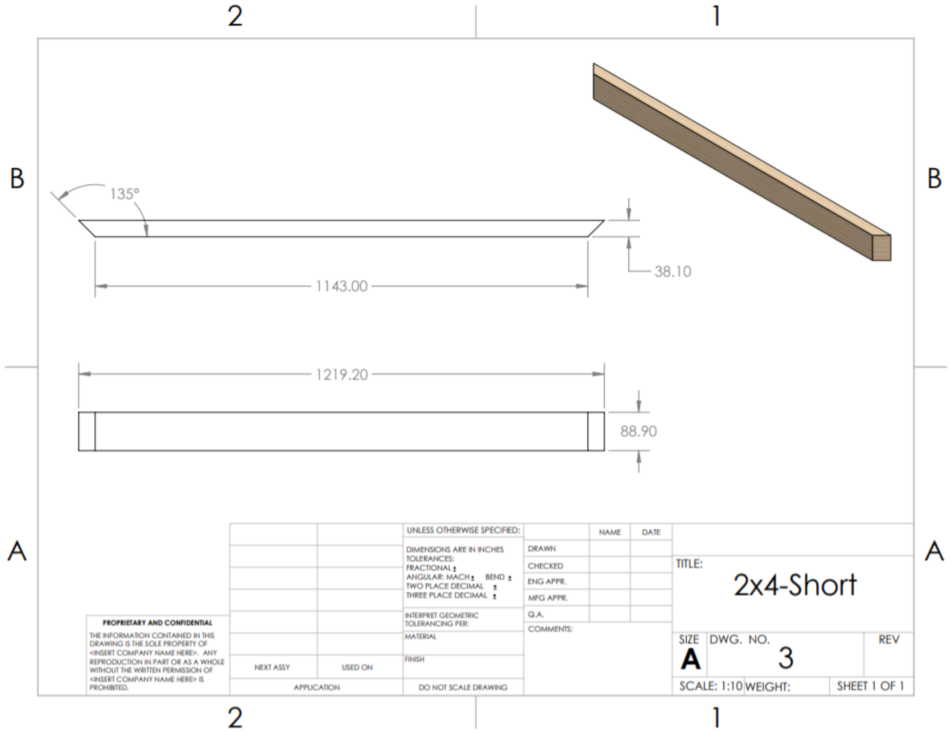
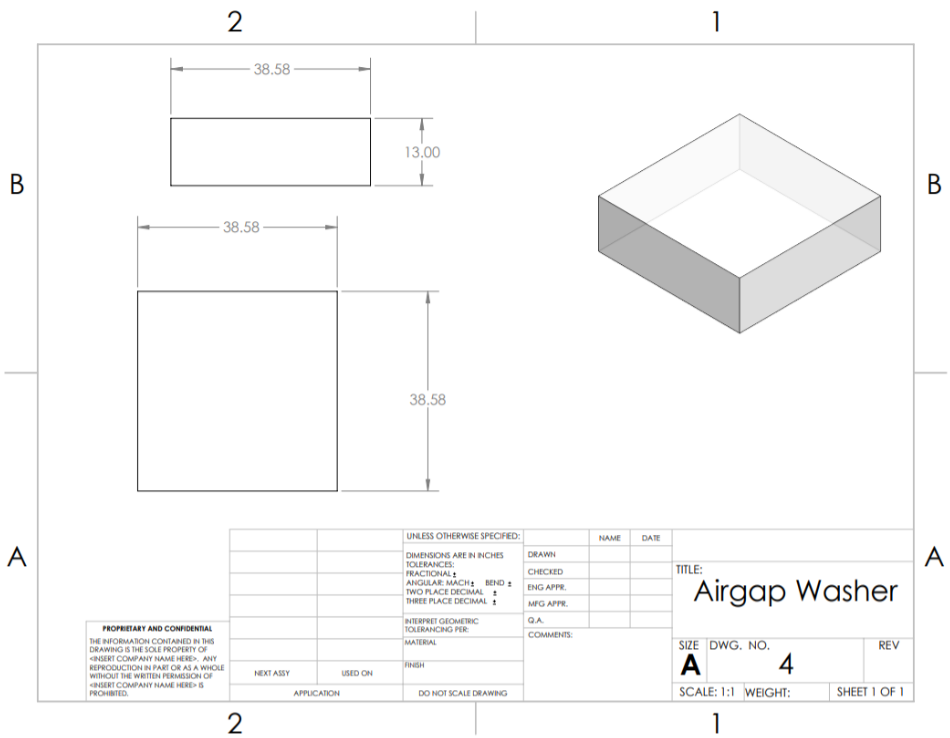


Figure B.4: 2x4- Short



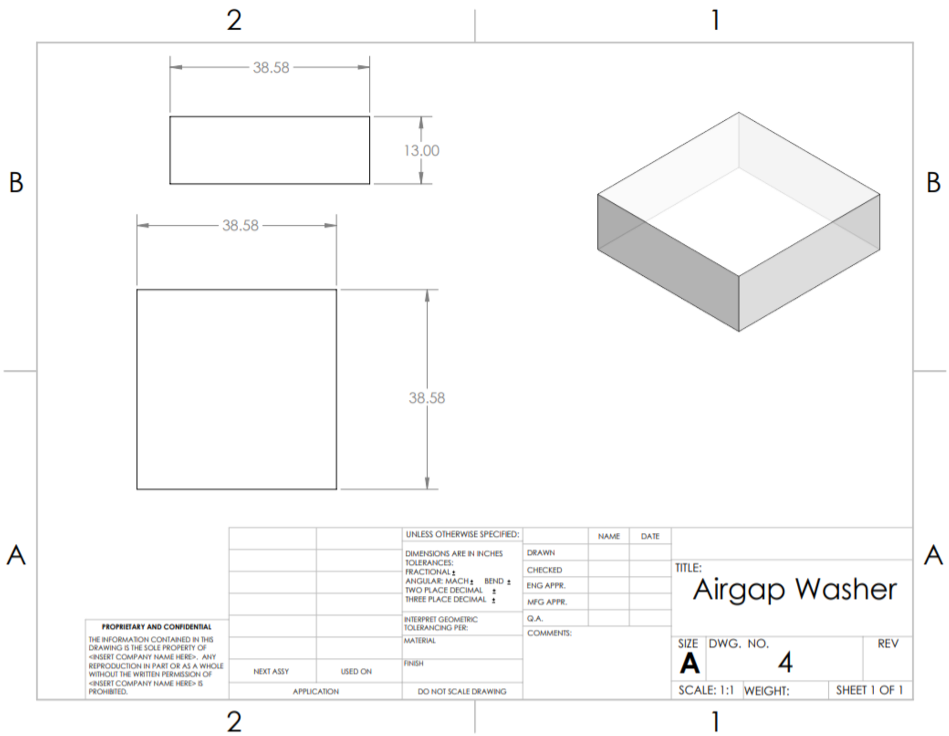
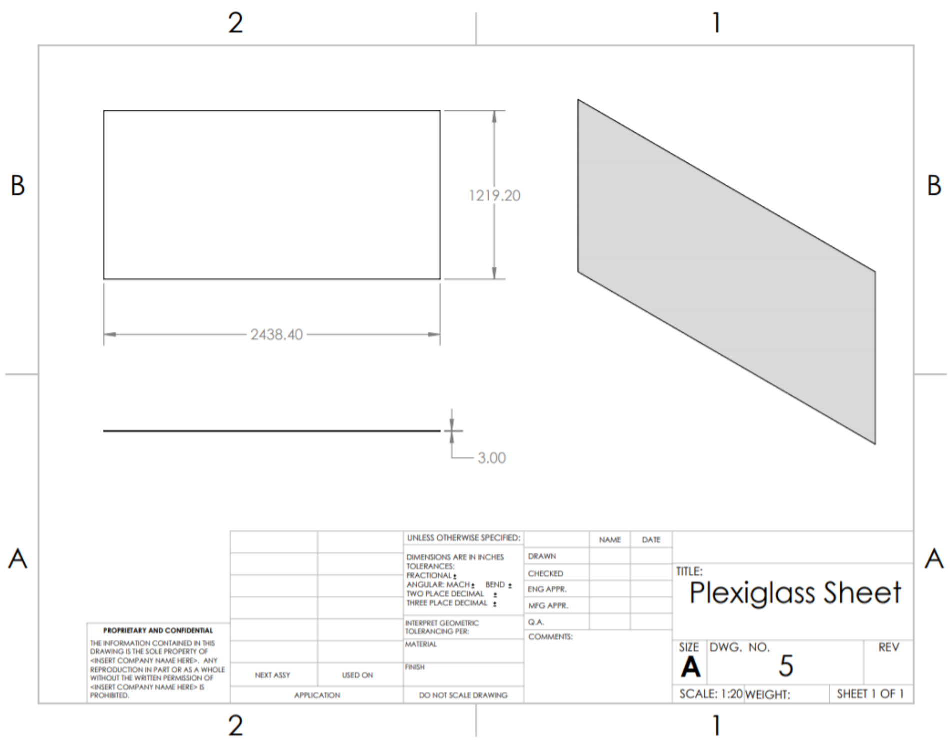


Figure B.5: Airgap washer



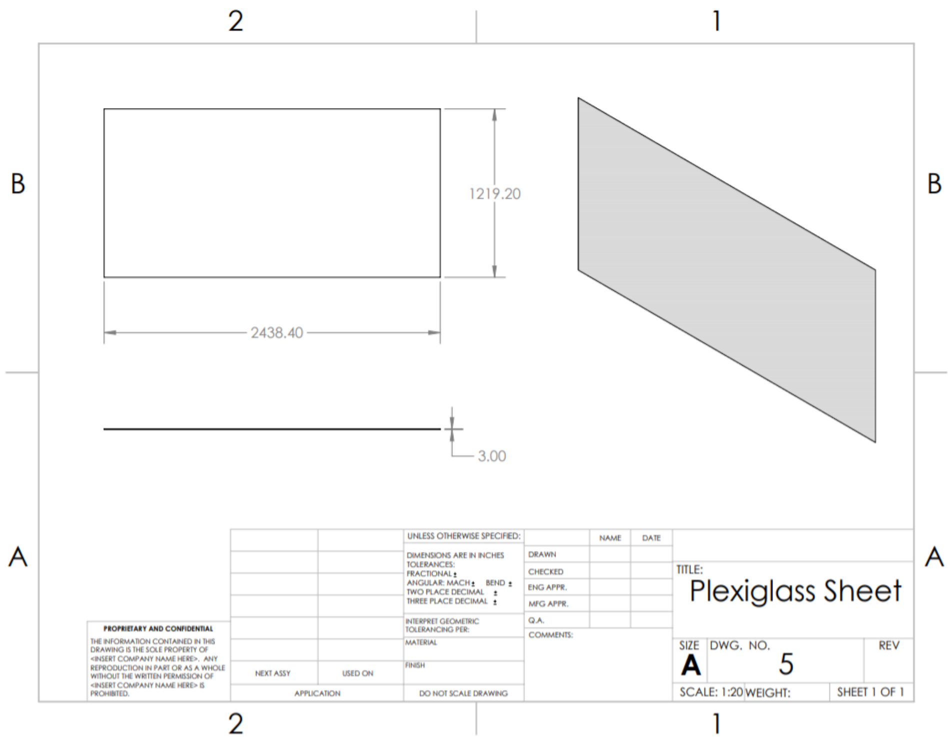
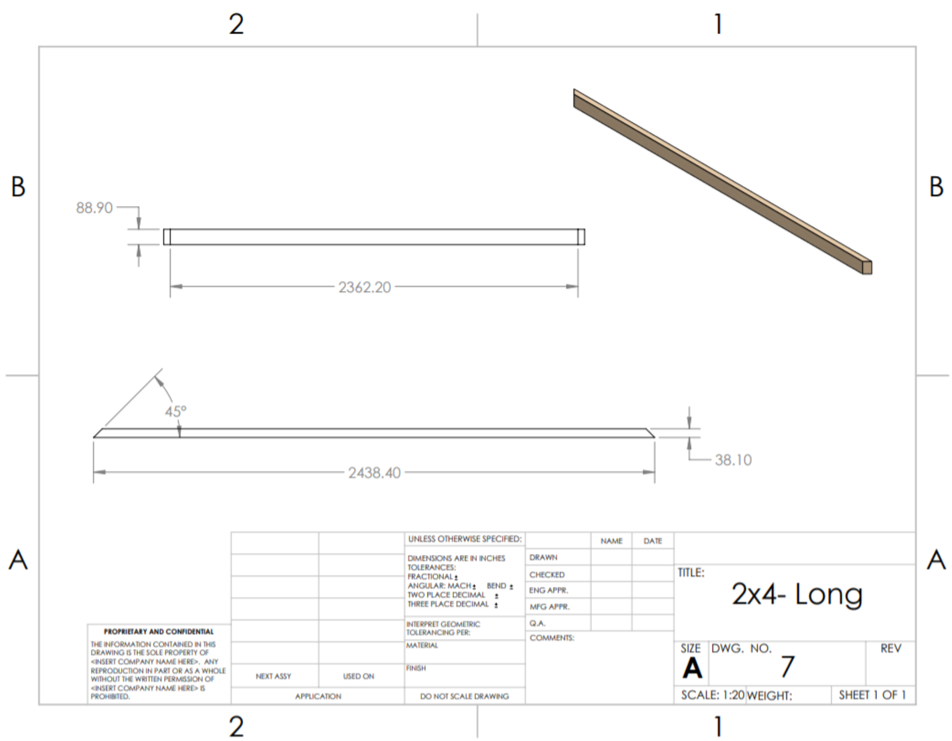


Figure B.6: Plexiglass sheet



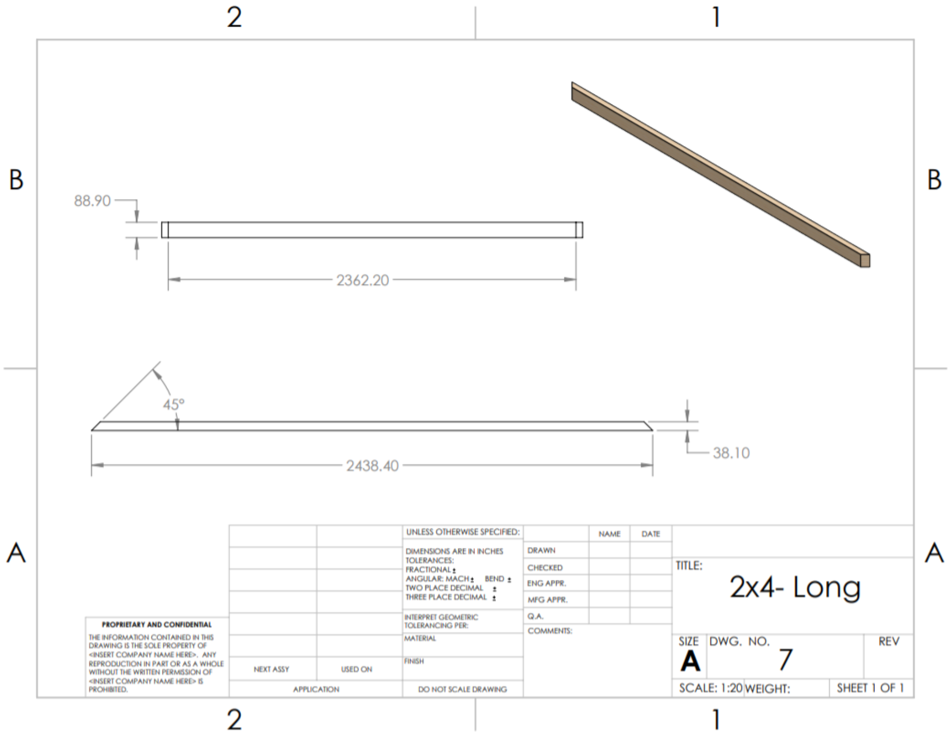
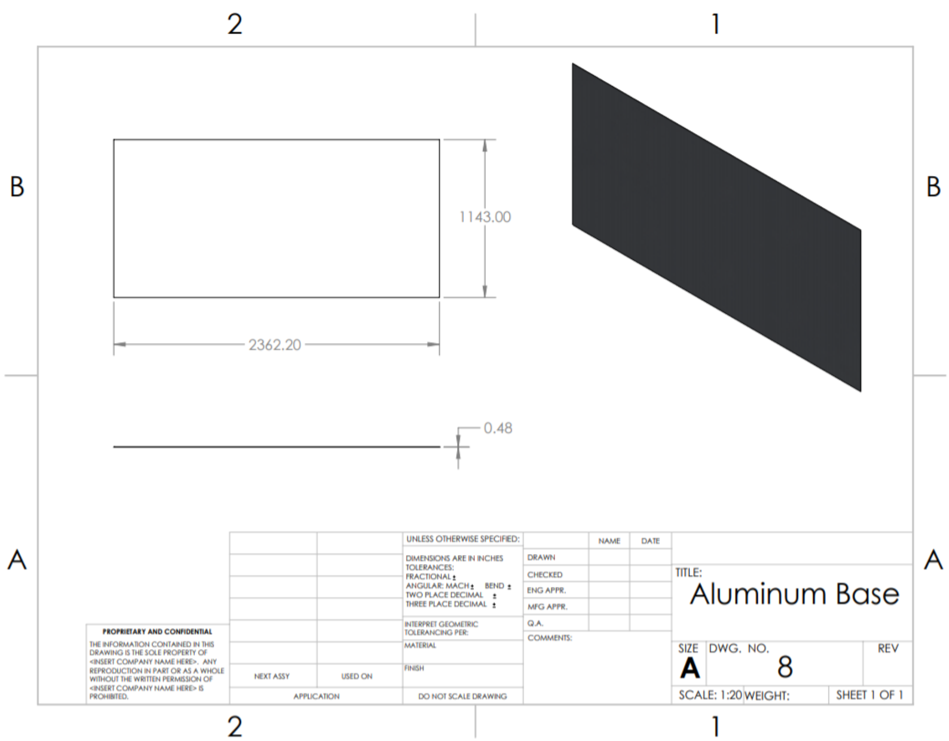


Figure B.7: 2x4- Long



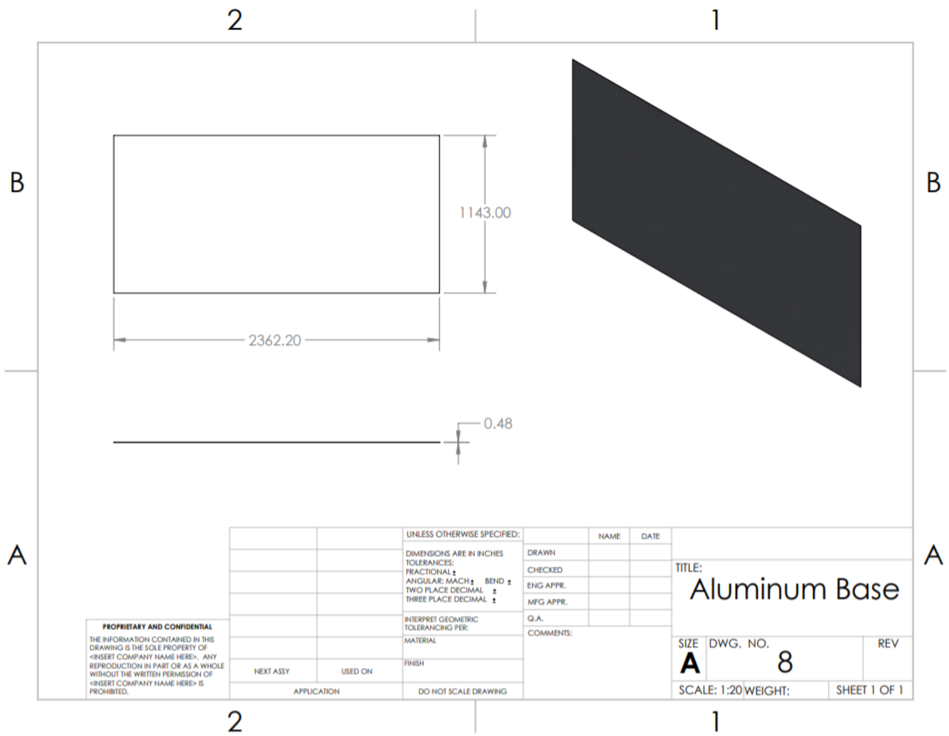
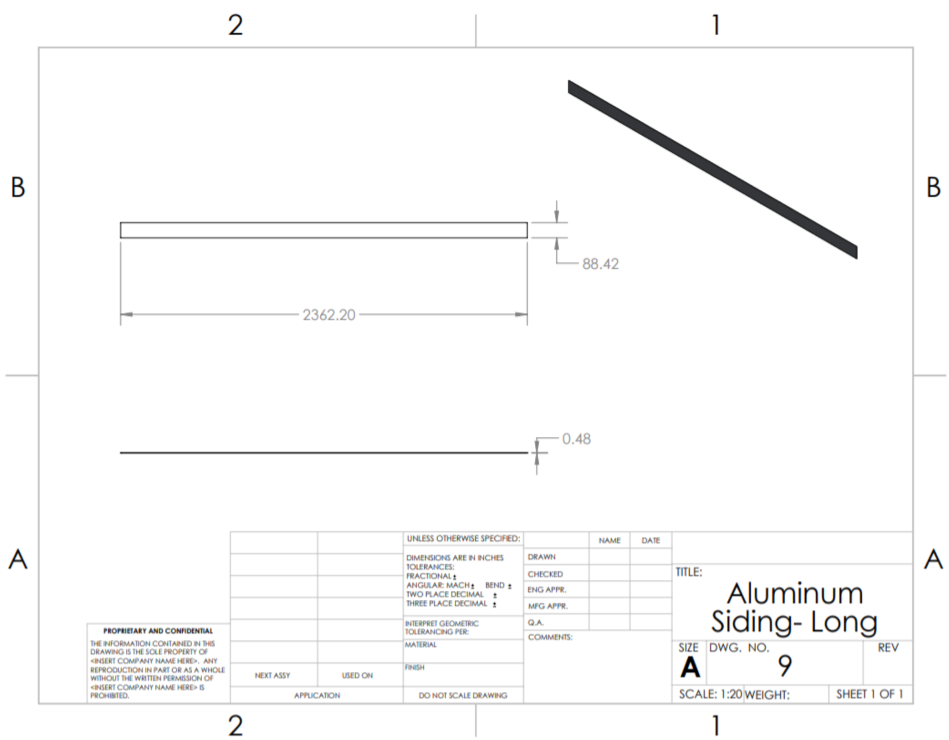


Figure B.8: Aluminum Base



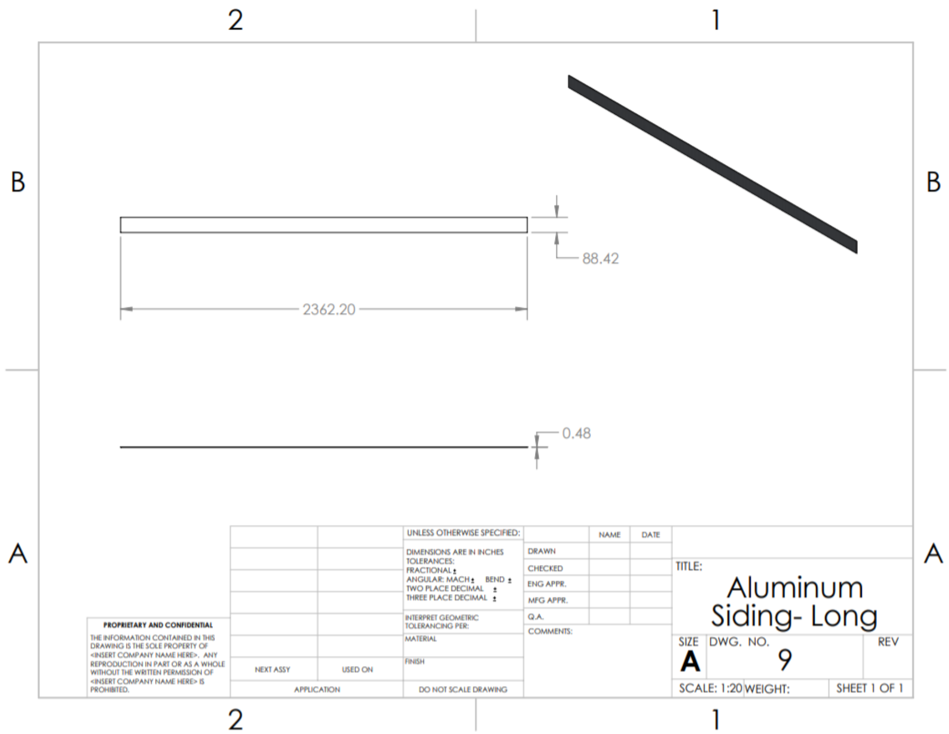
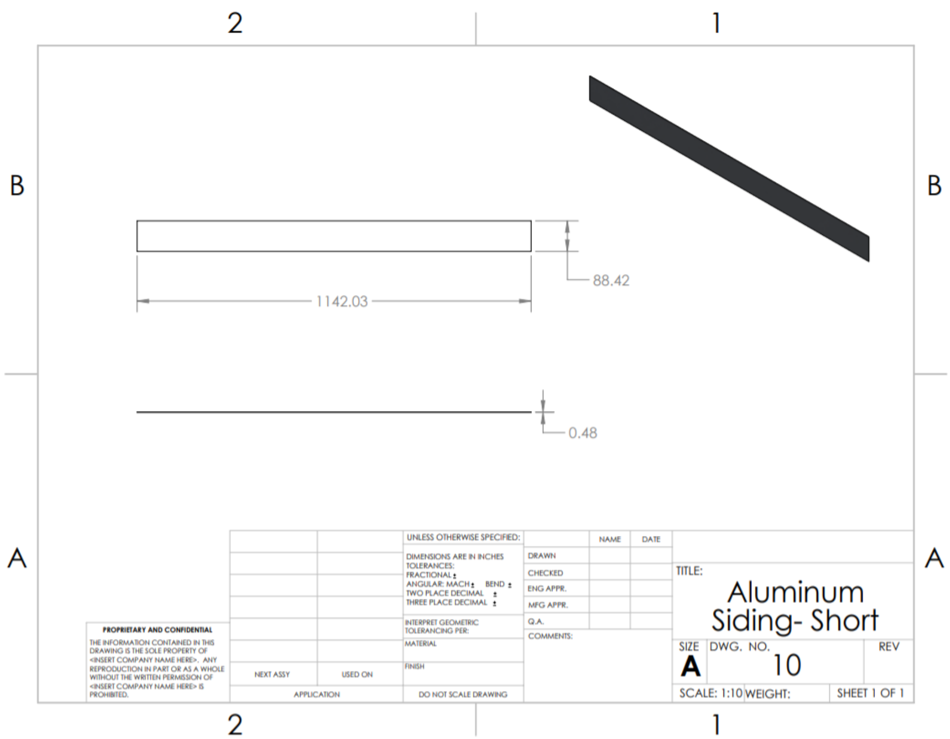


Figure B.9: Aluminum siding- Long



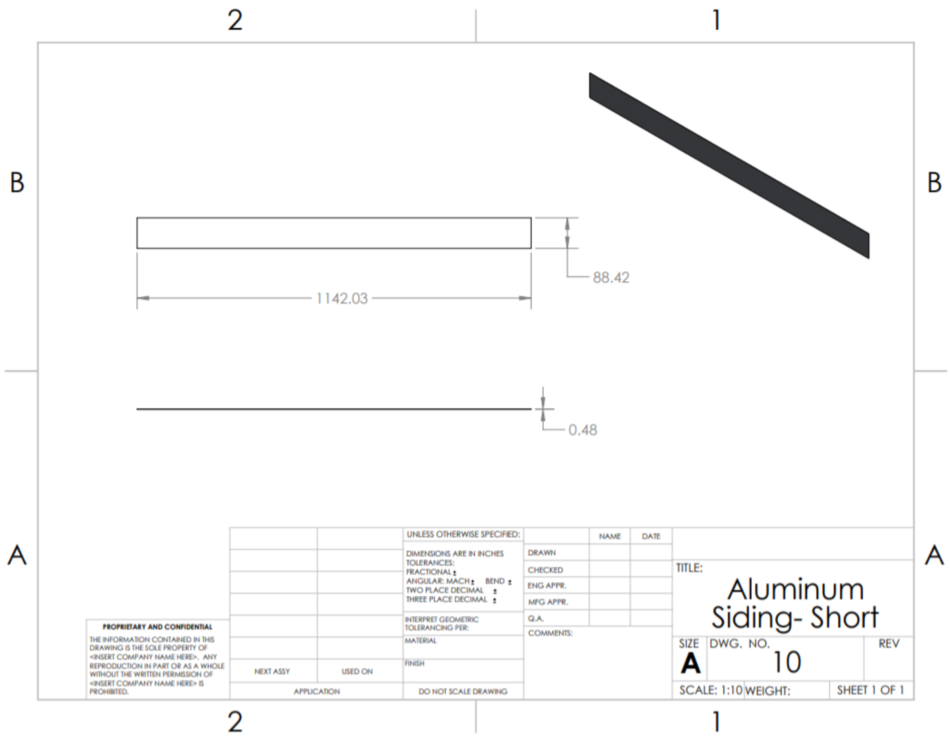
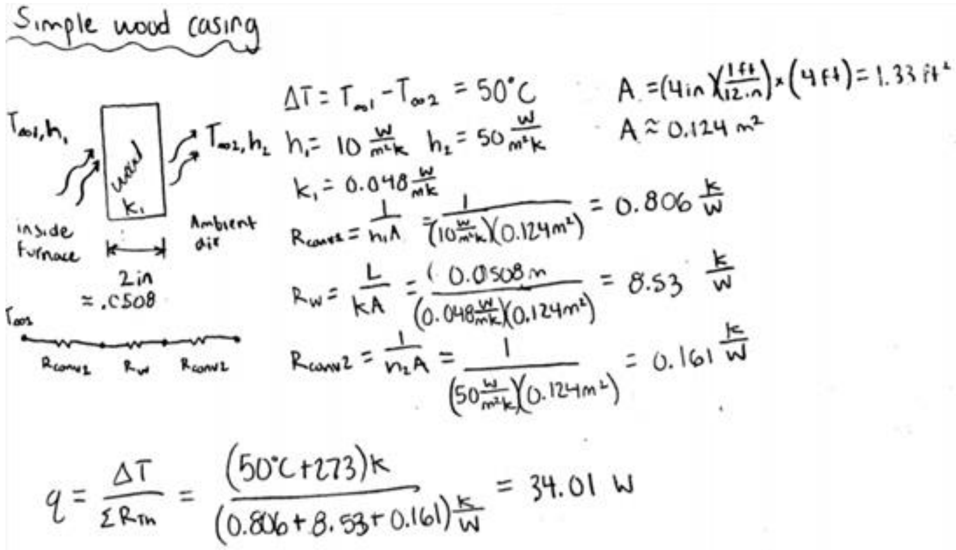
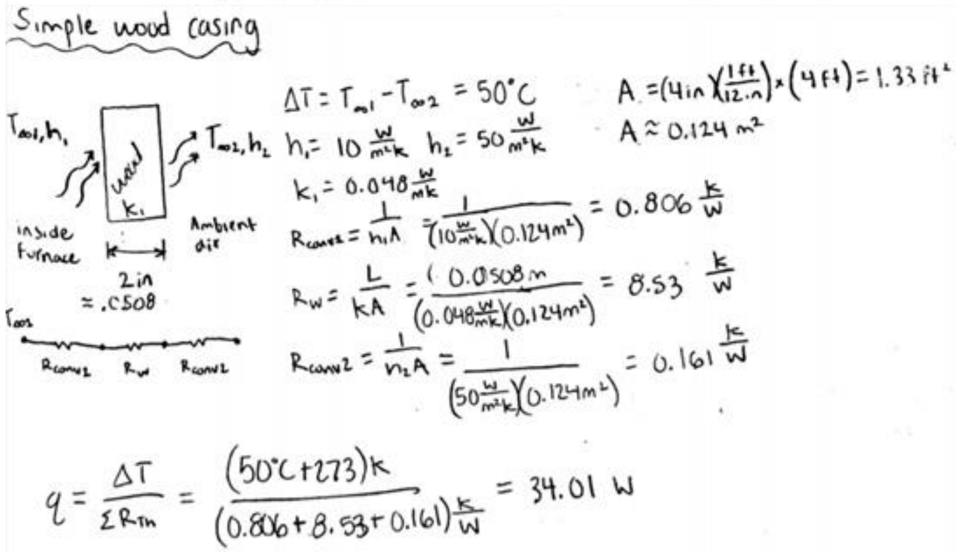


Figure B.10: Aluminum siding- Short

8.3 Appendix C: Design Selection

8.4 Appendix D: Engineering Analysis





Simple wood casing
$T_{\infty 1}, h_1$
$T_{\infty 2}, h_2$
wood
k_1
inside Furnace
Ambient air
2in ≈ .0508
$T_{\infty s}$
R_{conv1} R_w R_{conv2}
$\Delta T = T_{\infty 1} - T_{\infty 2} = 50°C$
$A = (4in)\left(\frac{1ft}{12in}\right) \times (4ft) = 1.33 ft^2$
$A \approx 0.124 m^2$
$h_1 = 10 \frac{W}{m^2K}$ $h_2 = 50 \frac{W}{m^2K}$
$k_1 = 0.048 \frac{W}{mK}$
$R_{conv1} = \frac{1}{h_1 A} = \frac{1}{(10\frac{W}{m^2K})(0.124m^2)} = 0.806 \frac{K}{W}$
$R_w = \frac{L}{kA} = \frac{(0.0508m)}{(0.048\frac{W}{mK})(0.124m^2)} = 8.53 \frac{K}{W}$
$R_{conv2} = \frac{1}{h_2 A} = \frac{1}{(50\frac{W}{m^2K})(0.124m^2)} = 0.161 \frac{K}{W}$
$q = \frac{\Delta T}{\Sigma R_{th}} = \frac{(50°C + 273)K}{(0.806 + 8.53 + 0.161)\frac{K}{W}} = 34.01 W$

Figure D.1: Simple wood casing calculations

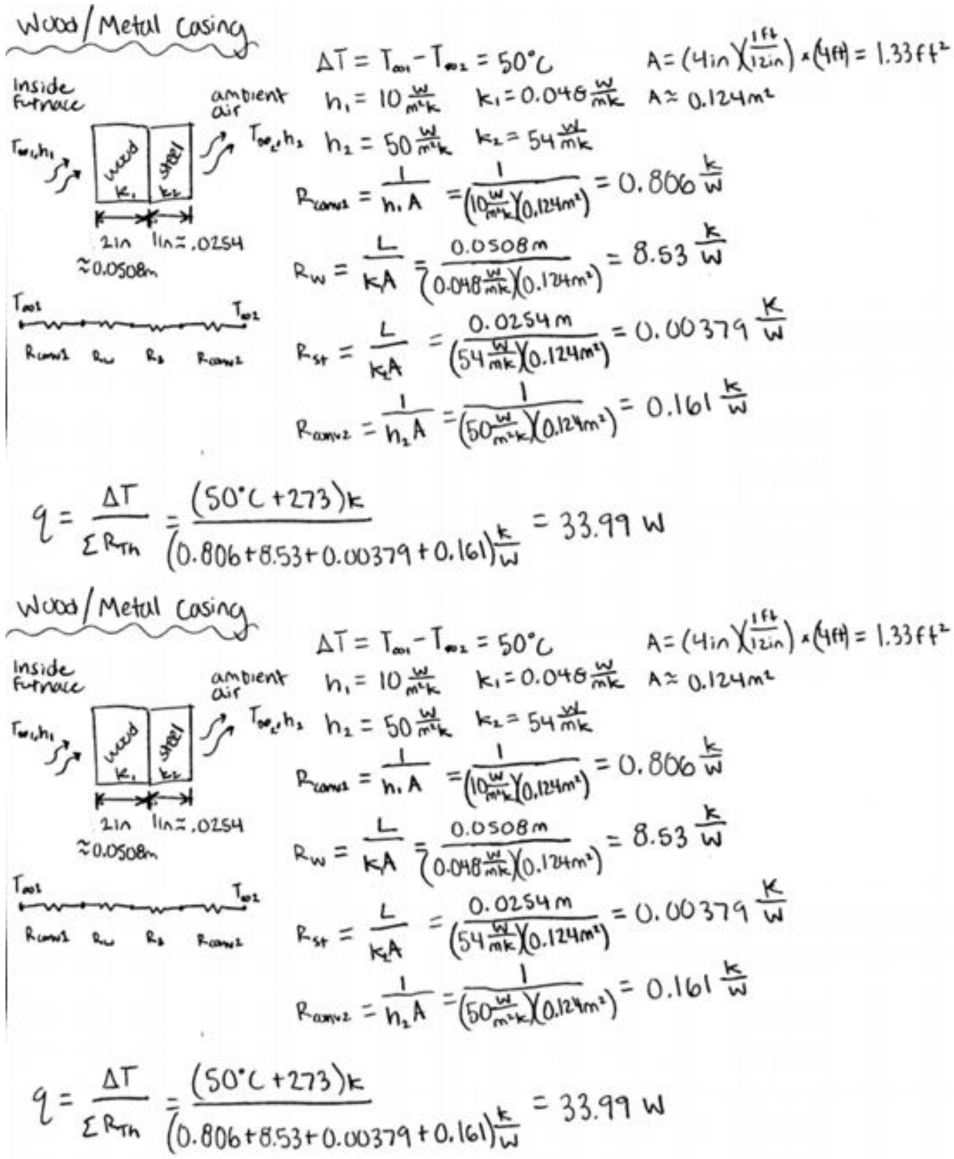
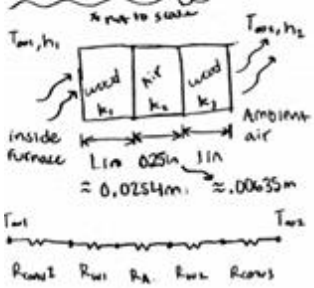


Figure D.2: Wood/Steel casing calculations

Wood Casing w/ Air Gap



$\Delta T = T_{\infty1} - T_{\infty2} = 50°C \quad A = (4in)\left(\frac{1ft}{12in}\right)(4ft) = 1.33\,ft^2 \approx 0.124\,m^2$

$h_1 = 10\frac{W}{m^2K} \quad h_2 = 50\frac{W}{m^2K}$

$k_1 = 0.048\frac{W}{mK} \quad k_2 = 0.025\frac{W}{mK} \quad k_3 = 0.048\frac{W}{mK}$

$$R_{conv1} = \frac{1}{h_1A} = \frac{1}{\left(10\frac{W}{m^2K}\right)(0.124m^2)} = 0.806\frac{K}{W}$$

$$R_{w1} = \frac{L}{k_1A} = \frac{0.0254m}{\left(0.048\frac{W}{mK}\right)(0.124m^2)} = 4.27\frac{K}{W}$$

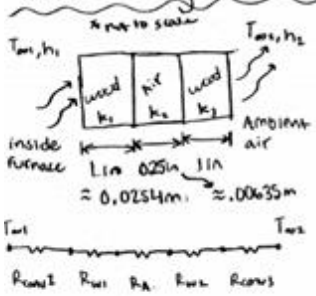
$$R_A = \frac{L}{k_2A} = \frac{0.00635m}{\left(0.025\frac{W}{mK}\right)(0.124m^2)} = 2.05\frac{K}{W}$$

$$R_{w2} = \frac{L}{k_3A} = \frac{0.0254m}{\left(0.048\frac{W}{mK}\right)(0.124m^2)} = 4.27\frac{K}{W}$$

$$R_{conv2} = \frac{1}{h_2A} = \frac{1}{\left(50\frac{W}{m^2K}\right)(0.124m^2)} = 0.161\frac{K}{W}$$

$$q = \frac{\Delta T}{\Sigma R_{th}} = \frac{(50°C + 273)K}{(0.806 + 4.27 + 2.05 + 4.27 + 0.161)\frac{K}{W}} = 27.95W$$

Wood Casing w/ Air Gap



$\Delta T = T_{\infty1} - T_{\infty2} = 50°C \quad A = (4in)\left(\frac{1ft}{12in}\right)(4ft) = 1.33\,ft^2 \approx 0.124\,m^2$

$h_1 = 10\frac{W}{m^2K} \quad h_2 = 50\frac{W}{m^2K}$

$k_1 = 0.048\frac{W}{mK} \quad k_2 = 0.025\frac{W}{mK} \quad k_3 = 0.048\frac{W}{mK}$

$$R_{conv1} = \frac{1}{h_1A} = \frac{1}{\left(10\frac{W}{m^2K}\right)(0.124m^2)} = 0.806\frac{K}{W}$$

$$R_{w1} = \frac{L}{k_1A} = \frac{0.0254m}{\left(0.048\frac{W}{mK}\right)(0.124m^2)} = 4.27\frac{K}{W}$$

$$R_A = \frac{L}{k_2A} = \frac{0.00635m}{\left(0.025\frac{W}{mK}\right)(0.124m^2)} = 2.05\frac{K}{W}$$

$$R_{w2} = \frac{L}{k_3A} = \frac{0.0254m}{\left(0.048\frac{W}{mK}\right)(0.124m^2)} = 4.27\frac{K}{W}$$

$$R_{conv2} = \frac{1}{h_2A} = \frac{1}{\left(50\frac{W}{m^2K}\right)(0.124m^2)} = 0.161\frac{K}{W}$$

$$q = \frac{\Delta T}{\Sigma R_{th}} = \frac{(50°C + 273)K}{(0.806 + 4.27 + 2.05 + 4.27 + 0.161)\frac{K}{W}} = 27.95W$$

Figure D.3: Wood with an air gap casing

8.5 Appendix E: Semester 1 Schedule

Table A1: Semester 1 Schedule

Name	Begin date	End date
Customer Needs and Engineering Req...	2/5/20	2/14/20
Concept Generation	2/18/20	2/27/20
Self Learning	2/20/20	2/26/20
Functional Model, Black Box Model	2/18/20	2/26/20
SOTA	2/5/20	2/19/20
Research Emissivities	2/5/20	2/19/20
Research Thermal Storage	2/5/20	2/19/20
Research Solar Technology	2/5/20	2/19/20
Work on subfunctions conepts and be...	2/9/20	2/22/20
Benchmarking, BOM, Design	2/9/20	2/22/20
Benchmarking Subfunctions, Flow ...	2/9/20	2/22/20
Design Subfunction, Design	2/9/20	2/22/20
Work on preliminary desing and BOM...	2/29/20	3/10/20
Benchmark Solar Arctica, Your Solar H...	2/25/20	3/10/20
Continue more in depth research on in...	3/10/20	3/29/20
Final Design	3/30/20	4/18/20
CAD Model	4/13/20	5/7/20
Final BOM	4/13/20	5/7/20
Final Presentation	4/16/20	4/23/20
Design, Tolerances	4/16/20	4/23/20
Background, Scheduling, Design	4/16/20	4/23/20
Testing NAU Capstone Team Design a...	3/15/20	5/3/20

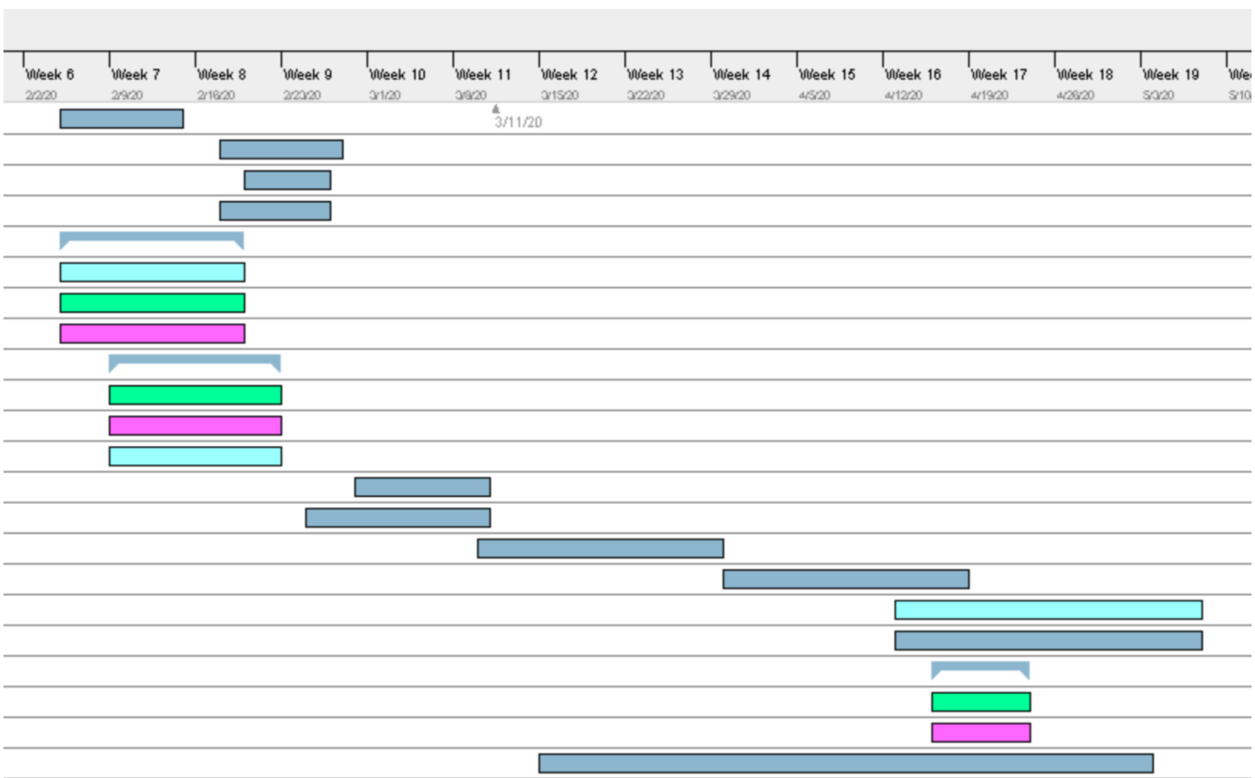


Figure A1: Semester 1 Gannt Chart