Red Feather Solar Furnace

Final Report

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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. There have been multiple design changes for the second semester of building the prototype. The final design consisted of corrugated aluminum fins, plexiglass, and a plywood base. The design was tested using an Arduino Uno and a thermocouple. The heat output was 1684 W which surpasses the original engineering requirement of at least 1500 W. The final prototype cost $438 for a 3' x 6' model. A cost analysis was conducted for bulk pricing on 100 units in which the price per unit would be $384.

ACKNOWLEDGEMENTS

Thank you to Red Feather Development group for allowing us to design for them for our Senior Capstone Project. We would also like to thank Chuck Vallance for meeting with us and being our sponsor mentor. In addition, thank you to Dr. Trevas and Dr. Oman for instructing the class and having weekly meetings with us to help guide us in the right direction. We would also like to thank the NAU Mechanical Engineering department for providing the funding to construct our prototype.

TABLE OF CONTENTS

Contents

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 residing in the Navajo Nation and surrounding areas. 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

Customer requirements were discussed with the client to find out the goals of the project. There were 5 major customer requirements.

2.1 Customer Requirements (CRs)

The customer requirements are listed below.

- Low cost
- Heat a home
- 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 and be wall or roof mountable. Originally the client wanted a way for the heat to be stored but the team decided it would not be cost effective to do so.

2.2 Engineering Requirements (ERs)

Table 1: Engineering Requirements

Technical Requirement	Technical Requirement Goal
Cost	$450
Heat Generation	1500 W
Weight	<100lb (45kg)
Durability	20 years
Noise Level	40 dBa
Install Time	3 hours

Based on the customer needs, engineering requirements were made. Red Feather currently pays $700-900 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 solar furnace cost requirement changed to $450 later in the project. 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. Originally a heat capacity of 2 hours was required but was later found that the cost would be too high and not worth it to put a battery system in to store the heat. 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, and fan. Originally the team wanted to add a battery system but that was not feasible due to price. This has changed the functional model from the first semester.

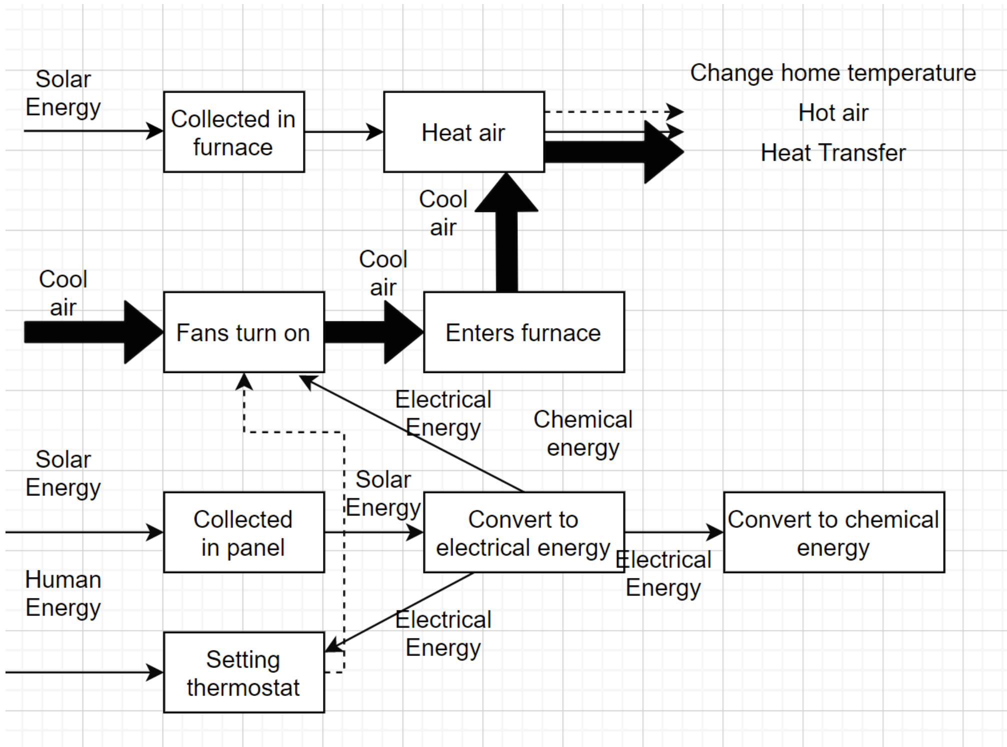

Figure 2: Functional Flow Diagram of Solar Furnace

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.

System QFD

Project: **Red Feather Solar Furnace**

		Cost	Heat generation	Heat Capacity	Weight	Durability	Noise level
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
			Technical Requirements							**Customer Opinion Survey**				
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		$450	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					

Figure 3: House of Quality (Update this)

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 team originally wanted to add a battery to store heat once the sun went down. The team found that it was not worth the price to add a battery. The second most important engineering requirement is heat generation because it must be enough power to produce 1500 W. The next 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.

2.4.1 Testing Procedures

Multiple testing procedures were 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.

2.4.2 Testing Procedure 1: Cost

2.4.2.1 Testing procedure 1: Objective

The objective is to meet the engineering requirement of being under $450.

2.4.2.2 Testing procedure 1: Method and Result

The resources required was 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 include testing materials. The total cost of the prototype was $438. If 100 units were purchased using bulk pricing, then the price per unit is $384.

2.4.3 Testing Procedure 2: Heat Output

This procedure tests the engineering requirement of heat generation of at least 1500 Watts. This was accomplished using tools such as thermocouples and an Arduino board.

2.4.3.1 Testing Procedure 2: Objective, Method, and Result

The test was to see the heat output of the solar furnace and if it reaches 1500 Watts. Thermocouples was placed on the inside of the solar furnace. An anemometer was used to measure the mass flow rate of the air. An Arduino board was be attached to the thermocouples to send data onto a laptop. The following equation were 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] The heat output was 1682 watts which surpassed the engineering requirement.

2.4.4 Testing Procedure 3: Durability

2.4.4.1 Testing procedure 3: 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. The metal was analyzed to find the thermal conductivity of the metal. In addition, a failure modes analysis was conducted to estimate the durability of the system.

2.4.5 Testing Procedure 4: Weight

2.4.5.1 Testing procedure 4: Objective, Method, and Result

The objective was to measure the weight of the solar furnace. The targeted engineering requirement was 45 kg. The solar furnace was weighted using a scale and is about 80 lbs. This would be installable by two people.

2.4.6 Testing Procedure 5: Noise Level

2.4.6.1 Testing Procedure 5: Objective, Method, and Result

The engineering requirement of being less than 40 decibels was tested. The sound of the solar furnace was not louder than a refrigerator which is less than 40 decibels.

2.5 Standards, Codes, and Regulations

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.
ANSI E2846	Standard Guide for Thermocouple Verification	Ensures the calibration and accuracy of the thermocouple used for Arduino testing

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.

ANSI E2846 is used to find the thermocouple calibration to ensure a more accurate reading during testing. [5]

3 DESIGN SPACE RESEARCH

3.1 Literature Review

System heat loss was analyzed for choosing the casing options of the solar furnace. Three different casing options were analyzed: simple wood casing, wood and metal casing, and wood with an air gap casing. The use of thermal conductivities was used to find the following heat loss values. Web searches, similar systems, and engineering toolbox was used to find these heat loss values. [6]

Table 3: 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

Fan optimization was also researched for the design using mass flow rate and examining similar systems. The mass flow rate for the fan needed to be around 101 ft^3/min. The fan does not need to be perfectly rated for 101 ft^3/min as a slightly faster flow rate will still conduct the same heat energy into the home, just at lower temperature. [7] In addition, the heat that escapes from a home was analyzed to find how it would affect how much heat is needed for the solar furnace. [8]

3.2 Benchmarking

Multiple other systems were researched to learn more about designing a solar furnace.

3.2.1 System Level State of the Art - Benchmarking

Three existing designed were analyzed to better understand solar furnaces. The subsystems of each design are also shown. The existing designs analyzed were Your Solar Home, Arctica Solar, and NAU Capstone 2018-2019 team.

3.2.1.1 Existing Design #1: Your Solar Home

The Your Solar Home 1500 GS has been the main design used by Red Feather to date. The design is a large 87” x 43.15” x 3.8” panel that uses a photovoltaic panel or standard AC outlet (with inverter) to run a DC fan. It weighs 82 pounds and is made of an aluminum shell, glazed tempered glass, and is insulated with Polyisocyanurate R4 insulation. The panel has a max flow rate of 150 CFM and runs at a temperature of about 120 degrees Fahrenheit. It claims to put on an average of 20,400 BTU/day or about 6000W/hr./day. The advertised price at the time of this report is $1,780. [9]. The testing method to determine these outputs is unavailable from Your Solar Home, but the team hopes to test the actual output in the future. An image of the Your Solar Home 1500GS model can be seen below in figure 6.


Figure 4: Your Solar Home 1500 GS [9]

3.2.1.2 Existing Design #2: Arctica Solar

Arctica Solar's 1500 series panel is newer model being implemented by Red Feather. It is a smaller panel than the 1500GS by Your Solar Home, making it more modular and better able to accommodate the small size of many homes on the reservation. It is made of an aluminum housing with a tempered glass and "high R-value insulation" [10]. The panel weighs 50 pounds and uses a 10 W photovoltaic solar panel to run a small DC fan. It claims an output of 1500W/hr./day by heating the air to 75 degrees above ambient Fahrenheit with a flow rate of 65 CFM. The advertised price at the time of this report is $899 [10]. An image of the Arctica Solar 1500 Series model can be seen below in figure 7.


Figure 5: Arctica Solar 1500 Series [10]

3.2.1.3 Existing Design #3: NAU Capstone 2018-2019

The 2018-2019 Red Feather Capstone team developed an alternative to commercial alternatives above. Their scale prototype is shown in figure 8 and produces 1296.8 BTU/day. They estimated that a full size 4' x 8' model would be capable of 20,748 BTU/day at a price of around $900 [11]. This outcompeted commercial options but left Red Feather with further questions of longevity and manufacturing procedures. The prototype uses steel fins in a wooden housing with a small computer fan to be run by a battery [11].

Figure 6: Red Feather 2018-2019 Capstone Prototype [12]

3.2.2 Subsystem Level State of the Art Benchmarking

Each existing design from Your Solar Home, Solar Arctica, and the NAU Capstone Team 2018-2019 has been broken into their subsystems to better analyze their designs. This helped the team develop a better design by individualizing analyzing the subsystems. The subsystems analyzed are the heat absorber, heat transfer mechanism, front panel design/material, and the casing design/material. How a home is heated using a solar panel system is shown in figure 7.

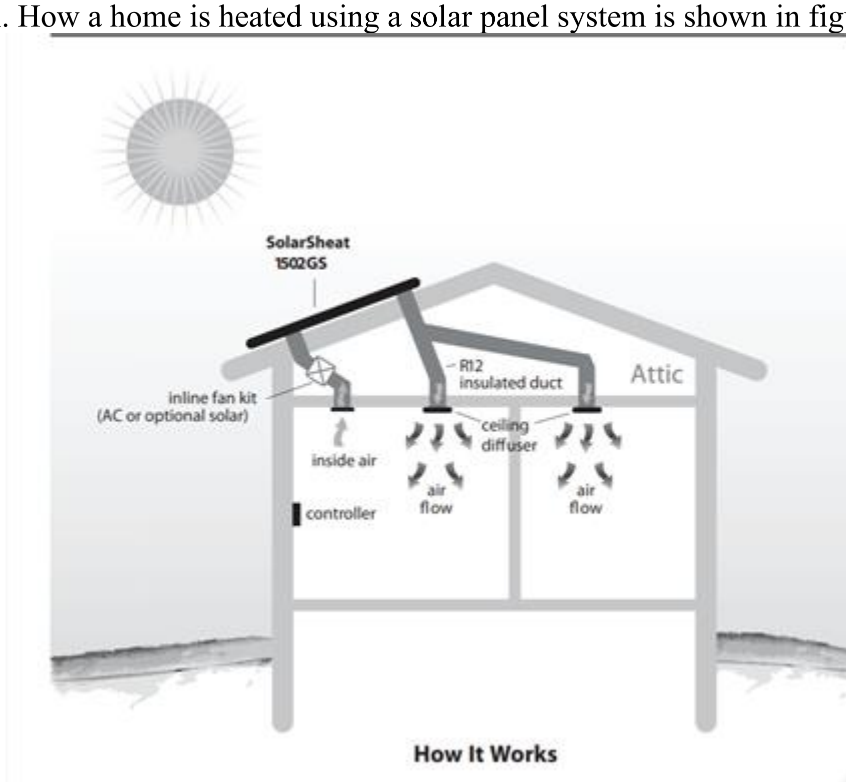

Figure 7: How a Solar Panel System Heats a Home [12]

3.2.2.1 Subsystem #1: Heat Absorber

Solar heating is captured by photovoltaic cells converting the radiation from the sun to electricity. An inverter will convert DC electricity to AC electricity which powers appliances in a typical home. The conversion of energy can heat a home. If too much electricity is made, then the electricity flows back into an electric grid. Solar panels are great for people who do not have access to be connected to typical electricity systems. [11] This relates to the team's engineering requirements because the team must produce a certain heat output. Different materials can be used for the heat absorber. This is important because different materials will have a different emissivity.

3.2.2.1.1 Existing Design #1: Your Solar Home

In some products by Your Solar Home has a Kynar on a corrugated aluminum plate as the heat absorber. Kynar is often used to coat steel roofing panels. According to NREL, a 22.9-27.9 micrometer coat of Kynar which produces a 91.5% absorptance when painted onto aluminum absorber plates. Your Solar Home also mentions that they use a high temperature foam to provide insulation for the SolarSheat collector [9].

3.2.2.1.2 Existing Design #2: Solar Arctica

Arctica Solar has high performance absorber material. It is a metal substrate with a high absorptivity, a low emissivity coating. It has 1500 W heating capacity. Arctica Solar does not require any assembly [10].

3.2.2.1.3 Existing Design #3: NAU Capstone 2018-2019

The NAU Capstone team used steel with a black coating for their heat absorber. They estimated that a full size 4' x 8' model would be capable of 20,748 BTU/day at a price of around $900 [11].

3.2.2.2 Subsystem#2: Heat Transfer Mechanism

Fans are used to blow the inside air through a duct. An attic fan is used to exhaust hot air out of the home. The attic fan makes sure the home does not get too hot. They regulate the temperature better than regular vents do. Attic fans allow moisture to escape [12]. Excess moisture in a home can lead to mold and bacteria growth in an attic which could spread to different parts of the home. The team will need to select a fan for their solar furnace design.

3.2.2.2.1 Existing Design #1: Your Solar Home

The Your Solar Home has a DC fan with ball bearing built in. The fan has solar electric power with 14.5 watts and a fan service life of 70,000 hours. The flow rate is 151 CFM [9].

3.2.2.2.2 Existing design 2: Solar Arctica

They also have a 4" air outlet and 4" air inlet on the back of the PV panel. The fan is powered through the solar panels so electrical wiring is not needed. Air comes in form the bottom of the heater and flows out of the exhaust located at the top of the heater [10].

3.2.2.2.3 Existing Design #3: NAU Capstone 2018-2019

The NAU Capstone 2018-2019 team used a small computer fan in their solar furnace design.

This fan was used to regulate the air flow around the solar furnace [11].

3.2.2.3 Subsystem#3: Front Panel Design/Material

The front panel design is important because the inner parts of the solar panel must be enclosed by a material. Glass such as polycarbonate or plexiglass is commonly used in solar furnace designs. The price of the material used is important because a highly important customer need is lowering the overall price of the solar furnace.

3.2.2.3.1 Existing Design #1: Your Solar Home

The front panel is protected with tempered glass and has polyisocyanurate and R4 insulation. This is a great R-value for conducting heat transfer. The higher the R-value then the better the insulation is. The frame material is an aluminum extrusion. The team must choose a higher R-value for their solar furnace design [9].

3.2.2.3.2 Existing Design #2: Solar Arctica

The PV panel is 383.379” by 64.950.” Arctica Solar claims this is designed for 1500 W/hr/day which would heat about 150ft^2 of living space. On a sunny day, temperature can be heated 75° F higher than the ambient air temperature. The PV panel is about 50 lbs which is much lighter than the team’s current engineering requirement. It is made of an aluminum housing with a tempered glass and “high R-value insulation” [10].

3.2.2.3.3 Existing Design #3: NAU Capstone Team 2018-2019

The NAU Capstone Team 2018-2019 used polycarbonate to protect their solar furnace. They used wood to enclose their design due to price. The longevity of the choice of using wood is questionable because they have not built a full-scale model but only a prototype [1`].

3.2.3 Subsystem #4: Casing Design & Material

3.2.3.1.1 Existing Design #1 Your Solar Home

The Your Solar Home model has a metal casing. The frame material is an aluminum extrusion, manufactured to be highly durable [9].

3.2.3.1.2 Existing Design #2 Solar Arctica

The Arctica Solar design is made of an aluminum housing with a tempered glass and “high R-value insulation” to reduce heat loss through the boundaries of the system [10].

3.2.3.1.3 Existing Design #3 NAU Capstone 2018-2019

The NAU Capstone Team 2018-2019 used wood as their enclosing to contain the insides of the solar furnace. Wood was used for the cheap price and the availability of the item such as at Home Depot [11].

4 CONCEPT GENERATION

Generating concepts is one of the most important stages of design, as it is the foundation for a feasible design in the future. To create the designs that will discussed below, the Red Feather capstone team utilized a morph matrix. This morph matrix contained five distinct design features that contributed to twenty concept variants. A decision matrix was then employed to evaluate these designs, resulting in the three full system concepts that will be discussed below. The morph matrix and decision matrix can be seen in figures A-1 and A-2 of appendix A and will be discussed in more detail in the following Full System and Subsystem Concept sections of the report.

4.1 Full System Concepts

Using the morph matrix, discussed in detail later in this report, 20 unique concepts were generated. To determine the most suitable designs, a decision matrix was utilized. Using this decision matrix, seen in appendix A, the 20 concepts were narrowed down to the three highest scoring designs. The criteria for the decision matrix are explained in section 5 of this report. Those three full system designs are described in detail below.

4.1.1 Full System Design #1: Wood Casing/Air Gap/Corrugated Fins/Plexi Glass

Developed using the morph matrix, this design is cheap, durable, and partially insulated. This design utilizes an entirely wooden casing, with in air gap between the inner geometry and an extra outer shell. The air gap will insulate the heat absorbing portion of the system. To transfer the heat into the home, a low power DC fan will be utilized. Corrugated fins increase the surface area of the heat absorbing geometry. This design can be seen below in figure 8.

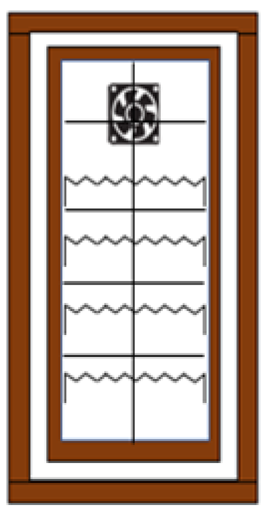

Figure 8: Corrugated Fins + Fan + Composite Plexi Glass + Air Gap

4.1.2 System Design #2: Wood & Metal Casing/Corrugated Fins/Plexi Glass

Developed using the morph matrix, this design is also cheap, and durable, and slightly insulated. This design utilizes a metal casing around the inner heat absorbing geometry, with a thin wood outer casing to increase insulation. To transfer the heat into the home, a low power DC fan will be utilized. Corrugated fins increase the surface area of the heat absorbing geometry. This design can be seen below in figure 9.

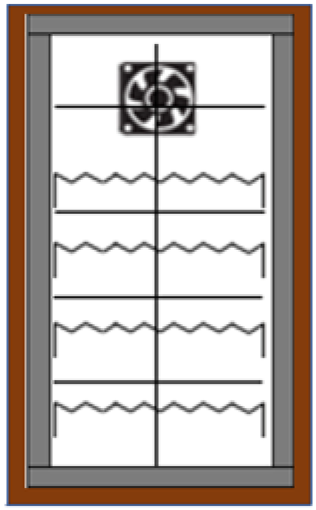

Figure 9: Corrugated Fins + Fan + Composite Plexi Glass + Metal/Wood Casing

4.1.3 Full System Design #3: Wood Casing/Corrugated Fins/Plexi Glass

Developed using the morph matrix, this design is also cheap, and durable, though it lacks insulation. This design utilizes a single wood outer casing. This design would be the most cost effective, but would be the least insulated, though wood does have a low thermal conductivity compared to most metals. To transfer the heat into the home, a low power DC fan will be utilized. Corrugated fins increase the surface area of the heat absorbing geometry. This design can be seen below in figure 10.

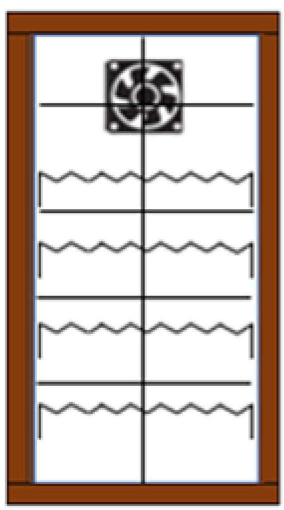

Figure 10: Corrugated Fins + Fan + Composite Plexi Glass + Metal/Wood Casing

4.2 Subsystem Concepts

In order to develop the three designs discussed above, a much larger pool of concept variants was first created. This was accomplished using a morph matrix seen in figure A-2 of appendix A.

Mentioned above, there were five separate design components included in the morph matrix: The heat absorber (inner geometry), the heat transfer mechanism, the front panel design (heat window), the front panel material, and the case design/material. Possible concepts for all five of these subsystems will be discussed below. The front panel design and material will be discussed in the same section (4.2.3).

4.2.1 Subsystem #1: Heat Absorber (Inner Geometry)

The heat absorber generates heat by exposing a metal surface to sunlight to generate heat from the solar radiation. The heat generated is then transferred to the air inside the box and conveyed into the space to be heated. A higher thermal conductivity material and higher surface generally creates more heat.

4.2.1.1 Design #1: Flat Plate

The flat plate designs utilize a simple sheet of metal painted black to generate heat. It has a relatively low surface area compared to the other designs but is simple and cheap to implement.

4.2.1.2 Design #2: Corrugated Plate

The corrugated plate design uses a corrugated sheet of steel to generate heat. It would be as simple as the flat plate to install but has a slightly higher surface area to generate heat with.

4.2.1.3 Design #3: Fins with a Flat Plate

The design uses fins paired with a flat back plate to generate heat. This was the design used by the last capstone team. It creates more surface area for heat generation at the expense of increased complexity and cost.

4.2.1.4 Design #4: Corrugated Fins with a Flat Plate

This design uses fins made from corrugated sheet metal to generate heat. It is the same design as #3 but uses corrugated metal to increase the surface area of the fins and generate more heat.

4.2.2 Subsystem #2: Heat Transfer Mechanism

In order to heat the home, hot air needs to be forced into the desired room, and room temperature air needs to be drawn back into the furnace. This is accomplished by a low power DC fan that forces the circulation of air.

4.2.2.1 Design #1: DC Fan

The DC fan will use a simple DC electric fan powered by a small photovoltaic solar panel to force air through the system. The forced air increases convection and a heat transfer into the home. The photovoltaic can be moderately expensive (~$50) and the fan will need to be long lasting and able to withstand the heat of the air.

4.2.2.2 Design #2: Passive Air Flow

The passive airflow design uses the temperature potential created by the heat difference between the interior of the solar furnace and the home to move heat. It is very inexpensive to implement but reduces the amount of convection and airflow into the home.

4.2.3 Subsystem #3: Front Panel Design & Material

The way solar energy enters the furnace is through a translucent panel on the front of the furnace. This "window" needs to be resistant to long term sun exposure, as well as natural weather variations. This front panel also needs to withstand any possible vandalization (i.e. rocks, bb guns, etc.).

4.2.3.1 Design #1: Composite Window

The composite window design will use multiple pieces of material glued together. This creates cheaper prices for window material and allows individual panes to be replaced should one be damaged. The main con is that the pieces will need to be fixed together which could block some light.

4.2.3.2 Design #2: Single Sheet

The single sheet design uses one sheet of material to create a window. This window would allow the most light through but increases cost. Furthermore, if the window were damaged or broken the entire thing would need to be replaced.

4.2.3.3 Design #3: Plexi-Glass

Plexi-Glass is made from acrylic and offers a strong, clear window that is more affordable than glass. It is shatterproof, light, and easy to cut. It also does not degrade in sun and remains clear for decades.

4.2.3.4 Design #4: Tempered Glass

Tempered glass is extremely clear and allows a large amount of light through. It is the preferred material in commercial designs due to its high performance. It is expensive and can be shattered.

4.2.3.5 Design #5: Polycarbonate

Polycarbonate is a cheap plastic material that is resistant to impact and damage. The plastic degrades with exposure to the sun and clouds over time, reducing its ability to let light through.

4.2.4 Subsystem #4: Furnace Casing

All of the subsystems discussed above need to be contained within the same system. This outer casing can be made of a range of materials, though for affordability, they are usually constructed with wood or a cheap metal (steel/aluminum).

4.2.4.1 Design #1: Wood

A wood casing is a viable option for two main reasons. First, wood is cheap and widely available. Second, wood has a low thermal conductivity, so it is basically self-insulated. Wood, however, can be heavy depending on the amount used, and is not always weather resistant.

4.2.4.2 Design #2: Polymer

The idea of a polymer casing was discussed purely for weight measures. Unfortunately, a design made of polymer would be expensive to custom manufacture, and most likely would not hold up to durability standards. Most designs utilizing this concept did not score well in the evaluation stage.

4.2.4.3 Design #4: Metal

Metal is a possible casing material since it will increase heat absorption within the inner geometry. Unfortunately, due to its high thermal conductivity there will be a higher heat loss associated with a metal case. Depending on the metal, the system could be lighter if something like aluminum is utilized however, some metals can be somewhat expensive to obtain.

4.2.4.4 Design #5: Insulation

Any heat lost during generation relates directly to a necessary increase in overall generation. Use of some type of insulation would theoretically reduce this heat loss by a significant amount. Insulation however can be unhealthy if inhaled, and somewhat difficult to work with.

4.2.4.5 Design #6: Air Gap

This idea is very similar to insulation concept above. In order to reduce heat loss during generation, an air gap will be used as an insulator. Air is an affordable, and effective insulator.

5 DESIGN SELECTED – First Semester

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.

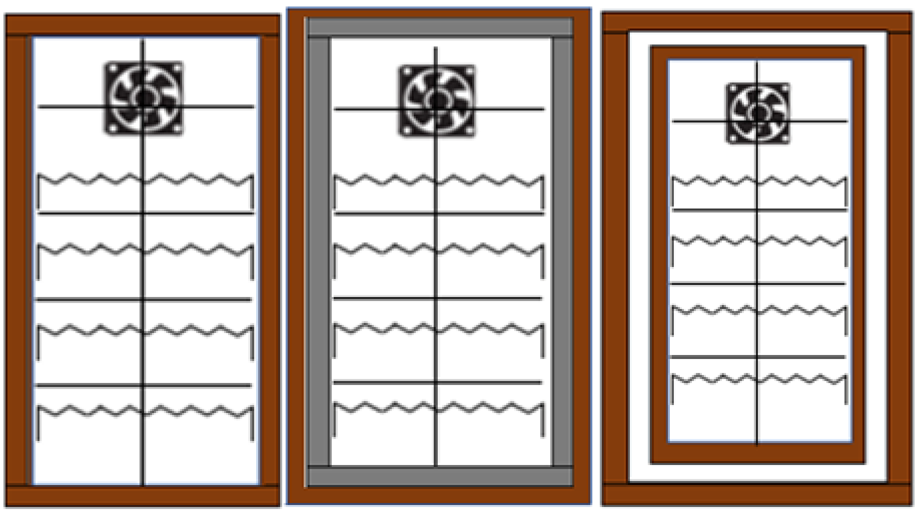

Figure 11: Casing design options

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.

$$q=\Delta T\sum R_{Th}$$

Equation 1 [16]

$$R_{conduction}=LkA$$

Equation 2 [16]

$$R_{convection}=1hA$$

Equation 3 [16]

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 [14]. 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 4: 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 [15]. 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. [15]. 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 [9]. 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

$$Q.=m. Cp\ \Delta T$$

Equation 4 [16]

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

$$m.=Q. Cp\ \Delta T$$

Equation 5 [16]

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

$$\rho$$

is density

$$Q=m.\rho$$

Equation 6 [16]

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. [17] Radiation is defined as energy transfer through electromagnetic waves. [18] 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%. [19]

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. [17] In solar thermal technology, energy from the sun is used to heat an engine, which then powers a generator that makes electricity. [18] 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 [19].

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.[20]

6 IMPLEMENTATION – Second Semester

6.1 Design Changes in Second Semester

Multiple changes were made between the original design and the finished prototype. These designs were made based upon cost requirements as well as other justifications outlined below. The CAD models of the previous design as well as the updated and constructed design can be seen in Appendix C.

6.1.1 Design Iteration 1: Furnace Downsize

The original plan was to try to match the heat output of the larger solar furnace used by Red Feather, the Your Solar Home. This model was to be 4' x 8' and be able to put out an ideal of 26,000 BTU over the course of a sunny day. Red Feather has begun partnering with Arctica Solar, whose product measures about 3' x 5' and advertises about 1/5 the heat energy of the larger model at about a quarter of the cost. Red Feather has found these smaller models to be effective and easy to install and has fostered a good relationship with the company. As a result of the lower funding and Red Feather's satisfaction with smaller furnaces, the team has decided to downsize their model to compare to the Arctica Solar's heating capability and size. The team plans for a 3' x 6' design to meet the same output of the Arctica Solar model.

6.1.2 Design Iteration 2: Custom Fin Geometry

Corrugated metal fins were originally planned for the design to increase surface area and maximize heat absorption by the fins while also being widely available. However, sourcing corrugated metal panels made of aluminum proved to be difficult for the team as most corrugated metal is used for roofing and is made of cheap metal without advertised heat properties or even alloy makeup. To solve this problem the team has moved to a fin design of a trapezoidal profile. This design can be made by hand bending over breaks, allowing the team to source plain sheet metal, which is more widely available with proper specifications to ensure adequate heat transfer properties. The revised and constructed fins can be seen below in figure 12. The CAD model of the fin can also be seen in Appendix C. This specific fin design increases surface area by a factor of 1.3 and produces 2.7 times the effective heat absorption of a flat fin.

Figure 12. Heat absorbing fin prior to install (unpainted)

6.1.3 Design Iteration 3: Single Layer of Plexiglass

The use of an air gap between two panels of plexiglass significantly increases the heat retention of the device, however it also increases both cost and complexity. Due to this, the air gap was rejected however, heat loss mitigation solutions related to the front panel are discussed in the future work section of this report (9.2)

6.1.4 Design Iteration 4: Flat Inner Aluminum Panel

Originally all inner wood surfaces of the device were intended to have aluminum on them. However, this significantly increased the complexity of the device, as well as the cost for aluminum. Instead, there is not a single sheet covering the inner side of the back of the device. Due to the steep angle between the sides of the device and the entrance angle of sunlight into the device, these side panels of aluminum were not determined to significantly increase the heat output of the device. In addition, the fins described above are the main heat absorption units of the system, and thus more time and resources were shifted towards their creation.

6.1.5 Design Iteration 5: Commercial Mounting option

Originally the team was planning on designing a custom mounting plate to be fastened to the home and the device. This idea was rejected due to the added cost and complexity since there are many commercial mounting options that are rated to hold items up to and exceeding the weight of this device. These commercial options are more reliable and would be cheaper to purchase for bulk production.

7 RISK ANALYSIS AND MITIGATION

The solar furnace is a relatively simple 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 E. 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.

7.1 Potential Failures Identified First Semester

7.1.1 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.

7.1.2 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.

7.1.3 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.

7.1.4 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.

7.1.5 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.

7.1.6 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.

7.1.7 1.1.7 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.

7.1.8 1.1.8 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.

7.2 Potential Failures Identified This Semester

Nearly all of the potential failures of the solar furnace were identified during the creation of the FMEA in the previous semester. The only additions to the possible failures are those noticed in relation to the plexiglass during construction, and a consideration of the ducting that will be attached to the device.

7.2.1 Potential Critical Failure 2: Further Plexiglass Damage

The previous analysis of plexiglass failure failed to consider damage that may occur during the construction and install of the device. During these stages, the plexiglass could be cracked, scratched or even shattered. Shattering is not a major issue, other than cost, because it is easily identified and will simply be replaced. Scratching and cracking however are more difficult to recognize and if installed without repair, may lead to decreased system performance.

7.2.2 Potential Critical Failure 3: Damage to Ducting

Although the ducting is a subsystem purchased from an outside manufacturer, that does not mean it can be neglected in terms of possible failure. If anything, the ducting should be more highly scrutinized than the components built on site. Possible failures include the ducting coming apart from the inlet or exit to the device or the possibility of the inner ducting material cracking. Both are unlikely occurrences but would result in significant heat loss as well as the introduction of the insulation surrounding the ducting into the home.

7.3 Risk Mitigation

In order to address and act on all necessary failure modes, an FMEA was created to determine what items needed to be improved. This FMEA can be seen in Appendix E. Due to low cost being one of the main customer requirements, and the relatively low RPN scores of most failure modes, recommended actions for the most part involve double checking assembly steps and creating a regular maintenance plan to check on subsystem components once the device is installed. All mitigation steps and any suggested actions that were not already undertaken can be found in the “Recommended Action” column of the FMEA (Appendix E.)

8 ER Proofs

For a design to be successful it must satisfy all of the engineering requirements derived from the customer needs. These requirements and proof of their completion is discussed in the following section.

8.1 ER Proof #1 – Cost

Seeing as cost was one of the engineering requirements with the highest importance to Red Feather, it is necessary that it was met. The requirement was that the device be manufactured for less than $450 although the capstone team set a personal goal of $350. Based off the Bill of Materials (BOM) for the 3ftx6ft model, which can be found in Appendix F, the final device cost for a single unit came out to be $438. If the 100 units were to be constructed, at bulk pricing the cost per unit would come in at $384 This is not only lower than the required cost but is almost half the cost of similar commercial models. The device is scalable to larger sizes which would increase cost, however not by a significant amount.

8.2 ER Proof #2 – Heat Generation

To determine the heat output of the device in Watts, equation (x) below was utilized. In this equation $\dot{Q}$ is the heat output in Watts, ρ is the density of air, Q is the volumetric flowrate of air leaving the device, C_p is the specific heat of air, and ΔT is the temperature difference between the inlet and outlet temperature of the device.

$$\dot{Q} = \rho Q C_p \Delta T \quad (1)\ [18]$$

The values used in equation (1) above, based off testing, can be seen in table 5 below. The calculated heat output for the device can also be seen in the bottom row of said table.

Table 5: Testing values and heat output of device

Variable	**Value**
Density	1.204
Volumetric Flow Rate (Q)	0.0684
Specific Heat	1.023
Temperature Difference	20K
Heat Output	**1684.95W**

As can be observed in table 5, the heat output of the device is 1684.95W, surpassing the engineering requirement of 1500W. However, further testing is necessary in order to determine the full range of heat generation based upon different ambient conditions that may be experienced throughout the year.

8.3 ER Proof #3 – Weight

The engineering requirement for weight was basically that it be installable by 2 people. To ensure that this requirement was met, a weight range was set at between 60lb and 100lb. The device was weighed simply by placing it on an everyday bathroom scale and was determined to be 81.4lb. In addition to this, the device was constructed and regularly moved by only two people.

8.4 ER Proof #4 – Durability

It can be difficult to estimate the actual use time of a device based off the limited resources at the team's disposal however to meet the ambitious requirement of a 20-year life cycle, durable materials were chosen. The frame was made from dimensional lumber and OSB board. Although wood is not as durable as the aluminum construction of commercial models, it should last if the everyday wood frame home especially after being painted with heat resistant paint and a clear sealant. All components of the device were fastened together using either steel wood screws, a high heat silicone sealer, or a combination of both. This will ensure the components stay together and the device stays sealed. The fins and inner backing of the device were constructed out of aluminum and then spray painted with heat resistant paint. Aluminum is resistant to rust and is highly durable. The clear panel on the front that allows light into the device is made of acrylic. This was chosen due to low cost but is more flexible than glass and has a high melting point greatly reducing its chance of failure. The fan, used to cycle air through the device, is a marine blower fan. This means it is meant for use in the engine area of a boat and due to its essential nature, in that it removes fumes from the engine compartment, it is built to be highly durable. Lastly the solar panel, solar controller and thermostatic controller are all made for RV use, meaning they are meant to be exposed to the elements for long periods of time. In addition to all of this, each component is easily replaceable if it were to break down, or malfunction.

8.5 ER Proof #5 – Noise Level

The engineering requirement of a sound level of less than 40 dB was based loosely around the noise level of a modern refrigerator. By inspection upon use during testing, it was determined that the fan met this requirement. Although it does put off a noticeable amount of noise, it will only be running for a few minutes at a time. There is also the possibility that it be used in line with a voltage regulator and ran continuously. In this situation, the fan speed would be reduced significantly and thus the noise level would decrease as well.

8.6 ER Proof #6 – Install Time

It is estimated that install time will meet the goal of less than 3 hours due to the simplicity of the device and the recommendation that Red Feather use a commercial mounting option, the device should be installable in well under this time. Red Feather volunteers also have significant experience installing Arctica Solar and Your Solar Home models that mount on homes in almost the exact same fashion as the capstone prototype. Unfortunately, the exact install time will not be known until Red Feather attempts to install in on a home.

9 LOOKING FORWARD

9.1 *Future Testing Procedures*

To better understand how the device will perform in various weather conditions, more testing will need to be conducted. The primary test will be comparing the devices performance to the solar irradiance and solar incidence. Solar irradiance is the power per unit area cast by the sun onto a surface and solar incidence is the angle the light travels to the ground. Other tests include a max temperature test for hot climates, a life cycle analysis for all components, and tests for other electronic systems such as one with a voltage regulator.

9.1.1 Testing Procedure 1: Solar Irradiance & Incidence Standardization

9.1.1.1 Testing Procedure 1: Objective

To better understand how the solar furnace will perform in various lighting conditions it will need to be tested in varying conditions where the solar irradiance and solar incidence are known. These known solar values can then be plotted against the measured output of the device to correlate performance with the conditions.

9.1.1.2 Testing Procedure 1: Resources Required

A measure the of the solar irradiance available to the can be found with a pyranometer. Another method would be to use measurements reported by weather services however this will likely cause error. Thermocouples and a measuring tool such as an Arduino microcontroller will be used to measure the input and output temperatures of the solar furnace. If fan speed is not known an anemometer can be used to measure it and ultimately find the flowrate through the device.

9.1.1.3 Testing Procedure 1: Schedule

Solar incidence changes over the course of the year as the position of the Sun and Earth change and the sun rises higher or lower in the sky. To best measure the effect of the angle on the device, it should be tested over the course of an entire year. Furthermore, varying solar incidences should be tested as well at each angle to account for its effect on the device as well.

9.1.2 Testing Procedure 2: Maximum Temperature

9.1.2.1 Testing Procedure 2: Objective

The acrylic used for the window of the device has a relatively low melting temperature compared to the other materials used (~320 ˚F). During initial testing the device reached a max temperature of 149 ˚F with the fan off at an ambient temperature of 52 ˚F. To understand if the plexiglass will fail in more extreme climates, it should be tested at higher ambient temperatures.

9.1.2.2 Testing Procedure 2: Resources Required

A thermocouple and measuring tool such as an Arduino microcontroller can be used to measure the internal temperature of the solar furnace. Any thermometer will work as well, provided it can be placed and read from inside the device.

9.1.2.3 Testing Procedure 2: Schedule

This test can be conducted any time when the ambient temperature is high enough.

9.1.3 Testing Procedure 3: Life Cycle Analysis

9.1.3.1 Testing Procedure 3: Objective

The solar furnace prototype was constructed out of the most robust materials available to the team, however their true lifespan in direct sunlight remains to be seen. To determine their exact lifespan and what maintenance will need to be done on the device, a complete life cycle analysis should be conducted.

9.1.3.2 Testing Procedure 3: Resources Required

Testing the lifecycle analysis could be accomplished by testing each material used by leaving them in the sun for long periods of time, however this could take many years. To better analyze this the life cycle analysis should be conducted through researching each material's UV resistance.

9.1.3.3 Testing Procedure 3: Schedule

The life cycle analysis research can be conducted anytime. Direct testing would involve inspecting an installed prototype for wear over several years or testing individual materials in similar conditions.

9.2 Future Work

9.2.1.1 Thermal Battery Team

Work on the solar furnace prototype is to be continued by the Thermal Battery capstone team. They are attempting to add a way to store some the heat created by the device so that it can be used past sunset, further reducing the need for other heating methods. The current team has also identified areas the furnace could be improved in future prototype iterations.

9.2.1.2 Improvement 1. Double Paned Acrylic

The first improvement would be in the acrylic panel. The single layer of acrylic has little insulation and has the potential to lose a large amount of heat from convection over its surface. In high wind conditions, this could noticeably reduce the effectiveness of the device. To increase the insulation, a second layer of acrylic separated by an air gap should be added. This air gap will drastically improve the insulation and therefore effectiveness of the furnace.

9.2.1.3 Improvement 2. Acrylic Attachment

Next, the team recommends experimenting with different ways to attach the acrylic panel to the frame of the device. Holes were drilled through the panel on the current prototype and wood screws and washers were used to fix it in place. Both drilling through the panel and attaching the screws through it cracked the panel in multiple locations. Options such as angled brackets or stronger adhesives should be explored as they do not require adding holes or otherwise weakening the panel and subjecting it to large stresses during construction. These methods will also reduce the warping and bowing observed in the current panel creating air gaps.

9.2.1.4 Improvement 3. Voltage Regulator

During testing the team found the thermostatic controller difficult to implement in the device. The controller currently activates the fan when the programmed high temperature is reached, and then stop the fan when the low temperature is reached. This requires some forethought to program to the desired settings and cycles the fan, at full speed, on and off. The team feels a better solution would be to implement a voltage regular to control the speed of the fan rather than cycle it completely. Slower speeds would create a larger temperature difference and reduce fan speed. The voltage controller could be place inside the home to allow for easy intuitive control of the device.

10 CONCLUSIONS

The team was able to successfully create the working prototype of their solar furnace design shown in figure 13. During construction and testing the team achieved all of their engineering requirements. The device created 1685 W of continuous heat, satisfying their goal of matching the commercial option's 1500 W. Furthermore, they did it at a much lower price of around $438, beating their goal of being under $450 and being much cheaper than the commercial option which costs between $700-900. The team also conducted an analysis to determine what larger scale production of the device would cost Red Feather. They found that producing 100 units would lower the per-unit cost to only $384. The client was extremely satisfied with the results of the project and hopes to pursue manufacturing of more devices.

Figure 13. Completed Prototype and Testing Setup

10.1 Reflection

One of the main goals of the project was to create a device that will not only save money for Red Feather but also provide a free, safe, and renewable source of heat. The team takes pride in the creation of their device that uses only solar energy to generate as much heat as a standard space heater without the same risk of fire. Furthermore, reducing the need to burn coal and wood in homes will contribute to a reduction in respiratory illness from smoke inhalation.

The client stated plans to explore grant options that will allow for a fabrication shop to be set up to produce solar furnaces of the team's design. This would allow for more solar furnaces to be created and implemented across the Navajo Nation, providing clean heat and creating jobs.

To ensure the design was safe the team used robust materials that pose little fire risk and used proper methods to ensure materials such as fiberglass insulation are properly contained and cannot come loose. The device itself poses no other major risks as it uses only a small amount of electricity to power the fan, with the entire electrical system located outside of the home.

10.2 Postmortem Analysis of Capstone

10.2.1 Contributors to Project Success

The team's most positive performances were those of time management and implementation. They found frequent, flexible meetings about assignments where work could be completed together or split up to be the most effective time management system. Due to the small size of the team, communication was never an issue, so rigorous scheduling felt tedious and wasteful. This was found to be especially true when it came to tools like the Gantt chart. Due to the rapidly changing nature of the project, the Gantt chart became only useful for generic, long term goals. Ultimately a simple calendar with assignment deadlines and project milestones was found to be the most effective time management method. When coupled with frequent meetings, the team was able to rapidly assign and change roles for pieces as needed.

The design of the device was also positive, the team was able to complete basic analysis across many parts of the design and factor it into creating a realistic CAD model of the solar furnace. This CAD model was then used to create a physical prototype of the design that was ultimately found to be a success once tested. Consistent and often work on the project, namely in the construction of the prototype was helpful for ensuring the device was constructed in a timely manner. Even when only an hour could be put into the design or while the team was waiting on a part, they still worked on the device to complete what they could. This was extremely useful when problems arose, or design changes had to be made as problems were found quickly and enough time remained to properly address them.

The team gained many valuable skills related to online communication because of the COVID-19 pandemic. They adapted well to communicating online and collaborating remotely. Often, they found the remote meetings to be more valuable than in person would have been, especially for quick meetings that travel would be hard to justify for.

10.2.2 Opportunities/areas for improvement

The most influential problem the team encountered was the COVID-19 pandemic which shifted the first semester online halfway through it. This resulted in one member of the team moving to fully remote learning in Phoenix, physically separated from the other two members in Flagstaff. This resulted in some difficulties for the team in terms of meeting and physical device construction in the second semester, however the team adapted relatively well, using Microsoft teams to communicate and collaborate. The team also faced setbacks in terms of prototype construction as they originally planned to begin construction prior to the end of the semester but put it off until the second semester to follow social distancing guidelines. This left less time for the team to test the electronics and better test the system over the variety of weather that they originally planned.

To improve team performance is to necessary that the voice of every team member is heard. Once everyone's constructive feedback is expressed, that information can be used as a team to drive organizational and functional improvements. It is important to understand not only the failures but what has been done well in the past as well. By identifying successful practices, not only can those actions be improved upon further, but they can also be adapted to other aspects of a project. Team Red Feather's main organizational action to achieve better project performance is an overall increase in team communication. This involves practices such as full team reviews of previous assignments and the provided feedback. Actions such as these will also improve the quality and functionality of the final design and will facilitate easier prototyping and testing. This also requires that team members be objective when providing and receiving constructive criticism, or praise.

Multiple technical lessons were ascertained through the successes and failures experienced over the duration of the project. Communication has shown itself as one of the most important facets of a successful team. With a limited number of team members, and multiple project duties to complete regularly, communicating progress across the team was essential. It is important to convey personal setbacks with team members to allocate the proper resources to help wherever needed. Another technical skill imperative to success is time management. Time management skills were developed in both a personal, and team wide sense throughout the first months of the design process. Meaning, team members learned to improve time management with respect to their own auxiliary work, and to that of their team members. Optimization of this skill allows for highly efficient, and highly successful, work.

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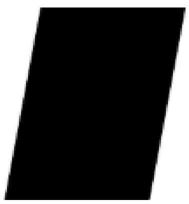
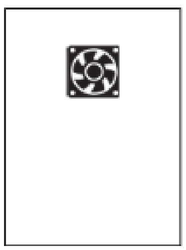
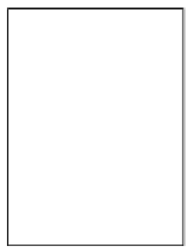
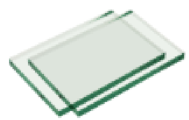
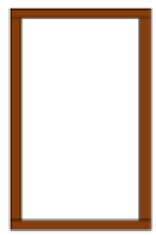
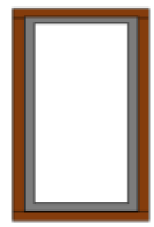
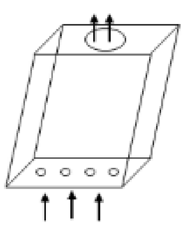
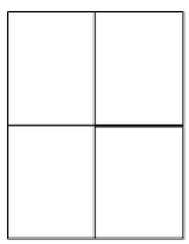
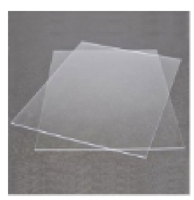
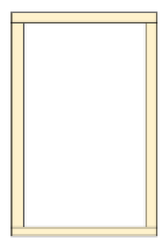
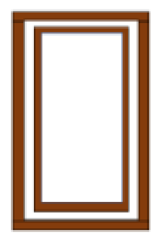
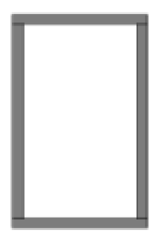
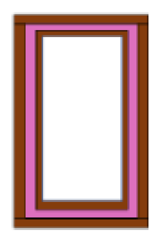
12 APPENDICES

12.1 Appendix A: Concept Generation & Design Selection

Table A.1: Decision Matrix

Redesign																					
Criteria	**Weight**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Cost	**0.35**	3	2	3.5	2	3	2	4	3	3.5	4	3	2.5	2.5	4	3	3	3	4.5	4	5
Heat Gen	**0.35**	4.5	4.5	4	4	3.5	3.5	3	3	2.5	2.5	2.5	3	3.5	2	3	3.5	2	2.25	2.5	1.5
Manufacturability	**0.15**	4	4	4.25	3	3.5	3	4	4	4	3.5	3.5	3	2.5	4	3	4	4	3.5	3.5	4
Durability	**0.15**	4	4.5	4	4.5	4	3.5	3	3	4.5	3	3	2	3	2.5	2	2	4	4	4	2
Sum (out of 5)	**1**	**3.83**	**3.55**	**3.86**	**3.23**	**3.40**	**2.90**	**3.50**	**3.15**	**3.38**	**3.25**	**2.90**	**2.68**	**2.93**	**3.08**	**2.85**	**3.18**	**2.95**	**3.49**	**3.40**	**3.18**

Table A.2: Morph Matrix

Heat Generation	Heat Transfer (to home)	Front Panel Design	Front Panel Material	Case	Case Cont.
 Flat plate	 Forced air (fan)	 Single sheet	 Tempered Glass	 Wood	 Wood/Metal
 Corrugated plate	 Passive air flow	 Composite	 Plexi-glass (Acrylic)	 Polymer	 Air Gap
 Fins			 Polycarbonate	 Metal	 Insulated
 Corrugated Fins					

12.2 Appendix B: Heat Loss Calculations

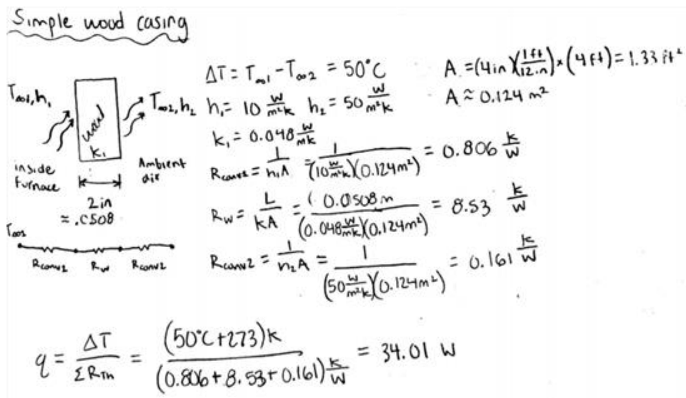


Figure B-1. Heat loss out the boundaries of a simple wood casing.

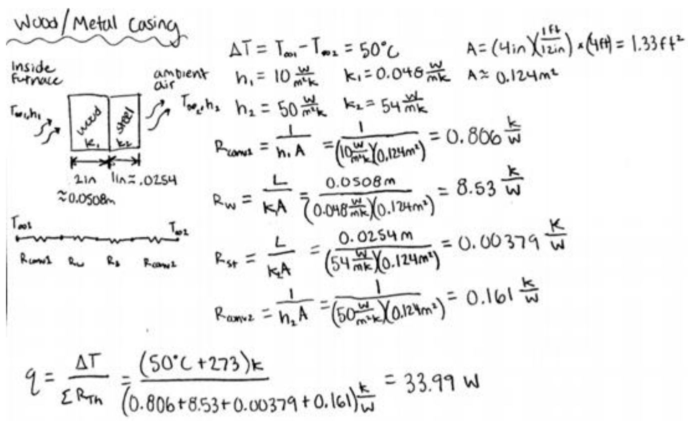


Figure B-2. Heat loss out the boundaries of a simple wood/metal hybrid casing.

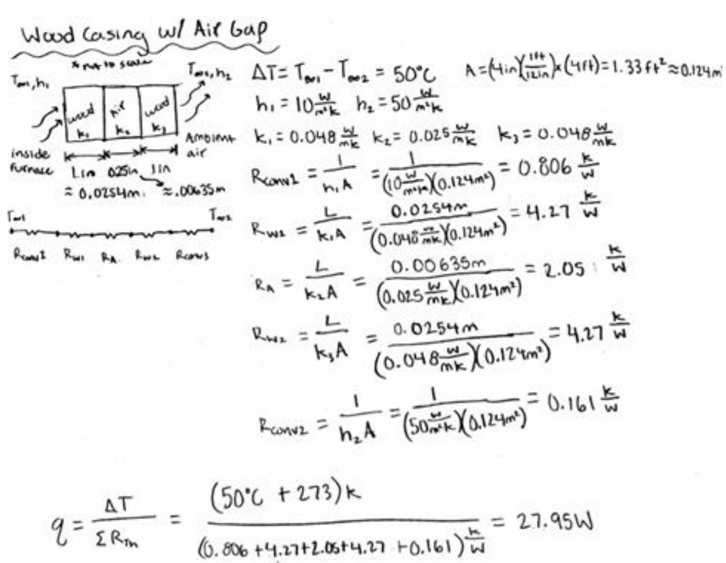


Figure B-2. Heat loss out the boundaries of a wood casing with an air gap.

12.3 Appendix C: Design Changes

Figure C-1: Finished prototype (3ftx6ftx5.5in)

12.4 Appendix D: CAD Model

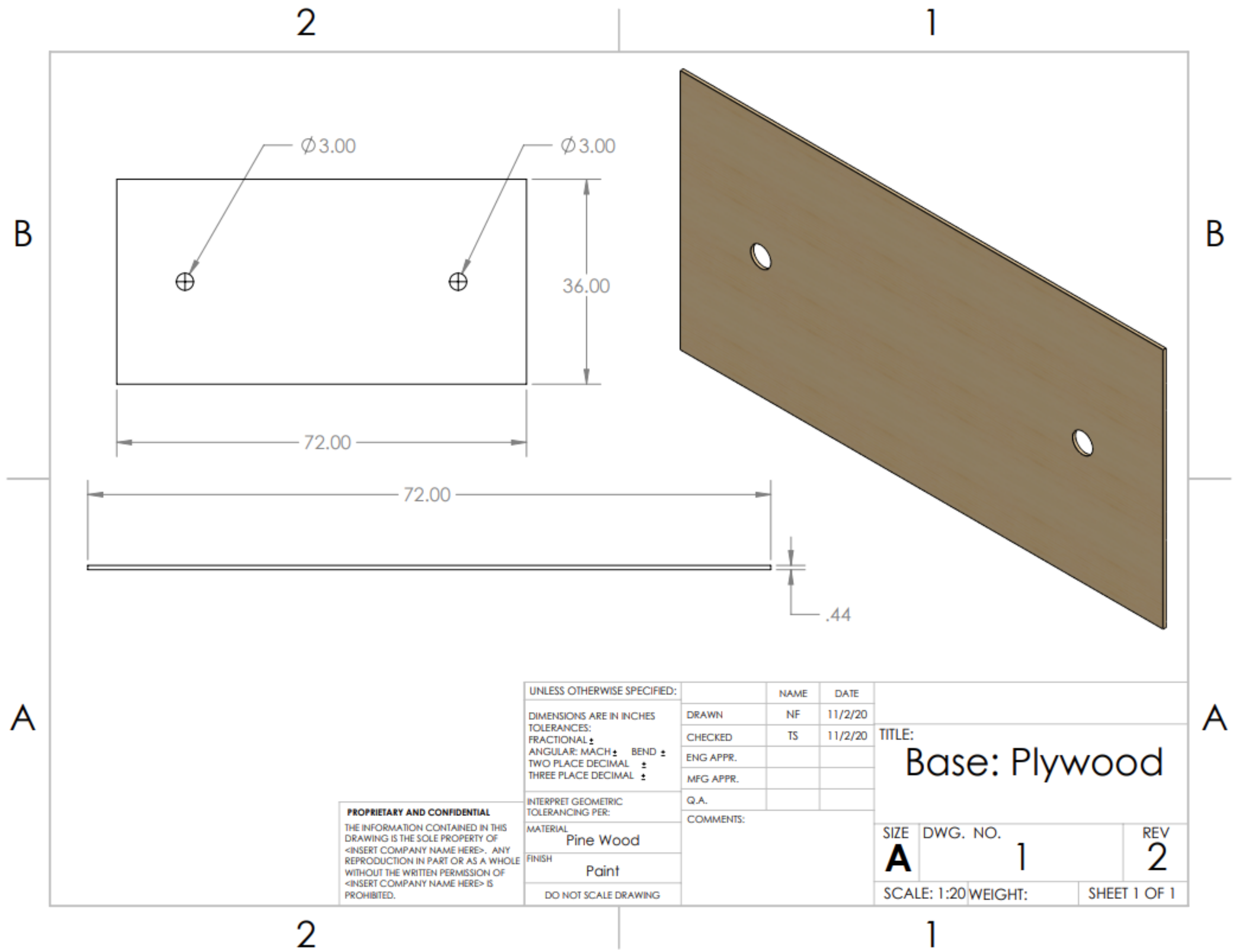


Figure D-1. Plywood base drawing.

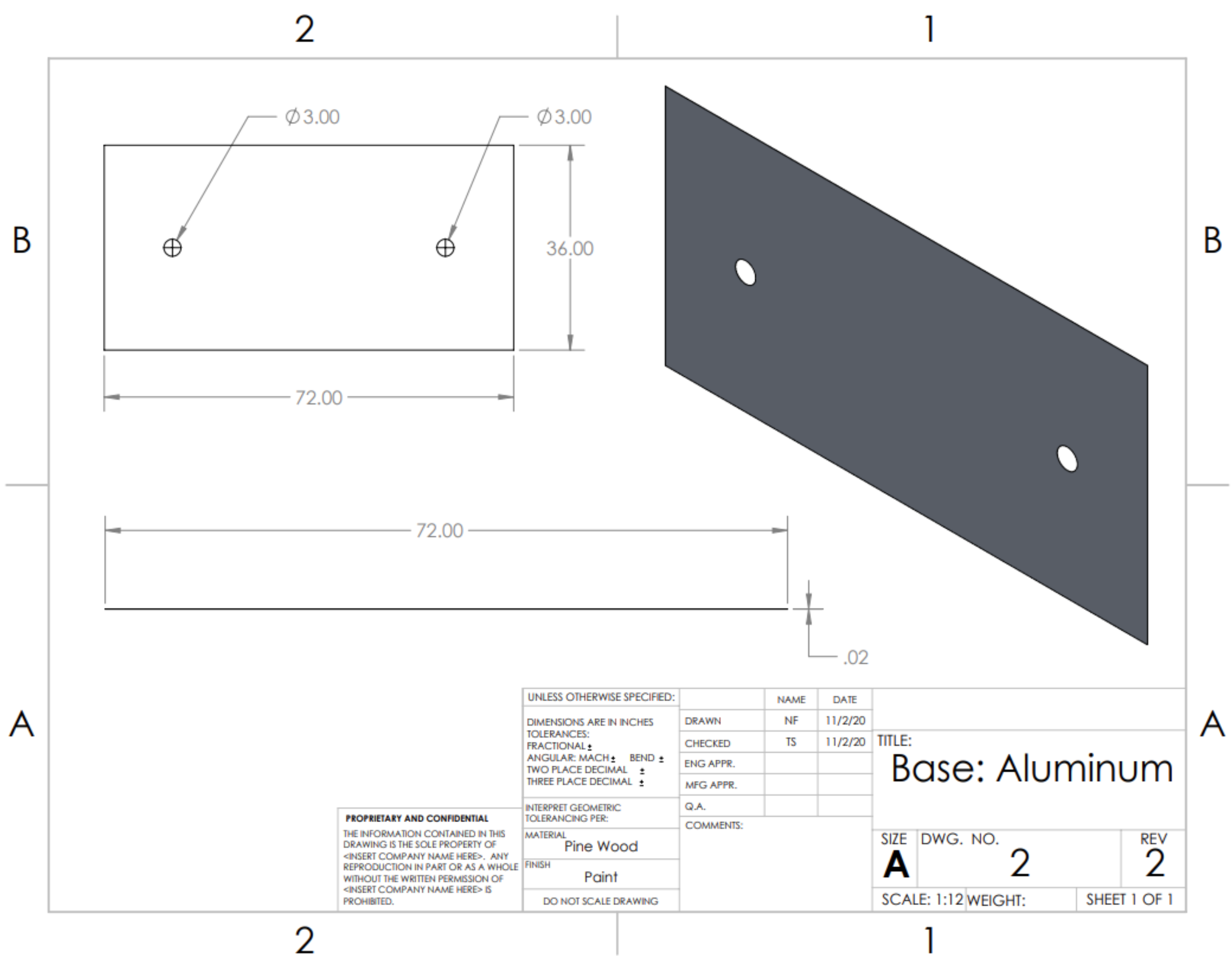


Figure D-2. Aluminum inner backing drawing.

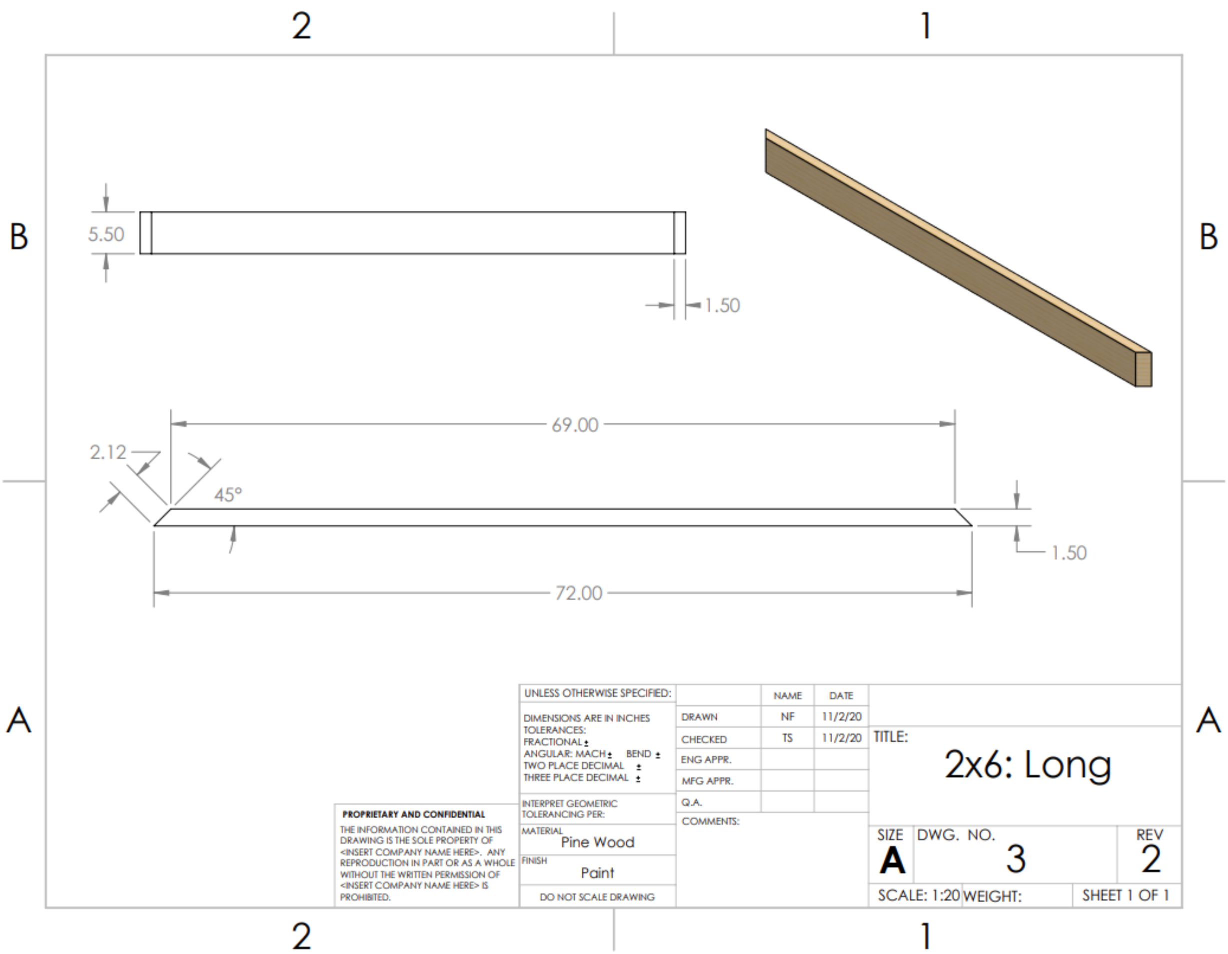


Figure D-3. 2inx6inx6ft frame member drawing.

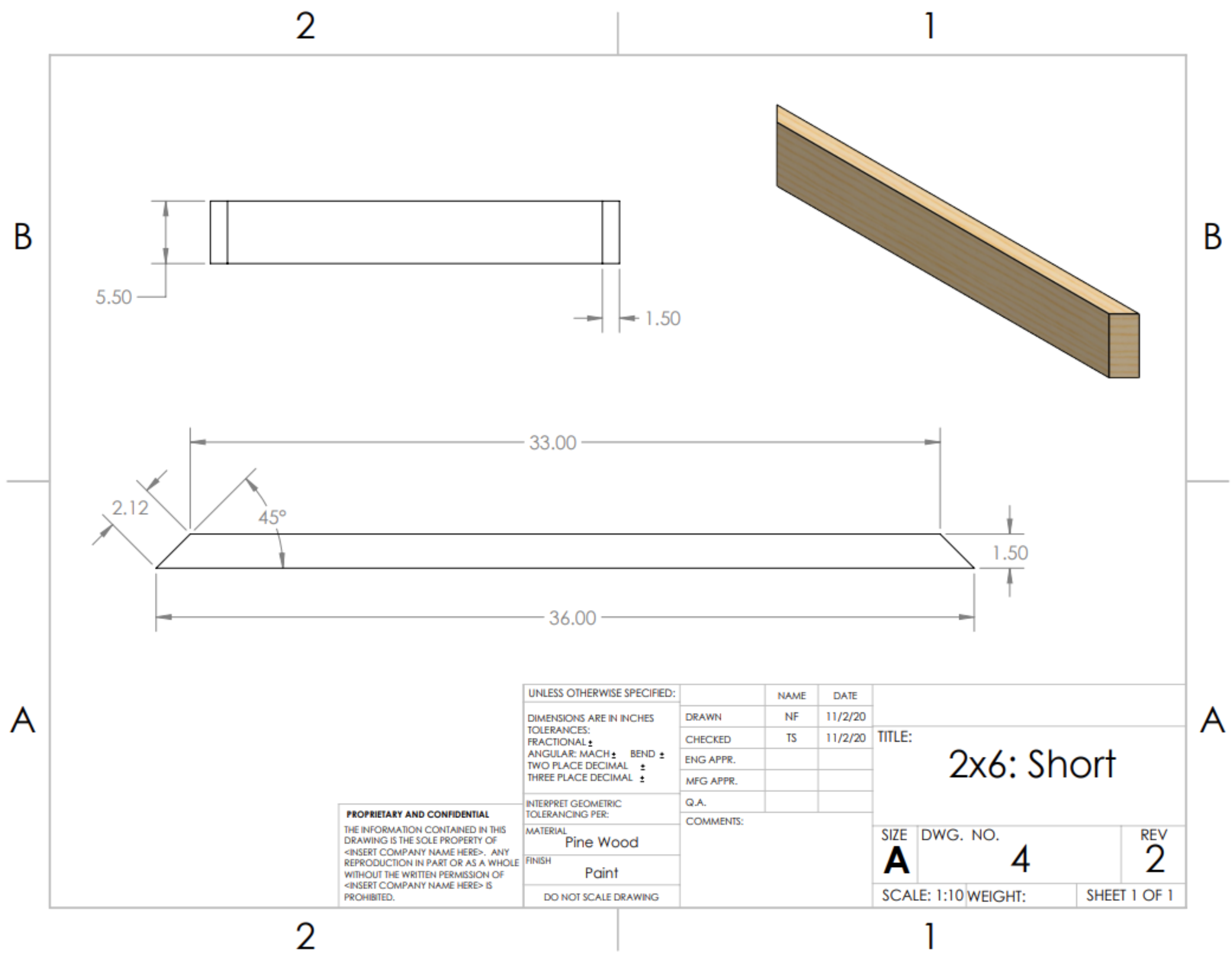


Figure D-4. 2inx6inx3ft frame member drawing.

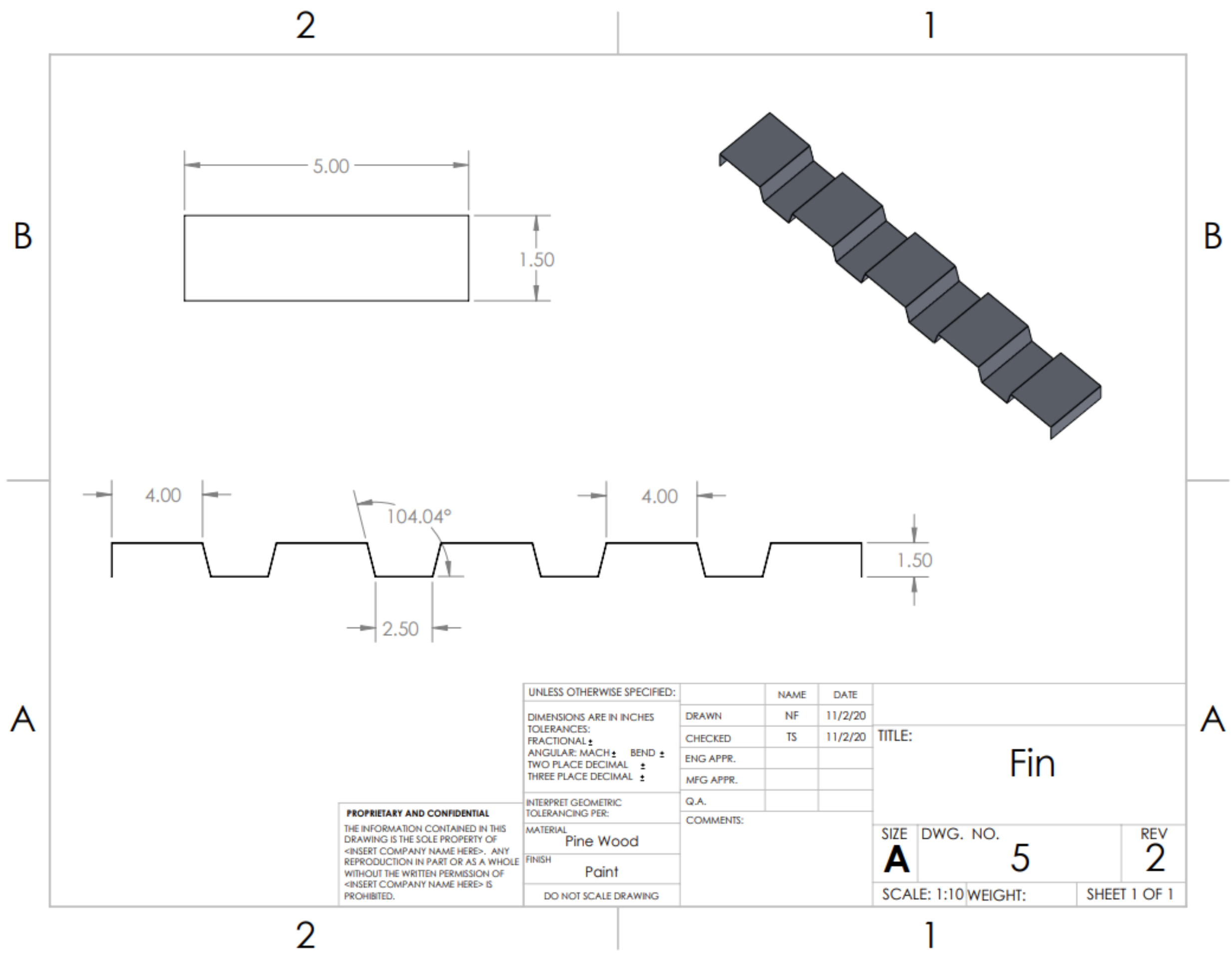


Figure D-5. Heat absorbing fin drawing.

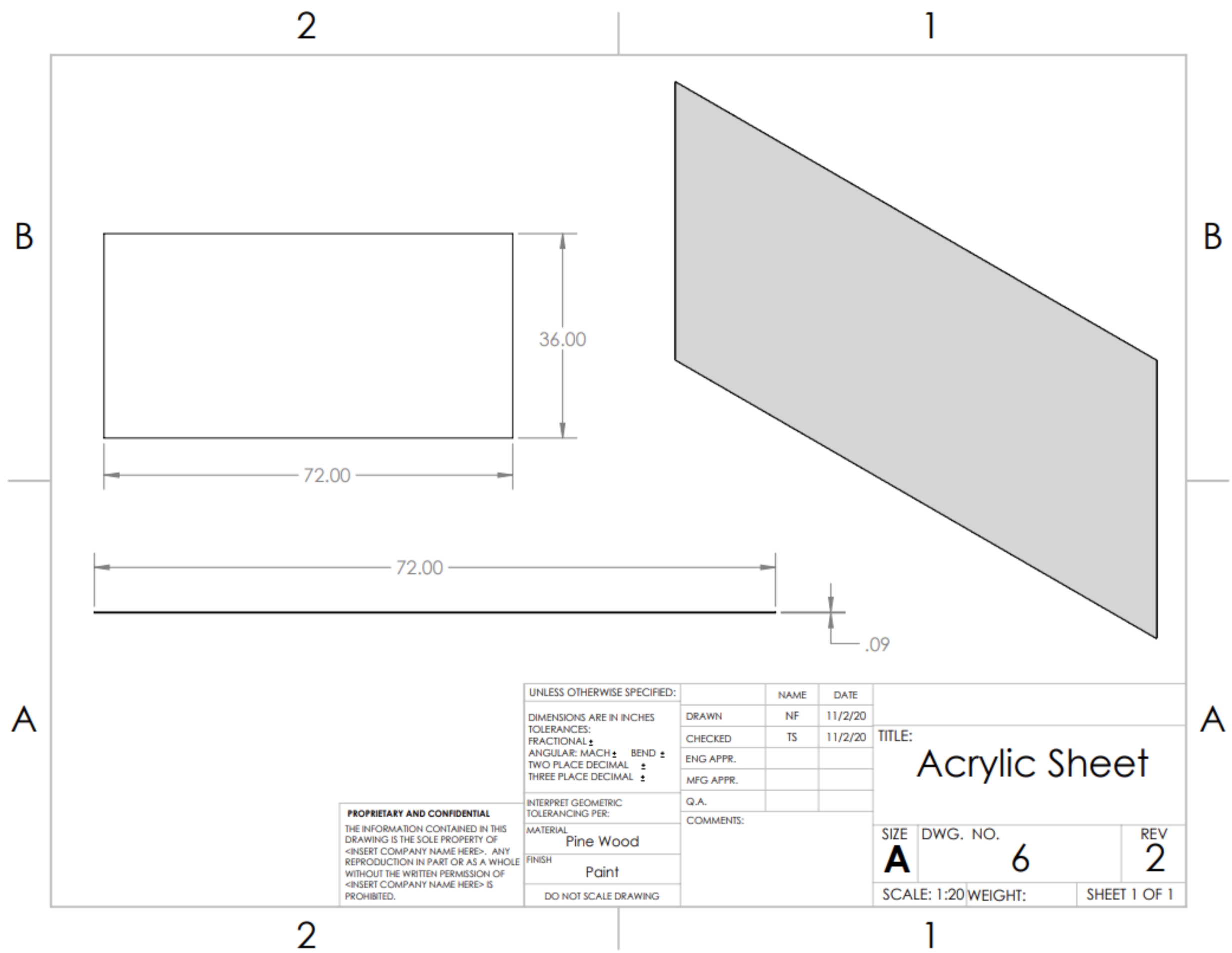


Figure D-6. Acrylic sheet drawing.

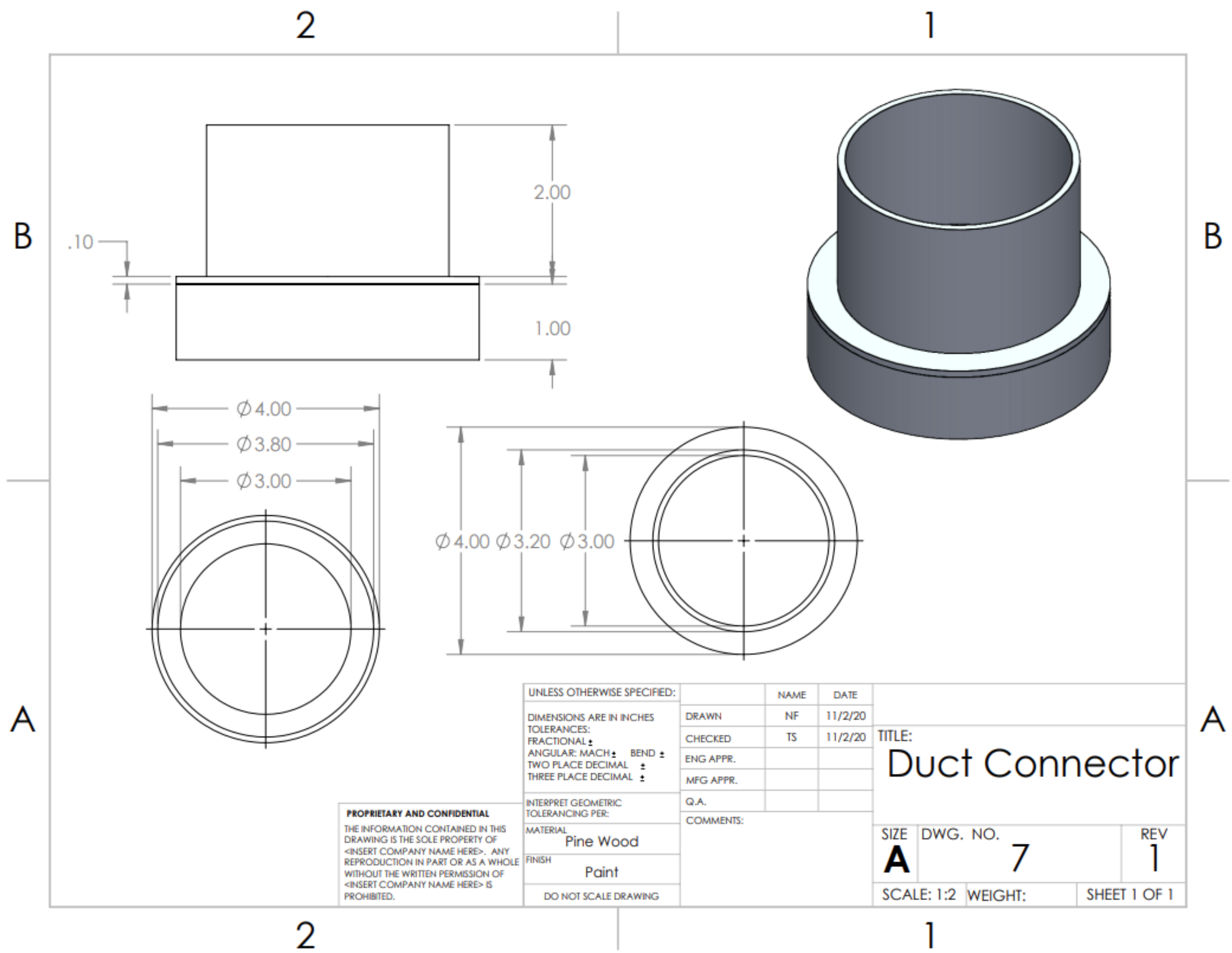


Figure D-7. Duct connector drawing.

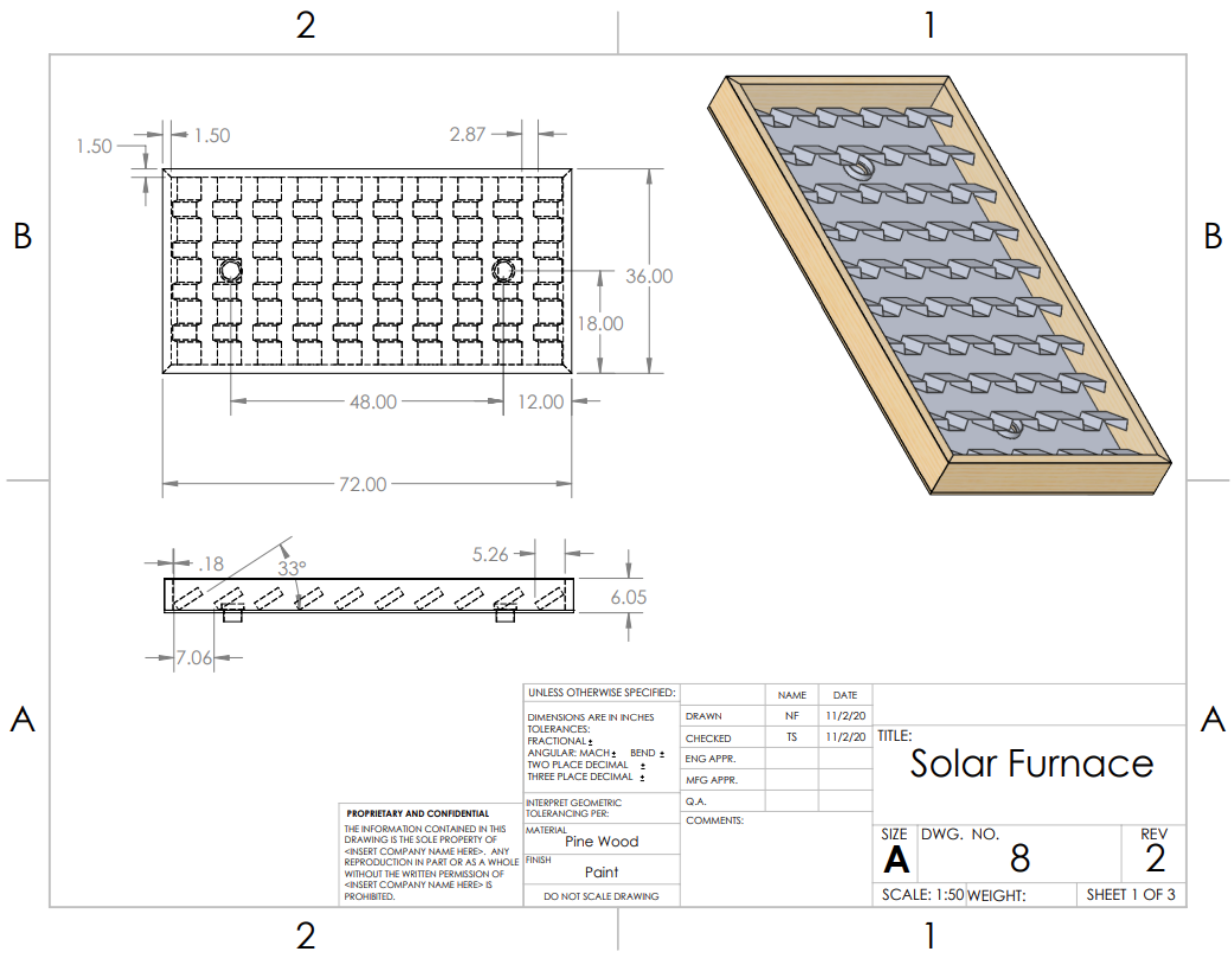


Figure D-8. Solar furnace assembly drawing: sheet 1 (dimensioned).

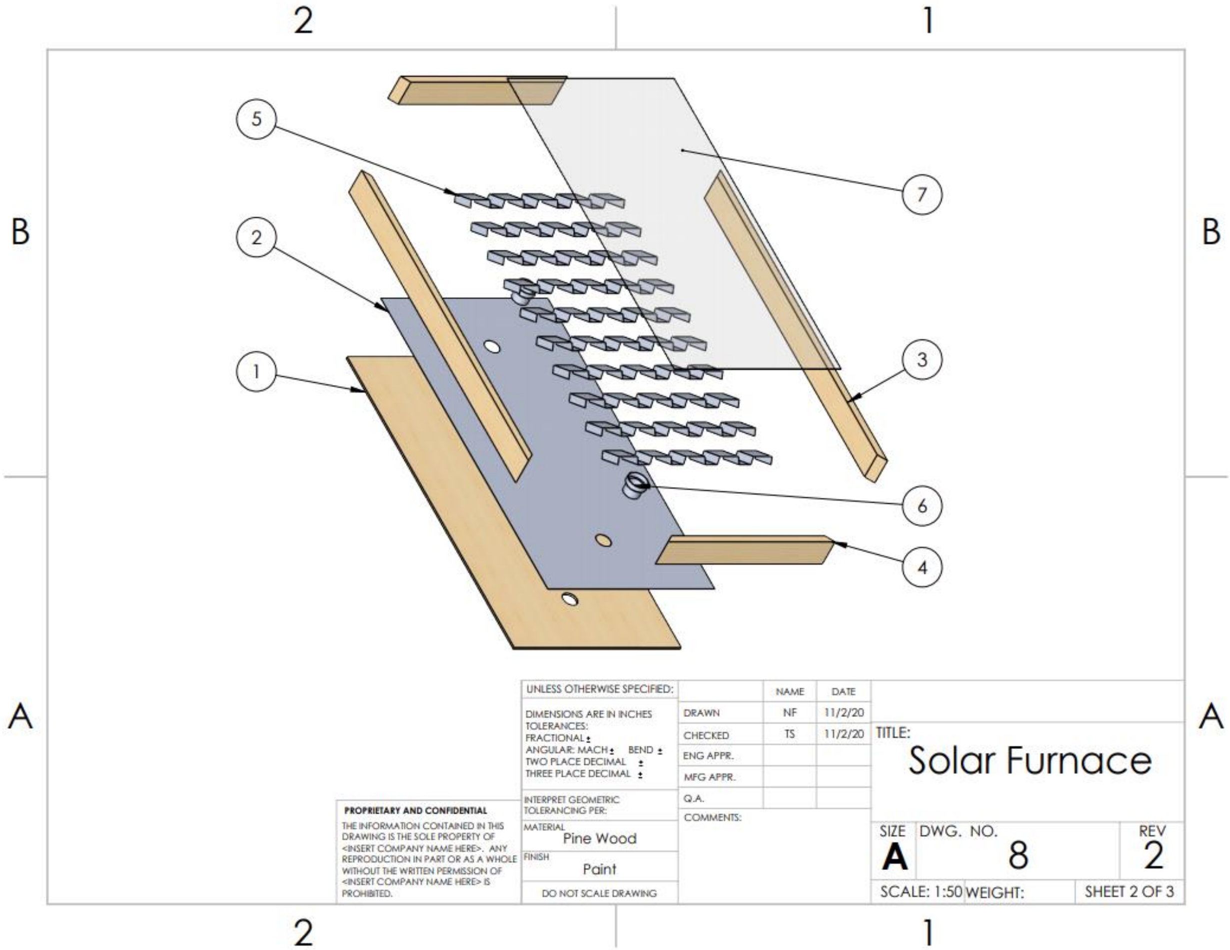
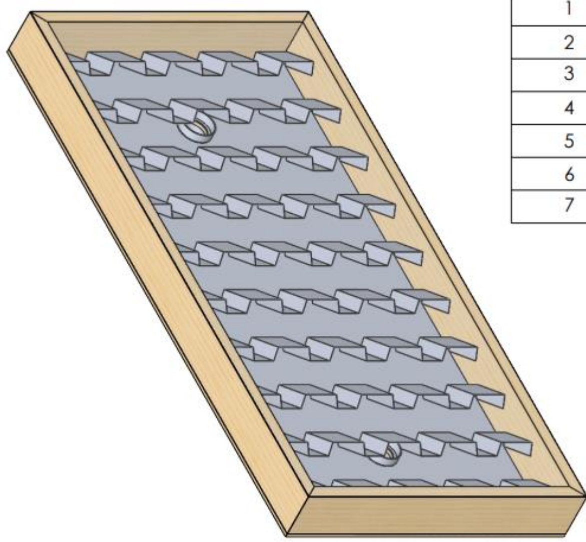


Figure D-9. Solar furnace assembly drawing: sheet 2 (exploded view).



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Base: Plywood		1
2	Base: Aluminum		1
3	2x6: Long		2
4	2x6: Short		2
5	Fin		10
6	Duct Connector		2
7	Acrylic Sheet		1

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL Pine Wood
FINISH Paint
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	NF	11/2/20
CHECKED	TS	11/2/20
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE: Solar Furnace

SIZE A | DWG. NO. 8 | REV 2

SCALE: 1:50 WEIGHT: SHEET 3 OF 3

Figure D-10. Solar furnace assembly drawing: sheet 3 (simple BOM).

12.5 Appendix E: FMEA

Table E.1. FEMA Analysis

Product Name: Red Feather Solar Furnace
Development Team: Red Feather Capstone Team
Date: 10/27/20

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
	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.
Mounting Bracket	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.
	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.
DC Fan	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.
	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.
Solar Panel	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.
	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.
Thermostatic Controller	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.
	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.
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.
	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
Wood Screws	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
	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.
Silicon Adhesive	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
	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.
Paint coating	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.

	Shattering during use	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.
	Cracking during manufacturing/install/use	Increased risk of damage to interior components; lack of heat generation; injury to somone in the visicnity of falling plexiglass pieces.	5	mishandling during construction; mishandling during intall; Inclement weather; wildlife interference; vandalism.	2	Refined manufacturing methods; Final checks before use	3	30	Develop acrylic repair method. Check state of acrylic panel periodically (once per month)
Plexiglass damage	Scratches during manufacturing/install/use	lack of heat generation to due to decreased clarity of panel.	5	mishandling during construction; mishandling during intall; Inclement weather; wildlife interference; vandalism.	2	Refined manufacturing methods; Final checks before use	3	30	heck state of acrylic panel periodically (once per month), replace if necessary
	separation of ducting components	lack of heat transfer into home; transfer of insulation material into home	7	wildlife interference; vibration from fan	1	Check ducting (purchased commercially) before install	4	28	none
Ducting	cracking of inner ducting material	lack of heat transfer into home; transfer of insulation material into home	7	wildlife interference; extended use	1	Check ducting (purchased commercially) before install	4	28	none

12.6 APPENDIX F. BOM

Table E.1: BOM bulk pricing 100 units for 3’x6’ model

New Price	Quantity	Unit Price	Source	
2'x6'x10'#2 Dimensional Lumber	3	45.69	Home Dep	https://www.homedepot.com/p/2-in-x-6
2'x4'x3/8" Plexiglass	1	95.19	acme plast	https://www.acmeplastics.com/acrylic-sl
7/16"x4'x8' OSB Board	1	24.35	Home Dep	https://www.homedepot.com/p/7-16-in-
12 oz. High Heat Spray Paint	1x3	27.38	menards	https://www.menards.com/main/paint/s
4"x 12ft" insulated ducting	1	18.77	Home Dep	https://www.homedepot.com/p/Master
Heat Resistant Caulk	1	2.083333333	Hotmelt	https://www.hotmelt.com/products/high
36"x36" Plain Aluminum Sheet	4	48	industrialm	https://www.industrialmetalsales.com/5
50-Watt Polycrystalline Solar	1	54.45	Home Dep	https://www.homedepot.com/p/Grape-S
Fan	1	32.16	Home Dep	https://www.homedepot.com/p/Attwoo
Solar Controller	1	14.99	Amazon	https://www.amazon.com/gp/product/B
Temperature Controller Module	1	8.99	Amazon	https://www.amazon.com/gp/product/B
Fiberglass Insulation	1	4.99	Home Dep	https://www.homedepot.com/p/Owens-
Switch	1	6.99	Amazon	https://www.amazon.com/gp/product/B
Subtotal			384.0333	