Red Feather - Team 20F02

Final Report

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EXECUTIVE SUMMARY

Red Feather Development group would like a design for a thermal storage device that can provide heat for a home at night. The goal for this team is to develop a prototype of a thermal storage device that can store heat during the day in a tank of water. The heat will then be released during a cold winter night. The materials for the device should be locally available materials. They should be within the price range set by the Red Feather group and their customers. The final design selected for prototyping was the cumulative result of the concept generation and selection process, as well as several weeks of deliberation and consultation both amongst the teams and with outside advisors. The constructed prototype design uses an insulated polyethylene storage tank to contain the thermal storage fluid and two separate pipe networks for charging and discharging the thermal storage device. These networks are driven by a pump and blower, for the purpose of transferring heat into and out of the system, respectively. The team then has an Arduino and thermocouples to measure the temperature of the water, heat transfer fluid, and air in the system. This prototype system is designed to be ultimately powered by a solar panel during the day and by a charged battery at night, to ensure continual operation once it has been started. This continual operation is reliant on the four main subsystems: the air pipe network, the fluid heating network, the storage tank, and the power supply. This report will examine their design and how they have changed from the initial selected prototype. In total, following weeks of research, construction, and careful budgeting the total cost of the constructed prototype is $1,870.90, according to the Bill of Materials, which can be found in **Appendix A**: Bill of Materials.

ACKNOWLEDGEMENTS

During this capstone we had several people make a large impact on our project. At the beginning Dr. David Trevas helped us to build a strong foundation for our project. Along with him Chuck Valence was a mentor for us throughout our design and building process. He had a lot of useful input and helped us to consider new ideas and broader concepts. The past capstone team that worked on a similar Red Feather capstone project was also useful in providing us with useful information and project materials. Along with these people Terry Smith was our client, and he had a lot of useful input on the direction of the project and how it needed to evolve. Finally, Dr. Sarah Oman was a mentor to us during the second semester of our capstone. She provided helpful feedback throughout the building process and kept us on track to finish everything on time.

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1. BACKGROUND

1.1 Introduction

The Red Feather Development Group is an organization that primarily does work on the Hopi Reservation and with the Navajo Nation. A problem that the people currently face is that there is no adequate heating source for a lot of homes on the reservation. On the Navajo Nation and Hopi Reservation they have been primarily using wood and coal stoves as the main heat source. This creates problems due to the lack of coal, which makes an inconsistent heat source. Another problem is that coal and wood stoves create a poor air quality which can increase the amount of asthma related health problems. Since it can hurt the lungs of the families living there, it can make it worse if COVID is caught. Another type of heat that is used is propane or natural gas, which can be expensive for long term use. Red Feather Development group has been installing solar furnaces on several homes however those only heat the homes during the day when the sun is shing, which still allows for the problem of inadequate heating at night.

1.2 Project Description

Previous capstone groups have designed solar furnaces that are reliant on the sun to produce heat for daytime use, however this left the problem on how the house would be warmed at night. To solve some of these problems Red Feather Development group would like a design for a thermal storage device that can provide heat for the home at night. The team is meant to prototype this design to prove the viability of their selected concept. The following is the original project description provided by the sponsor, "Red Feather Development Group is currently sponsoring an NAU capstone project to design a solar [furnace] used to heat a home on the Navajo Nation during the day. A solution is still required to keep the home comfortable throughout the night. Concept generation, evaluation, and design of thermal storage devices to be used in conjunction with thermal furnace solutions to keep indoor temperatures at or above 50+ deg F are the product deliverables. Use cost as a design parameter. The idea is to identify practical thermal storage designs using locally available resources. Phase change materials are not allowed due to cost." Based on this description a design prompt was more concisely filed out by the capstone team.

From the given project description, the team decided to focus on creating a device capable of storing heat in a given thermal storage medium that is subsequently released at night. The materials for the device should be locally available. Everything used for the system needs to be easy to transport to the home location. The design needs to be durable and able to handle the weather conditions that it will be exposed to. Lastly, the system should be within the price range set by the Red Feather group and their customers.

2 REQUIREMENTS

Constraints for this project were created based on the stated and inferred needs of the customer, which could be transformed into clear engineering requirements. To gather these, statements from the client were first recorded during an initial meeting. These were then interpreted to create specific customer needs, from which engineering requirements were derived and given specific measurement units and target values. These customer needs and engineering requirements are tabulated below in **Table 1**. A brief description of how the engineering requirements will be measured and what equations will be used given the measurements is also included. A total of ten customer needs were created and included in the tables below and from these, nine engineering requirements were derived.

2.1 Customer Requirements (CRs)

The client for this project is the Red Feather Development Group. The teams specific contact from them is Terry Smith. When meeting with Terry for the first time, the team composed a set of questions, and his responses were then used to design a set of specific Customer Needs. These needs ranged from information regarding the functions of the device and the kind of setting the device would have to perform in. The two most crucial pieces of information involved the temperatures the device would need to accommodate and the exact parameters of what the team needed to develop. With this information in hand ten customer needs shown in **Table 1** below were developed.

Table 1: Customer Needs

Question/prompt	Customer statement	Interpretation/Need
What is the main problem?	"A solution is still required to keep the home comfortable throughout the night."	Device should provide consistent heat source to keep houses warm at night, storing heat during the day and releasing at night.
What is the scope of the project?	"Current solar furnace is Arctica solar. Run by solar panel that runs the thermostat inside and monitors the temperature... Runs thermostat, fan, takes care of all electrical needs."	Device should store heat during the day and release it at night.
Where do you primarily work on homes in the reservation?	"Predominantly doing Hopi and western side of Navajo... Tuba City, Cameron, Leupp, Bird Springs. Currently [fall] temperature drops [from 100] to 40 °F in the evening... Gets colder as progress into fall. In the summer it is 100-50 °F. In the fall it is 100-40 °F. In the winter, goes down to 20's."	Device should be suited to functioning in Western Agency Council and Hopi Mesa regions.
How warm does the device need to keep the house?	"The [deliverables are the] design of a thermal storage device to be used in conjunction with thermal furnace solutions to keep indoor temperatures at or above 50 °F."	Device should maintain comfortable indoor temperature throughout night.
What is the budget?	"Comfortable with $1200/$1500 per unit." [Likely in tandem with Arctica Solar Air Furnace, for $500/unit]	Device should be within purchasing capabilities of Red Feather and the relevant clients.
Are there any readily available resources?	"Could ask Arctic solar if they would consider donating one [furnace] to look at. Resources available would be donations." [Donators must easily understand design]	Design should be straightforward.
What are our limits to size and dimension?	"If you start drilling holes in the roof, though, you could cause enormous problems. Exterior wall mounted systems work. Even in those systems, avoid a roof-mounted system. Any attempt to mount something on the roof will present a problem."	Device geometry should fit a variety of housing situations (no roof cave-ins).
What are the limits to the available materials?	"Device should be constructed with locally available materials."	Materials should be readily available in the region.
Will the device be reliable?	The device needs to consistently work for people in homes without maintenance.	Design a reliable design.
Will the device remain intact if dropped or damaged?	The device needs to withstand normal, everyday conditions, including different applications of force and different ranges of weather.	Create a durable and robust design.

The most important needs were that the device should provide consistent heat, store heat during the day, release it at night, and be capable of keeping a comfortable indoor temperature. It’s worth noting that the customer needs that had the highest importance were those pertaining to the effectiveness of the device. Next were qualities about the device's functionality on the reservation based on material availability in the Hopi region. This includes it being easy to operate, straightforward, low cost, and being reliable.

The customer needs from the preliminary report in ME 476C did not change last semester. However, a greater importance was placed on testing the concept and design versus having a fully operational solar thermal device. This made it so that the solar thermal panels could be replaced by heating tape that provided the heat stored in the device. This was so that the full potential of the thermal storage device could be evaluated rather than testing thermal solar panels. This was also intended to reduce the budget, and the time constraints to meet to test the concept, however this was not entirely the case. Despite this, once the solar thermal panels or a solar furnace are added to the design it will be able to function properly with some additional revisions.

2.2 Engineering Requirements (ERs)

The team derived nine engineering requirements from the ten customer needs, which are shown in **Table 2** below. The first is that there needs to be an engineering requirement measuring the temperature inside the home and outside the home. This ensures the device can keep the home at a comfortable, warm temperature, as one customer need presents. It also checks for the usefulness of the device in different climates, from the information that the Navajo Nation and Hopi reservations climates range from an outside temperature of 20 °F to 60 °F when the device would be heating during the night. Another important measurement is heat output from the device, taken by applying the heat equation, simplified to:

$$Q = mc_p\Delta T \qquad (1)$$

In which Q is the Heat Energy in BTUs, m is the mass of the medium fluid, in pounds, is the specific heat in BTU/°F/lb., and is the change in temperature, in Fahrenheit. If is negative, heat is lost, and if is positive, heat is gained. The target ER is 10,000 BTU/h.

During the Fall 2020 semester one of the engineering requirements included that the budget be within $1,500, which is the target ER, for the device alone. However, this engineering requirement has been increased where it is now $2,000. This comes from a desire for the device to be affordable and reliable for the Navajo and Hopi reservations. To create a straightforward design which is not too complex, the team required the device to have a maximum of 12 unique parts. For this purpose, the fewer the parts required indicates a better mechanical design. Due to the need for a device that adapts and functions on a variety of styles of homes, the team requires the device to meet certain device dimensions and weight, so that it is not unavailable to certain types of homes. The target ER is for the device to be within 4 ft. by 8 ft., which is the size of a typical truck bed, and less than 500 lbs.

Because resources are difficult to deliver to the customers’ locations, and to address the customer need of using readily available materials, the team uses distance as a metric for how justifiable it would be to use different resources for our device. Later the team will also look at how often a resource is needed for the device, thus determining how often this delivery time will occur as a barrier to the customer. The target ER is a maximum of 150 miles, which can be measured using an odometer.

Another important engineering requirement is for the device to be durable and robust, withstanding different weather conditions. This is tested by submerge the electronic components case within a bucket of water to see if the water is sealed out. The target ER for water that the case can be submerged in is 5 gallons.

Table 2: Engineering Requirements

Engineering Requirement	Derived from this Customer Need.	Method of measurement	Unit of Measurement	Target ER	Testing Procedure
Device maintains consistent house air temperature (60deg F)	Device should maintain comfortable indoor temperature throughout night.	Thermometer or Temperature Sensor for temperature of air	Fahrenheit BTU/h	60F 10,000 BTU/h	Over a 14-hour period, the device outputs 10,000 BTU/h
Device works in environments with outside temperatures ranging from 20 °F to 60 °F.	Device should provide consistent heat source to keep houses warm at night, functioning within standard season range of Navajo Nation and Hopi Reservation temperatures.	Thermometer or Temperature sensor	Fahrenheit	20-60F	Run device for several day/night cycles with projected lows around 20 F; if device maintains minimum heat output over 20 or sub 20 F nights, it passes the test.
Device stores heat in an effective method.	Device should provide consistent heat source to keep houses warm at night AND device should store heat during the day and release it at night.	Heat equation, using mass, material qualities such as the specific heat of the medium fluid, and a measured change in temperature.	Fahrenheit	175F	Measure the temperature of the water of the storage tank. Over 14 hours, does it maintain 175 F?
Device budget is within $2,000.	Device should be within purchasing capabilities of Red Feather and the relevant clients.	Pricing	Dollars	$2,000	Bill of materials
Device has no more than 12 unique parts.	Design should be straightforward.	Counting	Unitless	<=12	Bill of materials
Device able to install onto a variety of homes.	Device geometry should fit a variety of housing situations (no roof cave-ins)	Device dimensions and weight	Feet, Lbs.	4ft.x 8ft <500 lbs.	Measuring tape Bill of materials
Materials should have minimal delivery (transit) time.	Materials should be readily available in the region.	Transit time of materials	Miles	<150 miles	Odometer
Device should work without interruption or maintenance.	Design a reliable design.	Amount of time device works without stopping.	Days	7 days	Device functions without stopping for at least one week.
Device should be able to withstand all weather conditions.	Create a durable and robust design.	Amount of water on the electronics case that can be withstood over time.	Lbf, Volume of water	5 gallons of water	Submerge the electronic components case within a bucket of water to see if the water is sealed out.

2.2.1 ER #1: Home temperature

2.2.1.1 ER #1: Effectively heat the home - Target = 60 °F

This engineering requirement was decided on because the team wanted to make sure that their device created a place that could make a home comfortably warm.

2.2.1.2 ER #1: Effectively heat the home - Tolerance = +/- 5 °F

This tolerance was decided on by considering the loss due to a change in degree and the capabilities of the device to always match exactly 60 °F.

2.2.2 ER #2: Environmental Resistance

2.2.2.1 ER #2: Device Operates Outside - Target = 20 to 60 °F

This design range was decided on after considering the average low and high temperatures for the region during the winter months the device would likely be used in.

2.2.2.2 ER #2: Device Operates Outside - Tolerance = +/- 10 °F

This tolerancing was chosen to provide the device with a buffer in case the temperatures do reach further extremes. With this tolerancing in mind the device can still function in colder/hotter climates. It will just operate less efficiently.

2.2.3 ER #3 Effective Thermal Storage

2.2.3.1 ER #3: Stores and holds Thermal Energy - Target = 175 °F

This target value was deemed necessary as it allows for the required thermal energy to be stored and does not exceed the limits of how much heat the tank can withstand before damage.

2.2.3.2 ER #3: Stores and holds Thermal Energy - Tolerance = +/-5 °F

This tolerancing was chosen as it represents a fair assessment of the kind of ranges, we might see before the system becomes less efficient.

2.2.4 ER #4 Budget

2.2.4.1 ER #3: Cost under $1,500 - Target = $1,250

The client was able to increase the overall budget to $1,500 from the $1,000 that was set last semester. The team believes the cost should not exceed $1,250 based on the current Bill of Materials.

2.2.4.2 ER #3: Cost under $1,500 - Tolerance = +/- $250

The maximum cost for this project is now set at $1,500, but the team is set to design towards only using $1,250 to allow a contingency of $250.

2.2.5 ER #5 Straightforward Design

2.2.5.1 ER #3: Low Total Part Count - Target = 12 parts in total

It was decided that the device should be twelve parts to keep the design from becoming unnecessarily complex and keep the building time as short as possible given the multiple functions of the device.

2.2.5.2 ER #3: Low Total Part Count - Tolerance = +/- 2 parts

While the device is still held to a manageable number of parts, it is realistic that the number of parts required will be in flux as the team discovers what does and does not work. This tolerance realistically considers how the design may change.

2.2.6 ER #6 Easy Installation

2.2.6.1 ER #3: Minimum Size and Weight - Target = 4ft x 8ft and Less than 500 lbs.

This target was decided on as it became clear the device would be set up a small distance away from the home and after calculations were taken for how much water would be required in order to store the thermal energy.

2.2.6.2 ER #3: Minimum Size and Weight - Tolerance = +/- 6 in. And +/- 20 lbs.

These dimensional tolerances were decided given the flux of the design and that the total weight and size may shift by a small margin.

2.2.7 ER #7 Delivery Time

2.2.7.1 ER #3: Minimal Transit Time - Target = Less than 150 miles

This requirement was decided on to ensure that the device could be effectively available to the people that need it. It was decided that 150 miles would be reasonable to reach people who are living throughout the reservation.

2.2.7.2 ER #3: Minimal Transit Time - Tolerance = +/- 25 miles

While our target can consider everyone on the reservation the device would be projected to go to, this tolerance accounts for anyone else who may get the device installed.

2.2.8 ER #8 Reliable Design

2.2.8.1 ER #3: Works without Stopping - Target = 7 continuous days

Due to the nature of the device needing to collect heat during the day and give it off at night, it is expected to operate all 7 days of the week.

2.2.8.2 ER #3: Works without Stopping - Tolerance = +/- 12 hours

The tolerance chosen for this Engineering Requirement is mostly present to account for time where the device is made to sit idle due to any number of factors.

2.2.9 ER #9 Dealing with Weather

2.2.9.1 ER #3: Electronics Work When Wet - Target = 5 gallons of water

The target of five gallons is meant to account for the large amount of rain and snowfall that can occur in the region where the device will be used.

2.2.9.2 ER #3: Electronics Work When Wet - Tolerance = +/- 1 gallon

This tolerance of 1 gallon is primarily used in order that the device be able to function even under the more extreme and rare weather occurrences.

2.3 *Functional Decomposition*

For functional decomposition, the team created a black box model to show a basic concept of what the device should be doing. Furthermore, the team created a Functional Model to show the broken-down components at each step of the process in our system. The functional model changed significantly between this report and the preliminary report. One reason for this is that the design has been compacted and simplified to have both heat exchangers inside the storage tank. Another reason is that there is now a loop of cold air and cold air recycled and blown into the house and then back into the tank when the air cools.

2.3.1 Black Box Model

The Black Box Model shows sunlight and water as physical inputs. Sunlight comes in naturally to the solar panel without a physical interaction. Water remains available in a closed loop system where the water is recycled after first being heated to transfer heat to the air and then cooled down and recycled. There is a signal input in the form of temperature data from the Arduino. The function of our system is to store thermal energy throughout the day to dispense during the night. The physical output of the system is heat in the form of warm air to be provided to the home. The signal output is temperature data from the Arduino. The Black Box Model can be seen below in **Figure 1**.

Figure 1: Design Black Box Model

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

The process starts with a liquid pump that pumps a heating fluid, propylene glycol, into copper piping that is heated with heating tape and a heating element, such as a thermal solar panel. This copper piping leads to an insulated storage tank which keeps fluid heated at 175 °F throughout the night. During the day, this fluid is heated with the heating tape so long as there is thermal energy provided through means such as the solar panel. Then, at night, this fluid is exchanged with water in the tank to make the fluid even hotter, then the fluid goes through a second liquid-to-air heat exchanger which takes cold air recycled from the house and makes the air hot through heat transfer of the hot fluid. Then, this hot air is blown through a blower into the house. Liquid is recycled back into the pump at the beginning of the cycle. Meanwhile, electricity is provided to the blower to blow hot air into the house through a subsystem with an electric solar panel which stores electricity in a battery throughout the day to be provided to the blower during the night when the solar panel is not actively providing electricity. This source of electricity, the solar panel, and the battery also provide constant monitoring of temperature at four different points in the system using thermocouples and an Arduino. The first part monitored by the Arduino is the liquid going from the pump into the storage tank, before it is being heated up. It should not be a high temperature yet. The next thermocouple is placed in the storage tank to monitor how hot the fluid is inside the tank, which should be 175 °F. The third thermocouple is placed at the blower which blows hot air into the house. This hot air should be up to 70 °F. The last thermocouple position is inside the house. The air in the house should be at least 60 °F. The functional model depicting this process is included below in Figure 2.

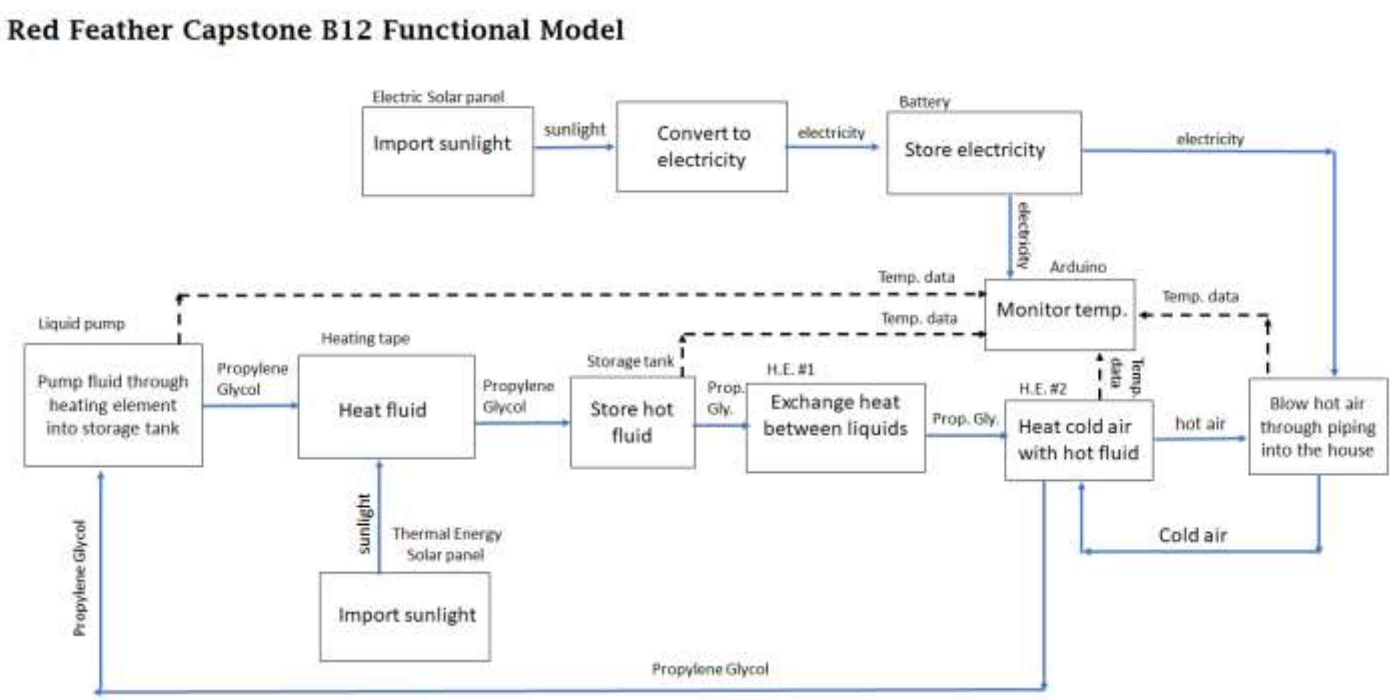

Figure 2: System Functional Model

2.4 House of Quality (HoQ)

The House of Quality presented all the customer needs and weighed them alongside corresponding engineering requirements to find which engineering requirements weigh most heavily in the concept selection stage. A table of the House of Quality can be seen below in **Table 3: House of Quality**. The results were that the most weighted engineering requirement is the heat transfer rate of the device with an Absolute Technical Importance (ATI) of 186, and a Relative Technical Importance (RTI) of 0.1862. The second most weighted engineering requirement was the device cost, with an ATI of 148 and an RTI of 0.1481. Following these, the next most weighted engineering requirements were, in order, the outdoor temperature range, indoor air temperature, cycles without failure, number of parts, dimensions and weight, force withstood, and finally, max material delivery time as the least weighted engineering requirement.

Table 3: House of Quality

Customer Needs	Customer Weights	Engineering Requirement	indoor air temp. (°F)	heat transfer rate (BTU/h)	Temperature of storage tank liquid (°F)	Device cost ($)	Number of parts (unitless)	Dimensions (ft^2)	Weight (lb)	Max material delivery distance (mile radius)	Outdoor temp. range (°F)	Volume of Water withstood (gal)	Cycles without failure (Days)
1. Consistent heat source at night	5		3	9	9	3		1	1		3		9
2. Store heat during day	5		3	9	9	3		1	1		9		1
3. Maintain comfortable indoor temperature throughout night	5		9	9	9	3		1	1		3		1
4. Device should be within purchasing capabilities of Red Feather and the relevant clients	5		0	0	0	9	6	3	3	3		1	1
5. Design should be straightforward.	3		0	0	0	3	9	1	1			1	1
6. Functions within standard season range of Navajo Nation and Hopi Reservation temperatures.	4		3	6	3	3					9	3	
7. Device geometry should fit a variety of housing situations	4		0	0	0	1	6	9	9			1	
8. The device should be efficent as possible.	3		6	9	3	3	1	1	1		3		6
9. The device should be durable	4		0	0	0	3	1	1	1			9	6
10. Materials should be readily available in the region	2		0	0	3	6	1			9			
Absolute Technical Importance (ATI)			105.00	186	162	148	90	76	76	33	120	60	105
Relative Technical Importance (RTI)			0.09044	0.1602	0.1395	0.1275	0.08	0.065	0.07	0.03	0.103	0.052	0.09
Target ER values			60	10,000	175	1200	<=12	4'x8'	<500	<150	20-60	5	7
Tolerances of Ers			(+-) 10	(+-200)	(+-5)	(+) 500	(+-)1	(+)0.1	(+)10	(+)10	(+)3	0	0
Testing Procedure (TP#)			#1	#1	#3	#4	#5	#6	#6	#7	#2	#9	#8

2.5 Standards, Codes, and Regulations

Table 4 below provides the standards, codes, and regulations that apply to this project. Standards and codes vary from the ASME, IEE, Mechanical residential code (MRC), International residential code (IRC), and the International plumbing code (IPC) [1, 2, 3]. These codes and regulations must be considered for this project to ensure the safety of our clients. Since water will be heat to approximately 175 °F then the storage tank must be safe and under code to withstand the water temperature. The type of piping material for the heat exchangers cannot degrade or build residue from the high-water temperatures. Also, the air temperature cannot exceed temperature values of 250 °F.

Table 4: Standards of Practice as Applied to this Project.

Standard Number or Code	Title of Standard	How it applies to Project
ASME BPV Code, Section VII Division I	Design and Fabrication of Pressure Vessels.	Helps in the design of selecting the right type of heat exchanger that is safe and effective.
IEE 937	Recommended Practice for Installation and Maintenance of Lead-Acid Batteries for Photovoltaic Systems	Helps ensure the PV solar panel is installed correctly and safely.
2018 IRC Chapter 16	Duct systems	Making sure the duct system is safe, proper installation, and is durable for the warm air.
2018 IRC Chapter 23	Solar thermal energy systems	For choosing the correcting heating fluid for the heat exchangers.
2018 MRC Section 1003	Pressure vessels	Choosing the right material to withstand the pressure for the heat exchangers and be accessible.
2018 MRC Section 1202	Hydronic piping	Choosing the proper material for the piping within the tank.
2018 MRC Section 1404	Heat Transfer Fluids	To ensure the heat exchangers have leak protection.
2018 IPC Section 504	Safety Devices	Providing a pressure and temperature relief valve for the hot water storage tank.

3 DESIGN SPACE RESEARCH

3.1 Literature Review

To create a successful design capable of fulfilling the given criteria, it was first necessary for the team to do background research on a variety of topics related to the project. Their findings are detailed below.

3.1.1 A feasibility study of a stand-alone hybrid solar–wind–battery system for a remote island [4]

This journal explored the possibility of creating an almost entirely self-sustaining home on an island. For such a system a deep cycle battery was used. Through this section of the journal the authors discuss all the specifications going into the device. Though it has impressive capabilities such a battery would be much too expensive for small scale budgeted ventures. However, the paper outlines many of the calculations one might make when considering a similar kind of battery used for solar storage.

3.1.2 Design Features and Benefits of a Spiral Heat Exchanger [5]

Spiral heat exchangers consistent of two long metal plates, rolled together around a central axis to create concentric spiral flow paths for the two fluids. Their shape and exact dimensions can be optimized for specific heat transfer fluids and applications. There are certain advantages to this design: first, spiral heat exchangers are highly efficient. Next, they are often self-cleaning, as the shape of the passages induce shear that removes deposits. Finally, they are relatively small and accessible, making maintenance and installation easier [5].

3.1.3 Seasonal Solar Thermal Energy Storage [6]

The next article is, "Seasonal Solar Thermal Energy Storage" discusses the use of solar energy to be thermally stored for heating or cooling. It discusses the first uses of solar water heater in 1891. It states that it is believed that thermal storage will be preferred over batteries because of the large loads it could support and that it is generally a cheaper solution. One of the systems discussed is pictured in Figure 3, a solar system that heats a water tank and when the water has enough heat, then it releases excess through the sand-bed usually under the garage floor through radiation [6].

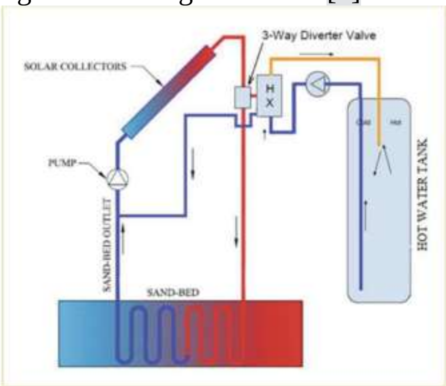

Figure 3: Sand-Bed Thermal Heat Storage [6]

This is a good example because it heats the home in many ways. The next example is one that is commonly used already in Figure 4.

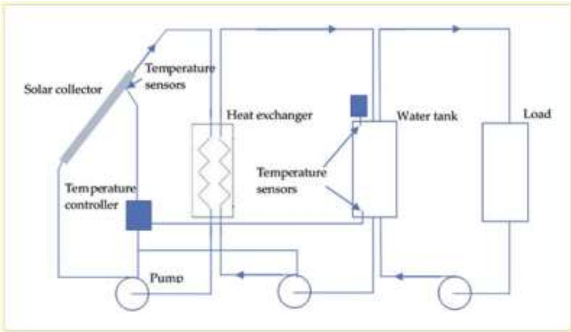

Figure 4: Commonly Used Water Thermal Storage System [6]

Figure 4 shows a system that uses a solar thermal collector to heat the water in the tank to supply enough heat for the load [6]. It utilizes heat exchangers and pumps to do this which is like the team's design.

3.1.4 Everything You Wanted to Know About Solar Water Heating Systems [7]

The article "Everything You Wanted to Know About Solar Water Heating Systems" was looked at next since it talks about a lot of specifics when designing a solar water heating system. This discusses a system design that uses solar power to heat the water, which is then pumped in order to be used in the home. It discusses how the size of the tank is chosen based on the household needs and the collector are needs to be at least 20 sq feet for two people. It states that a tank storage of 50 to 60 gallons will be sufficient for

1-3 people. However, this talks more about a system providing hot water the team is choosing a similar design to heat the hot water which will need an additional step of releasing hot air. This is another good example of a system that represents the heating method [7].

3.1.5 Solar Thermal & Solar Thermal Storage Tanks [8]

The next article is, "Solar Thermal & Solar Thermal Storage Tanks" which discusses all the uses and benefits to solar thermal storage. It discusses three different useful space heating designs. The first design talked about is radiant floor systems. The benefit to this type of domestic heating is that the tank only needs to reach 95 °F which means that less solar generation is necessary. However, this design requires the floors to be ripped out which increases installation costs greatly. The next design discussed is forced air systems. This needs a water to air heat exchanged and then some form of fan to release the air. This tank size generally needs to be 120 °F. The last design is using a hydronic baseboard. This usually generates 225 Btu per foot when the water is 120 °F [8]. This article was helpful, because it discusses uses that this company sells to produce heat with their water tanks. It talks about a closed system like the team's design.

3.1.6 Analyzing Different Types of Solar Water Heating Systems and Costly Savings [9]

Four-person households in Phoenix, Arizona are expected to save 80% in energy using a SunEarth® solar system. There are direct and indirect circulation types for this water heater solar system with actively cycled or passively cycled water, both with a collector to capture solar energy from sunlight. The active systems pump water through the system while the inactive, or passive, systems move water through natural convection, from collector to storage tank as the collector heats up. Direct systems force water through the system pipes to heat up through the collector and then into a storage tank or into the house. This makes direct systems less practical for cold climates where the water may freeze. The indirect system cycles a non-freezing heat transfer fluid, usually a mix of this fluid and water, through the collector to heat up before passing through a heat exchanger to transfer the heat from the fluid to water. A schematic of this can be seen below in Figure 5.

Figure 5: Indirect System with Active Circulation [9]

3.1.7 Use of a Closed Loop Thermosyphon in Thermal Storage [10]

Thermosyphons make systems more cost effective, because they eliminate the need for a water pump as temperature change causes buoyancy that will circulate the fluid. Such a system has a storage volume for the heat transfer fluid, a heat exchanger or heating component, and a flow restrictive component, which is a thermosyphon in this case. Heat in warmer fluid, with the assistance of gravity, causes pressure to push the fluid through the heating part until enough energy from the heat has accumulated to stop the flow. A schematic of a thermosyphon can be seen below in Figure 6**.**

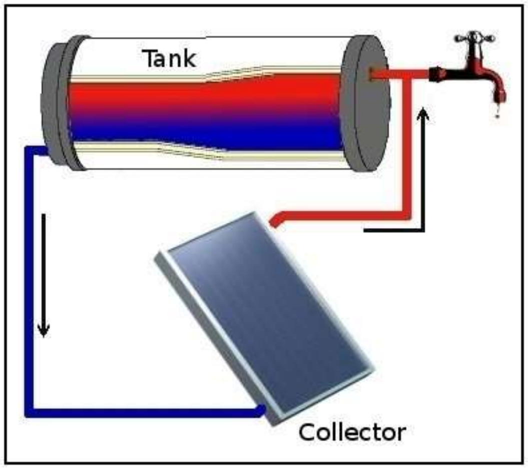

Figure 6: Thermosyphon and Solar Collector System [10]

3.1.8 Experimental Study on a Forced-Circulation Loop Thermosiphon Solar Water Heating System [11]

Tao Zhang analyzed wickless gravity loop thermosiphons (LTs), which proved to be a useful component for long-distance heat transfer in solar water heaters. Instead of using gravity, there is forced circulated with a pump to push fluid through the system. This is less cost-effective but has better thermal performance.

3.2 Benchmarking

The team compared the specifications and output of several different components of design through the process of benchmarking. The team decided on these benchmarks in the first semester before changing design decisions throughout the prototyping process in the second semester.

3.2.1 System Level Benchmarking

Three different system-level designs were examined for the purpose of benchmarking. They were chosen based on relevance- all designs are either current or proposed solutions to heating homes on the Navajo Nation and Hopi Reservation. They include the current, outdated wood stoves, more modern hybrid stoves, and the solar air heater currently being used by the Red Feather Development Group.

3.2.1.1 Existing Design #1: Current Heating Device: Wood Stove

This benchmark reflects the current, most-common form of heating in the given area. While the exact model of stoves varies, in general many of those in use on the Navajo Nation are inefficient, with poor ventilation and sealing of the stove exhaust. In many cases, stoves designed for use with wood are used with coal instead, further contributing to inefficiency. Furthermore, the poor ventilation and exhaust problems can have significant consequences for the indoor air quality of the home, with carcinogenic particulate leading to increased breathing problems and other health issues. This is a particular issue with home-made stoves, such as the example shown below in Figure 7. For these reasons, these stoves have been targeted as part of the Navajo Stove Change-Out project, which is intended to provide higher quality heating devices as detailed below [12]. In general, this design is highly inefficient and rather dangerous.

While the exact heat output of these varies, health effects remain the primary concern, so creating a healthier heating method will be a key goal of the team.

Figure 7: Home-made Barrel Stove from Lupton, AZ [12]

3.2.1.2 Existing Design #2: Updated Stove: Wood/Coal Hybrid from Change Out Project

This benchmark is intended to reflect more modern, health and environment-conscious forms of the stoves detailed above. While still combustion driven, these stoves are designed to provide a healthy and cheap way for members of the Navajo Nation to heat their homes and are being installed as part of an indoor air quality program created by the Navajo Nation Environmental Protection Agency (NNEPA) in order to counter the health and environmental effects caused by the deficient stoves described above. These are hybrid, and as such are specially designed to use coal or wood to heat buildings up to 1000 sq ft in size. When burning wood, they have a minimum output of 15,000 BTU/hr, and a maximum of roughly 27,000 BTU/hr. Conversely, when burning coal, they are capable of outputting roughly 7,000 BTU/hr at minimum, and 10,000 BTU/hr at maximum [13]. It also weighs roughly 280 lbs, with an adjustable height of 28” – 34” and a footprint of 17” x 24”. They also come in a variety of colors, with design intended to fit a “Navajo Aesthetic” [12]. In general, this device will likely provide a valuable standard for the team’s design to meet, due to its high heat output in a relatively compact package. Of note is the minimum heat output value, which will provide the team with a useful basis for the necessary minimum heat output by their device.

Figure 8: Change-Out Project Stove [13]

3.2.1.3 Existing Design #3: Arctica Solar Air Heater: Current Daytime Heater for Navajo Communities

Currently, the Red Feather Development Group has implemented many installations of the company Arctica Solar's solar air heater which provides significant heating during the day. The heater uses a solar heating panel made of solar-absorptive materials on the side of the house. It generates its own electricity to circulate the hot air into the house, and it has a thermostat [14]. It weighs 50 lbs., is 74.013" total in height, and 38.279" in width. It heats 150 ft^2 rooms, heating incoming air to be 75°F higher than as it comes in [15]. The Red Feather Development Group reported the homes being heated to 80°F. This solar air heater can be seen below in Figure 9**.**

Figure 9: Arctica Solar Assembled 1500 Series Solar Air Heater

3.2.2 Subsystem Level Benchmarking

To determine the ideal components for use in the final design, the team undertook benchmarking of different key subsystems. This allowed them to review and compare the options, and make an informed selection based on the needs of the system.

3.2.2.1 Subsystem #1: Heat Exchangers

The role of the heat exchangers in this system is to transport thermal energy into and out of the thermal storage device. As such, they are critical for ensuring the appropriate charge and discharge of the system throughout the day and must be selected carefully.

3.2.2.1.1 Existing Design #1: 12x24 Water to Air Crossflow Heat Exchanger [16]

This heat exchanger is made of 1” copper ports. It provides 115,200 BTUs, has a fin area of 12”x24”. The tubing is ¼” copper. The heat exchanger is hooked up to a boiler or a chilled water source to provide water as the second medium fluid to heat the air.

3.2.2.1.2 Existing Design #2: Shell and Tube Heat Exchanger [17]

This type of heat exchanger is small and compact. They are easily built and effective heat exchangers. The three main types of shell and tube heat exchanger are the u-tube heat exchanger, the fixed tube sheet exchanger and the floating head exchanger. The floating head exchanger is the most expensive type, but it has the best efficiency and maintenance. The u-tube exchanger is good for when there are high temperature differences, because it allows for room to expand and contract, however the curves are hard to clean. The fixed tube sheet exchanger is the easiest to build and the cheapest, but the temperature difference must be small, due to no expansion room.

3.2.2.1.3 Existing Design #3: Existing Design #3: Cast Iron Radiator, 18 Sections, 19"H, 4 Tubes [17]

These kinds of radiators tend to be reliable and capable of spreading heat throughout a room. For our design, a system like this could be useful in taking the warmth from our water and heating up space. Being a comfortable 19 by 31 inches the device is large enough to heat a decent sized area while not being too cumbersome. It also provides a simple system for heating that doesn’t require many complexities.

3.2.2.2 Subsystem #2: Water Tanks

The water tanks are also critical for the function of the design, as they are responsible for holding the fluid which will act as the thermal storage medium. As such, they must be capable of storing the necessary amount of water, in addition to withstanding the expected temperature ranges for fluid. As such, these tanks represented another key subsystem to benchmark.

3.2.2.2.1 Existing Design #1: 40 Gallon Tamco® Vertical Natural PE Tank with 8" Lid & 3/4" Fitting - 19" Dia. x 41" High [17]

The first design I explored is an actual water heater tank. This design is useful to include as it is reasonably priced and something that most people are familiar with. ITs also useful to understand the components that make up the tank along with the purposeful insulation that uses a foam type substance of ¾ inches thick. Along with this a tank of this make is already intended to be attached to a full system leading to a design that may be more easily integrated into our system. With all of this in mind the device itself is not designed for the purpose of being a thermal storage device. This means it would have the tradeoff of being a need to rework the tank to better fit the design goals.

3.2.2.2.2 Existing Design #2: Hydroflex Flexible Thermal Storage Tank – T100 [18]

Unlike the tank above this water storage tank is specifically designed to store hot water for later use. It uses a similar insulation method with an inner and outer shell-based design that includes a foam-based insulation between the shells. The tank itself does appear to be less structurally stable being stated as being able to be compressed more easily. It is also stated to be able to hold 100 gallons which is a useful amount given the scope of what our team is trying to accomplish.

3.2.2.2.3 Existing Design #3: DN Tanks [19]

The DN Tanks largest advantage is that they have been produced by the same company for over 30 years. This suggests a large amount of reliability and trust that can be placed in their tanks design. Like the example above these tanks have been made specifically for the task of storing thermal energy in the form of water. Made pf concert these designs are highly durable and lily able to work in most areas. Unfortunately, their design mostly benefits large scale thermal storage situations and may not be viable for individual homes.

3.2.2.3 Subsystem #3: Solar PV systems

[Describe this subsystem from your functional decomposition. Discuss why this subsystem is important to your overall project.]

Since the device battery and other key functions are to be charged with solar power, the panels selected for this task must be capable of providing the necessary output, in addition to withstanding the anticipated conditions. As such, solar panel benchmarking was done carefully in order to ensure ideal function of the design’s electrical systems.

3.2.2.3.1 Existing Design #1: SunPower [20]

The first solar PV system that was looked at was the Sunpower solar panel. The solar panel has a good efficiency compared to competitors at 22.8% [20]. Compared to the other two manufactures this is the highest panel efficiency. This panel has a temperature coefficient of –0.29, which compared to LG it rates higher, but it rates lower compared to Panasonic [20]. For the materials warranty it is 25 years which is the same as the other two manufacturers [20]. However, this is much longer from the industry standard of 10 years.

3.2.2.3.2 Existing Design #2: LG [20].

The next solar PV system design looked at was from the manufacturer LG monocrystalline solar cells design. This design had a panel efficiency of 22%, which is slightly smaller than the Sunpower system [20]. However, this efficiency is much greater than that of Panasonic. Then for the panel's temperature coefficient it is –0.30 which is the worst for the three solar panel manufacturers [20]. For the materials warranty it was the same as the other two designs at 25 years which is greater than the industry standard of 10 years [20].

3.2.2.3.3 Existing Design #3: Panasonic [20].

The last solar PV design to be analyzed is the system from Panasonic. The design is made with monocrystalline solar cells, which is utilized by the best competitors. This system scored the worst out of the three for panel efficiently at 20.3% efficiency [20]. However, this panel has the best temperature coefficient out of the competitors at –0.26, which is greatly better than the other two systems [20]. It has the same materials warranty of 25 years as the other two designs [20].

4 CONCEPT GENERATION

4.1 Full System Concepts

4.1.1 Full System Design #1: Sand Box

Shown below in Figure 10 is the first full system design, the Sand Box.

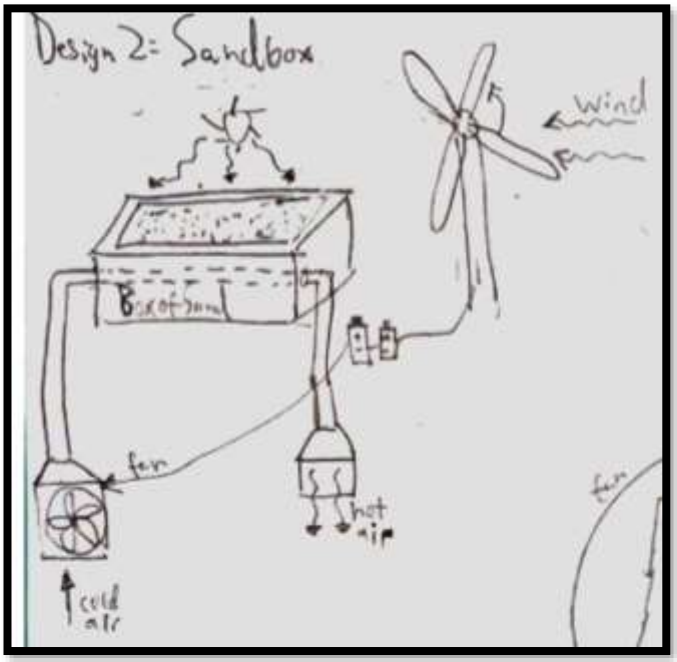

Figure 10: Sand Box Concept

The focus of this design was to explore the viability of using sand. The design used sand in order to store all the thermal energy given off by the sun during the day. This design used a small number of parts and mostly relied on sand and a simple heat exchanger to convert the hot water to hot air. Though the design was simple it still scored quite low. The low success rate of sand as a thermal medium along with using more challenging parts like a wind turbine led to the device scoring low overall.

4.1.2 Full System Design #2: Lifted Tank

The next design, which features a lifted tank, is shown below in Figure 11.

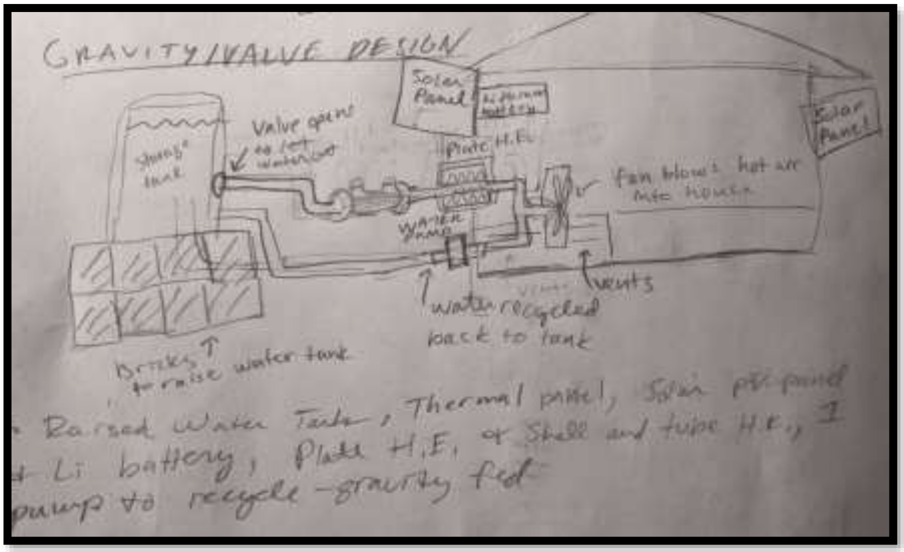

Figure 11: Lifted Tank Concept

This was one of the more complex designs with several pumps, heat exchangers, and multiple forms of energy production. Though its complexity made it less practical it did allow it to do a thorough job of heating the home. Along with this by being buried it was able to reduce heat loss to its environment allowing it to be more efficient with the heat it collected.

4.1.3 Full System Design #3: Resistive Network

The third full system design, featuring a resistive network as the primary heat source, is shown below in Figure 12.

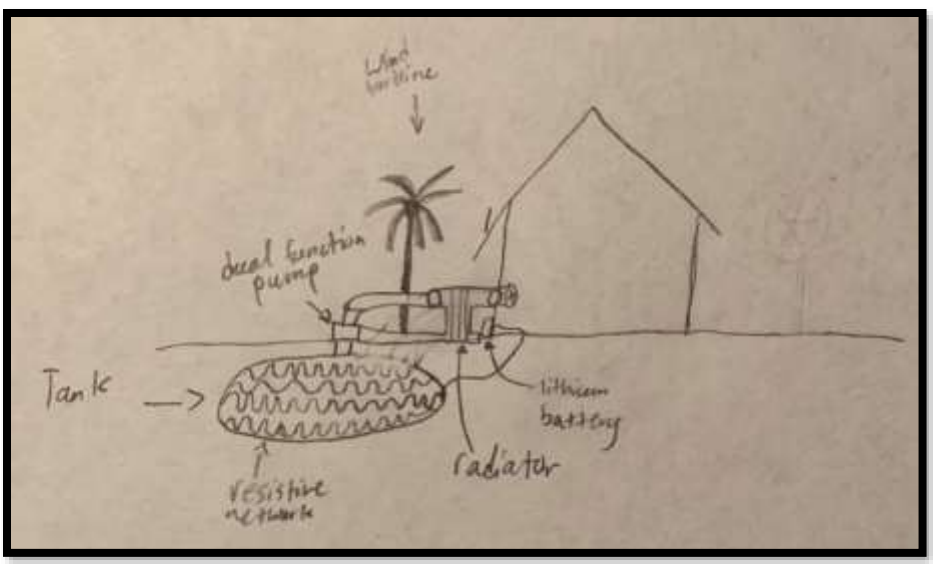

Figure 12: Resistive Network Concept

This design was creative but required elements that made it less realistic to actually implement. Mostly this is because it is entirely independent of solar heat. The whole system uses a resistive network to heat the liquid that would be used for heating the homes. Due to this it required several forms of energy creation including a lithium battery and a wind turbine. Overall, the device performed within the higher range of design concepts. This is due to the way it balanced simplicity and some more unrealistic elements.

4.2 Subsystem Concepts

When generating concepts for these designs, a variety of subsystems were considered. Variations in these subsystems was used to create diverse concept ideas via a morphological matrix. The most critical of these subsystems were heat generation, thermal storage, and electricity generation. These are shown in the section of the morph matrix below (**Table 5**).

Table 5: Morphological Matrix

Sub-function	1	2	3	4	5
Thermal Storage	Phase Change Material	Single water tank	Rocks	Buried water tank	Raised water tank
Heat generation	Thermal panel	Resistive network	Direct solar radiation	propane	Heating tubes
Electricity Generation/Storage	Solar PV Panel + Li Battery	Wind turbine + Li battery	Stirling engine	Propane generator	Grid Power

4.2.1 Subsystem #1: Thermal Storage

This subfunction refers to the portion of the design intended to absorb and store heat. The variants take a variety of forms, as detailed below.

4.2.1.1 Design #1: Phase Change Material

This thermal storage medium would take the form of some material that changes phase as it heats up, going from a solid to a liquid (changing phase). The advantages of this variant are its ability to store heat, as well as be stored as a solid when not heated. The main disadvantage relates to cost and availability, making it less ideal for rural, low-cost application.

4.2.1.2 Design #2: Single Water Tank

This concept variant involves using a single tank filled with water to store heat. The main advantages are simplicity, as well as the high specific heat of water, which allows it to store a great deal of thermal energy. The main disadvantage of this design is weight and the potential for heat loss through the surface of the tank.

4.2.1.3 Design #3: Rocks

This subsystem variant would use solid rocks, heated either via the sun or by warm air moving through them. The primary advantage of this design is cost and availability; rocks could be dug up on-site in most cases. The main disadvantage is the low thermal conductivity of rock, as well as high mass and weight, making it difficult to implement in a single-home use.

4.2.1.4 Design #4: Buried Water Tank

This subsystem variant is similar to #2, with the additional specification that the tank is to be buried underground. The primary advantage to this would be the thermal insulation provided by the ground, which should significantly reduce heat loss. The disadvantage of this variant is the required amount of labor to dig a sufficiently large hole, and the accompanying cost of that labor.

4.2.1.5 Design #5: Raised Water Tank

This is another variant on the water tank design. Unlike the buried water tank, it would involve a tank perched on some form of elevated platform. The advantage of this design is that it reduces the need for a pump; once the water is pumped into the tank, it can be returned via gravity. The disadvantage is its relative size, in addition to the additional cost of structural materials and insulation for an elevated tank.

4.2.2 Subsystem #2: Heat Generation

This subfunction refers to the method in which the device generates the heat stored in its thermal storage medium. These variations are useful in order to consider which systems the device may have to interface with. Said systems are detailed below.

4.2.2.1 Design #1: Thermal Panel

This functional variant is a solar-thermal water heating panel, which uses energy from the sun to heat water passing through. The primary advantage of this system is that it is proven and has a relatively developed market with a great deal of variation. It is also environmentally friendly and efficient. The main disadvantage of this system is its size, and the relatively high cost of the panels.

4.2.2.2 Design #2: Resistive Network

This subfunction would use a network of resistors, installed within or adjacent to the thermal storage medium, to create the heat. The primary advantage of this system would be its relatively robust and low-cost design; most water heater systems use similar devices. The drawback of such a system is its reliance on electricity for heating, and the associated issues with providing consistent, large amounts of power on the Navajo Nation and Hopi Reservation.

4.2.2.3 Design #3: Thermal Radiation (rocks)

This subfunction would involve the use of direct sunlight to heat the thermal medium, with the thermal medium itself being heated within its container by the sun. The main advantage of this design is its extremely low cost and accompanying robust nature. The disadvantage is that it is an inefficient method of heating and may be insufficient for the purposes of the device.

4.2.2.4 Design #4: Propane Heater

This subfunction variant would use a simple propane heater to warm the thermal storage medium. The main advantage of this design would be relatively low cost, and very high heat output. The main disadvantages are the need for regular resupply, the potential for the system to fail, and the health and safety concerns associated with the use of natural gas.

4.2.2.5 Design #5: Heating Tubes

This variant also uses solar radiation to heat the thermal storage medium, with the medium circulating through heated glass tubes in the sun. The advantage of this design is that it is relatively efficient, and cheaper than similar devices. The main disadvantage is the potential for it to be fragile, in addition to potentially taking up a lot of space.

4.2.3 Subsystem #3: Electricity Generation

This subfunction refers to the device's method of electricity generation. It is important that the device has power throughout the night in order to maintain heat output, and that power will be generated with one of the following subfunction variations.

4.2.3.1 Design #1: Solar PV Panel and Li+ Battery

This design would use a solar photovoltaic panel and lithium-ion battery to generate and store electricity. The primary advantage of this is that it is a proven technology, with relatively low maintenance costs. The disadvantage is its size, and the initial cost of the panel and battery setup.

4.2.3.2 Design #2: Wind Turbine and Li+ Battery

This design would use a wind turbine and lithium-ion battery to generate and store electricity. The main advantage is its relative low cost, with technology that is proven and has been used for some time. The disadvantage for wind turbines is that they require frequent maintenance and take up a great deal of space.

4.2.3.3 Design #3: Stirling Engine

This subfunction variant, the Stirling Engine, uses a temperature differential to generate electricity. The main advantage of this would be that, in theory, it does not require a battery to store electricity, due to the ever-present temperature differential. The disadvantages are high cost, low reliability, and general fragility of this design.

4.2.3.4 Design #4: Propane Generator

This variant, a propane generator, would use propane to generate electricity that would be stored in a battery. It would best be used in tandem with a propane heater for the thermal storage medium. The advantages of propane are its relatively low cost, and high efficiency. The disadvantages include size, weight, the need for frequent resupply, and the loud noise created by the generator.

4.2.3.5 Design #5: Grid Power

This subfunction variant requires a direct connection to some sort of electrical grid. It has the advantage of being the cheapest variant by far, and the simplest. The disadvantage of this design is that it makes the design inoperable in certain locations, and as such would significantly limit the versatility of the device when it comes to home type and location.

5 DESIGN SELECTED – First Semester

This section examines in detail the design selected for prototyping at the end of the Fall 2020 semester. To do this, it first describes the various physical details of the design, including the various key subsystems, before providing a detailed diagram intended to explain the operation of the device, how it works, and when it performs the tasks necessary to its operation. Once that is done, this section then describes the implementation plan for the device, including both the stages of the design and prototyping process as well as a detailed bill of materials.

5.1 Design Description

The final design selected for prototyping was the cumulative result of the concept generation and selection process, as well as several weeks of deliberation and consultation both amongst the teams and with outside advisors. This design, as shown in the CAD model below (Figure 13), uses a buried polyethylene storage tank to contain the thermal storage fluid, and two separate pipe networks for charging and discharging the thermal storage device.

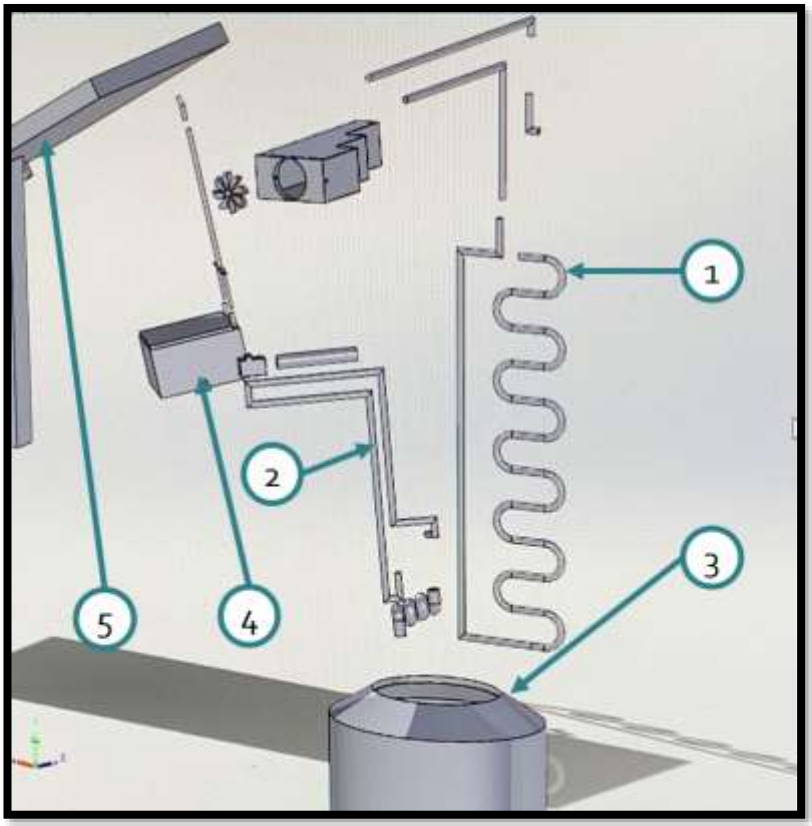

Figure 13: CAD Model Exploded View with Numbered Subsystems

1: Air Pipe Network, 2: Fluid Heating Network, 3: Storage Tank, 4: Control System, 5: Power Supply

These networks and their driving turbomachines (a pump and blower) are managed by the control system, which monitors temperature of the house and the storage fluid to determine flow rates needed to ensure consistent heating to the home. This system is powered by a solar panel during the day, and by a charged battery at night, to ensure continual operation. In order to examine the operation of each element of this system, it is useful to divide them into five main subsystems: the air pipe network, the fluid heating network, the storage tank, the control system, and the power supply.

5.1.1 Air Pipe Network

When the thermal storage device is discharging, this subsystem is responsible for moving the air through the storage device. It does this by first pulling air from the house with a blower and pushing that air through the pipe network and into the thermal storage tank. Once there, the air is heated in a liquid-gas heat exchanger submerged in the tank fluid, before being returned to the house via more copper piping. This subsystem only operates at night and is necessary for delivering heat from the thermal battery to the house as it discharges. During this time, the blower operates on battery power. This subsystem does not operate during the daytime, while the system is charging.

Originally, the Air Pipe Network used a fan at the end of the network (the outlet to the house) to drive airflow. However, after suggestions to do so from both advisors, the team decided to replace this with a blower at the inlet to the pipe network.

5.1.2 Fluid Heating Network

The Fluid Heating Network performs a similar role to the Air Pipe Network, albeit during the day. In this subsystem, heat transfer fluid is circulated through the pipes, transferring heat from a section of pipe wrapped in heating tape to a liquid-to-liquid heat exchanger inside the thermal storage tank. This process is used to heat the storage device throughout the day, ensuring that it is at the desired temperature when the sun sets. A small, temperature-resilient pump is used to drive this flow, the current desired temperature of which is 230 °F. The transfer fluid used will be some concentration of propylene glycol solution of at least 20% concentration.

In order to determine the necessary thermal output of this system, the team first evaluated the necessary amount of heat stored by the device by comparing the heat loss of a simulated building to the heat produced by a comparable thermal device currently used on the Navajo Nation and Hopi Reservation [12]. To calculate heat loss, the following equation was used:

$$Heat\ Loss = \frac{A_{surf} * \Delta t}{R_{surf}}$$

Where A_{surf} and R_{surf} are the area and thermal resistivity of the surface, and Δt is the desired temperature changed. This determined a necessary heat output of 10,000 BTU/hr, with a total of 140,000 usable BTUs needed to heat the house over a 14-hour night. Since this system will be used to charge the thermal storage device, it is reasonable to assume that it must output 140,000 BTU during the charging process. Since this is based on a 14-hour night, it follows that this must be done during a 10-hour day; as such, the required thermal output of the Fluid Heating Network was determined to be 14,000 BTU/hr. This should be achievable with the 8’ heating tape selected for the project [21].

Note that the heating tape heating system is a stand-in, used in lieu of a different source of heat for the purpose of creating a functional proof of concept prototype. The team had originally intended to include a solar thermal water heating panel, with the intension that it would allow the device to be fully autonomous, requiring no grid electricity. However, this led to the team being far overbudget, and as such it was decided that, for the purpose of the prototype, it would be best to use the tape heating system instead.

5.1.3 Storage Tank

The storage tank is perhaps the most critical subsystem in the design, largely because it is responsible for the thermal storage component of the thermal storage device. It is filled with thermal storage fluid and is heated up by the Fluid Heating Network during the day, before discharging the heat via the Air Pipe Network at night. The subsystem itself is simple, being composed only of a polyethylene liquid storage tank and storage fluid, with holes in the lid of the tank for the heat exchangers and pipes involved in the two pipe networks. The current storage fluid selected is a 20% concentration propylene glycol, much like the heat transfer fluid. These concentrations may vary according to the needs of the project.

In order to determine the necessary amount of heat transfer fluid, the following equation was used:

$$Q = cm\Delta t$$

Where Q is the amount of heat stored, m is the mass of fluid, c is the specific heat, and Δt is the desired temperature change of the fluid. This equation was used to compare the thermal properties of a variety of candidate thermal fluids, using an assumed Q = 140,000 BTU to determine the necessary volumes of each fluid. The results of this analysis are tabulated below (**Error! Reference source not found.**).

Table 6: Required Mass and Volume of Different Thermal Storage Fluids

Name	Density	Specific Heat	delta T (F)	Q (BTU)	mass (lb)	volume (ft^3)	volume (gallon)
Fresh Water	62.4	1	115	140000	1217.391	19.50947603	145.9410256
Salt Water (Sea)	63.93	0.938	115	140000	1297.859	20.30124407	151.8638623
Ammonia (176°F)	38.55	1.29	115	140000	943.7142	24.48026432	183.1251068
20% Propylene Glycol Solution	62.7	0.968	115	140000	1257.636	20.05798477	150.0441562
20% Ethylene Glycol Solution	63.8	0.96	115	140000	1268.116	19.87642542	148.6859979

The results of this analysis suggested that the ideal thermal storage solution was a 20% propylene glycol mix. This is for a variety of reasons, chief of which are that it is relatively affordable, has properties that reduce corrosion, it will not freeze or boil at operating temperatures, and most importantly it is not as toxic as ethylene glycol (with which it shares many properties) [22, 23, 24].

5.1.4 Control System

The control system is responsible for ensuring that each of the subsystems performs its role as needed, and to monitor various parameters of the system in order to ensure that the system operates as intended. It uses thermocouples to determine the temperature at various key steps within the process, such as the air outlet and the pump inlet, as well as the tank itself. It also controls the blower, pump, and heating tape, to ensure that the system discharges heat at the appropriate rate without overheating or becoming too cool. This component is crucial for the continued operation of the device, as it ensures that the correct charging or discharging cycle is running at the correct time. Additional information on these cycles is included below.

5.1.5 Power Supply

This subassembly is relatively simple, being only responsible for ensuring that certain other components remain powered throughout the duration of the device's operation. It consists of two major components- a battery, which shares a waterproof container with the control system, and a solar photovoltaic panel. During the day, the solar panel charges the battery, while also providing power for the control system and pump. At night, the battery provides power for both the blower and the control system, to ensure continual operation of both. Note that neither of these are responsible for powering the heating tape; this is because this component is a "stand-in" for a different heater that will not require electricity. As such, the heating tape will be powered by grid power for this prototype.

5.2 Full System Schematic

In order to demonstrate how each subsystem works together, it is helpful to use a schematic that details the full extent of the system. Said schematic is included below in Figure 14.

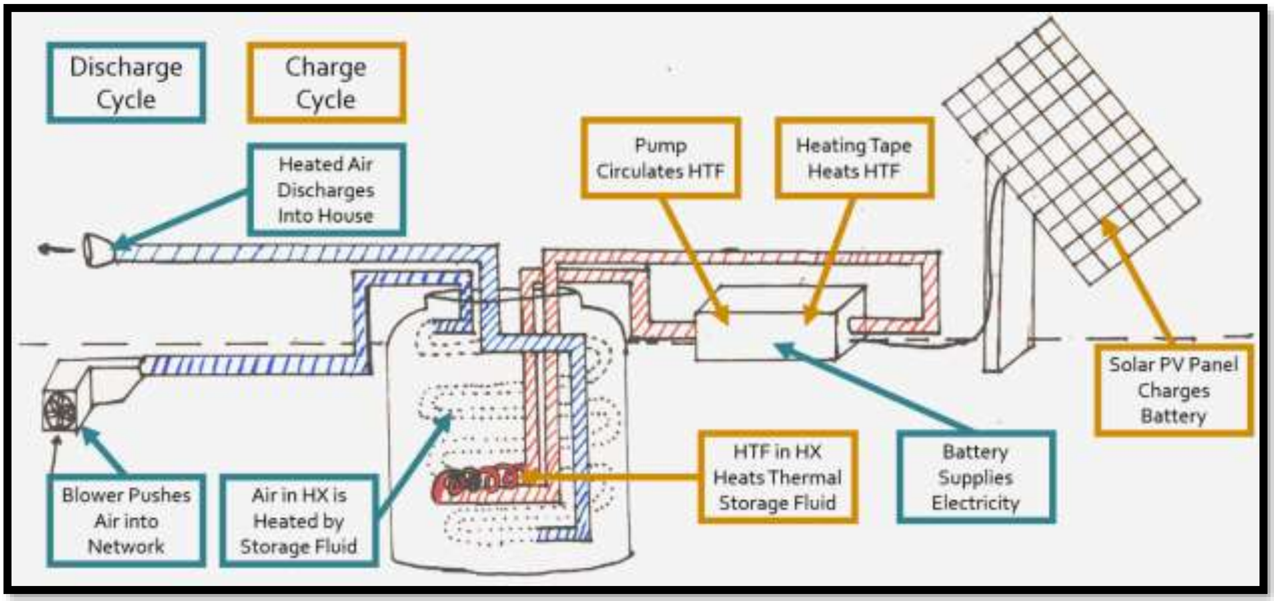

Figure 14: Full System Schematic

The system goes through two different cycles while in operation, one during the day and one at night. These are distinguished by color in the image shown.

During the day, the system goes through the charge cycle. In this cycle, the pump circulates "cool" heat transfer fluid (HTF) through the heating tape section of fluid heating network, where it is heated. From there, it moves through the pipe network into a fluid-to-fluid heat exchanger (HX) immersed in the tank. Here, heat moves from the transfer fluid to the storage fluid, "charging" the thermal battery. This cycle continues until the tank reaches a pre-determined temperature threshold.

At night, the system goes through the discharge cycle. In this cycle, a blower pushes air from the house into the air pipe network. Here, air passes through the heated thermal storage tank, where it is warmed in a liquid to gas heat exchanger. From there, it flows through the remainder of the pipe network out of the tank, and back into the house. This cycle continues throughout the night, with air speed and heat transfer varying according to the inputs of the control system.

6 IMPLEMENTATION – Second Semester

This section discusses the many iterations the project went through during the second semester. It also includes information regarding changes made close to the end of the semester and those made both for practice reasons and due to time constraints.

6.1 Design Changes in Second Semester

As a result of teamwide concerns surrounding project time and remaining budget, as well as input from both clients and advisors, the team made several significant changes to the project design. These primarily relate to project scope and expenditure reduction. The first major change, implemented towards the end of the Fall 2020 semester, was a significant reduction of the project's scope. The team, with help from their non-academic advisor, made the decision to remove the solar furnace component of the design as well as related support systems. This gave them more time to focus on the primary component of the system, that is the thermal storage device.

The team's second major design change occurred at the start of the Spring 2021 semester and was largely motivated by budgetary concerns. The team decided to forego purchasing the first heat exchanger, the liquid to air heat exchanger, in favor of building their own using coiled soft copper piping. This was done due to the cost of the heat exchanger, and how expensive it is compared to the copper piping. After seeing how viable this option was, the team also decided to make the liquid-to-liquid heat exchanger using a similar copper coil design method. By doing this the team was both able to conserve more budget and have a greater control over the dimensions of both heat exchangers. Along with these changes we have designed the two heat exchangers to be placed on top of each other inside of a metal duct work. This design change was chosen for the way that it will minimize the space taken up inside the tank and better secure the heat exchangers once inside the tank. Later in the semester after performing an air flow test the team decided that there was too much friction in the liquid to air heat exchanger for the air flow to be sufficient. From this the team decided on the design change of cutting down the heat exchanger which resulted in an air flow of 1.1 m/s.

The third design change was made when building was already underway. Once the team had coiled the first heat exchangers and begun to consider the exact nature of the pipe infrastructure for the tank, they decided that to minimize gravitational losses it would be useful to place the pump, working fluid reservoir, and other key elements above the bulk of the tank. This droves the design for the tank cap, which became the third iteration of the design.

The fourth design change made by the team was to add insulation to the heating tape and the tank itself. The insulation to the heating tape was fiberglass that wrapped around the piping with the heating tape with a mylar exterior and then for further waterproofing the team added a tarp around that. However, this design was changed because over time it got too hot and melted the insulation. The other insulation design change that the team made was in order to represent the benefits of burying the heating tape a layer of insulation was placed around the tank.

The fifth design change made was a 3D printed part that made it, so the blower outlet fit onto the piping better so there wasn't as much loss in air flow. This is visible along with the rest of the CAD assembly in **Appendix B**: CAD Drawings.

6.1.1 Design Iteration 1: Change in Solar Furnace Discussion

The original system design was far broader in scope and encompassed a great deal more than just the thermal storage device that the team is currently focused on. It included the tank, solar PV panels, pipe networks, and was generally similar to the current design, with the inclusion of additional heating systems in the form of a solar thermal panels and a resistive heater. These elements were not only costly, but they also required a great deal of work to ensure consistent and reliable function. Additionally, the team did not believe it could perform tests to validate and check the design if it had to create a working system with that large of a scope. As a result, the team chose to remove these heating elements from the design, as proving the thermal storage device itself was deemed more important to the project. This allowed the team to be able to focus on getting a working heating loop and discharge loop inside the tank to work with the pump and blower. The team was also able to perform basic testing on the solar PV system and test to see that the components were functioning. If the team was focused on the solar thermal heating system, the budget and time frame would not have been sufficient, and the results would have been not helpful at deeming that the prototype for the thermal storage system was a good design and possible source of heat to solve the problem. In order to represent the heating that the system would receive from the solar thermal panels the team used a heating tape in order to heat the propylene glycol going into the heat exchanger. The heating tape design can be seen below in Figure 15.

Figure 15: Heating tape wrapped around copper piping.

As seen in Figure 15 above the heating tape wrapped around the piping leaving the pump and entering the tank into the liquid-to-liquid heat exchanger.

6.1.2 Design Iteration 2: Change in Heat Exchangers Discussion

The decision to build heat exchangers was much easier than other design decisions because it was forced by unexpected budgetary issues. These issues, related to the steep cost of shipping certain other key components, which meant that the team would not be able to afford both heat exchangers along with the other parts necessary for the design. Making heat exchangers would save around $300, and the heat exchanger could be manipulated to fit the team’s design. They decided then to replace the liquid to air heat exchanger with one that they bend and fit themselves, as shown Figure 16.

Figure 16: Heat Exchanger Coiling and Soldering

After a successful creation of the first heat exchanger, the team decided to also build the second, liquid to liquid heat exchanger themselves as well. Thus, both heat exchangers have a spiral design and are stacked on top of one another within a heating duct inside the tank. The heating duct holds up the top, liquid to air heat exchanger with piping through the middle, so that the heat exchanger is not suspending in the air and compressing the bottom, liquid to liquid heat exchanger. The duct also contains the heat exchangers within a certain diameter, giving them a frame, so they do not deform or fall to either side. Finally, the duct acts as extra insulation for the heating exchangers, allowing maximum heat transfer for the thermal storage design. The heating duct can be seen with the heat exchangers and supporting piping in Figure 17. Though the team's budget has since increased since this decision was made, it helped the team be able to have a safety cushion for when problems occurred.

Figure 17: Heating duct with heat exchangers inside of it

After performing one of the first preliminary tests on the liquid to air heat exchanger in the form of an air velocity test the team found a problem that since there were a lot of coils and the pipe had a small diameter there was too much friction created that the air didn't flow through the heat exchanger sufficiently. In order to fix this the team altered the design by cutting down the number of coils. The new heat exchanger can be seen in figure below which shows it in the ducting.

Figure 18: Heat exchanger ducting with smaller heat exchanger

As seen in Figure 18 above you can see the major difference in the number of coils from Figure 17 in the top heat exchanger. This change really helped the design of the system, because with this change the air flow was now a consistent 1.1 m/s which helped the team get the heat transfer results.

6.1.3 Design Iteration 3: Housing and Platform Discussion

The decision to move the pump, heater, and other tank support infrastructure from the ground near the tank to the top of the tank was made largely in the interest of minimizing pump loss. The original design had the pump placed at the base of the tank, which would require it to overcome the force of gravity before even entering. With the addition of a housing and with ample platform space for the pump, heating tape, reservoir, and blower then all components will be protected from the weather or other potential dangers. A CAD mock-up of the cap can be seen in Figure 19.

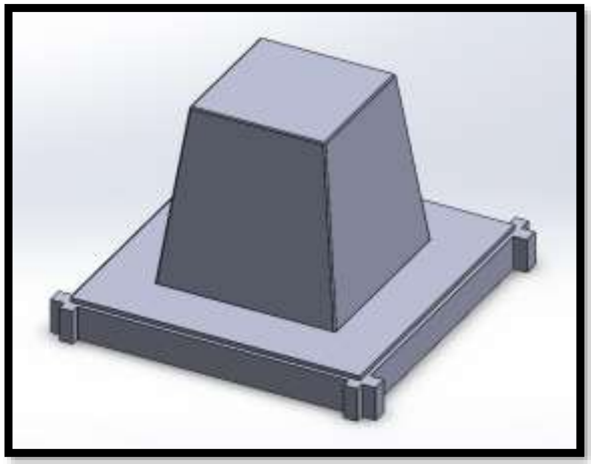

Figure 19: Tank Cap with Platform Space

The current plan for this component is for it to be made of a combination of 2x4 wood beams, a cut sheet of plywood, and a sprinkler box. It would also be insulated to minimize heat losses through the top of the tank, and include space for the pump, fluid reservoir, heating tape, and most other support infrastructure. This design change will maximize the effectiveness of the pump, and further contribute to the modularity of the design by making most of the support equipment fit on a single platform.

6.1.4 Design iteration 4: Insulation Changes Discussion

Originally the team had planned to insulate the heat tape with fiber glass and a tarp to protect the heating tape from water and reduce heat loss. However, over time as the heating tape increased temperature the tarp covering the heating tape started to melt but not the fiber glass. This had happened during the first testing session and the team stopped the test to remove the fiber glass and melted tarp from the heating tape. Instead, the team came to conclusion that the heating tape would not be covered for the next testing session. The team decided to insulate the tank to mimic the tank being buried and to reduce heat loss.

Figure 20: Insulation wrapped around the tank

R values from the insulation around the tank will be taken account and compared to R values as if the tank were buried beneath the ground. Figure 20 displays the insulation on the tank during the team's last testing session.

6.1.5 Design iteration 5: 3D Printed Part for Blower.

Another design change that the team made was that the team needed better air flow from the blower. When testing the blower for the first time we found that the air outlet was too large for the piping, which created a lot of loss. Therefore, the team 3D printed a connection for the blower to reduce the outlet diameter to connect it to the heat exchanger piping. This part was constructed by creating a CAD part and then drawing so that the 3D printer could create it. The CAD model for this part is shown below in Figure 21.

Figure 21: 3D Printed Part for Blower

Then the part was attached to the blower with the use of gorilla tape. This design iteration greatly decreased the amount of loss and allowed the air velocity through the piping to be 1.1 m/s and the air velocity out of just the 3D printed part to be around 5 m/s.

6.1.6 Design iteration 6: Reservoir design change

Another design change that was made at the end of fall semester was that the design would need some form of reservoir so that the heat exchanger could be its own closed loop. This is so that the pump would have the ability to pump the propylene glycol through the heat exchanger and back to something so that it wouldn't ever run dry and so that the water and propylene glycol can be separate. We solved this design problem by using a gas can with 2 holes drilled into it that would sit on the platform with the pump so that the loop can be completed. The gas can prior to the holes being drilled is shown below in Figure 21.

Figure 22: Gas can reservoir prior to drilled holes.

The reservoir is made up of a plastic gas tank that can hold up to 2.5 gallons of liquid. To integrate the reservoir with the heating loop two holes were cut into it. The first is near the bottom of the tank acting as an out flow to the pump. The next is on the side of the pump allowing water to flow into the reservoir from the heating loop. The hole in the side of the reservoir can go without a fitting and simply acts as an opening for the exit pipe. The hole near the bottom of the reservoir that can be seen in Figure 23 below uses a fitting with a washer, was threaded into the tank, and uses a sealant to prevent leaks.

Figure 23: Reservoir pump fitting

Figure 24 shows how the reservoir is connected to the pump. As you can see the connection involves a series of various fittings that are threaded to each other. PTFE tape is applied to each threaded component to ensure a secure fit to prevent any leakage. There are two different thread types involved with the connection. The first type is garden hose thread, and the second type is regular pipe thread. The operation manual discusses explicitly how each fitting is connected.

Figure 24: Pump connection to reservoir

7 RISK ANALYSIS AND MITIGATION

This section will expand on how the team began identifying potential failures and risks associated with the device. Along with this the section expands on how the team mitigated the risks associated with the device.

7.1 Potential Failures Identified First Semester

By considering all the components of the design, we can analyze the potential risks and failures that can occur with these components. The components of the system include the heating fluid pump, liquid-to-liquid heat exchanger, liquid-to-air heat exchanger, heating band, copper piping, storage tank, fan, battery, electricity solar panel, Arduino, and thermocouples. Most risk involves corrosion, because this is a piping system with heated liquids travelling at a velocity above still water. Other forms of failure involve fatigue, chemical damage, or thermal shock. First, we discuss the 10 most concerning critical failures gathered from the score of the RPN, from a full FMEA calculation. The full FMEA sheet can be found in **Appendix C**: Full FMEA Sheet.

7.2 Critical Failures from First Semester

The ten greatest critical failures are sorted by RPN. The greatest critical failure is corrosive wear of the electricity solar panel, where weathering causes cracks in the cells, therefore making the panel not output the full amount of power as it did before the critical failure. This failure mode has an RPN of 48, and the recommended action involves regular maintenance and check-ups on the panels. This includes cleaning the panels monthly, performing a maintenance check annually, and covering the panels with a tarp or protective layer if there is a hailstorm or damaging storm coming.

The second greatest critical failures are tied, both involving thermocouples with an RPN of 42. One critical failure is thermal fatigue, where temperature changes within the thermocouples eventually cause expansion and contraction of the metal, weakening the thermocouples. Eventually, this may cause the thermocouple to break, where it cannot read temperatures properly. The other critical failure involving thermocouples is hydrogen damage, where oxygen gets into the sealed thermocouple, reacting with the metal and damaging it. This would cause the temperatures of the thermocouple to be inaccurate. The recommended action for this is to switch out the thermocouples on a routine basis.

The fourth highest RPN, at 40, has critical failures for the liquid to liquid and liquid to air heat exchangers, both failing from thermal fatigue. This could occur from high temperature differentials of liquids or from freezing from the outside environment if the tank is not insulated properly. If the heat exchangers were to fail, the liquid would not be heated, the piping would break with holes or cuts in the material. The recommended action is to choose a heat exchanger with increased temperature limits.

The next most likely critical failures, with RPN values of 32, involve the heating band or heating tape. One critical failure is crevice corrosion, where moisture builds and is trapped between sheets of metal on the heating band. This causes the heating band to be overwhelmed by moisture and fail. The recommended action is to make sure the heating band is properly protected from the elements and weather conditions. Another heating band critical failure is high cycle figure, caused by the wire diameter being reduced over time, which melts and breaks down the insulation of the wire. This would cause power shorts in the heating band, causing it to no longer work. The recommended action is to use the lowest wattage necessary. The last critical failure for the heating band is thermal fatigue, where the low or high temperature affecting the efficiency of heat transfer. This is often caused by the heating band or tape being at too high of a power over a short period of time. The recommended action is to make sure the heating band is tightened and properly fitted, using as low an amount of wattage, as necessary.

The final critical failures making up the 10 most concerning critical failures regard the copper piping. These two critical failures have an RPN of 27. One critical failure is erosion corrosion of the copper piping. This happens because of electrical-chemical reactions or bacteria causing corrosion. It creates holes in the piping, making the liquid leak or spray into either the storage tank or the surroundings, depending on the location of the leak. The recommended action is to check and confirm that the piping system is properly grounded, to check the pH levels of the water to see if they are lacking balance, and then to consider adding phosphate or algae to the water to combat chemical or bacterial damage on the piping.

7.3 Risk and Trade-offs Analysis

The different types of critical failures exist around high temperatures and high temperature differentials in fluids causing damage, as well as corrosion from the weather, high velocities of water, and chemical reactions. The team originally chose high temperature resistant components so they could operate at 175 to 200 °F for the liquid in the storage tank. Thus, there are not many trade-offs in design for choosing high temperature components. All the modifications to decrease risk work synchronously with each other. The only trade-off is with the budget and maintenance time. By making additions to the piping, such as adding phosphate or algae to the water, or adding thicker material to the piping, the cost of the system increases. To reduce risk, the owners should check up on components annually or monthly and maintain them by cleaning them. The team chose a 1/2-inch diameter piping. The diameter could possibly be further increased, if necessary, to reduce the damage from high velocity in the pipe, but this is a low possibility failure.

7.4 Potential Failures Identified This Semester

Throughout the building process, the team identified some possible failures. One of these was the possibility of the device leaking from any of the soldered areas. Another possible failure was the pump overheating and failing over an entire heating cycle. The blower has a possibility of failure from being run for too long, having a lifespan of 3-6 years. The heating tape could have caught on fire or caused an electric shortage if it overlapped with itself or the power source of 240V was used.

7.5 Risk Mitigation

To mitigate the chance of soldering connections leaking, the team performed several leak tests to identify any leaks. One leak was identified on one of the heat exchangers, but the area was resoldered, and another leak test was performed. The leak persisted, so the team resoldered the identified connection again. After the third test, there were no leaks in the heat exchanger.

To keep the pump from burning out, the team checked the temperature and function of the pump every hour to make sure it was not overheating and to make sure it was still running properly. The team unplugged the pump for 3 minutes after roughly 4:38 minutes, because it seemed excessively hot. It was plugged back in and continued to run successfully for the remainder of the 8-hour test.

The blower does not have a realistic close timeline for failing, so the team did not take any action to mitigate risk.
The heating tape was given 50" of piping on top of the tank, so that the entire span of the tape could be wrapped around the piping without overlapping. This was a trade-off in terms of head loss for the flow rate of propylene glycol, as the number of bends in the piping created loss and decreased the flow rate. A technical analysis of the piping showed the amount of loss the piping had created with its height and number of bends. **Table 7** and **Table 8** show these calculations [25].

Table 7: Liquid Loss Calculations

Equations:	Values	Units
Reynolds Number	19952.15	
Swamee-Jain	0.024944	
Major head loss	61.76753	ft
Elbow	0.263975	
Minor Head loss	1.583851	ft

Table 8: Air Loss Calculations

Equations:	Values	Units
Reynolds Number	919.8529	
Swamee-Jain	0.063578	
Major head loss	20.40386	ft
Confusor	0.003421	
Minor Head loss	0.003421	ft

The heating tape was also made to not be exposed to any liquids or leaking pipes, to not cause electrical failure.

8 ER Proofs

The team conducted a variety of tests to ensure the system ran properly to meet the engineering requirements. These tests included leak tests, air velocity tests, liquid flow tests, liquid-heating tests, and a heating cycle 8-hour test. The leak tests were performed on the heat exchangers by pouring water into the heat exchangers. The air velocity tests were performed by using the blower to blow air through the inlet of the liquid-to-air heat exchanger and measuring the outlet air velocity. The first test showed an air velocity of 0.1 m/s, which was too low for providing proper air flow. The team then cut down the liquid-to-air heat exchanger and performed the test again, getting 1.1-1.2 m/s air velocity. Testing inside the tank, the air velocity was 1.1 m/s. The liquid loop tests ensured that the pump was able to pump liquid throughout the liquid-to-liquid heat exchanger and through the piping to the reservoir and back to the pump to complete its part of the heating loop. Finally, an 8-hour test was performed to focus on the heating loop's ability to heat the water within the tank, to reliably run the entire liquid heating loop for 8 hours without interruption, and to test the temperature of air after the 8-hour heating loop was run to see its effects on the discharge cycle. Below, the team indicates how each engineering requirement was met or not met by the team and uses these tests and data to reach those conclusions.

8.1 ER Proof #1 – [Device maintains consistent house air temperature (60deg F)]

Calculations show that with 200 gallons of water, the water should be able to maintain a high enough temperature to heat the house over the course of the night. The team performed an 8-hour test with 200 gallons of water that showed that with a starting temperature of 52-degree Fahrenheit water, the air could be heated to 59.45 °F over 8 hours. This did not reach the goal of 60 °F that the team set. It did, however, increase the temperature of the cold water 7.45 °F. After plugging in the blower, the air's temperature increased from 56 °F to 58.5 °F, showing that the cycle does heat up air as it goes through the tank. However, this temperature was low because the temperature of the water in the tank was low, and thus that low amount of heat transferred to the air. The air values in the 8-hour test can be seen below in Figure 25.

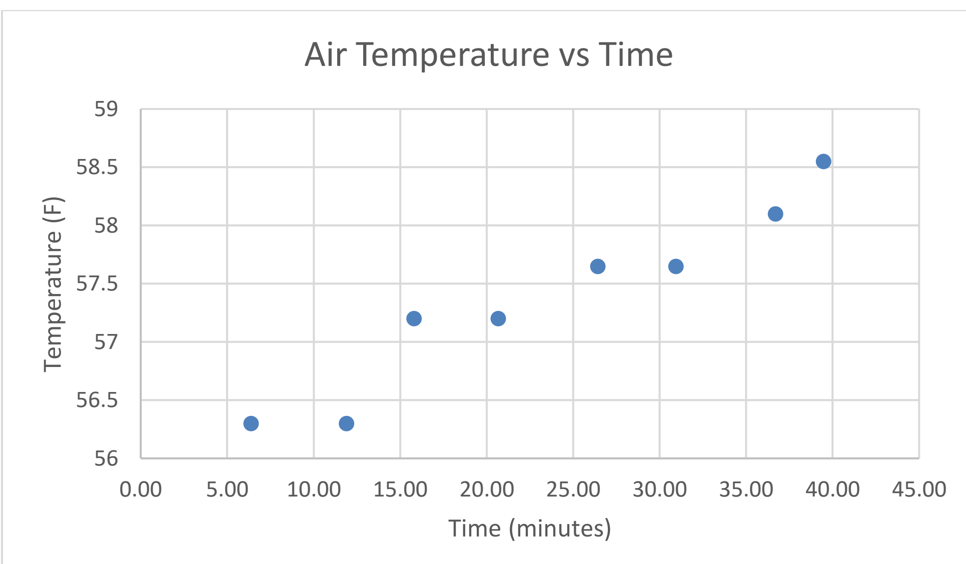

Figure 25: Air Temperature vs. Time data from 8-hour test

Furthermore, air velocity tests on the liquid-to-air heat exchanger and its discharge loop showed that the height of piping and number of turns of the liquid-to-air heat exchanger is acceptable for providing airflow to a house when using the team's setup.

8.2 ER Proof #2 – [Device works in environments with outside temperatures ranging from 20 °F to 60 °F]

Although the tank was not tested for a full 8-hour period outside, the tests showed that the water in the tank is less affected by outside weather and is more affected by the temperature of the water entering the tank, and the temperature of that water will increase or decrease greatly depending on the heat source of the water. The team attempted to create insulation around the tank and to house piping with a housing cap, but this was not tested in outside weather. It was tested in a 60-degree Fahrenheit garage. The team planned to bury the tank for insulation purposes but implementing this proved to be difficult as the action would likely be irreversible.

8.3 ER Proof #3 – [Device stores heat in an effective method]

The water and propylene glycol stored and transferred heat. We saw this in the 8-hour test, where the starting temperature of the reservoir propylene glycol was 52 °F, and the ending temperature was 59 °F. The ending temperature of the air, flowing through the system for 30 minutes, was also 59 °F, and the water in the storage tank was also 59 °F. This shows that the heat from the propylene glycol heated up the water in the tank which in turn heated up the air in the air loop. Thus, with a greater heating source, the heat transfer to air should be successful in heating a home. The graph of the reservoir's propylene glycol temperature over time can be seen below in Figure 26.

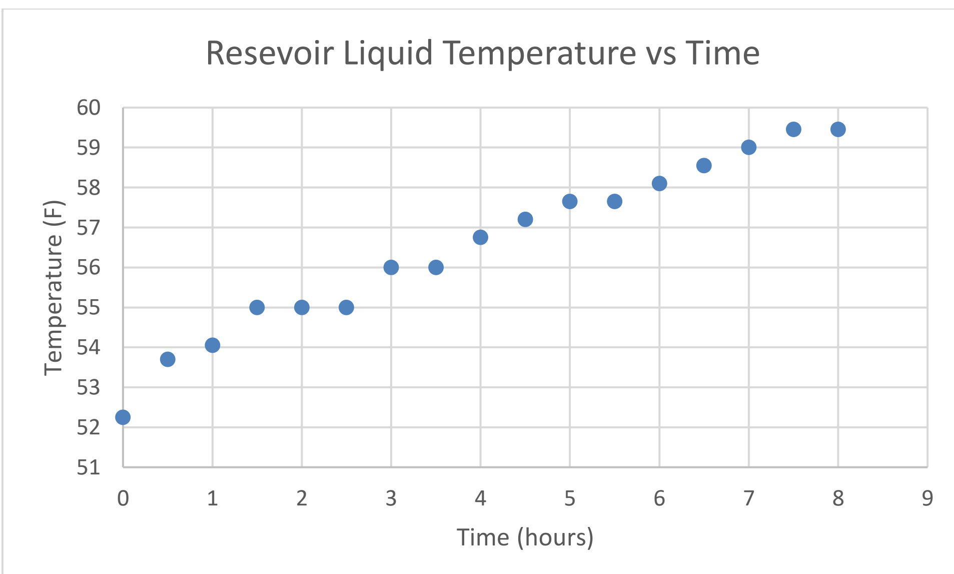

Figure 26: Change of Temperature of Propylene Glycol in the Reservoir over time, conducted during 8-hour test.

8.4 ER Proof #4 – [Device budget is within $2,000]

The total cost of the design was $1,870.90 according to the Bill of Materials.

8.5 ER Proof #5 – [Device has no more than 12 unique parts]

The design is simple and compact. The system has two heat exchangers, one pump, one blower, one heating tape heat source, one reservoir, hard copper piping, a battery, an inverter, solar panels, a housing cap, insulation, a platform, an Arduino, and thermocouples, totaling the number of unique parts to 15. This is above the target ER from last semester, but it is not far above the target of 12 parts. Additionally, the design evolved to be more complex over time as we did more functional prototyping and testing this semester. The number of parts is low, and each part has multiple functions, making the design simple to implement.

8.6 ER Proof #6 – [Device able to install onto a variety of homes]

The dimensions of the device within desired constraints of 4-ft x 8-ft. This was measured as the average size of a truck bed, so that anyone with a truck should be able to transport the components to be assembled on site. The platform, heat exchangers, and storage are the largest components, with the platform being 3-ft x 4-ft, the heat exchangers are fit within a 5-ft long duct that is 1-ft in width, and the storage tank is roughly 5.9-ft in length and 3-ft in width.

8.7 ER Proof #7 – [Materials should have minimal delivery (transit) time]

All materials besides the tank were locally sourced. Most materials obtained from Home Depot, aside from the storage tank, which was obtained online. Our prototyping process showed the ease of finding locally available resources, as the team was able to quickly purchase parts from the store and use them in person. Although 200 gallons of water is a large amount of a valuable resource initially, the tank will not need to be refilled, and the system uses a closed loop which will retain the water, showing it will be a worthwhile long-term investment. The closest source for the storage tank would likely be a Tractor Supply Co., Lowe's Home Improvement, from a local manufacturer in a larger manufacturing city in Flagstaff, AZ, Prescott, AZ, or from a state manufacturer online, such as National Tank Outlet. These options, aside from the online manufacturer, are all within the target ER of 150 miles. The goal would be to avoid shipping costs from the storage tank manufacturing.

8.8 ER Proof #8 – [Device should work without interruption or maintenance]

The team tested the full system 5 times, and there were no issues with running it. There was only an issue with the heating tape melting insulation, but the system always ran with complete confidence. The team also tested the system over an 8-hour period, and it ran without interruption. This amount of time was the targeted because it shows that the device runs a full day time cycle without interruption. Parts within the tank are easy to access with the duct containing the heat exchangers easily accessible.

8.9 ER Proof #9 – [Device should be able to withstand all weather conditions]

A breakdown of the Navajo County temperature data can be seen in **Table 9** [26]. The 8-hour test with 200 gallons of water showed that with a starting temperature of 52-degree Fahrenheit water, the air could be heated to 59.45 °F over 8 hours. Starting at 52-degree water is a good indicator of the cold weather conditions the device might be under in Leupp, AZ, and the Navajo Nation. Leupp also has warmer weather conditions and more sunlight than Flagstaff does on a regular basis and in colder months. The average heating degree day is a measurable based on the number of cold days, to determine how much energy is needed to heat a region to keep a home warm. The average heating degree day for Navajo County, measured with the NREL *solar for all* map is 5,041.42. The average for Flagstaff is 5,304.48. The average for Arizona, including many extremely warm areas such as Phoenix and Tucson, is 4184.742 [27]. Thus, we can see from this that Flagstaff is a good indicator, with some margin of error, of the Navajo County's heating energy requirements, compared to the rest of Arizona.

Table 9: Navajo County Temperature Data

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Freezing Days (below 32) in Navajo County	28.4	24	21.7	12.2	2.8	0.2	0	0	0.2	6.5	21	28.2
	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Average High Temp (deg F)	46.5	51	58.1	66.3	75.7	85.4	88.2	85.1	79.6	68.9	56.4	46.3
	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Average Low Temp (deg F)	20.5	23.6	28.4	34.2	42.2	50.2	57.6	56.8	49.5	38.1	27.9	20.5
Freezing Days Total	145.2											

Finally, the device proved to be robust, remaining outside in snow and cold weather for months without any damage. The platform holding the components never broke, holding all components and weights, the heat exchangers had no leaks after performing leak tests and resoldering, and the thermocouple measured temperatures without damage from weather.

9 LOOKING FORWARD

Since the design created by the capstone team is only a simple prototype of the intended final concept, there is a great deal of additional work to be done in the future. This includes both additional tests related to the function of the device and improvements to its design intended to improve viability. Some of these tests should be done prior to the implementation of the work, while others are best left for after their completion; however, all these testing procedures would contribute to ensuring proper function of the device.

9.1 Future Testing Procedures

The first set of tests should be performed when the next team takes over the project, after they have obtained the prototype device created by this team. These are grouped together as a single procedure because their intention is to verify that all components of the prototype remain functional after the storage period. This test should also help to improve understanding of the original prototype, and the specific aspects of it that require improvement. Following this, the remaining procedures described in this section are intended to be performed after improvements to the system have been made, in order to gauge the success of these improvements as part of an iterative design process. If implemented correctly, these should help guide this process towards the creation of a fully functional thermal storage device.

9.1.1 Testing Procedure 1: Prototype Systems Check

9.1.1.1 Testing Procedure 1: Objective

The objective of this series of small tests, as stated above, is to verify that all major components of the prototype are functioning properly and as they were prior to the device being stored. It closely mirrors many of the tests already run by the team, however it is intended to be performed as a single series of tests.

In order to run this test, the team must first set up the device; this means securing a location, filling it with water to the appropriate level, and then filling the charging loop with the propylene glycol solution via the removable reservoir cap. Once it has been prepped, thermocouples should be placed in the reservoir and the tank, as well as on the heating tape. A fourth thermocouple can be set up to monitor ambient air temperature, but this is less critical for the first stage of the experiment. Once the thermocouples have been set, the first stage of the testing procedure is started, during which the heating tape and pump are plugged in, and the charge loop runs for some time. During this time, the team should periodically check the temperature of both fluids and the heating tape, to verify that they are increasing (note that the tank temperature increases very slowly). Once this has been run for approximately eight hours, or after the tank temperature has raised by 10 °F, the team then moves on to the second stage of the test. During this stage, the pump and blower are shut off and the thermocouples removed from the heating tape and the reservoir and allowed to reach ambient or near-ambient temperature. These two thermocouples are then placed at the outlet of the discharge loop and at the inlet of the blower, which is then turned on. After giving some time for thermocouple temperature to stabilize, the team can then record the temperatures in order to determine the change across the full length of the discharge loop. Once this has been done the test will conclude. The team can then record the temperatures in order to determine the change across the full length of the discharge loop, finishing the procedure.

If performed successfully, this testing procedure should demonstrate the design, in addition to verifying the functionality of each key part within the system. Note that an abridged version of the test could also be run, wherein the first stage is run for a reduced span and the second stage intended only to demonstrate blower functionality, but this would be less likely to result in a noticeable temperature change in air temperature across the charge loop.

9.1.1.2 Testing Procedure 1: Resources Required

Running this test will require a variety of materials, chief among which is the original prototype in its entirety. Additionally, the new team will need to supply at least 150 gallons of water to fill the tank to the required minimum test volume, as well as 2.5 gallons of 5% propylene glycol solution with which to fill the charge loop. Additionally, they will need a minimum of three thermocouples, though four would be ideal for the purpose of monitoring ambient temperature. K-type thermocouples will require chips to run, as well as an Arduino to translate the data; for the type already used by the team, it is recommended to either use two separate Arduino units with two thermocouples for each, or an additional power source. The recommended test location is some sort of garage or other enclosed space with access to electrical plugs and sufficient drainage to prevent water damage in the event of a leak. Finally, this test can be run by at least two people, though more are recommended for setting up the tank.

9.1.1.3 Testing Procedure 1: Schedule

Prior to running this test, the new team must find a way to obtain the original prototype. Once this has been done, the test can be run in Flagstaff between the months of October and May, which should ensure the necessary range of outdoor temperatures to avoid significant deviation from this team's testing. For the full-length test, the total length of testing time is roughly 10 hours; this includes one hour for setup, 8 hours to run the first stage (charging the tank), and one hour to run the second stage (tank discharge), collect data, and clean up. This is a very lengthy test and could be adjusted by reducing the amount of time spent on the first stage, however this will result in a less noticeable air temperature change for the second stage. Note also that the tank does not need accompaniment for the entire span of the test but should instead be checked on every 30 minutes to ensure that there have been no significant failures or other issues.

9.1.2 Testing Procedure 2: Revision Evaluation Tests

9.1.2.1 Testing Procedure 2: Objective

Once the first set of tests intended to evaluate the performance of the prototype parts has been completed, it is expected that the successor team will begin implementing changes according to the current team's recommendations. The second battery of tests was created in order to evaluate the efficacy of these improvements and is intended to be implemented as part of an iterative design process for the device.

These tests will be run in a similar manner to the prior set; the improved prototype device must first be set up, filled, and set in an appropriate location, ideally with a test house set up for proper CR validation. Once this is done, thermocouples should be placed inside the heating loop, either in the reservoir or at an analogous point within the revised system. Thermocouples should also be placed on the tank surface and in the interior, as well as at the outlet and inlet of the discharge (air) loop. Once this has been done the testing will begin, with the team starting the device and allowing the charge loop to run for 8 hours while evaluating the temperatures at consistent time intervals. After the charge loop has completed, the device should automatically switch over to the discharge loop, at which point air will begin flowing through the blower, which can also be monitored. The test will continue until there is no change in temperature across the inlet or the outlet, or until 24 hours have passed from the beginning of the test. Once this point has been passed, the data can be used to evaluate the device's ability to maintain the required heat in a home throughout the night. This completes the main objective of the test.

9.1.2.2 Testing Procedure 2: Resources Required

For this test, the main materials needed are the revised prototype design, as well as 200 gallons of water and 2.5 gallons propylene glycol needed to fill the tank and reservoir, respectively. Measuring the data will involve a minimum of five thermocouples and their chips, though the future team is encouraged to use more if it is feasible, as well as multiple Arduino devices and a computer to review the results. Most importantly, this test will also require a carefully selected location, with the tank itself placed outside at night and the inlet and outlet of the discharge loop connecting to the test facility. This test facility can either be a model home or simply a garage, but it should ideally be at a minimum of 50 °F at the start of the test. This test will also rely on a minimum of two people, though more are suggested for the setup portion.

9.1.2.3 Testing Procedure 2: Schedule

Once the successor team has implemented some or all of the suggestions made by the current team in this report, this series of tests should begin. It is recommended that this be done between the months of October and May in Flagstaff, Arizona, so long as temperatures do not exceed 60 °F outdoors at night. The total length of the test will be roughly 24 hours, with 8 devoted to charging the tank and 16 devoted to the discharge; it is likely that the criteria for the completion of the second phase of testing will be met prior to this mark, but it is still recommended that the team set aside a minimum of 24 hours. Note that, once again, the device need not be monitored this whole time; it should operate mostly autonomously and need only be checked periodically for major system errors.

9.1.3 Testing Procedure 3: System Fatigue Testing

9.1.3.1 Testing Procedure 3: Objectives

The purpose of the third and final set of tests is to evaluate the performance of the design when operating over a long time period. It will involve testing the same cycles as the previously described test sets, but over a much longer span in order to evaluate the device's ability to perform the stated customer requirements. Running this test will require the same setup as before, this time ideally with a more accurate model house, and a testing configuration devised to allow the team to leave the device for long periods of time. In order to perform this test, the device must first be capable of autonomous operation, based on the time of day and measured temperatures of the inlet and outlet; it also must be capable of recording the data, either directly to a nearby computer or by saving it to a storage device. To run the test, the team should simply start the charging cycle of the device at the appropriate time and run it for 8 hours; after these 8 hours, the blower should be set to run only when the ambient temperature in the testing facility falls below a certain threshold. If the test is set up appropriately, this should determine whether the system is capable of outputting the necessary heat, by displaying whether the temperatures in the testing facility fall below the minimum temperature threshold set by the client (50 °F). Once 16 hours has elapsed after the end of the charging loop, it should start up once again. The system will operate in this way for at least a week, charging for 8 hours a day and then discharging at an unsteady rate throughout the night. If performed successfully this will provide a clear indicator as to the chances of the device's success.

9.1.3.2 Testing Procedure 3: Resources Required

To perform this test, the same materials will be required as procedure 2, with the addition of a computer and data acquisition system set up to collect data over a longer span of time. Additionally, the device should be filled to the full 200-gallon mark, to ensure accurate reflection of the intended system operation The heating loop should similarly be filled with 2.5 gallons of propylene glycol. It will also be more important for the team to select an appropriate testing environment, in order to ensure that the device is being accurately tested against conditions that would occur during its normal operating times. Ideally, the facility used in procedure 2 would be sufficient, however it is possible that a more accurate model home could be found or created. This test could possibly be done with only one person, whose job it is to monitor the system and its parameters at predetermined individuals, but this is likely unnecessary.

9.1.3.3 Testing Procedure 3: Schedule

This test will take a minimum of 1 week and can be run for longer periods of time if the team deems it appropriate. It should be run in Flagstaff, due to the fact that this ensures that the team will have access to the device. It should also be run during the same months specified for procedure 2, that is, between October and May. It is recommended that the tank be checked at least daily, so that the team will be aware in case of any major system failures. If this testing procedure is performed appropriately, it should clearly establish whether the revised design constructed by the successor team meets the requirements provided by the client. It will either validate or invalidate the initial design proposed by this team, providing final proof as to whether or not the basic principle is capable of meeting the given criteria.

9.2 Future Work

There are several design recommendations for future work. The first one is having a stronger heating source to heat the water in the reservoir faster. The heating tape was not a sufficient heating source for the system. Another component is replacing the blower with a HVAC suction fan. There was too much loss using the blower causing the team to reduce the length of the copper coil. Finding better alternatives for insulating the tank and the exposed piping network is another recommendation. The team wanted to bury the tank to reduce heat loss. For the piping network the team used a plastic housing that was also insulated. However, burying the tank was too expensive and the plastic housing was not durable. The platform was not as durable because some parts of the wood were cracked and started to give once the components were placed onto it. So, finding a better design for the platform to support the blower, pump, and reservoir would be ideal. The team achieved an outlet velocity of 1.1 m/s with a half inch pipe diameter. Increasing the diameter of the piping will also increase the volumetric flow and that should be considered for a redesign. A redesign of the entire system while still being a thermal storage device would be okay as well. Using a 210-gallon tank was difficult transporting and filling with water. Finding an alternative smaller thermal storage design would be convenient.

10 CONCLUSIONS

After assembling the project and running many tests the device was determined to work in taking in heat and releasing it. Unfortunately, after the 8-hour test, it was seen that the device needed more heat in order to properly increase the temperature of the water inside the tank. The team concluded that another capstone team would be able to build on the current design. Likely they could create a functioning device that would be fully ready to be implemented on a home. Along with this the device has a lot of potential to be manufactured at a low cost and implemented across the reservation.

10.1 Reflection

The major goal of this team was to design a system that would provide safe, renewable, and cheap heat for those living on the Navajo Reservation. Currently the people of the Navajo nation only had wood/coal burning stoves in order to create heat for themselves during winter nights. This caused a threefold problem. It created an environment that was bad for a person’s lungs, unsustainable for the environment, and was expensive as the deal providing the Navajo nation cheap material to burn had ended recently. The hope of the project was to create a system that would store thermal energy during the day heating up a mass of water inside a tank to then be released during the nighttime. This would create a system that would allow for cheap, renewable, and clean hot air. In order to develop this solution, the team preformed research and began developing a series of design options which were backed by their research. Once an acceptable design was selected the team began creating the device. With our design, the main concern was the risk of the tank and piping reaching temperatures that could burn someone. The design had two alternatives that would delegate those problems. First the exposed pipe would have a housing with insulation in order to make them safe. Along with this insulation would be added to the tank so that the heat is kept from seeping out of the tank. The second design prompted that the tank be buried. This would also add the benefit of keeping heat in and making the tank less of an exposed risk.

10.2 Postmortem Analysis of Capstone

10.2.1 Contributors to Success

During this past school year, the team accomplished its primary objective of developing a proof of concept for a thermal storage and dispersal device. This device had a simple design with the intent of making it fully solar powered in order that it could be implemented easily in the Navajo Nation Community. While the end result was a functioning device, the total device did require more work. Primarily it needed to be given a stronger heat source and more piping so that it could properly network with a home. The team arrived at a series of ground rules and coping strategies for group conduct. Since the team was happy with their performance from first semester, they used the same system of conduct. The team set a minimum requirement of three meetings per a week. Along with this the team members consistently showed up to their meetings on time, split work evenly among each other, spoke up early if they needed help, and communicated often. As a team everyone's time and work were valued. With these rules and strategies, work was consistently taken care of and kept at a high standard.

With this intention set in place early, many positive aspects of our performance were present throughout the year. The most positive of these were largely related to the organization, communication, and collaboration of the team. The team consistently began work well in advance of the due date, following the plan made by their project lead and the Gantt Chart that laid out when things were due. Similarly, communication between team members worked very well. In addition to meeting regularly as agreed upon, they consistently communicated via text and Microsoft teams. This was done to coordinate meetings, send emails to clients and advisors, and notify each other when problems appeared. This collaboration allowed for the frequent division of tasks. The division of tasks typically involved each member volunteering for specific tasks, and any remaining work being assigned according to workload. This method contributed significantly to the team’s ability to work together, timely complete project deliverables, and finish all other tasks.

10.2.2 Opportunities for improvement

During the first semester there were places where the teams saw they could have improved. The most negative aspects of project performance were the technical writing done by the team as well as a lack of attention to certain details. In terms of technical writing, the team at times struggled with the use of personal pronouns, informal language, and consistent proofreading. Additionally, different writing styles and the use of overcomplicated or long-winded language tended to make reading certain documents tedious.

During the spring semester the team learned many practical and technical lessons. The team learned about working with copper piping, soldering, pumps, sensors, and electrical components and wiring. The team learned how to prepare and record presentations. This was extremely useful when all the presentations were online because it made it so everything could be recorded separate and added together. Our team found it the most useful to utilize the meeting recording tool from Microsoft Teams for our presentations. Another technical lesson that was learned during ME 476C was how to utilize Microsoft Teams best. The team learned how useful Microsoft teams is for sharing files and for collaborating on documents. All members could work on an excel sheet, a presentation or word document at the same time and there could be a meeting happening to make collaboration easier. The last technical lesson that was learned was how different aspects of design, work or do not work based on technical analyses. The technical analysis was helpful to provide detailed calculations and analyses of different design aspects, which led the team to decide which products were best or if a design would fail.

Alongside the previously stated issues, the team encountered some problems in ME 486C that the team needed to adapt to improve upon in future work. Due to the scope of the project being too broad, narrowing ideas were challenging. After the scope was minimized, the main ideas changed. The team should be ready to adapt to any design changes. One problem that the team encountered was struggling to fit an entire HVAC system independent of electricity into a $2,000 budget. While the team managed this amount well, they still struggled to complete everything, including prototyping, given the amount. This resulted in the team having a clear vision for how the solar, battery, and thermal storage device would work, but the team had only time to prove that the thermal storage aspect of the device would work. The team primarily focused on the heating liquid loop rather than the air loop because the team believed that the heating liquid loop was more fundamental to testing if the heat transfer concept than the air loop was. The team did, however, make sure that the air loop was successfully blowing air from the inlet, through the liquid-to-air heat exchanger, and into the outlet with a velocity of 1.1 m/s. When testing the solar and electricity element of the project, the team found that there were possible incompatibilities with the battery and solar panel, as the battery did not charge despite being connected to a 50W solar panel for two days. The team verified this by connecting Air Pods directly to the solar panel controller, and the Air Pods were being charged. Thus, the team believed that the issue lied within compatibilities with the battery or with connections from the solar panel to the battery that were not secure enough.

Throughout this semester the team ran into several issues. These problems ranged from issues with getting supplies that were needed, overreaching with what could be done, and jumping into things blindly without doing required research. When it came to ordering and buying supplies the team was quick to order and get the supplies they needed. The issue that arose was primarily with the storage tank. While the correct one was chosen, the team failed to realize the shipping tax far outweighed the need for that specific tank. Regarding overreaching, the team worked to develop a nearly fully functioning device based on parameters understood from last semester. However, they found their efforts may have been better suited focusing on a proof of concept that was smaller in size and possibly scope. The technical analysis layout several of these shortcomings. While the team took steps to learn and research many of the techniques for manufacturing, the device still had functional issues that led to several setbacks. These included redesigning the blower system, selecting new piping, and unforeseen operational problems with the solar element of the capstone.

The team's technical analyses revealed some design challenges that the team could learn from for future design recommendations. One revealed problem that the team found is that while heating 200 gallons of water in the tank to 175 °F is necessary to keep the house warm at a temperature of at least 60 °F at night, heating 200 gallons of water is very difficult, and the heating tape the team used for prototyping purposes is greatly insufficient in doing this task. According to a technical analysis, the heating element will need to have a power of 4,566 W to heat a 200-gallon tank of water to 175 °F in 8 hours [28]. Insulation becomes extremely helpful in retaining this heat over night, but the greatest need was found to be finding a way to heat water of such large volume. A separate technical analysis found that it would be necessary to heat the liquid in the heating loop, propylene glycol in this case, to 185 °F to maintain a temperature of 175 °F in the water in the tank. Additionally, in an idealized scenario with no heat loss occurring with the tank, a first-order temperature response shows that over the course of eight hours, the temperature of the tank will increase significantly in the beginning and then begin to slow down in its temperature increase, eventually reaching 166.8 °F rather than the necessary 185 °F or the goal of 175 °F. With heat losses considered, the temperature the heating liquid reaches is 161.52°F. A visual of this model can be seen in Figure 27 below. The visual model of heat losses in the tank over time can be seen in below Figure 28.

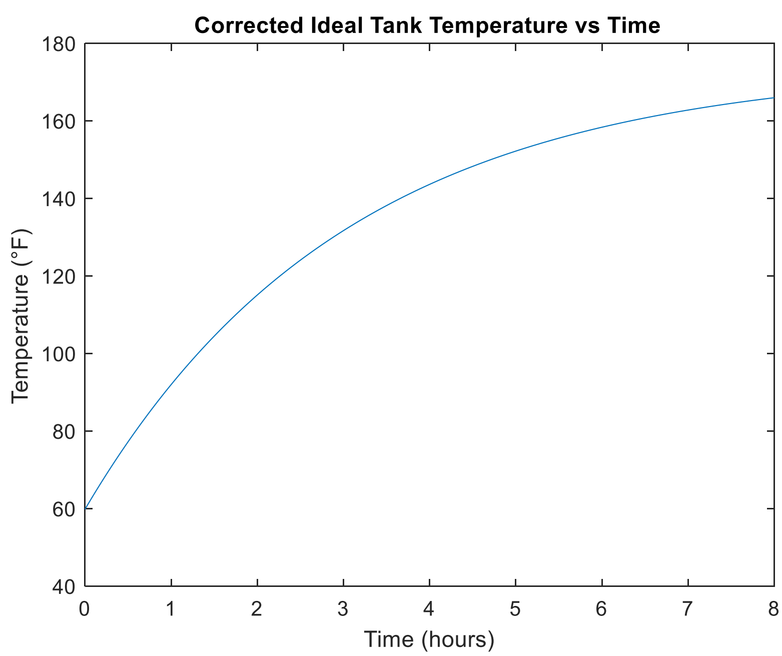

Figure 27: Corrected Ideal Tank Temperature vs Time

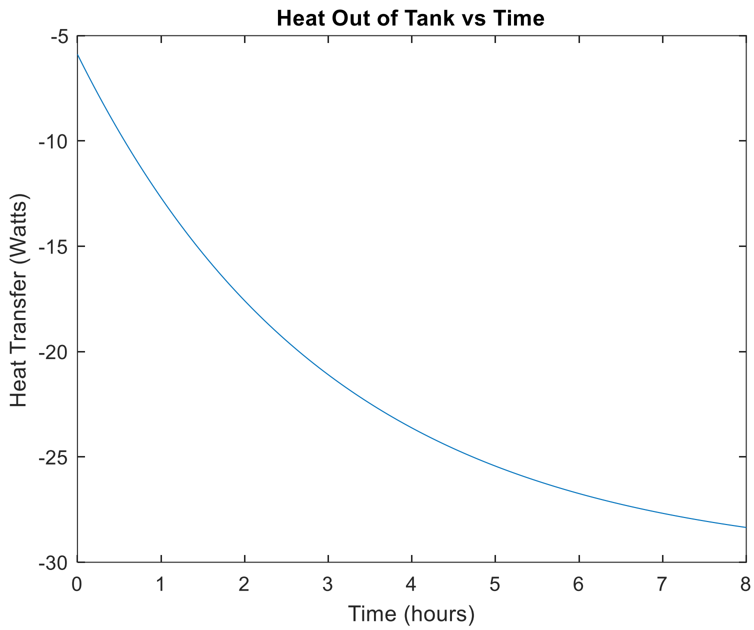

Figure 28: Heat Transfer Out of Tank vs Time

Finally, this technical analysis also found that the required power to perform the desired heat transfer is over 4,000 W, much like the previous technical analysis found, and that the current heating element, the heating tape, was greatly insufficient for the target temperature [29].

Another technical analysis showed that for lower scale solar panels, such as the 50W the team was using, placing the panels in parallel is most efficient. Upon analysis, the team's solar setup would be sufficient for providing power for the chosen pump and blower, which require a total monthly load of 15.95 kWh, and the projected lowest monthly load throughout an entire year is 17 kWh [30]. The chart showing the energy production of the three chosen 50W solar panels can be seen in **Appendix D**: Solar System Projected Output [31]. In the future, a blower that requires less power or incorporating higher wattage panels could be useful for creating a greater margin of error for this energy requirement. Furthermore, it is important to remind that this power is not incorporating the heating source element.

From this postmortem, the team has concluded with some future design recommendations. The greatest need for improvement is a greater heating source. The heating tape proved to be a good method for directly contacting the pipes above the tank. However, the heating tape had a small wattage and had a limit to how much it could heat the propylene glycol in the heating loop. One consideration is using a solar-thermal system or heating the water outside the tank before transporting it into the tank. The blower the team chose had great blowing power, with 600 CFM, but it required a large amount of power, 0.15 hp, and the outlet was shaped in an inefficient way, where the team had to create a 3D printed part to act as a nozzle, shaping the large outlet of the blower to fit the ½" inlet of the copper piping going into the liquid-to-air heat exchanger. For this reason, we recommend that a blower that has strong air flow but is shaped to function specifically as an HVAC device. Ideally, the system could have a suction device at the outlet of the device to improve airflow going into the house. Another point of improvement is better insulation for the tank and exposed piping. Due to the heating tape being placed onto the exposed piping above the tank, insulation could not be placed onto the heating tape without the insulation melting. With a different heating element and without heating tape, this should not be an issue, and insulation can be placed on the piping to reduce heat loss. The tank also had foil insulation, but fiberglass would be better. Additionally, the tank could be buried, which would greatly improve insulation, and it would make access to the elements easier, because the tank is nearly 6-ft tall. Another idea is to build a makeshift building, such as ones built around wells, to insulate the tank from outdoor elements and temperatures. The system could also benefit from the reservoir being insulated, because it holds propylene glycol for quite some time before being recycled back into the liquid-to-liquid heat exchanger. We hope further implementations and designs can explore the solar and battery aspect of the design more, because the team focused primarily on the heating and thermal storage element of the scope. The solar component would be highly beneficial to those in areas with limited electricity.

Altogether, the team created a design that we thought laid a solid foundation for future designs and reiterations. The team proved the concept of heat transferring from a massive water unit to heat an air loop, increasing air temperature within the loop, and increasing heat transfer liquid in the heating loop through testing. Although difficulties with the scope of the project hindered the team’s ability to accomplish all that we wanted to, we believe future designs can create a thermal storage device that is functional and reliable with the information gathered from our analyses and prototyping. We believe that this was a new concept that required a lot of learning through trial and error, and we are satisfied with the number of tests and the amount of building accomplished to learn that information, so that future teams do not.

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12 APPENDICES

12.1 Appendix A: Bill of Materials

Table 10: Bill of Materials

Bill of Materials							
Part number	Part description	Manufacturer	Dimensions	Weight	Quantity	Unit Cost	Total Cost for Part
1	Heating Fluid Pump	Ferroday	10.2 x 7.6 x 6 inches	4.59 lbs.	1	$79.99	$79.99
2	Liquid to Liquid Heat Exchanger	AB	3"x8" 10 plates	3.29 lbs	1	$89.99	
3	Heating Band	heating Element Plus	1" x 96"		1	$119.90	$119.90
4	Copper Piping	Cambridge-Lee	10' and 1" dia		1	$34.77	$34.77
5	Storage Tank	Norwesco	32" dia. x 67"H and 210 gallons	65 lbs.	1	$578.33	$578.33
6	Fan	Ridgid	13 x 12.3 x 10.6 in	12.25 lbs	1	$79.97	$79.97
7	Battery	Crown	12.19 × 7.19 × 14.13 in	92 lbs.	1	$235.00	$235.00
8	Electricity Solar Panel	Grape Solar	26.18" x 24.4"	10.58 lbs	2	$51.41	$102.82
9	Arduino	ELEGOO	3.15 x 2.36 x 0.39 in	2.24 oz.	1	$12.98	$12.98
10	Thermocouples	Aideepen	3.7 x 3.1 x 0.3 in	0.81 oz.	5	$2.60	$13.00
11	Piping Clamp				1	$80.28	$80.28
12	Propylene Glycol	Dynalene		10 lbs	1 (gal)	$38.00	
13	Copper Piping	Home depot	10' and 1/2" dia		3	$11.27	$33.81
14	Round metal pipe duct	Home depot	12" x 5'		1	$16.80	$16.80
15	Gas can	Home depot	5 gallons; 14" x 7"		1	$23.97	$23.97

16	Copper coil piping	AZ central supply	1/2" x 50' Copper coil		2	$62.00	$124.00
17	90-degree bronze fittings	Home depot	1/2" 90-degree bronze elbow		2	$7.93	$15.86
18	Solder	Home depot	8oz. lead free solder		1	$20.95	$20.95
19	90-degree fittings	Home depot	1/2"		12	$0.74	$8.88
20	cover	Home depot	20"		1	$39.98	$39.98
21	wood	Home depot			3	$1.69	$5.07
22	couplings	Home depot	3/8" x 1/2"		4	$1.76	$7.04
23	cpvcpipes	Home depot	3/4" x 2'		6	$2.16	$12.96
24	SharkbiteCoupling	Home depot	3/8" x 3/8"		1	$6.97	$6.97
25	PTFE Tape	Home depot	1/2" x 260" (width x length)		1	$0.98	$0.98
26	Male Adapter Fitting	Home depot	1/2" x 1/2"		1	$1.58	$1.58
27	Copper Coupling	Home depot	1/2" x 1/2"		3	$0.56	$1.68
28	Stud Size Ring Terminals	Home depot	0.8125" x 0.3125"		1	$1.98	$1.98
29	15A Straight-Blade Non-Grounded Plug	Home depot	1.5" x 2"		1	$2.19	$2.19
30	Fiberglass Pipe Wrap Insulation	Home depot	3" x 25'		1	$7.12	$7.12
31	Power Inverter	Walmart	3"x6"x8"		1	$34.99	$34.99
32	Female to Male Adapter	Home depot	3/4"x1/2"		1	$5.18	$5.18
33	Weather Resistant Electrical Tape	Home depot	3/4" x 66'		1	$2.98	$2.98
34	Rubber O-ring	Home depot	5/8"		1	$1.54	$1.58
				Pre-Tax Sum			$1,713.59
				Sales Tax (FLAGSTAFF)			$157.31
				Total Cost for Design			$1,870.90

12.2 *Appendix B: CAD Drawings*

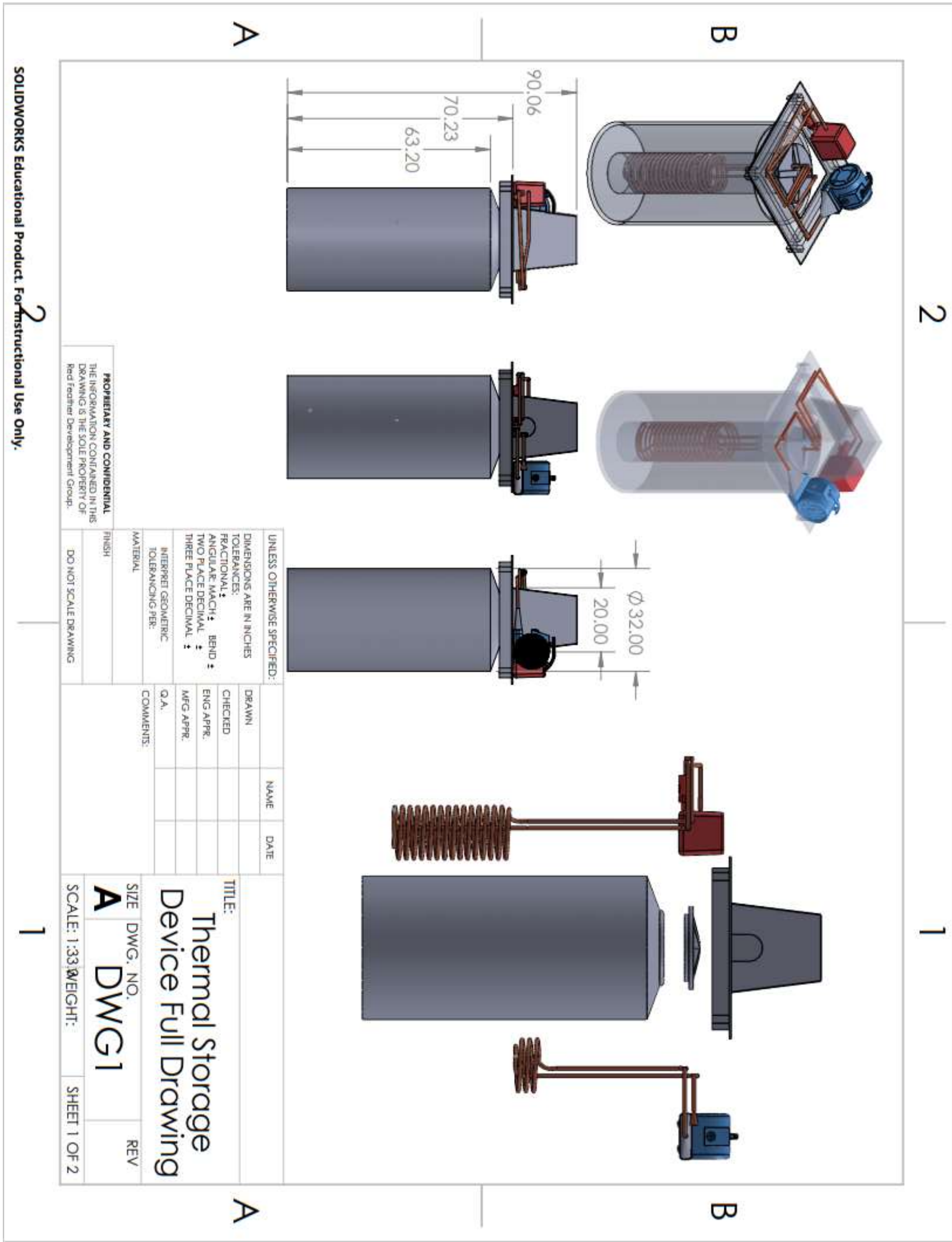

Figure A.1: Full Device Drawing (CAD)

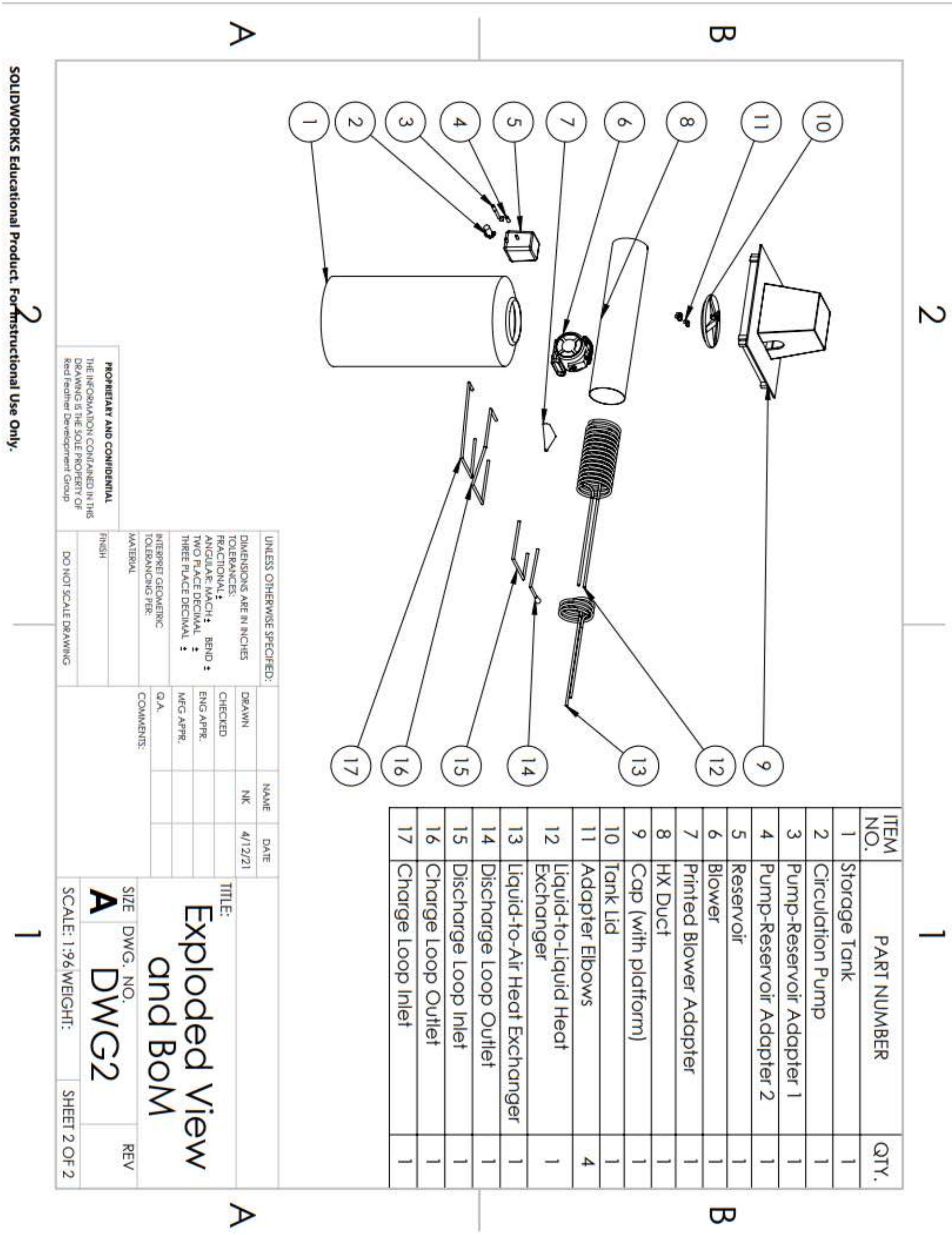

Figure A.2: Exploded View Drawing (CAD)

12.3 Appendix C: Full FMEA Sheet

Solar Thermal Storage Heating Device		Northern Arizona Unviersity Red Feather Capstone B12 Team				Page No 1 of 3 7-Nov-20			
Part # and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Causes and Mechanisms of Failure	Occurence (O)	Current Design Controls Test	Detection (D)	RPN	Recommended Action
#1 Heating Fluid Pump	Corrosion fatigue	Liquid not heated, leaking of liquid into storage tank	3	Loose/Broken Belt	3	Run system nonstop for 7 days	1	9	None
	Stress Corrosion	Liquid not heated, leaking of liquid into storage tank	3	Impeller Shaft Failure	3	Run system nonstop for 7 days	1	9	None
	Fretting Corrosion	Liquid not heated, leaking of liquid into storage tank	2	Liquid Leaking	5	Run system nonstop for 7 days	2	20	None
#2 Liquid to Liquid Heat Exchanger	Thermal Fatigue	Liquid not heated, leaking of liquid into storage tank	8	High Temperature differentials of liquids.	5	Run system nonstop for 7 days	1	40	Choose a heat exchanger with increased temperature limits
	Thermal Shock	Heat exchanger breaks, causing fluid to not flow	8	Freezing from outside environment	1	Run system at cold, 20 degree temperatures	3	24	Make sure the storage tank is properly insulated
	High Cycle Fatigue	Liquid not heated, leaking of liquid into storage tank	8	Higher fluid velocity than manufacturer's stated maximum causing vibrations	2	Run system nonstop for 7 days	1	16	Maintain a lower velocity of the fluid throughout the H.E.
	Erosion Corrosion	Liquid not heated, leaking of liquid into storage tank	8	Electrochemical potential from chemical reactions	3	Run system nonstop for 7 days	1	24	None
	Pitting Corrosion	Liquid not heated, leaking of liquid into storage tank	8	Higher fluid velocity than manufacturer's stated maximum	3	Run system nonstop for 7 days	1	24	Maintain a lower velocity of the fluid throughout the H.E.

Solar Thermal Storage Heating Device		Northern Arizona Unviersity Red Feather Capstone B12 Team				Page No 2 of 3 7-Nov-20			
	Erosion Corrosion	Liquid not heated, leaking of liquid into storage tank	8	Electrochemical potential from chemical ...	3	Run system nonstop for 7 days	1	24	
	Pitting Corrosion	Liquid not heated, leaking of liquid into storage tank	8	Higher fluid velocity than manufacturer's stated maximum	3	Run system nonstop for 7 days	1	24	Maintain a lower velocity of the fluid throughout the H.E.
	Thermal Shock	Heat exchanger breaks, causing fluid to not flow	8	Freezing from outside environment	1	Run system at cold, 20 degree temperatures	3	24	Make sure the storage tank is properly insulated
#4 Heating Band	Crevice Corrosion	Heat band fails	8	Moisture builds and is trapped between sheets of metal on the heating band	2	Power on the heating band and turn it to high wattage for long period of time	2	32	Make sure the heating band is properly protected from the elements and weather conditions
	High Cycle Fatigue	Power shorts, heating band no longer works	8	Wire diameter reduced, melting and breaking, wears down insulation	2	Power on the heating band and turn it to high wattage for long period of time	2	32	Use the lowest wattage necessary
	Thermal Fatigue	Heat band will die	8	Heat not transferred efficiently,too high wattage over short period of time	2	Power on the heating band and turn it to high wattage for long period of time	2	32	Make sure the heating band is tightened and properly fitted, on the lowest wattage necessary
#6 Storage Tank	Erosion Corrosion	The storage tank has a leak of hot liquid	10	Electrical-Chemical reaction or bacteria causing corrosion	1	Run the system for 7 days and check to see if there is any build up in the tank	2	20	Make sure the tank has regularlly scheduled maintanence
	Thermal Fatigue	The storage tank has a leak of hot liquid	10	If the material of the storage tank does not have a high enough melting point, the high temperatures may wear away the material	2	Run system nonstop for 7 days, check integrity of the tank	2	40	Make sure the tank's material has a high melting point, far above the max temperature of 175 F

Solar Thermal Storage Heating Device		Northern Arizona Unviersity Red Feather Capstone B12 Team				Page No 3 of 3 7-Nov-20			
	Low Cycle Fatigue	Battery dies.	8	The battery is undercharged (not fully charged after use) causing sulfation, where sulfate builds up on the battery electrodes, making it less effective	2	Run system nonstop for 7 days	1	16	
	Thermal Fatigue	Battery dies.	8	Battery overheats, causing overcharging.	2	Run system nonstop for 7 days	1	16	Keep battery out of direct sunlight
#9 Electricity Solar Panel	Corrosive wear	Solar Panel does not output fully	8	Weathering causes cracks in the cells	2	Run system in cold, 20 F temperatures for a long period of time	3	48	Clean the panels on a monthly basis. Cover the panels with a tarp if there is a hail or damaging storm incoming. Perform maintenance check annually.
	Thermal Fatigue	Junction Box stops working, panel does not work	8	Junction box frozen by humidity freezing or other types of freezing. Cells crack from the thermal stress	3	Run system in cold, 20 F temperatures for a long period of time	1	24	None
#10 Arduino	Thermal Shock	Arudino shorts, stops working. Temperature can no longer be monitored and pumps/fan cannot be controlled	8	Freezing or heating the electronic components can cause them to short or not work	1	Run system in cold, 20 F temperatures for a long period of time	1	8	Make sure the Arudino and electronic components are properly insualted
#11 Thermocouples	Thermal Fatigue	Thermocouple breaks, cannot read temperatures properly	7	Temperature changes cause expansion and contraction of metal, weakening the thermocouple	3	Run system nonstop for 7 days	2	42	Switch out thermocouples on a routine maintenance basis
	Hydrogen Damage	Thermocouple breaks, cannot read temperatures properly	7	Oxygen gets into sealed thermocouple, reacting with the metal	3	Run system nonstop for 7 days	2	42	Switch out thermocouples on a routine maintenance basis

12.4 Appendix D: Solar System Projected Output

RESULTS

Print Results

265 kWh/Year*

System output may range from 249 to 273 kWh per year near this location.
Click HERE for more information.

Month	Solar Radiation (kWh / m^2 / day)	AC Energy (kWh)	Value ($)
January	4.71	18	2
February	5.50	19	2
March	6.52	24	2
April	7.58	27	3
May	7.72	27	3
June	8.08	26	3
July	6.99	23	2
August	6.73	22	2
September	6.67	22	2
October	6.00	21	2
November	5.05	18	2
December	4.38	17	2
Annual	**6.33**	**264**	**$ 27**

Figure 29: AC Energy Month Production