Project 4 - Red Feather Thermal Energy for Homes

Preliminary Report

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DISCLAIMER

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1 BACKGROUND

1.1 Introduction

The Red Feather Thermal Energy for Homes Project was created by Mark Hall to provide efficient and low-cost energy solutions for warming homes on the Navajo and Hopi reservations. It is meant to benefit the native reservations by substituting the burning of coal and propane and consequently reducing air pollution. As a side effect of the reduction in air pollution, the project intends to maintain the overall health of the reservation members who were negatively affected by the use of coal and burning of propane. Completion of this project will potentially introduce a safer and more efficient heating option for the reservation communities. It will also push the Red Feather Development Group closer to their goal of creating sustainable solutions to the housing needs of people living on the reservation. The project will address issues such as eco-friendly energy production and energy efficient heating systems. The main objective of this project is to implement a heating system that is an improvement from current options available to residents in terms of air quality, efficiency, and cost.

1.2 Project Description

The following quote is the original project description given by the sponsor:

> Red Feather Development Group, a non-profit in Flagstaff, works with the Navajo and Hopi Tribes to develop and implement sustainable solutions to their housing needs. Currently, the majority of these two Nations use coal and or wood to heat their homes during the extremely cold winters. Wood and coal smoke is one of the leading contributors to the higher respiratory disease rates on American Indian Reservations (5 times higher). With the pending closure of a coal-fired electricity plant and the mine that supplies it, coal is expected to become very scarce over the next couple years. It is expected that the majority of households using primarily coal to heat their homes will switch to wood, since it can be burned in the same stove, and historically has been reasonably abundant. Tribal officials expect that this increase in demand for wood will strain local woodlands and rapidly create a similar scarcity for both fuels. The remaining fuel choices are electricity and propane, as only a very limited number of families have access to Natural Gas. Propane has a number of risks, including CO poisoning and risk of explosion, as well as being cost prohibitive for most families. Electricity is not available for thousands of Navajo and Hopi families, and when it is available, space heaters are the most common appliance used for heating. Not only are space heaters the most expensive way to heat a home but they are the number one cause of home fire deaths in the United States. This capstone project will task a team of 3-4 students to research and develop sustainable and lasting solutions to the different heating problems on the reservations. Factors such as yearly climate and weather patterns, types of homes, methods of insulation, costs of heating systems and fuel types, and available resources will play into the final solutions. Solutions such as SolarThermix and Phase Change Materials have potential, but all possible solutions should be considered and analyzed for viability. This project will begin as an analytical project where the team's final deliverables are in-depth theoretical models of the proposed solutions, thoroughly backed by analyses. However, there is a strong potential to procure extra sponsorship during the semester to provide resources for prototyping and testing.

2 REQUIREMENTS

Requirements for this project were compiled after meeting with our client. Customer requirements were constructed from project deliverables and goals mentioned during team meetings with Mark Hall. Engineering requirements were then interpreted from the approved customer requirements in order to accurately measure target values and increase or decrease them accordingly.

2.1 Customer Requirements (CRs)

The five customer requirements below encompass the most important needs of the team's client. Each requirement was selected due to its importance in fulfilling the final goals and constraints for the design. The team relies on customer requirements to ensure the final design is satisfactory to the client.

2.1.1 Cannot pose a safety hazard

The system must not pose a safety hazard to the occupants of the home or surrounding area. A current problem with home heating systems on the reservation is pollutants from burning coal, wood, and trash being released into homes. Particulates created by wood and coal stoves have the potential to vent back into the home, causing residents to breathe in the smoke and experience substantial health problems. In the context of this project, it is also important to account for the effect on surrounding air quality in the community, as even adequately ventilated systems can cause health problems if they are concentrated in a community.

2.1.2 Must be an Improvement From Current Heating Solution

The design the team creates must be an improvement from the original design in terms of cost, air quality, and efficiency. To justify the expense and difficulty of a widespread overhaul of home heating systems across the reservation, the new system must provide enough of a benefit over the original that the results are substantial.

2.1.3 Keeps Home at a Comfortable Temperature in Winter

The system must heat the home adequately enough to keep it at a comfortable temperature at all times. Regardless of the weather or temperature conditions in the region, the home should remain at the same temperature.

2.1.4 Must Account for Heat Loss from Home Related to Insulation/Windows/Doors

A home loses heat through walls, windows, and doors when these features are poorly insulated. The final team must provide enough well-placed insulating features to reduce the loss through the home, and account for the amount of extra work the heating system has to do to make up for the loss. Using these metrics, the final design must apply the best combination of heating power and insulation to minimize costs and energy usage

2.1.5 Must be Reliable with Temperature Fluctuations

The system should be able to hold up to variable temperature conditions caused by varying climates and seasons. The system should not experience damage or wear down under conditions of extreme temperature and should continue to heat the home under normal conditions. It should have a sort of backup system or redundancy if it is occasionally unable to operate due to failure or other circumstances.

2.2 Engineering Requirements (ERs)

The engineering requirements created are a list of 5 requirements that were developed to address all that the project entails. The list of engineering requirements can be seen below, while a signed list by the capstone client can be seen in Appendix B in Figure 6.

2.2.1 System must be safe in operation and use.

The amount of product pollutants(NO_2, NO_3, SO_2, SO_3 kg/KWH) generated must be about 10 µg/m3 annually and 30 µg/m3 maximum within 24 hours, both values with a tolerance of +/-5 µg/m3 [8]. Product also must not pose as a fire hazard.

2.2.2 Efficiency for low installation and material costs.

Material and installations costs should be within a range of cost of $1200 +/-$300 and the system must have an efficiency of 70% +/-10%

2.2.3 Comfortable temperature in a home must be set and retained

The system should be able to generate a comfortable temperature of 72F +/-3F and keep it constant.

2.2.4 High thermal resistance must be achieved.

The system must try and improve the resistance at the homes to reduce any heat losses. For a cinder block home, the resistance intended is R ~2.2 K/W+0.3 K/W

2.2.1 System must be durable

The system must be able to operate for a period of 10 years +/- 2 years and have a backup battery system that can keep the home warm for at least 10 hours +/-2 hours.

2.3 House of Quality (HoQ)

The house of quality was used to breakdown the project description into specific target areas and allow the team to fully understand the needs and constraints of the project. The team's house of quality can be found in Appendix A. The most important engineering requirements are thermal efficiency, cost, and thermal resistance value. Thermal efficiency relates to almost all customer needs and will provide a basis for how effectively the system uses energy. The most important customer needs are safety/health of the residents and improvement from current heating solution. Using this information, the team will be able to identify the areas of the project which will require the most attention. The house of quality also allowed the team to begin an outline of the final design based on target values for the engineering requirements. For example, the thermal resistance value of the home must be above 2.2 K/W which is the resistance of cinder block used in many reservation homes. The team will continue to utilize the HoQ during the duration of the project to ensure that target values are met and customer needs are followed.

3 DESIGN SPACE RESEARCH

To begin the development of a design concept, Team 4 has researched a variety of articles, websites, and books which will be listed below. These sources all provided specific information crucial to the project development and understanding of the systems involved in it. Additionally, benchmarks to compare the usefulness of the system are shown in these sources; hence this broadens the scope of the project by introducing varied systems that offer potential solutions through multiple approaches.

3.1 Literature Review

In this section, the literature that was gathered by each team member to be incorporated into the final product design will be presented. These sources will have a brief description of their contents followed after their citation.

3.1.1 Team Member 1 (Beraud Edwin)

The main focus of this team member is researching about Phase Change Materials to come up with a decision of a final PCM to use in the Capstone Project. This team member is also responsible for finding information about how to model PCMs with software to analyze the reduction in costs they can bring for its users in residential areas. The team member sources are:

3.1.1.1 "Thermal Energy Storage Using Phase Change Materials" [1]

This book has in-depth data about Phase Change materials. It covers different uses of PCMs, their operation, and their incorporation into different applications ranging from electronics, constructions, etc.

3.1.1.2 "Fundamentals of heat and mass transfer" [2]

This book contains data regarding heat transfer. It is useful to understand the theoretical functioning of Phase Change Materials. It also covers methods of heat transfer and specific terminology to the subject.

3.1.1.3 "Report: High-Temperature Phase Change Materials (PCM) Candidates for Thermal Energy Storage (TES) Applications" [3]

This article contains information on High-Temperature Phase change materials with corrosive properties. The article tests different kinds of PCMs and finds discrepancies between the data reported by the PCM manufacturer and experimental data.

While the PCMS used here are unlikely to be used due to their corrosive properties, they are not ruled out entirely in the design process since the temperature of operation for the final Capstone design might require them.

3.1.1.4 "Thermal Energy Storage with Phase Change Material" [4]

This article provides insight into the different types of PCMs. It explains their differences and provides tables with properties of the materials. Additionally, this article does not only give properties but explains the pros and cons of every type of PCM. It will come handy in the PCM selection process.

3.1.1.5 "Phase change materials for solar thermal energy storage in residential buildings in cold climate" [5]

This article has a detailed explanation of an experiment conducted using PCM's to heat residential buildings exposed to cold weathers in China. It contains plenty of information of the PCM selection criteria that was considered, as well as modeling data of the which can come handy to the projects as a way to approach the problem.

3.1.1.6 "Cost Analysis of Simple Phase Change Material-Enhanced Building Envelopes" [6]

This report provides data on modeling PCMs with DOE, Energy Plus. and also costs related to the improvements that can be achieved with these materials. The report also states the estimated costs PCMs should have to pay back their cost in benefit over the period of 10 years. Additionally, the article suggests improvements to reduce costs of PCMs while increasing their effectiveness.

This document is useful to determine appropriate PCMs based on their costs. It will also give insight into how to simulate PCMs.

3.1.2 Team Member 2 (Legrand Will)

3.1.2.1 "Navajo Home Heating Practices, Their Impacts on Air Quality and Human Health, and a Framework to Identify Sustainable Solutions" [7]

This article focuses specifically on heating homes on the Navajo Nation reservation. It explains many of the problems of current heating practices in terms of pollution and demographic health and explains where researchers currently stand in formulating solutions to this problem.

3.1.2.2 "NAAQS Table" [8]

This table, provided by the EPA, provides government standards for levels of air particulates. An excessive level of exposure to course or fine particulates over an amount of time can create an impact on human respiratory health. Using these measurements the team can formulate the impact the system will have on improving air quality and health standards if applied on the reservation.

3.1.2.3 "Home Insulation Types: Advantages and Disadvantages" [9]

This webpage lists several types of insulation, along with their respective costs and R values. R values determine how much heat loss insulation will be prevented across walls. Using software and calculations, the team is able to determine how much of what type of insulation will provide the ideal improvements.

3.1.2.4 "Alternative Energy Systems and Applications" [10]

This textbook overviews renewable forms of energy, including solar and wind energy, along with how they can be applied to generate power. It also considers how existing forms of energy generation can be modified to increase their efficiency. It provides applications of energy that have the potential to be used on the Navajo Nation Reservation.

3.1.2.5 "Solar Energy: Fundamentals, Technology, and Systems" [11]

This book focuses on solar energy specifically and includes sections on the types of Solar Thermal Energy we are using in the project.

3.1.3 Team Member 3 (Macauley Jeffrey)

3.1.3.1 "Renewable energy technologies for sustainable development of energy efficient building" [12]

Since this project lies within the realm of energy-efficient building techniques this article is a great source of information. It contains various green methods of reducing a homes energy requirements when it comes to heating and cooling, while also touching on the economics of such a system.

3.1.3.2 "Thermal analysis of a natural circulation solar air heater with phase change material energy storage" [13]

This article proves useful in that is provides insight into how a solar furnace operates with phase change materials with data on its results. This is of particular interest of the client to see if a home can be heated without producing extra pollution, health, and safety risks.

3.1.3.3 "Impact factors analysis on the thermal performance of hollow block wall" [14]

This article is an important resource because it provides information on the thermal performance of a hollow block wall. Modeling a cinder block home for testing purposes and benchmarking is an important part within the scope of this project.

3.1.3.4 “Solar Energy Applications in Houses” [15]

This is an old textbook that covers a wide range of important topics in regards to solar energy in homes. This book gives information on space heating requirements, different uses of solar energy as well as performance and the economics of these systems and much more.

3.1.3.5 "Types of Insulation" [16]

This website contains information on the various forms of insulation, their applications and notes briefly on resistance values. It also makes comments on effectiveness in different climates and cost efficiency depending on if insulating a home undergoing construction or working with an existing structure.

3.1.4 Team Member 4 (Shaw Jake)

3.1.4.1 “PreHeat: controlling home heating using occupancy prediction”[17]

This peer-reviewed article discusses a method for improving energy usage by using occupancy sensing and occupancy prediction when heating the home. Many homes have a scheduling feature on the thermostat but most Americans do not utilize this feature. The authors of this article experimented with this method in five different homes. Results found a 6x-12x reduction in miss time, which is defined as the time when the home is occupied but not warm. This article could be useful for the project because one of the main customer needs is regulating the home at a constant temperature to keep the occupants comfortable. This method could potentially be used to ensure that the temperature inside the home is comfortable and the system is energy efficient.

3.1.4.2 "Cost-effective methods to improve the power output of a solar panel: An experimental investigation" [18]

This peer-reviewed article discusses a method to improve the power generated by photovoltaic solar panels. The method uses a four-mirror system to direct sunlight onto the panel without any tracking of the sun. Experiments with this system showed a 30.54% increase in short-circuit current. Solar PV panels may be implemented into the final design of this project to power a small fan and a thermostat system. The team wants to ensure that the fan will always have a power supply or else, the home will not be heated with this system. The method described in this article is also very cheap because it only requires four mirrors directed at the correct angle.

3.1.4.3 “Radiant Heating” [19]

This webpage was created by the department of energy. It discusses a method for heat dispersal involving panels placed in the walls, ceiling, or flooring of the homes. The panels are heated up by tubes which run along the surface. The tubes may carry either hot water or air. The advantage of using air as the working fluid is that it can be implemented with a solar air heating system. However, air does not retain heat as well as water. Using water as the working fluid is the most popular and cost-effective radiant heating system. Most reservation homes also have access to running water so the team would only need to implement some sort of boiler to heat the water. The main disadvantage of this method is that it has high installation costs due to the invasive procedure of removing the walls or flooring. The design may have potential as a type of heat dispersal method associated with the solar furnace.

3.1.4.4 “Fundamentals of engineering thermodynamics” [20]

This book is used for many undergraduate thermodynamic classes. It covers a range of thermodynamic topics including efficiency, cycles, and heat transfer which may be useful during the project. The equations in this book may be useful to analyze a boiler or furnace in the home to find out heat transfer and work input. Multiple team members own the book so it should not be hard to acquire.

3.1.4.5 “Audel HVAC fundamentals” [21]

This book covers the basics of HVAC systems. It discusses the best climates and households for certain types of HVAC systems and explains how they work. The book will be useful if the team decides to implement an HVAC system in the future.

3.2 Benchmarking

Benchmarking data was acquired primarily by means of online research. This was done to establish a healthy base of information for proper evaluation of processes during functional decomposition, concept generation, technical selection and for other various uses throughout the project.

3.2.1 System Level Benchmarking

In order to benchmark system level designs of heating devices, the team has decided to evaluate potential heating sources related to the primary design objective. These include a combination of solar designs and with plausible circulation systems. Data gathered here will be useful in the selection of a final design after concept generation phases.

3.2.1.1 Existing Design #1: Solar Thermix Solar Air Heating System

Solar Thermix is a company that develops sustainable solutions to minimize the dependence of fossil fuels in society. It is the creator of the concept of solar air heating which heats air using the sun's radiation along with a fan which produces an air flow in the thermal system to cycle the air [1]. These solar thermal systems allow for the migration of 1000 square feet of carbon yearly and have an estimated ability to pay for themselves in operational cost reduction after 3 years [1].

The system relates to the design of the capstone team since the idea of solar air heating will be used to warm homes at the Navajo and Hopi reservations due to its affordability and environmentally friendly operation.

3.2.1.2 Existing Design #2: Solar Furnace

EcoSolaris’ design on a solar furnace was used as a benchmark to rate the final design. The solar furnace works by absorbing solar radiation throughout the day and warming the air within it. Once this air is warm enough to provide sufficient heat to the home, a fan will then circulate the warm air from the furnace into the home and draw the cooler air from the home into the furnace. This design is very similar to the designs presented in the concept generation section of this document.

3.2.1.3 Existing Design #3: Radiant Heating System

The most popular form of the radiant heating system involves panels placed in the flooring or walls of homes. The panels have tubing that runs along their surface. The tubes carry hot water which then radiates heat into the home. The water is heated using a boiler running off of electricity. This method is a highly efficient way to heat the home but it is expensive to install. This system is more efficient than coal burning and does not release any pollutants to the air which is a huge improvement from the current heating systems on the reservation. The main downside of this design is the cost and the fact that a solar panel will need to be installed to power the boiler.

3.2.1.4 Existing Design #4: Common Furnaces

Furnaces are a common method of heating homes throughout the world. Furnaces' popularity is due to the fact that they are inexpensive to run and easy to use. A furnace is designed to work by combusting materials within itself and then radiating that heat outwards into its surroundings, which would be the home. This inherently poses a fire safety hazard, which can be avoided with proper care and maintenance. Still, chimney fires are fairly common and can cause remarkable amounts of damage to a home. This form of heating method also poses an air quality risk. Without adequate air circulation throughout the home, it is easy for particulate matter in the air to reach hazardous conditions. While furnaces come with some attractive benefits such as cost and effectiveness, they also come with some potentially dangerous negative effects. Drawbacks to a furnace include reduced air quality and fire hazards. This system does have some advantages but the potential risk to one's health is large.

3.2.2 Subsystem Level Benchmarking

To achieve the most the best information regarding benchmarking designs, the team has broken down system level benchmarks into smaller components or subsystems for further evaluation. This is important in understanding the complex functions of design and each components specific purpose in the final product.

3.2.2.1 Subsystems for System #1: Solar Thermix - Solar Air Heater

Solar Thermix LLC., a small Phoenix-based company, is an example of an existing company that develops solar thermal energy systems to reduce external energy consumption in buildings. While Solar Thermix tends to apply designs on a larger scale in warehouses and commercial buildings, its systems serve as a model to better understand the ways a solar thermal energy system can be applied to be effective and viable.

3.2.2.1.1 Existing Design #1: Solar Heating

Solar Thermix uses a solar air heater as a source of heat for many of its designs. A solar air heater further explained in detail below, is a means of using solar thermal energy to locally heat air which can be transported throughout a building through integration with ventilation systems. Solar-Air-Heat generation is a fundamental part of Solar Thermix systems.

3.2.2.1.2 Existing Design #2: Solar Energy (PV)

Unlike solar air heaters which generate heat using solar thermal energy, Photovoltaic (PV) panels convert radiation from the sun into electricity. While electricity is easier to integrate into the functionality of a system, PV panels are more expensive and less efficient for heating purposes than a solar thermal energy collector. Solar Thermix incorporates PV panels to reduce electricity consumption within buildings for purposes not directly related to air and water heating.

3.2.2.1.3 Existing Design #3: Thermal Energy Battery

In order to compensate for the lack of available solar thermal energy during the night, Solar Thermix, in conjunction with Infinite R Phase Change Materials, is devising an application of phase change materials as a thermal energy battery within its systems to retain heat from the solar air heater during the day while solar energy is available and release it at times of day or during weather conditions in which solar energy is unavailable. This subsystem makes use of the latent heat released from phase change materials as their temperature lowers and they transform from liquid to solid form.

3.2.2.2 *Subsystems for System #2: Solar Furnace*

Breaking down a general solar furnace into its components for further analysis results in the following components for integral use within the device. This includes the furnace enclosure, the circulation fan, a photovoltaic panel, and a differential temperature controller.

3.2.2.2.1 Existing Design #1: Furnace Enclosure

The furnace enclosure is critical in the design of the final product as this is where heat is generated to be used inside the home. The enclosure is a simple box with a glass panel cover to encourage radiant heating also known as a solar collector. All surfaces are painted black to absorb as many different wavelengths of light as possible for maximum efficiency.

3.2.2.2.2 Existing Design #2: Turbine-Fan

The turbine fan is used for circulation of air through the system. Acting on the input ventilation tube, the fan forces air inside the home to be drawn into the furnace to be warmed. When the air is heated sufficiently to provide heat transfer into the home the air is then pushed through the output ventilation tube back into the home completing its cycle. This component is the main means of circulation within the system, making it crucial to get the flow rate of air just right in order to provide heat to the home.

3.2.2.2.3 Existing Design #3: Differential Temperature Controller

A differential temperature controller is used in this design in order to regulate the temperature of the home. This thermostat will signal when to turn on the fan by measuring when the temperature in the home drops below the desired temperature. The controller also needs to measure the temperature inside the furnace in the case that the temperature is not sufficient to provide heat to the home. The differential temperature controller is the main component in regulating the flow rate in the system.

3.2.2.2.4 Existing Design #4: Photovoltaic Panel

The photovoltaic panel is used in this system to power turbine fan and the differential temperature controller. This is also used to charge a battery for energy storage so the fan and thermostat can operate overnight. This component supplies the main source of power to the system to make it much more controlled and reliable.

3.2.2.3 Subsystems for System #3: Radiant Heating

The following sections list out the subsystems used in the radiant heating design described above.

3.2.2.3.1 Existing Design #1: Boiler

For this design, a boiler may be used to heat either air or water which will run along the tubing within the walls or flooring. Ideally, the boiler would run off of electricity that would need to be generated using a solar panel. However, the team could also use stoves or furnaces to heat the air/water by burning wood or coal. The problem with this method is that wood and coal are finite resources that may dry up in the near future. The boiler is an efficient and cost-effective subsystem that may end up in the team’s final design.

3.2.2.3.2 Existing Design #2: Water Circulation

As mentioned above, the radiant heating system may use either air or water as the working fluid in the tubes. The advantage of using water is that it can retain a lot of heat. The system is much more efficient if water is used. Also, it would be fairly easy to heat up the water using a furnace or boiler. Heating up water would prevent exposure to unwanted pollutants in the air. Research has shown that water as the working fluid is more popular and cost-effective. The disadvantage of using water is that not all of the reservation homes have access to running water.

3.2.2.3.3 Existing Design #3: Air Circulated

Although air will not retain heat as well as water, it has many advantages. For example, the radiant heating system with air as the working fluid could be integrated with the solar furnace. The furnace would heat up the air and a fan would blow the heated air into the tubing which is circulated around the house. The method may not be as efficient but it would certainly be effective. Using air in the tubing would also prevent the residents from constantly breathing in pollutants as opposed to burning coal or wood.

3.2.2.4 Subsystems for System #4: Common Furnaces

The following sections compare subsystems of common furnaces described previously in further detail. Furnaces are currently the main source of heat in many parts of the world, establishing a healthy base for benchmarking.

3.2.2.4.1 Existing Design #1: Coal Furnace

Coal furnaces are popular due to their ease of use and effectiveness. These work by burning coal loaded into the metal furnace to then radiate heat throughout the home. Once the coal fire has been started these take little upkeep for next to twelve hours. While the coal burns heat, smoke and ash are produced which is mostly directed up through the chimney. These systems are not completely sealed and can let some smoke and particulate matter into the home which can cause poor air quality conditions without proper ventilation. Regular maintenance is also required to reduce the risk of a chimney fire.

3.2.2.4.2 Existing Design #2: Wood Stove

Wood stoves are popular in forested areas due to the availability of fuel. These work similar to a coal stove by burning wood loaded into the metal stove and radiating heat into the home and come with similar health and safety risks. These do take more effort to keep a consistent temperature than a coal stove because wood burns more quickly. Regulating these stoves can also be difficult without experience, it is easy to load to much fuel or too little which will make the home uncomfortably warm or put the fire out respectively.

3.3 Functional Decomposition

The black box model described below is an optimal and brief description of the system. The whole concept behind this design is having a user input a specific temperature at home that will be regulated with the use of an external system which will collect air from the interior of the home and warm it up with an exterior source of heat.

The functional model goes more in-depth into what this system will be using. The base of the project will be using a solar furnace to cycle cold air and warm it up by using fans which take ambient air from the home and heat it up through a furnace. Moreover, an alternative generation of electric power will be desired as part of the project's goal to charge a battery that can power the fans cycling the air in the system. What is being strived is to create a user semi-independent system for them not to worry about minor tasks like turning on fans to cycle air. Instead, all they will have to do is set up a thermostat and let the system warm the home.

3.3.1 Black Box Model

The black box model for the design is shown below. The black box model starts with the main functional process of the design, heating the home. It then determines the inputs and outputs, as materials, energy, and signals, that contribute to this purpose. This model assumes the system uses a solar furnace to collect solar thermal energy to directly heat the home, as this is the design the team is most likely to select.

The black box model helps team members to define and break down the key inputs and outputs of the final design. It facilitates the development of a hypothetical or actual functional model by setting the parameters within which it must be built.

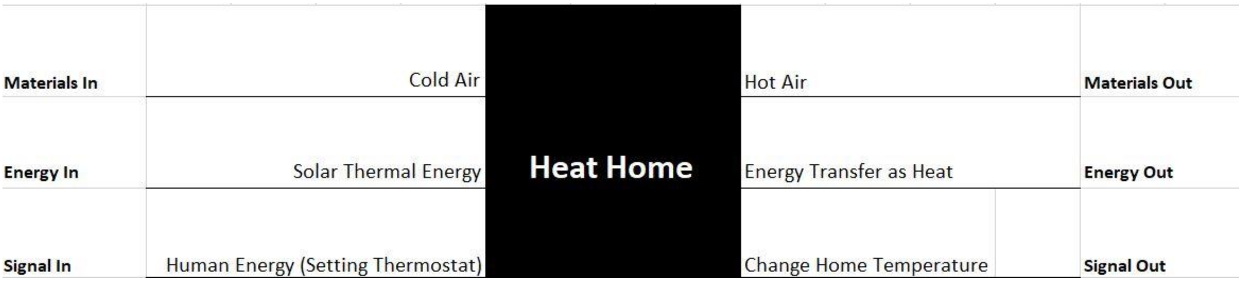


Figure 1: Black Box Model

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

The functional model for heating the home can be found below. The functional model essentially breaks down the black box model into the specific sub-functions that lead to the outputs of the design. The team found it difficult to generalize the functional model because all of the designs for heating a home are fairly unique. To make the process simpler, it was assumed that the team's design would use a furnace to heat air which would be circulated around the house using a small fan. The fan is powered using a solar panel. If the team ends up diverging from this design, the subfunctions of the functional model will be changed accordingly. The general outline of the model will not change, only the actions given to the subfunctions.

This model helped the team visualize the design by breaking down each task to its basic function. Analyzing the model reveals how the energy of the system is being used and converted. The diagram will be useful in the concept generation stage of the project because it will outline the exact sub-functions that need to be completed in order to achieve the desired outputs. The model below is subjected to change as the team researches and implements new ideas.

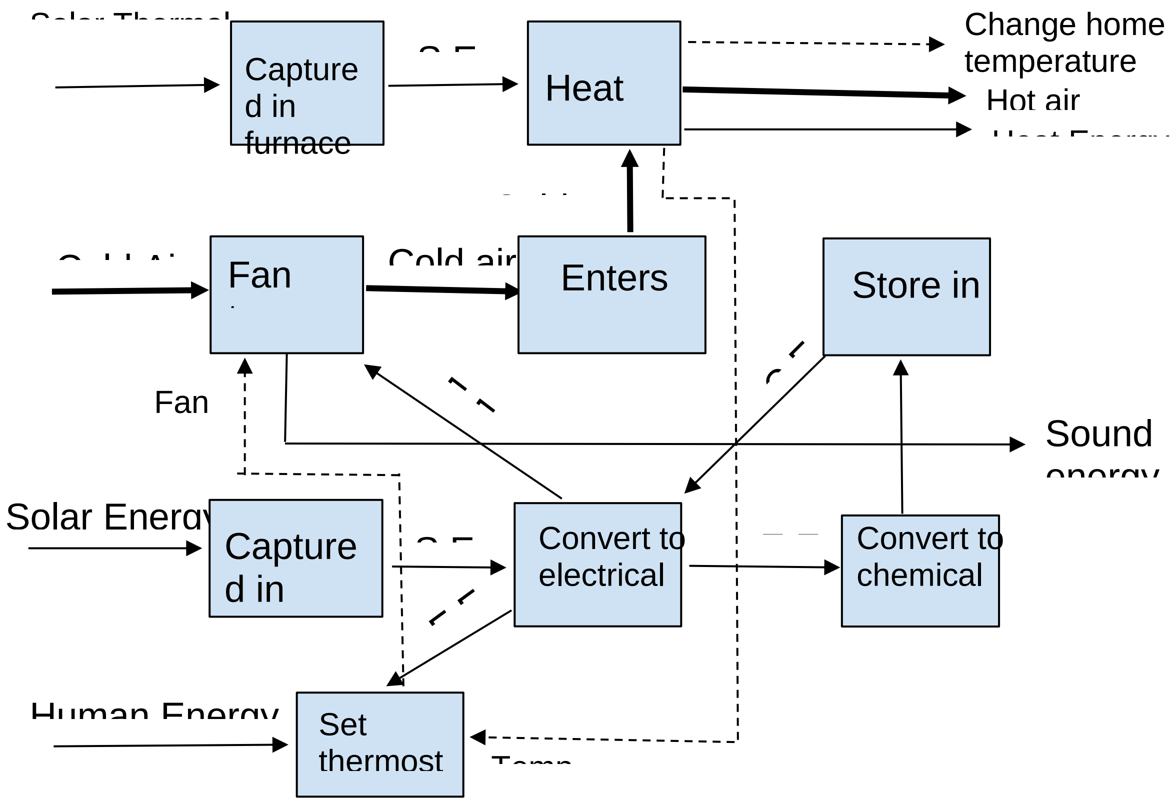


Figure 2: Functional Model Decomposition

4 CONCEPT GENERATION

For the concept generation process, the team decided to gather and discuss the multiple ideas that were in each of the members' minds. After brainstorming, three main systems were defined as concepts to look into. Each system can be comprised of different types of subsystems for which the team selected what they considered as the best designs.

4.1 Full System Concepts

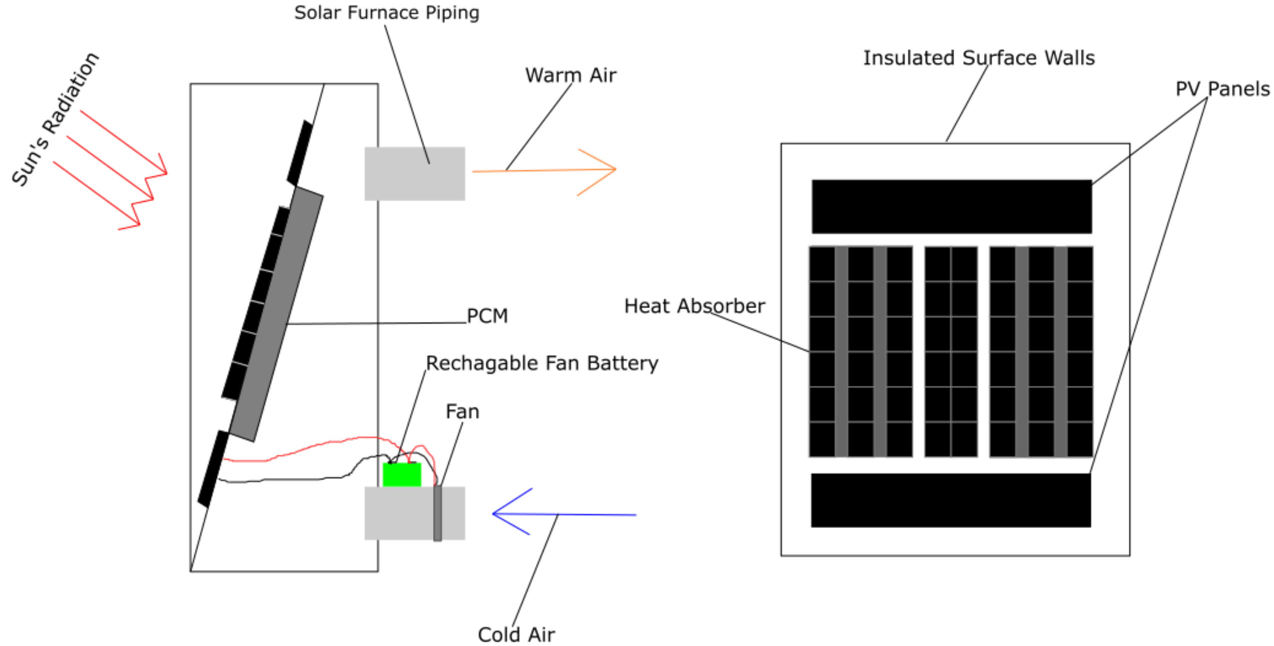
Three full system heating sources were conceived during concept generation. This includes various insulation types, a solar furnace, and an integrated combination of a solar furnace with phase change materials.

4.1.1 Full System Design #1: Insulation

Insulating a home can be a tedious process that largely depends on the construction of the home and proper installation. The goal of insulating a home is to increase the overall thermal resistivity (R) of that space. There are many different forms of insulation including but not limited to: rolls or blankets, various foams, loose-fill, and even reflective systems [16]. If building a home, insulating concrete blocks or spray foams are good options to consider but if insulating an existing home loose fills and rolls are available.

4.1.2 Full System Design #2: Solar Furnace

The solar furnace is an efficient and eco-friendly method for heating the home. It uses a large black panel placed on an outer wall of the home. The panel absorbs solar thermal energy and uses it to heat air within the furnace. Cold air is pulled into the furnace from the house using a fan. After the air is heated, the fan blows it out of a vent into the home. A thermostat can be integrated with a differential controller to constantly measure the hot air temperature and adjust the fan power accordingly. This method is eco-friendly and does not pollute the air in the house. Solar furnaces are also highly efficient when used correctly. The main disadvantage of this design is that the home will not be heated if the sun is not directed onto the panel. This will cause the temperature to drop at night which makes this system unreliable. If the home has very good insulation, then the heat provided during the day might be enough to keep the home comfortable during the night. This system would end up being expensive due to the high volume of insulation needed and the implementation of a solar panel.



4.1.3 Full System Design #3: Solar Furnace With PCM and PV Panels

Figure 3: To the left, there is a side view of the Solar furnace with PCM and PV Integration, while a front view of the design is presented to the right

A solar furnace with phase change material (PCM) and photovoltaic (PV) panels shown in Figure 3, is a standalone heating system concept, generated by combining heat absorbers, PCMs and PV Panels. The PV panels along with the heat absorbers are lying in the surface of the furnace that receives sunlight. In this way, the PV panels generate power for a battery that supplies energy to a fan which takes in cold air from the environment to cycle inside the solar furnace. This air is then released back into the environment to heat up a home. This solution is intended to work with a thermostat to set up a temperature regulating system and will have PCMs integrated to retain heat collected by the absorbers inside the system. The system's PCMs are intended to have the heating system operate efficiently when the sun is not out.

4.1.4 Full System Design #3: Solar Furnace With PV Panels and PCM Battery

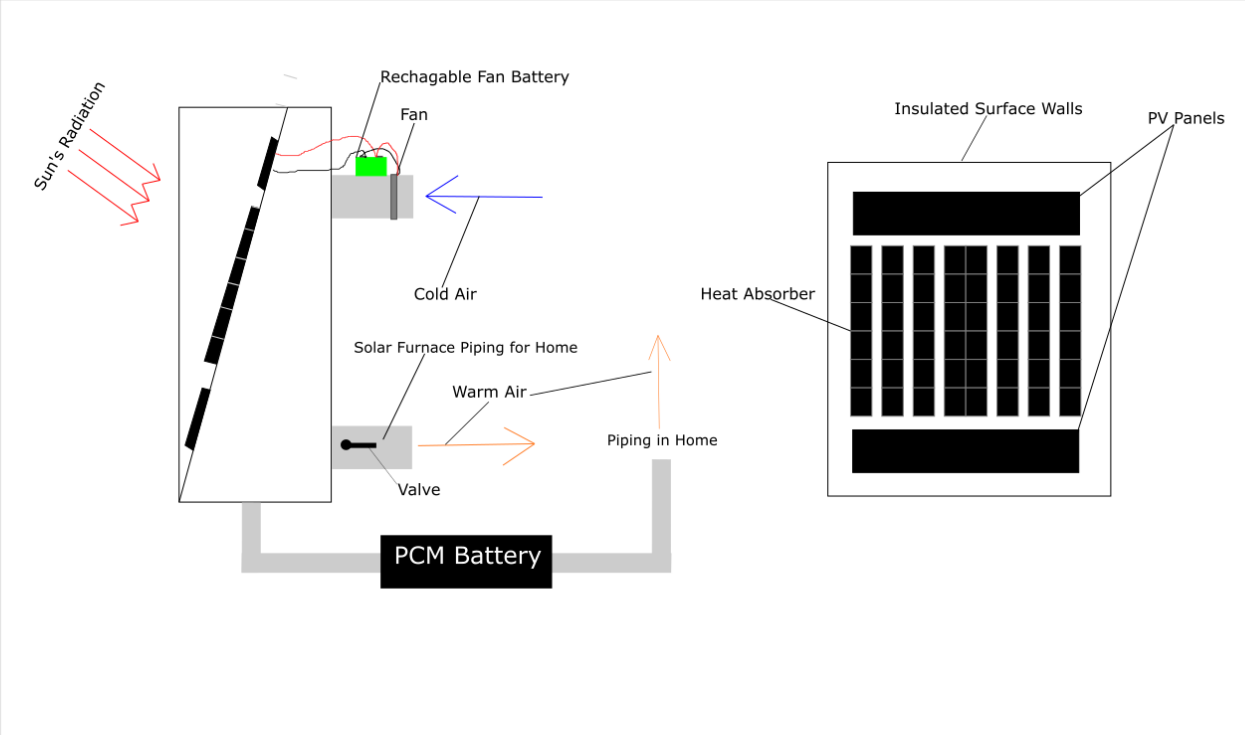


Figure 4: To the left, there is a side view of the Solar furnace PV Integration, while a front view of the design is presented to the right. The system on the left has a regular inlet and outlet but has also a pipe attached to its bottom which connects to a PCM battery for heat storage purposes.

Just as in the previous design, this concept generated has a solar furnace with a blackbody and PV panels integrated into the surface that gets radiation from the sun. A regular inlet and outlet are attached in the back of the panel for air to cycle inside the home, with the help of a fan operated with the PV energy. In addition to this, there is a second exit which leads hot air to a PCM battery for the sake of heat storage purposes. When the night comes, the user would just have to close off a valve from the exit pipe in order for the cold air to cycle through the PCM battery and collect heat that would then be used at the home.

4.2 Subsystem Concepts

In order to provide the best design regarding heating sources, the team has broken down system level concepts into smaller components or subsystems for further evaluation. This is important for technical selection due to the similarities between designs but also to make sure that the appropriate design is selected for the task of heating a home. ,

4.2.1 Subsystem #1: Insulation

In the following sections, various insulations types and their applications will be presented.

4.2.1.1 Design #1: Rolls and Loose-fills

Rolls and loose-fill insulation are used to fill walls and attics providing a thicker barrier to the outside and increasing thermal resistivity. Different materials are available such as fiberglass, plastic, cellulose and natural fibers like cotton or sheep's wool. Manufacturers are responsible for creating charts of resistance values with thickness for loose-fills since resistance does not change proportionally with thickness. These are relatively cheap and are easy enough for the homeowner to install without professional help.

4.2.1.2 Design #2: Foam

Foam can be used in several ways to insulate a home such as foam boards, liquid foam and spray foam. Foam boards can be used to line walls giving an added layer of resistance. Liquid foam can be sprayed or injected into hard to reach areas reducing air leaks. Certain foams called closed cell foams are used for hard to reach areas because it is filled with a gas that helps the foam to expand to fit an area.

4.2.1.3 Design #3: Reflective Systems

Reflective systems work by reflecting radiant heat. These are primarily installed in attics to reduce summer heat gain and lower cooling costs. Aluminum lined panels reduce radiant heat transfer from the underside of the roof to surfaces in the attic. These are most effective for warm climates and have little effect in cool climates.

4.2.2 Subsystem #2: Phase Change Materials

Phase change materials (PCMs) are materials that undergo the solid-liquid phase transformation, at a temperature within the operating range of a selected thermal application [1]. As this material changes phase from a solid to a liquid state, it absorbs energy from its surroundings while remaining at a constant temperature [1]. At the melting temperature, the atomic bonds in the PCM loosen and the materials transitions from a solid to a liquid and in this process release the energy stored from its surroundings [1]. It is due to these properties that PCMs are being considered for integration in the heating system that is being designed in this project as a method to retain heat at homes without relying directly on electric power. Among the main PCM considerations are inorganic, organic and microencapsulated PCMs.

4.2.2.1 Design Option #1: Inorganic PCMs

Inorganic PCMs have the benefits of high latent heat (heat that can be stored before temperature in PCM changes) and higher thermal conductivity [4]. These materials are not flammable and have lower cost in comparison to organic compounds, due to their high water content [4]. However, the downside to these PCMs is their corrosiveness, instability, and improper re-solidification [4]. On top of this, their properties can change due to decomposition or if the PCM is supercooled, but these two negative aspects can be avoided with nucleating agents applied to the PCMs [4].

4.2.2.2 Design Option #2: Organic PCMs

Organic PCMs made usually with paraffin, fatty acids, and sugar alcohols [6] which are more chemically stable than inorganic PCMs [4]. They are non-corrosive, have a high latent heat per unit weight, are recyclable, melt congruently, and have minimum susceptibility to supercooling [4]. Organic PCMs are suitable for heat absorption in building material [4]. Among their downsides are low thermal conductivity, high changes in volume during phase change, inflammability and they may generate harmful fumes on combustion [4]. Other problems that can arise from their use are reaction with the products of hydration in concrete, thermal oxidative aging, odor and an appreciable volume change [4].

4.2.2.3 Design option #3: Encapsulated PCMs

The encapsulation of PCM material is done to increase the conductivity of PCMs in general. This can be a microencapsulation, where PCM of any state is stored within tiny particles with diameters smaller than 1 mm and larger than 1μm [4, 22]. The microencapsulated PCM particles can then be incorporated in any matrix that is compatible with the encapsulating film, and this makes it so that low thermal conductivity is not a problem due to the ratio of surface area to volume being very high [4]. The main downside to microencapsulation is that capsules do not stand very high temperatures [2].

The second type of containment is macro-encapsulation, which sets the PCMs in packaging in the forms of tubes, pouches, spheres, panels, etc [4]. These containers can serve directly as heat exchangers, but previous experiments with large volume containment have failed in the past due to poor conductivity of the PCM [4]. This occurred when the heat in the liquid phase was to be recovered since the PCM material would solidify around the edges of its container, preventing heat transfer [4].

Based on these 3 types of design options, organic PCMs encapsulated in compact storage modules might be the best option to work with for efficient heat conductivity in a system; however, per clients request, the PCM will have to be set undefined until a model of this material is created. Once the model is set, the parameters are the only setup that will be needed.

4.2.3 Subsystem #3: Solar Furnace Circulation Systems

One drawback to using a solar furnace to heat a home is the variability of the heat in the system at a given time. Additionally, heat from solar thermal energy may be unlikely to make its way into the air of the house when solar energy sources are along the exterior walls. To harness the heat obtained from a solar furnace, it is necessary to employ a circulation system that is able to use the thermal energy from the solar furnace to heat the structure. A circulation system can also be used to vary the amount of air being heated and keep the temperatures within the home stable.

4.2.3.1 Design #1: Turbine Fan

An electrically powered fan is a simple and effective means of circulation for the design, as it provides a maximum amount of air movement while using a minimal amount of space and energy. Combined with an integrated duct system, it can provide the necessary circulation to cycle air from the solar furnace to the air in the home. It also is easy to control electrically through a simple module or computer system, making it easy to control temperatures within the home.

4.2.3.2 Design #2: Proportional–integral–derivative controller for potential regulation *Circulation*

Circulation can also be varied to regulate temperatures in the home. A proportional integral derivative (PID) controller located within the home can read temperatures within the home and determine when to run a circulation system from a heat source. This controller, combined with a fan or another circulation device, could serve as a means to keep home temperatures relatively stable. These controllers are commonly found in home thermostats.

4.2.3.3 Design #3: In-Wall Radiant Heating

As described above, this circulation system involved in-wall panels which radiate heat into the home. The method is very efficient, but installation costs would be high. Depending on the size of the home, it may be worthwhile to integrate this system with the solar furnace. This subsystem would drive up costs but also may be the most effective heat dispersal method.

4.3 Technical Selection Criteria

As can be seen, the PV/PCM Solar Furnace was selected as the main design for the Capstone due to its manufacture being affordable, plus the design being environmentally friendly and feasible to construct. Additionally, the system makes use of air inside the home instead of bringing air from outside which could induce nocive pollutants. Hence this can reduce the dangerous pollutants the users are exposed to such as, their neighbors burning coal for example.

4.4 Rationale for Design Selection

The team selected the solar furnace integrated with PV/PCM mainly based on the Design Matrix and the Pugh Chart which can be seen in Table 1 in Appendix C.

4.5 Back of the Envelope Calculations

For the back of the envelope calculations, the team decided to first calculate the maximum temperature a black body in a solar furnace can achieve by using Wien's Equation (Equation 1).

$$T = \frac{b}{\lambda_{max}} \quad (1)$$

Where the peak emission wavelength of the sun is approximately 500 nm [23], and b is Wien's displacement constant (b = 2.8977685 x 10^{-3} m/K)[24]. Based on these values, the estimated maximum temperature turned out to be 5795.537K at a focal point [24].

Since the temperature measurement calculated was for an ideal solar furnace, the team decided to approach the problem considering actual experiments where thermocouples were used to measure the temperatures solar furnaces can achieve on sunny days and in Winter times [25],[26],[27]. Based on this data collection it was found out that the average solar furnace temperature ranges anywhere between 155-180 degrees Fahrenheit on a sunny day.

Additionally, for PCM considerations, the heat storage term of the heat transfer equation using cartesian coordinates was considered. The heat storage term over time is the following:

$$\frac{\rho c_p}{k} \frac{\delta T}{\delta t} \quad (2)$$

(heat storage term)

In this term, rho represents the density of the PCM material, cp is the specific heat at constant pressure and k is the conductivity coefficient. Based on this term it was determined that the PCM that is needed is one with a high thermal conductivity to store more heat. The evaluation of the PCM to be selected will be conducted further on once software modeling takes place.

In addition to the previous equations, heat loss due to conduction through a cinder block wall of approximately 1.4 KW was calculated with Fourier’s Law in equation 3 for a 1-D heat rate approximation of a non-insulated wall. These calculation are seen in Appendix B in Figure 7.

$$q = -KA\frac{dT}{dx} \quad (3)$$

Since resistance (R) values vary across different types of insulation and materials due to their varying thermal coefficient (K) values and their cross-sectional areas(A) in materials the following equations were considered:

$$R_i = \frac{L}{KA} \quad (4)$$

$$R_{total} = (\Sigma R) \quad (5)$$

If a standard width (L) is set, the R-value would only increase if K and A are small relative to the width. Hence this equation will be useful in determining the type of insulation that will be needed for software modeling of a cinder block home.

To gain an estimate of resistance values, the team considered the home that is to be modeled per our client. The model is a cube of 500 square feet in base and 8 feet of height to the roof. It has three 4x4 foot windows and a 3x7-foot door. At this time, the team can only create a simplified thermal resistance network for the structure to determine an estimate of the total resistance at the home per m^2. By conducting some research, that a standard 300 mm width fiberglass insulation batt has an R-value per m^2 of 7.2 K*m^2/W. An average R-Value per m^2 for an 8-inch cinder block wall is 0.387 K*m^2/W, for a single pane window, 0.158 K*m^2/W, for a solid wood door, 0.382 K*m^2/W, and for a composite-shingle roof, 0.077 K*m^2/W. By applying equations 4 and 5 and running the calculations, the total thermal resistance of the structure without insulation is 0.001237 K*m^2/W, and with insulation is 0.02063 K*m^2/W. This difference is substantial enough that it strongly reduces the amount of heat required to keep the home at a comfortable temperature, making it easier to control the temperature inside the home and more energy efficient [28][29].

Unfortunately, since this method is very basic and does not convey the real world values needed to determine the proper insulation inside a home and potentially PCM integrations, software modeling will be performed to conduct accurate readings of heat rate passing through walls in this cinder block home assuming there is a source of heat generation inside the home.

Another equation that will be considered by the team to determine the amount of Phase Change Material (PCM) to be used in a thermal PCM battery is the following:

$$E = mL \quad (6)$$

Equation 6 where L is the specific latent heat of the PCM and m is its mass will be used to determine the mass of PCM that will be needed to maintain a home warmed up as air circulates and warms up with the latent heat(E) being released by the PCM as it changes phase from liquid to solid.

Future Goals for Capstone Project

Following this report, the main goals of the project will be software modeling and choosing the most efficient phase change material. The team has looked into Sketchup and E-Quest as potential modeling tools. Sketchup can be integrated with an analysis tool called Energy Plus. The main advantage of this software is that it can model different types of PCMs. E-Quest is commonly used for construction management and modeling insulation, but this software needs programming to implement PCMs. The team will likely choose Sketchup as the main modeling software for insulation and Equest for PCM modeling. Homes will be initially modeled with a fixed heating system and varying insulation and PCMs to identify the most efficient combination. There are many types of PCMs with differing costs and melting temperatures. The team has found that organic PCMs with melting temperatures in the range of 68-82°C will be the most effective for this project. After software modeling is completed, the team will begin a cost analysis of the design and potentially begin building prototypes.

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6 Appendix A: House of Quality

System QFD

Project:	**Red Feather Capstone Project**
Date:	3/2/19

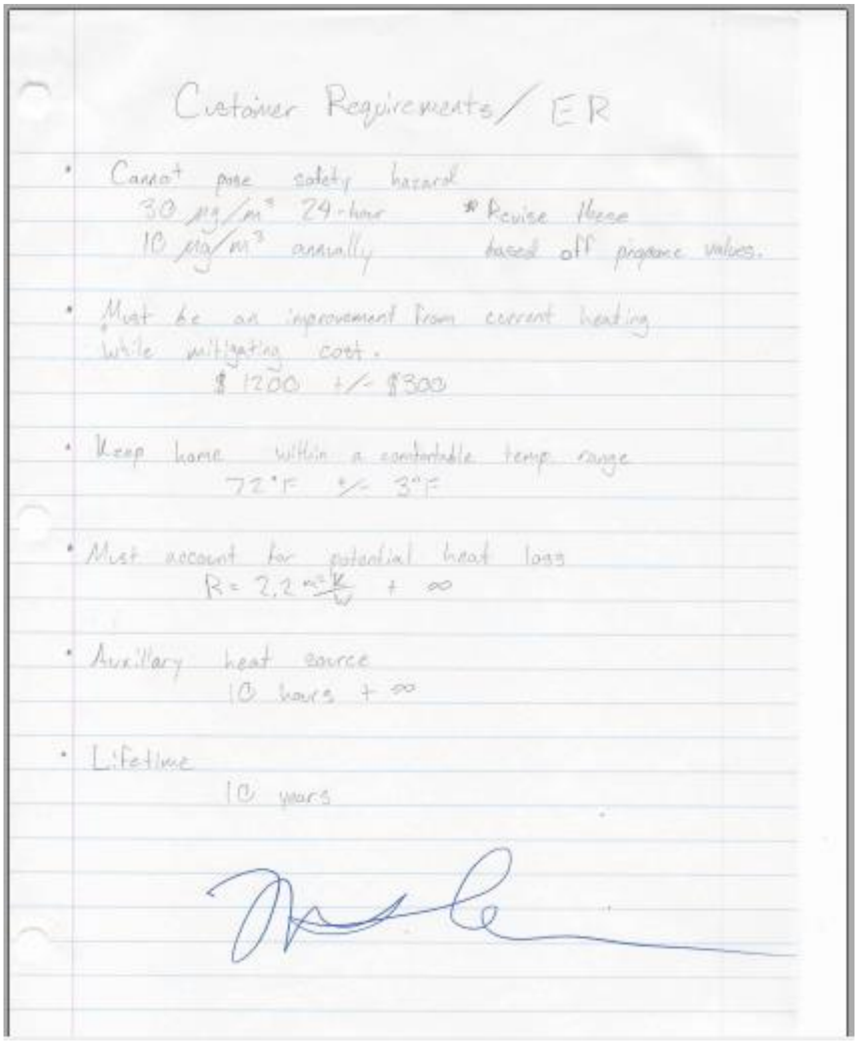
	Pollutants Produced (µg/m^3)	Cost of Materials ($)	Thermal Efficiency (%)	Temperature Maintained (F)	Thermal Resistance Value (R)	Backup System (hrs)	Lifespan
Pollutants Produced (µg/m^3)							
Cost of Materials ($)	-						
Thermal Efficiency (%)		-					
Temperature Maintained (F)		-	+				
Thermal Resistance Value (R)		-	+	+			
Backup System (hrs)		-		+			
Lifespan		-					

		Technical Requirements							**Benchmark Rating**				
Customer Needs	**Customer Weights**	Pollutants Produced (µg/m^3)	Cost of Materials ($)	Thermal Efficiency (%)	Temperature Maintained (F)	Thermal Resistance Value (R)	Backup System (hrs)	Lifespan	1 *Poor*	2	3 *Acceptable*	4	5 *Excellent*
	100%	↓	↓	↑	↑	↑	↑	↑					
Cannot pose unacceptable health or safety risks	25%	9	3	1	0	0	1	1	D			C	A,B
Must be an improvement from current heating solution	30%	1	9	3	0	1	3	0	D		C	A	A,B
Keeps home at a comfortable temperature in Winter	15%	0	3	9	9	9	1	3		A	B,C		D
Must account for heat loss from system	20%	0	1	9	3	9	0	0		A	B,C		D
System must be reliable with temperature fluctuations	10%	0	1	3	9	3	9	9		A	B,C		D
Target ER Values		10 µg/m3 - annually 30 µg/m3 - 24hr	$1,200	70%	72 F	R = 2.2 m^2K/W	10 hrs	10 years					
Tolerence of ERs		+/- 5 µg/m3	+/- $300	+/- 10%	+/- 3 F	+ 0.3 m^2 K/W	+/- 2 hrs	+/- 1 year					
Testing Procedure		Air Quality meter	BOM	Themodynamics	Thermometer	Analytical	TBD	Thermal Cycles					
Absolute Technical Importance		3.55	4.2	4.6	2.85	3.75	2.2	1.6					
Relative Technical Importance		4	2	1	5	3	6	7					

Legend
A Solar Air Heater
B Solar Furnace
C Radiant Heating
D Common Furnace

Figure 5: House of quality

6.1 Appendix B: Written Notes



Customer Requirements / ER

- Cannot pose safety hazard
  30 $\mu g/m^3$ 24-hour *Revise these
  10 $\mu g/m^3$ annually based off propane values.
- Must be an improvement from current heating while mitigating cost.
  \$1200 +/- \$300
- Keep home within a comfortable temp range
  72°F +/- 3°F
- Must account for potential heat loss
  $R = 2.2 \frac{m^2 K}{W} + \infty$
- Auxillary heat source
  10 hours + ∞
- Lifetime
  10 years

Figure 6: Customer & Engineering Requirements signed off by Mark Hall

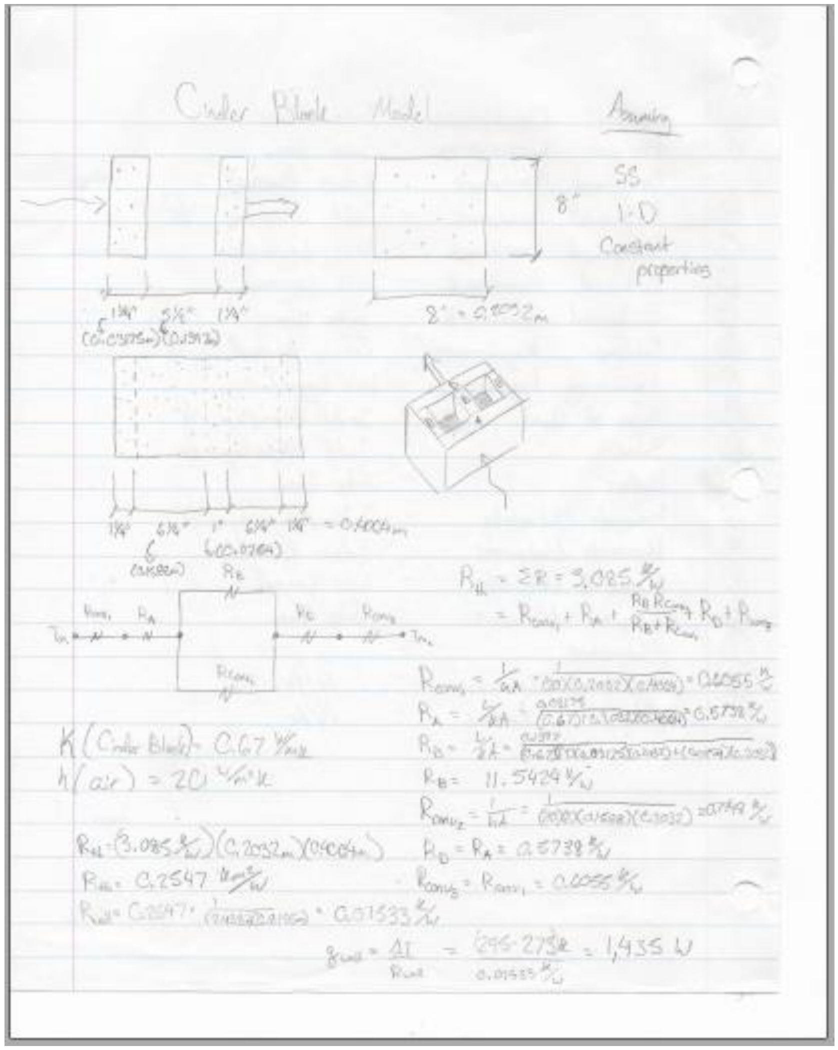


Figure 7: Cinder Block Wall Heat Transfer Approximation

6.2 Appendix C: Pugh Chart and Decision Matrix

Table 1: Pugh Chart

	System	Common Furnace	Solar Furnace	PCM/PV Furnace
Criteria	Weight of Importance	Met(1) , Neutral(0), Unmet(-1)	Met(1) , Neutral(0), Unmet(-1)	Met(1) , Neutral(0), Unmet(-1)
Safe	3	0	0	0
Affordability	4	-1	1	1
Grid-Independent	2	-1	-1	1
Can be Temperature Regulated	1	1	1	1
Efficiency	5	0	0	0
Sum of positives	-	1	5	7
Sum of Negatives	-	6	2	0
Sum of Neutrals	-	0	0	0
Total	-	-5	3	7

Table 2: Decision Matrix

Concept Variants (Software Models)						
Criterion	**Weight**	**Coal Stove**	**Coal Stove w/ Insulation**	**Coal Stove w/ Insulation and PCM**	**Solar Furnace w/ Insulation**	**Solar Furnace w/ Insulation and PCM**
Safe	**20**	**40/8**	**30/6**	**30/6**	**100/20**	**100/20**
Affordable	**25**	**100/25**	**90/22.5**	**70/17.5**	**80/20**	**70/17.5**
Grid-Independent	**20**	**100/20**	**100/20**	**100/20**	**100/20**	**100/20**
Easy to Regulate Temperature	**10**	**70/7**	**80/8**	**80/8**	**60/6**	**80/8**
Reduces Pollution / Efficient	**25**	**40/10**	**50/12.5**	**50/12.5**	**90/22.5**	**100/25**
Total Weighted Score		**70**	**69**	**64**	**88.5**	**90.5**
Relative Rank		**3**	**4**	**5**	**2**	**1**