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Project Omoverhi : a thermal storage solution

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Project Omoverhi

A THERMAL STORAGE SOLUTION

By

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I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

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ENTITILED

Project Omoverhi: A Thermal Storage Solution

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

BACHELOR OF SCIENCE IN MECHANICAL ENGINEERING

Mechanical Advisor

Mechanical Chair

Abstract

One principal energy source that is underutilized in the world today is solar energy. While the United States has tried to make a push for reusable and "green" energy sources, these sources are frequently overlooked in developing nations. While the set up costs of solar energy may be expensive due to installation and the high cost of certain parts, the savings over time is well worth the initial cost. In many developing nations large areas of the country are off of the power grid or have inconsistent power. One way to help people living in these areas is by introducing the use of solar power. Unfortunately one major drawback to using solar energy is the difficulty of storing it. While photovoltaic panels can store energy in batteries, they are extremely expensive and inefficient. Using solar collectors that are either manufactured or handmade rather than PV panels can be more than four times as efficient and cost much less. The one negative issue with solar collectors is that they will only work when the sun is out. The 2011 to 2012 Project Omoverhi team's goal was to utilize this energy from solar collectors and store it in a thermal storage container. The stored energy could then be used when direct sunlight was not available. Using paraffin wax as a phase change material because of its melting temperature and excellent storage properties, Project Omoverhi was able to achieve this goal and create an affordable, easy to use system that can be attached to a solar collector. The system was tested to determine if it would enable an incubator to keep a steady temperature that would meet the requirements of a premature infant or successfully hatch chicken eggs. Data collected showed that Project Omoverhi's design is an effective way to store heat and energy from a solar collector so that it can be utilized as needed.

Table of Contents

List of Figures

List of Tables

Acknowledgments

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1. Introduction

Project Omoverhi was started as a way to support people in developing nations who do not live on a consistent power grid or live off of the power grid completely. The goal of the project was to use solar power to be able to provide energy to these communities and their people in times when electricity is not an option. There are multiple applications that Project Omoverhi could be used for, many of them related to farming and livestock. This is very applicable because farming is common in areas in developing countries where there is no power. Over the last two years the project mainly focused its efforts on neonatal incubators and chicken brooders. Developing a system that could use solar energy to power a small incubator that could either hold a newborn or hatch chicken eggs, could positively impact the lives of many people.

In the 2010-2011 school year, the original Project Omoverhi team was formed as a solution for neonatal incubators that do not need electricity to be powered. The intention of the system was for it to be used in developing countries with inconsistent power or areas completely off of the power grid. This system had an incubator, a solar collector to heat the system, a solar thermal storage tank that was supposed to store the heat for use when there was no sun, and a small PV panel to power the control system and pumps. Incubators need heat 24 hours a day, which means that the solar power must be stored in order to provide that energy when the sun goes down and especially on days when the sun is hidden behind clouds. Last year's project had enormous potential, but a major flaw. The capacity of the thermal storage tank was not sufficient for most applications. Therefore the main focus for this year's project was the thermal storage container.

All solar powered products need sunlight to produce the necessary power to run them. When it is cloudy, or there is no sun, these products are inefficient or simply don't work at all. Solar panels and solar thermal collectors, which are the two main tools for collecting solar energy, do not gather energy during times of no sun and therefore the products they support will stop working once the energy they had originally gathered runs out. This issue has been somewhat resolved for solar photovoltaic panels by installing batteries that have the ability to store the energy and then can produce it later when it is needed. The drawback with solar thermal collectors is that they heat water, air, oil or other flowing materials, and that heated material cannot simply be put into a battery like the electricity generated by a solar panel can be.

This leads to the question: why use solar thermal collectors at all if there is a solution that works for solar panels? The main reasons are that photovoltaic panels are not particularly efficient and they are very expensive. The technology incorporated into solar panels is extremely complex and therefore only companies that have mastered the technique are able to produce them successfully. Even the companies that have succeeded in producing workable solar panels still have only managed to develop panels that capture about 20% of the sunlight that hits them. The other major issue with solar panels is the initial cost. Most solar panels cost an average of $7.00 to $8.00 per Watt. This may not sound expensive, but the average home that uses solar energy in the United States installs a 5kW system upon the initial install. That comes out to $35,000-$40,000 just for the initial install. Then there are cleaning fees, maintenance fees and general upkeep of the solar panels.

The high cost for solar panels it begs the question: what options are there for cheaper systems? This is where solar collectors can come in. While top of the line solar collectors run in the thousands of dollars, just like solar panels, cheap solar collectors can be built with basic materials and still work well. Commercial solar collectors can utilize over 80% of the energy possible for the square footage it is placed in. This is over four times that of the photovoltaic panels. However, the energy produced by solar collectors is used to heat a flowing material, not create electricity. Since systems that are run off of the energy from the sun need to run when there is no sun available, storing this energy is very important. That is why storing the heated water without losing too much of the heat to its surroundings is a major issue with solar thermal collectors. Essentially a thermal storage tank of some sort is needed that is able to keep the water hot even when the sun is not shining.

The way that this issue was approached by last year's Omoverhi team was to place two copper coils in a 55 gallon drum of water. The water flowing from the solar collector would go through one coil, and give heat to the drum of water. Then it would exit the drum and go back to the collector to gain more energy. Slowly over time the water in the tank would raise in temperature. While this was happening, the second coil had water flowing to and from the heat load. This would pick up heat from the water drum and then deliver it to the heat load where it would lose the majority of its heat, then returning to the tank to replace the lost energy. The problem was that the water in the tank took a very long time to heat up because the liquid form of the water would move about in the tank and the water contacting the coils never got any hotter than the water on the edge of the tank. Therefore the water was losing its heat to the surroundings very quickly and was not able to hold the necessary temperature needed for a long enough time to operate its applications safely. The necessary amount of time needed is dependent on the system and where it is being used. Variables include the consistency of the sun in the areas and what application the storage tanks are being used for. (In 2011 the Project Omoverhi team never actually tested the tank with the solar thermal collector. They used a hot water heater for all of their tests and never tested their incubator with a closed loop excluding the hot water heater. Therefore the amount of time the thermal storage tank could last was based on theoretical data.)

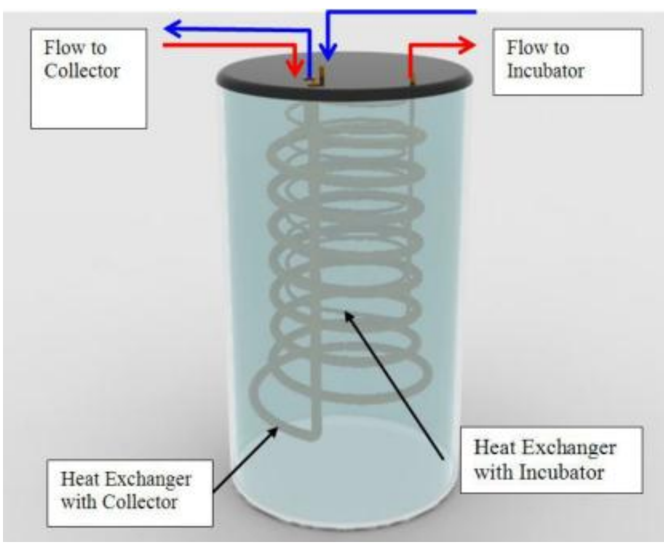


Figure 1: Schematic of thermal storage tank used by 2011 Project Omoverhi team.

The focus for this year's project was to explore phase change materials that would increase the efficacy and efficiency of the thermal storage tank. The team's research showed that even though phase change materials are more expensive than water, they are far more efficient. They add a lot more potential energy without having to increase the temperature a drastic amount. This is due to latent heat, the amount of energy that can be stored during the change from a solid phase to a liquid phase. Also, since each phase change material has a specific melting temperature a particular material could be chosen that fit the perfect melting temperature for the system at hand. By using phase change materials there was no need to heat the water in the solar collector to an extremely high temperature to store more energy and heat, the phase change material simply needed to be heated to its melting temperature for long enough for it to turn from a solid into a liquid. Then if extra heat is available after it is melted it can store more energy, or sensible heat, until the sun goes down and there is no more energy to be stored. When the sun is not available the heat can be given back to the system. This occurs when the water begins to lose energy to the heat load, application, and it is not being restored by the thermal collector. The system can then give back its stored energy to the water; first as sensible heat and then, once it reaches its melting point and begins to solidify, as latent heat.

While using phase change materials to store energy is not a new idea it is a method that has usually been used in expensive applications and therefore not practical for developing countries. Since Project Omoverhi is intended for developing countries the design team decided to apply the technology of phase changing materials and their excellent thermal storage abilities to create a design that could be developed easily and for a fraction of the cost by using locally available materials and a design simple enough that anyone would be able to build it by following a few simple instructions.

1.1. Project Objective

The design of the thermal storage system for the Project Omoverhi incubator was created based on the needs of people in the underserved developing world. The product was designed with cost and effectiveness as the two main focal points, and was compared to systems that have already been designed.

1.2. Statement of Goals

The goal of this project was to design a thermal storage unit that can provide heat at 99 degrees Fahrenheit for three days to a chicken brooder or neonatal incubator. It needs to be cost effective for developing countries, need only basic instructions for assembly and be easy to maintain.

The thermal storage unit receives its energy from heated water that runs through the system. This water is heated by a solar collector that is powered by the sun. The heated water melts the phase change material and in the process stores the energy. When no sun is available the solar collector is cut off from the sun and the phase change material slowly solidifies giving the energy back to the water and keeping it at the desired temperature. The design was created to be extremely cheap and simple. It uses materials that are readily available in developing countries which helps drive the cost down even further. The storage tank can be used for a variety of applications, but the focuses for this project its use with neonatal incubators and chicken brooders.

1.3. Review of Literature

Solar energy has been gaining popularity at a rapid rate in the United States and other developed nations. It has become so useful, in fact, that homes can be designed and built to run off of solar energy alone. One excellent example of this is the solar decathlon competition, held every other year for colleges and universities, to help prove this point. Santa Clara University has had a lot of success in this competition and it continues to spark excitement in its undergraduates every year. While these houses and others across the world have the ability to run off of the sun they need to use a variety of sun gathering techniques to be the most successful. While PV panels have a lot of advantages for gathering energy and storing it for a later use, they are extremely expensive and inefficient. Solar collectors on the other hand are much more effective at gathering energy per square foot and can gather over 80% of the sun’s energy. The only issue with this energy is that while photovoltaic panels can store the energy they gather in batteries, solar collectors heat water which must be stored in a different way. Therefore a thermal storage unit is needed in order to keep this water hot.

There are many thermal storage systems available today. Most of the ones available in the United States use complex and expensive parts. Tube in tube heat exchanges and coiled heat exchangers are a couple of examples of thermal storage systems that can be found in residential settings today. The other major issue with heat exchangers in America is that they are primarily designed for use in the industrial setting. This makes them difficult to translate into smaller versions because heat loss to the surroundings is a major concern. Compared to a large tank, a small tank has a lot more surface area by volume, resulting in significantly increased heat loss.

The reason why all of these systems are completely out of the question for a thermal storage tank in a third world country is cost. While it would be great to implement a perfect thermal storage system that could keep water hot for long periods of time, it is completely unrealistic when compared to the price tag. Many of the residential systems used in America today can run into the thousands of dollars. Project Omoverhi was hoping to get this price down to one or two hundred dollars at the most. The group discussed the viability of implementing the project with people who work in Haiti, one of the most applicable areas in the world for the system. The main concern they expressed was the importance of cost containment. The conclusion reached from the interviews and research was that efficiency can be sacrificed if it will decrease the cost of the system.

Another issue with most thermal storage tanks is that they are built as one size for one application. They are created individually based on a particular customer's needs or a common application's needs. This is unacceptable for Project Omoverhi because this product needs to be easily scalable to meet the specific needs of a particular community, hospital, or project and these can be quite variable. . Based on the amount of time the thermal storage system needs to store water and the heat load of the application it is heating, Project Omoverhi wanted a simple way to know exactly how many smaller thermal storage tanks would be needed to power that system and make a safe and effective storage tank.

2. Customer Needs

2.1. Information Sources

Information was collected throughout the fall of 2011 to determine customer needs through interviews and phone calls with various individuals and organizations. The primary individual that aided in the establishment of the group's customer needs was Susan Kinne, founder and current instructor of the solar culture course at the University of Nicaragua. Susan is the current director of PFAE, the university affiliated portion of Grupo Fenix, an organization whose primary goal is to research, develop, and apply renewable energy technologies in Nicaragua.

Ms. Kinne provided insight into what aspects of the design would be most important for the design team to focus on and why. By establishing the most crucial aspects of a solar thermal storage system, the design team was able to determine the driving factors associated with the real world implementation of such a product in developing countries.

Ms. Kinne conveyed the importance of the product's ability to be easily adopted into society. In order for the product to be successful, it would need to be simple and scalable to be used for a wide range of applications. One of the other important aspects of the design that she discussed was the durability of the product. The product would most likely be installed outdoors and subjected to the annual flash floods and hurricanes in Nicaragua. The thermal storage system would have to be able to withstand harsh weather conditions and remain functional after possibly being mishandled or misused. Many devices that are introduced into developing countries are often misused, broken, and forgotten about because the money and resources required to fix them are not available.

Through discussions with Professor Kinne, it was determined that the product would most likely be used in a community setting as opposed to an individual setting. Poverty would prevent most families from being able to make an investment in such a product because of what little money they have already. The product would ideally be purchased by, or donated to, a community so that more individuals could benefit from it and the cost per individual would be low enough to make it profitable for its operator.

In meeting with Ms. Kinne, a list of the primary concerns pertaining to the design and implementation of Project Omoverhi's design was generated in order of importance:

1. Cost
2. Durability /Lifetime
3. Ease of Use
4. Performance
5. Use of Local Materials

Ms. Kinne stressed the importance of two aspects over any others; durability and cost. While the efficiency and performance of the product itself is important, if it isn't simple, durable, and most importantly inexpensive, it would be almost impossible to actually implement in communities of developing countries. Money for such a product would most likely come from external funding from international organizations such as World Bank.

Ms. Kinne expressed concerns about the use of valuable metals such as copper for the heat exchangers in the team's design. In developing countries, materials such as copper are valuable on their own and unless the product is more profitable than the value of the materials itself, there is the possibility of it being scrapped or stolen for raw material profit. While using less conductive and thicker piping such as galvanized steel is an option, it actually would not be practical in such an application. Due to the thick walls and low thermal conductivity of galvanized piping compared to that of copper piping, the heat transfer rate through the walls of the heat exchanger would be roughly 3.5% that of using copper pipe. This would mean that almost 30 times as many units would be required in order to transfer the same amount of heat between the PCM and the flow of water. Because cost is the driving factor in the design of the system, it was decided that rather than using a different type of metal pipe for the heat exchanger, it would instead need to be protected somehow. This problem was addressed further in discussions with members of the original Omoverhi Team of 2011.

The design team met frequently with members of the previous Omoverhi team throughout the design process to brainstorm and troubleshoot challenges. The solution that resulted from these meetings solved the immediate possibility of theft while also increasing the efficiency of the system for no additional charge. It was suggested to the design team that if the thermal storage system were to be buried underground, it would not only be safer from theft and harsh weather conditions, but it would also allow the surrounding soil to act as an insulator and eliminate some of the cost associated with insulating the PCM columns. Further investigation into this possibility showed that after an initial period of time in which the surrounding soil dried out, burying the thermal storage system would, indeed, prove to be beneficial and help to insulate the system while protecting it from harsh weather conditions and tampering.

2.2. Market Analysis

There is a large market for a simple, cheap, and efficient thermal energy storage system in developing countries. While individuals may not have the ability to purchase units themselves, communities could make use of the product for a variety of applications to improve the overall quality of their lives. Farmers would be the primary beneficiary of the thermal storage systems initially for a number of reasons. Using the thermal storage system for chicken brooding applications would allow chicken production to multiply by up to 30 times without the need to buy more chickens and build a bigger coop. Profit would rise significantly because while the cost to feed and house the existing hens would remain constant, production would dramatically increase. The increase in profit and production would allow local farmers to expand and grow at a rapid rate, boosting local economies and protein production. The thermal energy storage systems could be utilized in other ways on a farm as well; such as to aid in dairy pasteurization or to keep the buildings warm at night. The market for a simple thermal energy storage product is large because of its vast range of applications.

On more of a grid connected community based level, efficient thermal storage systems could be implemented in any public electrically powered thermal system to make it cheaper and more efficient. The idea of hybridizing existing grid powered thermal systems by also drawing heat from a secondary solar thermal storage system would bring down operating costs. By hybridizing preexisting on-grid thermal systems, the systems also attain an emergency backup power source that can be used in the event of power loss, a frequent issue in developing countries.

2.3. User Scenario

The primary application that the thermal storage units were designed for is use as solar thermal heat storage systems for relatively small scale operations such as chicken brooding. As previously mentioned, by removing chicken eggs from nests and incubating them, almost 30 times the egg production is possible. Not only does this create a potential for major profit increases for local farmers, but it also allows for the establishment of a substantial protein source for developing countries in general. Ideally, the thermal storage system would be buried under ground outside in close proximity to the chicken hut. A solar trough and photovoltaic panel would be installed on the roof of the chicken hut. The solar trough would heat up water during the day and store heat in the thermal storage units before continuing on to flow under and heat up the chicken brooder. The water would be pumped using and electric pump run by the photovoltaic panel. An expansion tank would allow for the volumetric changes in the water and the two valve configurations used to change the flow to alternate the heat source could be changed electronically or manually by the operator according to weather conditions. By burying the thermal storage units, they can be sufficiently insulated without taking up any room above ground. Burying the thermal storage units also decreases the chances of theft or vandalism.

2.3.1. User Scenario Sketch

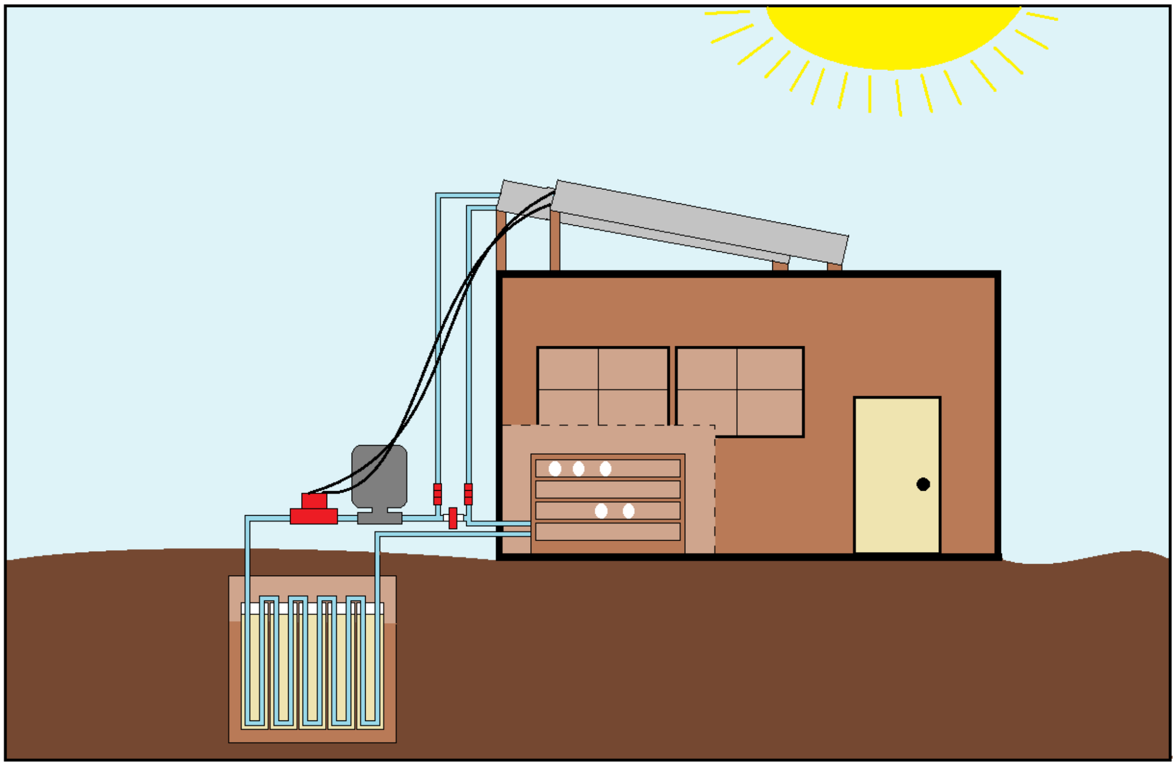


Figure 2: Sketch of the ideal user scenario of the thermal storage system

This user scenario can be seen in the sketch above. The two panels are shown on the roof; the solar thermal collector is connected to the piping of the system shown with blue tubes, while the photovoltaic panel is connected to the power supply shown with the black cables attached to the pump. The thermal storage tanks are shown stored underground in a box like unit to keep them close together and allow access if the wax needs to be changed or other maintenance needs to be done. The flow of the water can be seen going into a chicken incubator located on the side of the house and then returning back to the solar thermal collector. In this scenario the operation would most likely be next to a farm house or an off-grid house whose occupants wanted to create a small chicken business.

3. System Design

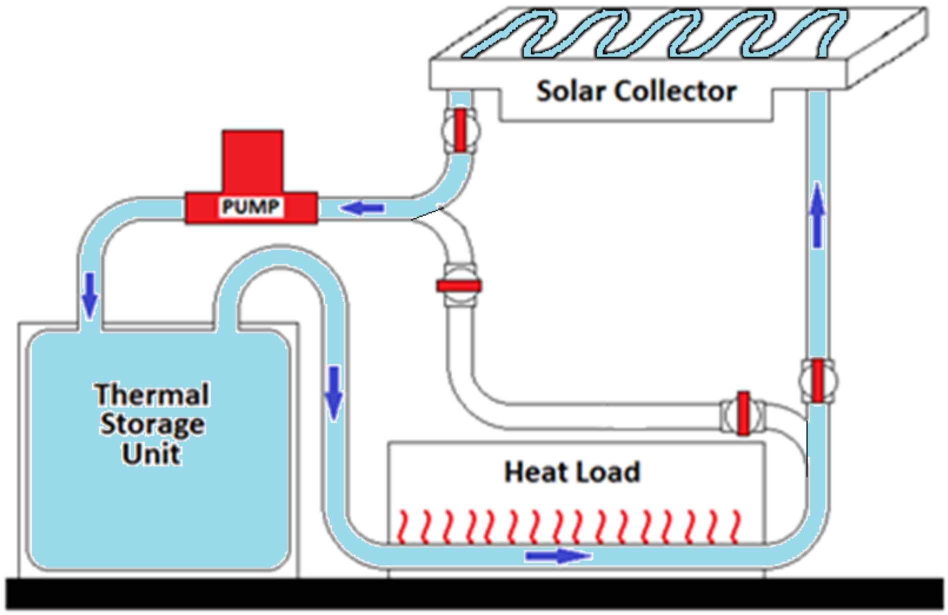


Figure 3: The ideal design of the system running during the day when the sun is shining

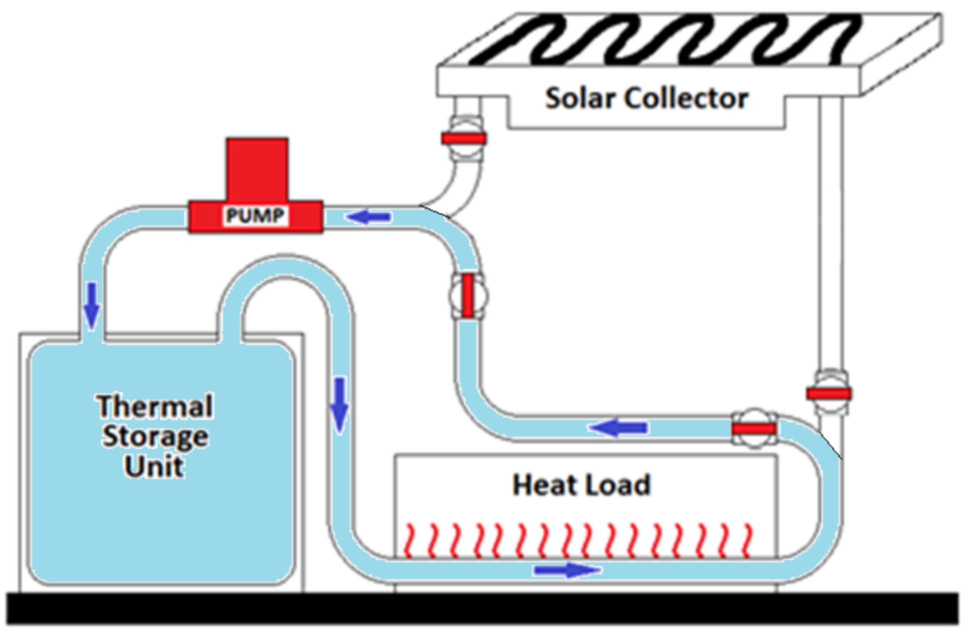


Figure 4: The ideal design of the system running at night or during the day when it is cloudy or raining

The Project Omoverhi thermal storage unit will use solar energy to heat water as it passes through a solar collector. A small photovoltaic panel will power a pump and the control systems in the heat load. When the sun is out the water will travel from the solar collector to the thermal storage unit. Here the water will release some of its heat to the thermal storage tank to be used later. Then the water will proceed under the neonatal incubator or the chicken brooder where, through forced convection, it will keep the incubator at a constant temperature. Once the water has left the incubator it will return to the solar collector to regain the heat it has lost in the system.

When the sun is not out the ball valves attached to the system are changed, either manually or automatically depending on the application, so that the solar collector is cut off from the system. Then the water, pumped by the same single pump, flows into the thermal storage unit. The thermal storage tank then gives back the stored heat to the water flowing through the tank. When the sun returns the system is switched back and the process begins again.

3.1. Mechanical Design

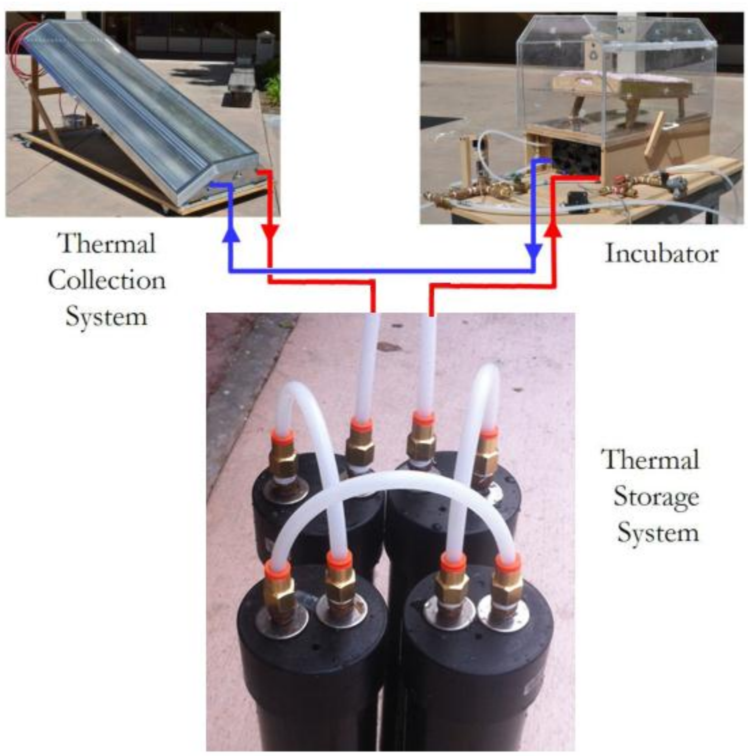


Figure 5: Mechanical design of the system showing the three major components

The mechanical design consists of the solar thermal collector, the thermal storage system (which was the main focus) and the heat load, which is dependent on the application. The thermal collector uses mirrors to focus the sun's energy onto two pipes that are running through it. As the water flows through the thermal collector it gathers energy and can increase in temperature by up to 5 degrees Celsius with as little as one pass, depending on weather conditions. Once the water has left the thermal collector it enters the thermal storage unit, which is to the thermal collector what a battery is to a photovoltaic panel. By storing the energy it allows the system to be able to run both when the sun is out and on cloudy days or at night. The third part of the system is the heat load. The water runs from the thermal storage tank to the incubator or chicken brooder. Here it splits into two flows of copper piping. Two fans, also powered by the small photovoltaic panel and battery, heat the system with forced convection off of the copper piping. After running under the heat load the water flows back either into the solar collector or to the thermal storage unit depending on whether the sun is out or not.

3.2. Thermal Storage System

The thermal storage system consists of cylindrical pillars that are made out of four inch ABS piping. The columns are approximately 4 feet long with one end closed. Inside the ABS columns are two 4 foot vertical pipes which are half an inch in diameter and made of copper. These two pipes are connected at one end by either bending an 8 foot piece of copper at the middle or taking two four foot sections and connecting them with a nipple at one end. This copper piping is placed inside the ABS pipe and then the two ends at the top are exposed through holes in a cap piece. The column with the copper piping in place is filled with melted paraffin wax until it is full and then the cap can be attached.

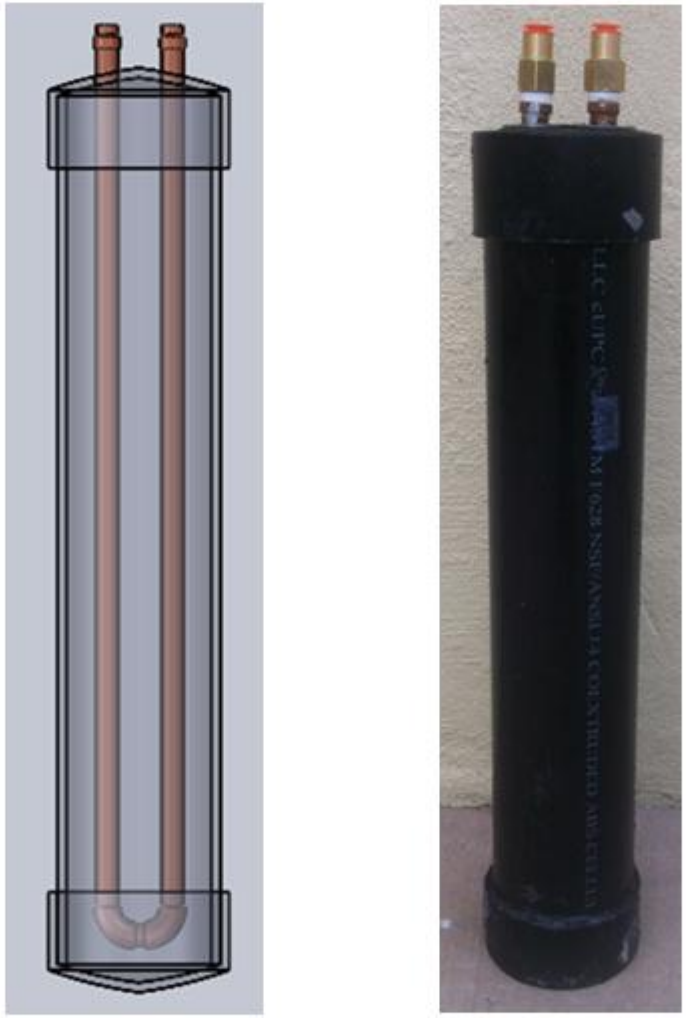


Figure 6: A SolidWorks drawing and photo of a constructed column of the thermal storage tank

This is considered one column of the system. The number of columns needed for a particular system varies based on the amount of heat load necessary and the length of time that it's needed for. The columns can be attached to one another with hoses or tubing and common hose clamps. While the prototype columns used ABS, copper piping and consistent paraffin wax, the system was designed to be able to be built with any type of outer tubing, any available metal piping and simple candle wax.

The way that the system works is quite intuitive. During the day the hot water in the system will release some of its heat to the phase changing paraffin wax that is inside each of the columns. Since it is a phase change material that has a melting point within the temperature range of the system the water does not need to be much hotter than the melting temperature to continue to store more energy. This is because the simple process of changing phases stores so much energy that no added energy by increasing the temperature of the liquid wax is required.

When the sun is not out the water in the system continues to flow through each of the columns. While doing so it gains a small amount of energy from each column to stay at the melting temperature of the wax. The paraffin wax slowly begins to solidify. Based on the number of columns the wax will either take a few hours to solidify or the process will last for a few days. As soon as the sun comes back out the system is reopened to the heat source and the wax, whether almost completely solidified or still mostly liquid, will begin the process again.

Depending on the application the paraffin wax has been designed to last anywhere from 8 hours (overnight) to 72 hours (three full sunless days). The reason Project Omoverhi decided to make such a scalable system was mainly due to cost. Some scenarios demand a system that can last 72 hours while others can get by with one that lasts for less time. If a system is being built for an infant incubator in a normally sunny location that is off the grid it is important to spend the extra money and build in a safety factor and be able to cover up to 72 hours because the life of a child is at stake. However if the same system were being built for a hospital with inconsistent power, but the power had never experienced failure for more than a day, then it would only cost one third the price to build a system that only needed to last one day. Another scenario would be with chicken brooders that do not need to last nearly as long because they can be used during times of the year when the sun is out every day. In that case, to save even more money the thermal storage tank could be built to only last overnight, which would end up costing only 1/9th of the price of the three day system.

3.3. Calculations of Thermal Storage

3.3.1. Heat Loss

The main sources of heat loss within the thermal storage tank will be through the sides of the tank and the mass flowing through it. To eliminate the amount of heat lost through the sides and increase the amount of energy that could be stored, the tank was insulated. For this calculation heat was lost due to conduction and convection. Heat lost due to radiation was assumed negligible because it is much less compared to convection and conduction.

3.3.2. Walls of Thermal Storage Tank

Heat loss through the sides of the thermal storage tank was assumed to be one-dimensional, at steady state conditions, and constant thermal conductivity. To calculate the heat lost, a thermal resistance circuit was used. Figure 7 shows the top view of thermal storage column and the corresponding radii measured to the inside and outside of ABS pipe and insulation.

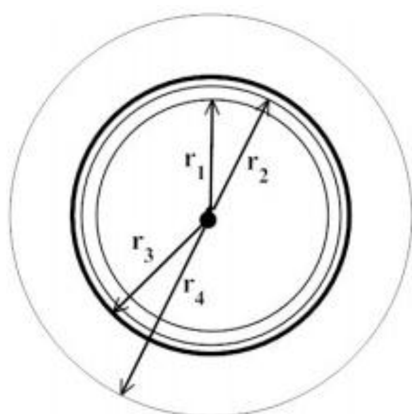


Figure 7: Top view of thermal storage tank showing different radius measured from center. r1 is to the inside of ABS pipe, r2 is to the outside of the ABS pipe, r3 is to the inside of the insulation, r4 is to the outside of the insulation

The thermal resistance for conduction of the walls made of ABS piping and surrounding insulation is:

$$R_{t,cond} = \frac{T_{s,1} - T_{s,2}}{q_{cond}} = \frac{t}{k_{ABS}A} \quad (1)$$

Where $T_{s,1}$ is the temperature on the outside surface of the wall, $T_{s,2}$ is the temperature on the inside surface of the wall, q_{cond} is the heat lost through the walls due to conduction, t is the thickness of the wall (ABS piping), k_{ABS} is the thermal conductivity of the wall, A is the surface area of the wall normal to the direction of heat transfer.

Convection on the inside and outside of the walls must be considered as well. The thermal resistance for convection is

$$R_{t,conv} = \frac{T_s - T_{amb}}{q_{conv}} = \frac{1}{hA} \quad (2)$$

Where T_s is the temperature on the surface of the wall, T_{amb} is the surrounding temperature (either ambient air temperature or wax temperature), q_{conv} is the heat lost due to convection, h is the heat transfer coefficient for the surrounding fluid. On the inside there is paraffin wax and on the outside there is air.

Heat lost due to radiation is assumed negligible since it is significantly less than the heat lost due to conduction and convection. Figure 8 shows a representation of the equivalent resistance circuit.

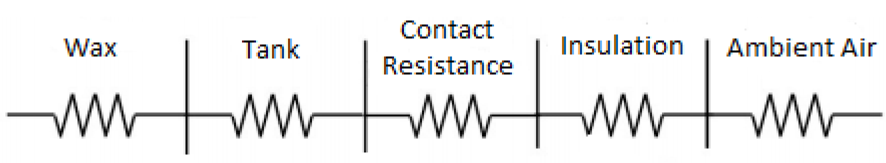


Figure 8: Thermal resistance model for the thermal storage column

The total resistance R_{total} of the thermal chamber is therefore calculated using Equation 3 below and takes into heat transfer due to conduction, convection, and the contact resistance between the ABS pipe and insulation.

$$R_{walls} = \frac{1}{h_{wax} * A_{walls}} + \frac{\ln(^{r_2}/_{r_1})}{2\pi * k_{ABS} * L} + R_{contact} + \frac{\ln(^{r_4}/_{r_3})}{2\pi * k_{ins} * L} + \frac{1}{h_{air} * A} \quad (3)$$

3.3.3. Heat Exchanger Length

A key component to any thermal storage tank is the heat exchanger (HEX). A heat exchanger allows for energy to be transferred from one fluid to another. There are many different types of heat exchangers available therefore finding one that fit our needs best was an important step in the development of our thermal storage tank. Once the type of HEX and material has been selected, the next step is to determine the optimal length of the HEX. For our analysis we used the NTU method to first determine the rate of heat transfer.

Equation 4 is used to determine the effectiveness of the heat exchanger. It is the relationship between the temperature of the wax inside the thermal storage tank and the water temperature as it enters and exits the heat exchanger. Using the graph shown in Figure 9, an NTU value of 1 can be determined assuming the minimum heat capacity rate over the maximum heat capacity rate is equal to 0. This is because the heat capacity of the wax is much larger than that of water.

$$\varepsilon = \frac{T_{w,e} - T_{w,i}}{T_{wax} - T_{w,i}} \quad (4)$$

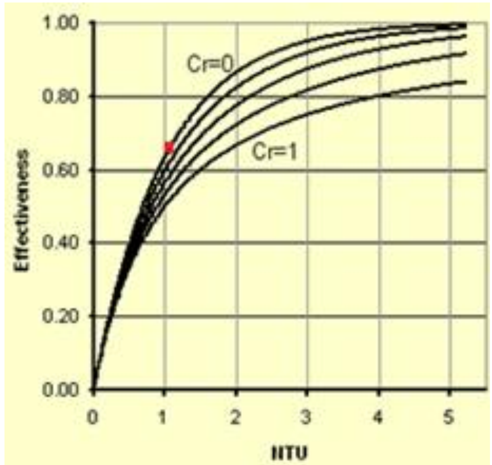


Figure 9: Shows the relationship between the effectiveness of a heat exchanger and NTU value with respect to the ratio of the minimum heat capacity rate over the maximum heat capacity rate.

After solving for the overall heat transfer coefficient (U), perimeter (P), mass flow rate ($\dot{m}$), and specific heat capacity (Cp), the length was determined using Equation 5.

$$NTU = \frac{UPL}{\dot{m}C_p} \quad (5)$$

3.3.4. Thermal Storage Medium

A phase-change material (PCM) is a substance with a high heat of fusion which is capable of storing large amounts of energy. Since the thermal storage tank will be storing energy as heat, a paraffin wax was chosen as our phase-change material. Heat is stored in a phase change material as latent and sensible heat. As shown in Figure 10, the temperature of the material only increases with respect to the amount of sensible heat. During a phase change, the amount of latent heat changes while the amount of sensible heat stays constant. Therefore, by utilizing the high heat of fusion of wax, large amounts of heat can be stored without increasing the temperature of the storage medium. This is beneficial because it enables large amounts of energy to be stored at lower temperatures compared to if all the energy was stored as sensible heat.

While heat storage fluids such as water also change phase at certain temperatures, water was not considered applicable due to the fact that the phase change does not occur within the operating temperature range of the system. Project Omoverhi chose to use paraffin wax because it melts at 50°C which is within our temperature range, it is cheap, and it is available in developing nations.

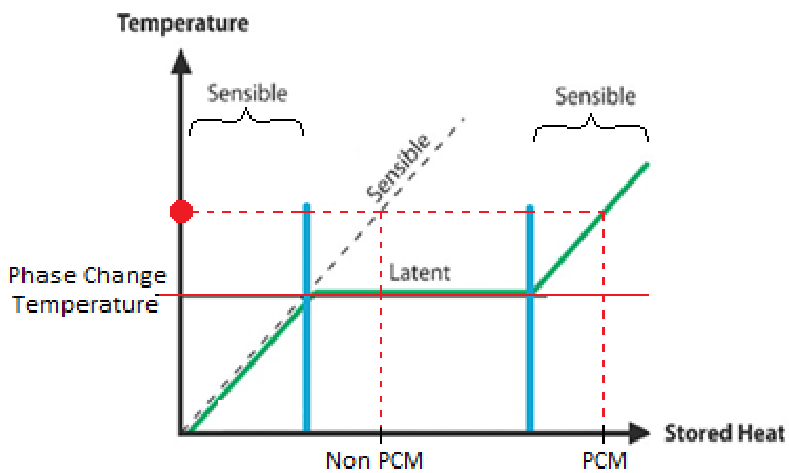


Figure 10: Graph showing the advantages of heat storage potential of a phase change material.

3.3.5. Load Supplied by Incubator

The load supplied by the incubator used for testing can be calculated using the first law of thermodynamics as stated

$$Q = \dot{m} C_p \Delta T \quad (6)$$

Where $\dot{m}$ is the mass flow rate of the fluid flowing through the incubator, C_p is the specific heat capacity of the fluid, and ΔT is the change in temperature of the fluid flowing through the incubator.

3.3.6. Storage Capacity

For phase change materials, thermal energy is stored as latent and sensible heat. Equation 7 is used to calculate the amount of sensible heat stored and Equation 8 is used to calculate the amount of latent heat stored. m is the mass of the thermal storage medium, C_p is the specific heat capacity of the thermal storage medium, ΔT is the change in temperature, and h_{sl} is the heat of fusion from the solid to liquid state. Equation 9 is the total storage capacity of the latent and sensible heat of our material.

$$q_{sensible} = \dot{m}C_p\Delta T \qquad (7)$$

$$q_{latent} = mh_{sl} \qquad (8)$$

$$q_{storage} = q_{sensible} + q_{latent} \qquad (9)$$

3.3.7. Determining Charge Capacity

To determine the size of the power source needed to "charge" the thermal storage column to full capacity in a desired amount of time, Equation 10 was used. The charge capacity is equal to the relationship between the mass, m, specific heat, C_p, change in temperature, ΔT, and heat of fusion, h_{sl}.

$$Charge\ Capacity = m(C_p * \Delta T + h_{sl}) \qquad (10)$$

3.4. Thermal Testing

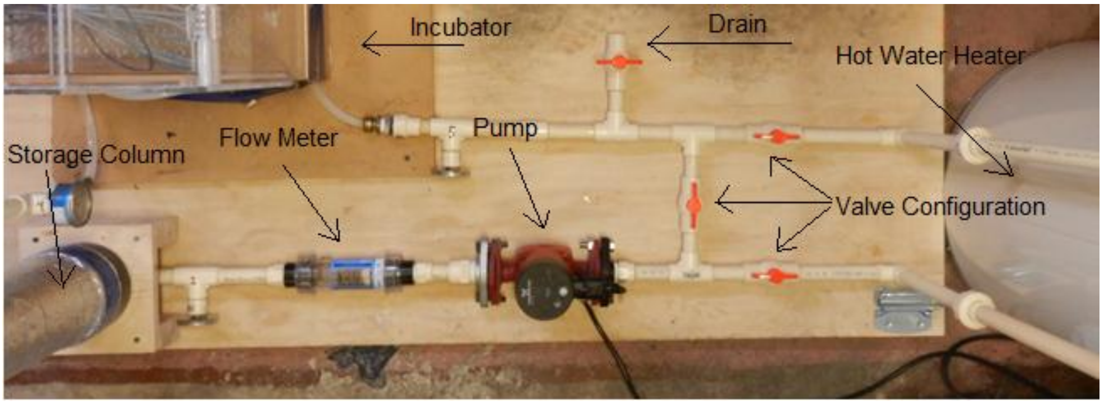


Figure 11: The setup of the main thermal storage test run on different columns and storage configurations

The main experiment that was run for the system was with a single column. By using only one column in the experiment it allowed multiple columns to be built using different parameters which could be placed in the system and compared to one another. The test system was designed to resemble the theoretical system that would be built later. The two biggest differences were that instead of using a thermal collector for the experiments a hot water heater was used, and rather than using a lot of columns only single column and four column experiments were run. The main reasoning for running the experiments with only one column to start and eventually four columns was to save time and money. By running the experiment with one column the wax only took a couple of hours to melt and then could be tested in the closed loop immediately afterwards. If the experiment had been run with multiple columns they would have needed to be run in the open loop with the water heater for much longer before the closed loop testing could begin. The other advantage to running experiments with one column was that the parts only had to be purchased to build one column and it saved a lot of time not having to melt the wax and fill multiple columns if the tested column turned out to not work as well as anticipated.

The reason that a hot water heater was used rather than a solar collector was to allow the results gathered to be more comparable. Since the solar collector is completely dependent on how hot it is outside and how exposed it is to the sun it makes replicating experiments very difficult. Therefore, by using a hot water heater that had an adjustable temperature, the system could be run similarly every time. The single and four column tests were run to save time and allow for more comparable tests to be run. For the first few months of testing only single column tests were run with different configurations, sizing of pipes, materials and lengths of melting times. Once most of the parameters were narrowed down, four columns were built of the two best configurations and then these were tested against one another. These new tests were run to gather a little more consistent data, and to prove that by increasing the system size the productivity of the system would increase.

During the tests the temperature was measured for the surrounding environment as well as at six points throughout the piping of the system; at the inlet and outlet of the hot water heater, at the inlet and outlet of the thermal storage column and finally at the inlet and outlet of the incubator. The temperature was also measured inside of the incubator throughout each test. These multiple temperature readings documented the heat lost in all parts of the system and facilitated determining how successful the column being tested really was. It was assumed throughout testing that negligible heat was lost through the piping. While this is not entirely true, the pipes were well insulated and even if there was heat lost to the surroundings, it would have been approximately the same for all tests. Other assumptions included that there was a constant flow rate, that there were no air bubbles in the system, and that the wax melted somewhat evenly throughout the cylinder. It should be taken into consideration that the thermocouples being used were only accurate to within plus or minus one degree.

3.5. Design of Experiments

There were several different variables that were adjusted when running the testing of the different columns. Some of the variables were not even related to the columns at all and these included the flow rate of the water, the fan speed underneath the incubator and the ambient temperature. All of these factors played a role in the effectiveness of the columns so they were tested and adjusted until the most ideal parameters were found. This was done by adjusting one variable at a time. First the water flow speed was adjusted between high and low. Then the fan speed was adjusted between high and low. While the ambient temperature was out of the control of the experiment it was recorded and taken into consideration for all of the test comparisons.

Table 1: Test to determine whether the high flow rate or low flow rate was more effective on heating the system

Parameters			Incubator Temperature (F)		
Flow Rate (GPM)	Fan Voltage (Volts)	Charge Time (Hours)	After 20 min	After 40 min	After 60 min
3	11	4	99	90	81
1	11	4	101	95	91

After running the experiment with different flow rates it was concluded that running the test at a lower flow rate made it easier to heat the incubator. The lower flow rate allowed the water to spend more time inside of the thermal storage columns and therefore it allowed the water to gather more energy as it passed through. The water also then was able to spend more time under the incubator and therefore was able to better satisfy the heat load requirements.

Table 2: Test to determine whether the high fan speed or low fan speed was more effective on heating the system

Parameters			Incubator Temperature (F)		
Flow Rate (GPM)	Fan Voltage (Volts)	Charge Time (Hours)	After 20 min	After 40 min	After 60 min
1	10	4	99	93	90
1	20	4	105	97	94

The next parameter that was tested was the fan speed. Using the flow rate that had been determined from the first tests the two fan speeds were compared. After just twenty minutes of running the system in a closed loop it can be seen that without running the fan on high voltage the incubator was losing too much heat too quickly. Therefore the decision was made to run the low flow rate and the high fan speed. While this decision would obviously impact how long a single column would last, that was not as important at this stage of testing because the system had to work to begin with in order to make constructing more like it worthwhile. After comparing both the flow rates and the fan voltage it became clear that in order to maintain the temperature in the incubator the fan speed needed to be at the highest, 20 volts, and the flow rate needed to be the lowest, one gallon per minute in order to have the most successful results.

It should be noted that while this test was run and these parameters were understood for the single column, it would be ideal to run these tests again when a larger 10-15 column system was built. The reason these tests should be run is based on how much heat would be able to be transferred back into the system from the thermal storage tank when it is closed loop. This is important because in a bigger system more heat would be picked up by the water as it flowed through the thermal storage tank as the tank becomes larger. If the flow rate were to stay at the minimum and the fan speed at the maximum the amount of heat transferred into the piping might become too high which would cause temperatures in the incubator to rise rather than stay steady which is not ideal. This would also waste the precious thermal energy because the heat would have to exit out of the bypass system rather than staying stored in the columns.

Other variables that played a major role were the diameter of the metal piping, the material of the piping, the configuration of the metal piping within the ABS tubing and the length of time the hot water heater was providing heat to the system.

Table 3: Test to compare the difference between using copper piping and galvanized steel piping

Parameters			Incubator Temperature (F)		
Flow Rate (GPM)	Fan Voltage (Volts)	Material	After 20 min	After 40 min	After 60 min
1	10	Copper	100	97	94
1	10	Gal Steel	98	95	90

While diameter tests were originally done with the galvanized steel, after finding that copper piping was actually cheaper and more effective the diameter tests were halted. This is because common copper piping is only easily available in certain sizes and the only one that worked for the application was half inch diameter.

A similar discovery was made with the configuration. While originally the configuration used one section of galvanized steel running through the middle of both the top and bottom caps, it was realized that the maintenance and difficulty of assembly was not worth the configuration. After discovering the double tubed section and understanding that not only would it work much better, but it would also be cheaper, it was an easy decision to switch configurations. The reason it was more effective was because it had twice the length of the original configuration, at the same time it was cheaper because it required fewer parts since there were no threads needed at the bottom of the ABS pipe and it was so much easier to assemble.

Table 4: Test to compare the difference between charging the system for 12 hours and 4 hours

Parameters			Incubator Temperature (F)		
Flow Rate (GPM)	Fan Voltage (Volts)	Charge Time (Hours)	After 20 min	After 40 min	After 60 min
1	10	4	100	95	90
1	10	12	101	98	93

After running all of these tests with four hour charges it became time to figure out how much of the wax was really melting during these four hours. Therefore the design team ran the hot water heater charge overnight for twelve hours to ensure complete melting and compared the results to those of the four hour test. As can be seen from the results in the table above the temperature was about two to three degrees higher after the twelve hour charge which leads to reason that the tanks were nearly completely melted after the initial four hour charge.

Table 5: Test to compare the difference between 4 columns in parallel and in series with a 4 hour charge

Parameters			Incubator Temperature (F)		
Flow Rate (GPM)	Fan Voltage (Volts)	Configuration	After 20 min	After 40 min	After 60 min
1	20	Series	100	96	90
1	20	Parallel	100	95	91

The final test that was run was the comparison of parallel versus series configurations. The design team realized that it might be more ideal to run the columns in parallel because it would split the flow more evenly and allow the water's flow rate to slow. The only problem that the team faced was that splitting the columns into parallel instead of series meant that more parts needed to be used to allow the flow to split and that the system would not be as scalable. Photographs of the two systems can be seen in the figure below.

Figure 12: Constructed columns in series and in parallel

After analyzing the results it became clear that there was not an obvious reason to choose the parallel over the series configuration. The two were nearly identical in their results which meant that the smart choice would be to use the cheaper more scalable option. Therefore the series configuration was chosen.

3.6. Experimental Results

After running several successful tests Project Omoverhi compiled the comparable results to show that the prototype worked.

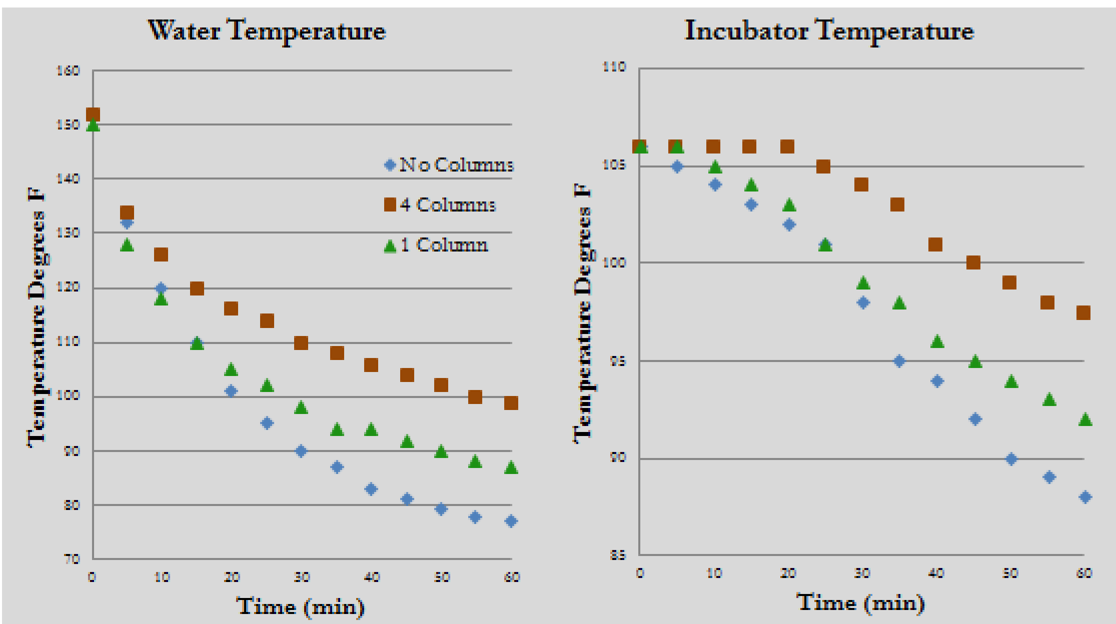


Figure 13: Results of water temperature and incubator temperature based on number of columns and a four hour charge

In the figure shown above the four hour tests run with different numbers of columns are compared. The first test run to get a basic idea of the heat lost to the surroundings and to the heat load was done with no columns. This test was run by placing a section of CPVC the same length of the column into the system and connecting the two lengths to the entrance and exit piping. This test was then replicated with one column to get an accurate comparison and finally with four columns. The graphs above clearly show that there is an increase in the temperature both in the incubator and of the water flowing through the pipes as the number of columns increases. While the temperature is still falling in all cases, it needs to be noted that there was not very good insulation of the thermal storage tanks compared to burying them under ground or placing them inside of their own large container which would be done for a real application.

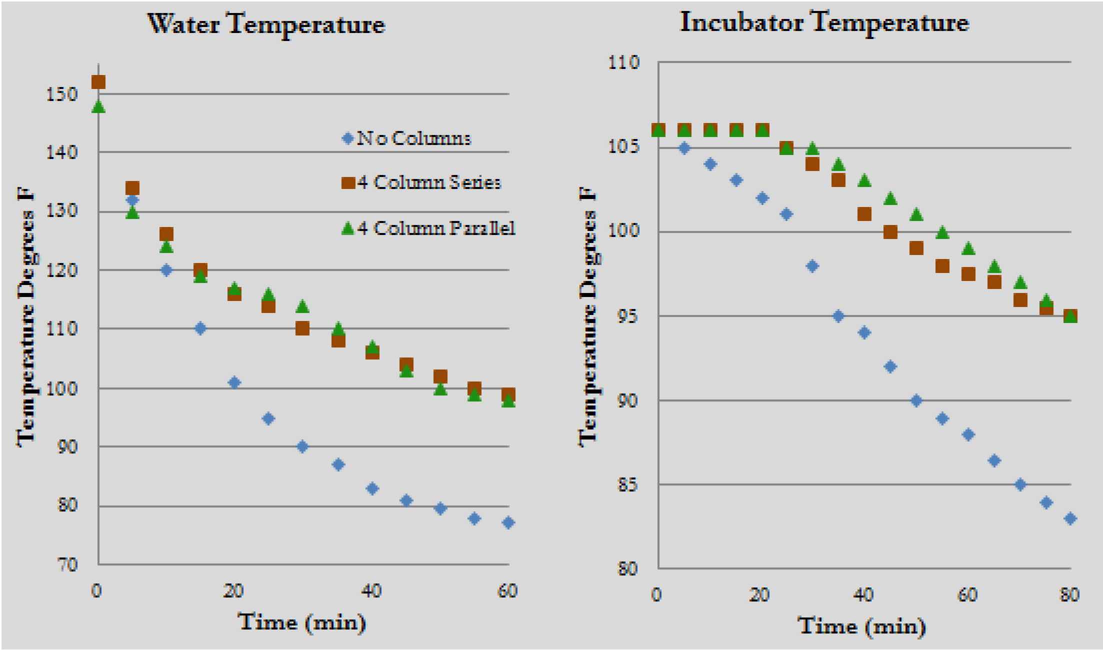


Figure 14: Results of water temperature and incubator temperature based on configuration and a four hour charge

The final important results are of the series versus parallel tests. For some general comparison the graph of the test run with no columns is also shown on the graphs. From these results it became clear to the design team that one did not really favor the other. Even though the incubator temperature seems to be about one to two degrees warmer during the parallel test, these measurements are only accurate to plus or minus one degree. Since one of the main requirements of Project Omoverhi was to keep it as cheap as possible it would not be worth the cost increase just to have the system run one or two degrees higher.

4. System Goals and Limitations

In the process of developing the paraffin thermal storage columns, several limitations of the current system design became evident. While considering possible ways in which to expand these limitations, future goals for both the design and performance of the system were established.

4.1. Key System Level Limitations

There are many system level design issues associated with the individual thermal storage columns that affect the use of them for larger scale system applications. When using a phase change material (PCM) as a thermal storage fluid, calculating expected results and geometric behavior are much more difficult than those for storage materials that maintain a single phase. This is because the rate of heat transfer through the PCM varies dramatically as the phase change occurs, and while some PCMs are said to demonstrate uniform melting, the melting geometry is never the same. These two factors make it difficult to accurately predict effective melting diameters, as well as performance characteristics such as charge time and conductive heat transfer through the heat exchanger walls. There are two main reasons that it is important to establish an effective melting diameter. If the column width is too narrow, there will be excess heat collected that will not be able to be stored. On the other hand, if the column width is too wide, not all of the wax will melt. In that case, cost could be cut almost in half in some cases by decreasing the ABS pipe width and the amount of PCM necessary for each unit. The reason that the uncertainty of the affected melting diameter limits the large scale implementation of the product is that the cost associated with excess spending or lack of sufficient storage volume increases as the size of the system increases. Therefore, the size and geometry of the heat exchanger must be much more finely tuned before large scale implementation becomes profitable.

Another potential issue for the thermal storage units is the fact that, due to the volumetric changes of the PCM during phase change, the heat storage column must be an open system, allowing the pressure inside the column to remain constant. This limits the possible geometric configurations of the columns and leads to problems such as contamination of the PCM from water and soil.

A final limitation of the thermal storage units deals with material selection. The maximum suggested operating temperature for ABS pipe is very close to the maximum operating water temperature in the system used during testing. If the flow were to become hotter than expected, it could cause deformation to the column, resulting in leakage and eventually failure.

The use of ABS piping is vital to the design because of its wide availability as plumbing pipe in developing countries. This temperature restriction means that the thermal storage units can only be used in certain applications. By identifying these system level limitations, possible developmental ideas have been researched for the implementation of the thermal storage units to larger scale applications such as dairy pasteurization.

4.2. Future Improvements

There are many future improvements that can be made to the design in order to increase the performance of the thermal storage units while maintaining a low cost product. The main areas for improvement involve the simplicity of design and ease of manufacturing, the use of local materials for insulation, and the heat storage and heat transfer capabilities of individual units.

For testing purposes, there were a number of parts used that would not normally be required. For example, compression fittings were used to connect multiple thermal storage units together. These compression fittings allow for temporary connections that can be changed very quickly and easily. These expensive copper fittings can be eliminated from the design after performance testing and analysis is complete. By directly connecting the rubber transport tubing to the tops of the heat exchanger pipes using very cheap compression bands, the expensive copper compression fitting can be eliminated, helping to eliminate leakage problems at connection points while also driving the cost of production down.

The ABS column and cap assembly is another part of the initial design geometry that can be simplified to help eliminate potential leakage problems and keep costs down. By melting scrap ABS down into a shallow box, the ABS columns could be set inside of the solidifying ABS to create permanent caps. This would eliminate the need for ABS slip caps and manufacturing processes such as sanding and epoxying the caps onto the pipe. This solution to closing the system also allows for the use of larger diameter ABS pipe.

The insulation used in the test setup could be eliminated from the design by burying the thermal storage system inside of a box. The geometry of the box would allow for the system to be sufficiently insulated while eliminating the cost of insulation and reflective tape. This solution to the issue of insulation would also protect the system from damage and theft.

There is a lot of room for improvement regarding the performance of the current system. Low solid state thermal conductivity of the PCM and a finite effective melting diameter are the two main factors that limit the performance of the system. There are many ways to improve these two main performance issues but some are simpler and more cost effective than others. The most obvious solution to this problem would be to somehow extend the surface area of the copper pipe radially out into the wax. Not only would this allow the effective melting diameter to be increased, but it would also the heat from the outer walls of the column to be transferred to the flow more efficiently by allowing the heat to be transferred through a more thermally conductive path. Chicken wire is the simplest, cheapest, and most widely available material that could serve this function. The chicken wire can be implemented by tightly wrapping it around the heat exchanger during construction and allowing it to uncoil and expand until bound by the inner walls of the ABS column. Once expanded, the PCM would be poured in and allowed to solidify while maintaining the geometry of the chicken wire. This addition would help to significantly improve the performance of the thermal storage units by expanding the effective melting diameter and allowing a more thermally conductive path for the heat to be transferred to the flow from throughout the PCM. These improvements allow for larger heat storage capabilities and quicker charge times to be achieved, while also allowing for a more consistent heat transfer rate from the PCM to the flow.

While the product developed by the design team does function properly and has to ability to be modified to improve some of the aspects that limit the performance of the system, there are also completely different system geometries that might allow for better performance. While the current design makes use of local materials and is easily scalable in that individual units are connected in series to create a large system, there are other possible ways to take advantage of the latent heat storage capabilities of phase change materials that may be cheaper and easier to implement into preexisting thermal storage systems.

One of the best aspects of using water as a thermal storage fluid is that, in low temperature range applications, it remains in fluid phase and allows for the geometry of the heat exchangers to be much simpler than if a PCM was being used. Without having to worry about significant volumetric expansion and low solid state thermal conductivity issues, the system is much more basic and the geometry of the heat exchanger can vary. The biggest problem with using phase change materials in direct contact with heat exchangers is that, in a temperature range of roughly 40 C to 60 C, the thermal energy storage capacity of paraffin is roughly 2.5 times greater than that of water, but the heat storage and heat removal processes yield performance coefficients of roughly 0.5. The majority of the challenges faced by the design team stemmed from phase change that occurs on the surface of the heat exchanger. By figuring out a way to utilizing the latent heat storage capabilities of PCMs while allowing the use of a single phase thermal storage fluid such as water to be in direct contact with the heat exchanger, the thermal storage capacity of the system can be significantly improved while maintaining the system's ability to store and remove heat efficiently.

The way to effectively utilize the benefits associated with PCMs would be to incorporate them into preexisting thermal storage tanks that use water as the primary thermal storage fluid in a way that indirectly affects the transfer of heat to and from the transport fluid flow. While simply adding paraffin or some other type of PCM into the water tank would cause undesirable PCM geometries over time, by somehow encapsulating small amounts of paraffin and letting them float on the surface or throughout the water, the PCM would continue to indirectly store and release heat into the transport fluid flow without having to address problems such as low solid state thermal conductivity and effective melting diameters. Capsules containing PCMs could be introduced into preexisting thermal storage tanks to increase the thermal storage capacity without affecting the ability to transfer heat between the flow and the surrounding thermal storage fluid. By combining the original Omoverhi team's thermal storage tank design with capsules of paraffin throughout the thermal storage fluid within, the performance of the thermal storage tank would be maintained while significantly increasing the thermal storage capacity of the system. Rather than having to overcome the geometry and thermal conductivity challenges associated with using PCMs as the primary thermal storage material in direct contact with the heat exchanger, it would be much more efficient and cost effective to indirectly use them to increase the thermal storage capacity of non-phase changing thermal storage fluids.

5. Project Management

Project Omoverhi is comprised of four mechanical engineers who were selected by last year's Project Omoverhi's group to work together and optimize their design. This group of mechanical engineers has collaborated on the research, design, and testing of an updated heat storage component of Project Omoverhi. This was accomplished through weekly meetings as a team as well as weekly meetings with each advisor. By setting up a shared Dropbox folder online, the team was able to effectively organize and update the project in real time from anywhere increasing the efficiency and communication within the team. Even though Project Omoverhi had only a single discipline of engineering working on the project, it had sufficient skills to develop all aspects of the heat storage device without limitations. During each team meeting, goals and objectives were created so that the team stayed on task and rarely strayed from the schedule. Each team member was held accountable for their individually assigned tasks.

5.1. Budget

Project Omoverhi's monetary goals were not initially discussed although it was known that it needed a design that was cheap enough for developing countries to afford. After interviewing Susan Kinne, a member of Groupo Fenix, a group of volunteers who are dedicated to international development especially in Latin American countries, the group realized it would need to incorporate a strong emphasis towards a cheap solution. Applying for funding from organizations that fund third world projects is competitive. It is important that a project be not only innovative and effective, it has to be cost-effective, too.

While performance was a key decision maker for the design configurations, cost became the other important factor. The question is whether or not the performance of the columns is worth the cost of manufacturing them. The original prototype cost was around $35 per 2ft. column. This cost was high because parts were purchased that were not necessarily the cheapest due to time constraints. Also, it was not reasonable to purchase parts in bulk because only a small number were needed for prototyping. An example is the push-to-connect fittings which make testing a whole lot quicker and easier, but drive the cost up considerably. Something to keep in mind is that the cost per foot can be decreased if column length is increased because it eliminates the number of more expensive parts in the long run.

Single 2ft. Unit Cost: ~$35

-Purchased Push-to-connect fittings

-Used extra parts/fittings for convenience

-Bought expensive parts

Because the prototype cost was so high, some drastic changes needed to be made in order to have the product make sense in developing countries. The group determined that the cost for a single 2ft column in a developing country would be about 1/10th the price that was originally paid. Parts can be purchased wholesale and in bulk. Many parts do not need to be purchased at all, but can be improvised. For example, instead of push to connect fittings, a simple scrap hose and hose clamps could do the job just as well and cost little to nothing. Similarly, instead of using the refined Paraffin 3032 wax, any candle wax would suffice. This price of $3 can possibly be decreased even further if consumers used more local materials that were not necessarily consider in the price. The key to Project Omoverhi's design is that every part can be found in scrap piles worldwide.

Single 2ft. Unit Cost: ~$3

-Use Local materials/scraps

-Use fewer parts

-Simplify the design

-Some parts assumed to be little to no cost

5.2. Timeline

5.2.1. Annual Timeline

Fall Quarter Timeline:

Task	October			November			December			
	Week #									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Project Declaration and Initial Report	X	X								
Established Year and Quarter Long Goals		X								
PDS Requirements, Customer Needs, Info Gathering		X	X							
Problem Definition			X							
Geometrical Design and Layout of Heat Exchangers		X	X	X	X					
PCM and Shell Material Research/Availability			X	X	X	X	X			
Initial and Functional Analysis				X	X	X				
Calculations of Energy Behavior Through the Thermal Chamber						X	X	X	X	
System and Sustainability Design							X	X	X	X
Initial System Drawings								X	X	
QFD and "House of Quality"								X	X	
Product Architecture									X	X
Cost Estimation								X	X	X
Design Review										X
CDR Written and Oral Reports								X	X	X

Winter Quarter Timeline:

Task	January				February			March		
	Week #									
	1	2	3	4	5	6	7	8	9	10
Review Progress and Schedule	X	X								
Re-Establish Year and Quarter Long Goals	X	X								
Revised Schedule, Hardware Goals, Parts List			X	X						
Construction and Integration of Heat Exchangers	X	X	X	X	X	X	X			
Ethics and Professionalism Update			X	X						
Societal Impact Report			X	X	X					
Budget Update and Re-evaluation				X	X					
Build Surrounding Columns for Contained PCM	X	X	X	X	X	X	X			
Manufacture Fixture for Columns	X	X	X							
Construct Piping Layout	X	X	X	X						
Detailed and Working Drawings For Manufactured Parts					X	X				
Analysis Report							X	X		
Testing the Thermal Behavior Within the Chamber					X	X	X	X	X	X
Iterating for Optimal Heat Loss						X	X	X	X	
Development of Design Due to Failures and Preliminary Testing							X	X	X	X
Experimental Results								X	X	X
Written and Oral Reports									X	X
Assembly and Hardware Drawings										X

Spring Quarter Timeline:

Task	April			May			June			
	Week #									
	1	2	3	4	5	6	7	8	9	10
Review Progress and Schedule	X	X								
Re-Establish Year and Quarter Long Goals	X	X								
Thesis Table of Contents and Introduction	X	X	X							
Experimental Protocol and updated PDS						X	X	X	X	
Senior Design Conference				X	X					
Analysis of Testing		X	X	X	X	X				
Societal and Environmental Impact Report			X	X	X	X				
Thesis Draft			X	X	X	X	X	X		
Patent Search/ Business Plan						X	X	X		
Experimental Results		X	X	X	X	X	X			
Future Goals and Challenges							X	X	X	
Find a Team to Take Over Project Omoverhi for Next Year								X	X	X
Open House										X
Final Thesis						X	X	X	X	X

*Shows progression of research, design, development, and analysis, and how they overlap

5.2.2. Gantt Chart

ID	Task Mode	Task Name	Duration	Start	Finish	Predecessors
1		**Research Geometrical Design and Layout of Heat Exchangers**	**26 days**	**Fri 11/4/11**	**Fri 12/9/11**	
2		Determine Heat Produced by Solar Collector	10 days	Mon 11/14/11	Fri 11/25/11	
3		Determine Wax To Be Used	7 days	Thu 11/10/11	Fri 11/18/11	
4		Determine Container Shape	4 days	Wed 11/9/11	Mon 11/14/11	
5		Research PCM and Shell Material Research/Availability	26 days	Fri 11/4/11	Fri 12/9/11	
6		**Calculations of Energy Behavior Through the Thermal Chamber**	**46 days**	**Fri 11/4/11**	**Fri 1/6/12**	
7		Calculate Needed Container Sizing	8 days	Mon 12/12/11	Wed 12/21/11	
8		Calculate Amount of Wax Needed	6 days	Thu 12/22/11	Thu 12/29/11	7
9		Calculate Amount of Water Needed	6 days	Fri 12/30/11	Fri 1/6/12	8
10		Calculate Amount of Power Needed to Melt Wax	6 days	Tue 11/29/11	Tue 12/6/11	
11		Detailed Drawings of Preliminary System and Testing Setups	12 days	Mon 1/23/12	Tue 2/7/12	
12		Inventory of Previous Projects Project	6 days	Mon 1/23/12	Mon 1/30/12	
13		Patent Research	22 days	Fri 12/9/11	Mon 1/9/12	
14		**Construction of Affected Diameter Testing**	**55 days**	**Mon 12/12/11**	**Fri 2/24/12**	**6,1**
15		Research Materials for Lowest Prices and Available in Haiti	22 days	Thu 12/15/11	Fri 1/13/12	
16		Purchase Needed Materials for Affected Diameter Testing	8 days	Mon 1/16/12	Wed 1/25/12	15
17		Purchase and Setup Water Heater and Bilge Pump	6 days	Thu 1/26/12	Thu 2/2/12	15
18		Construct Galvanized Piping	6 days	Thu 2/2/12	Thu 2/9/12	15,16
19		Construct Cylinder with Parrafin Wax; Acrylic Top for Viewing	7 days	Mon 2/6/12	Tue 2/14/12	15,16

ID	Task Mode	Task Name	Duration	Start	Finish	Predecess
20		Pipe Insulation if Necessary	7 days	Thu 2/9/12	Fri 2/17/12	15,16
21		Acrylic Piece Lasercut in Machine Shop	2 days	Tue 1/31/12	Wed 2/1/12	
22		Build Surrounding Columns for Contained PCM	35 days	Mon 2/27/12	Fri 4/13/12	14
23		Thesis table of contents and introduction due	1 day	Mon 4/9/12	Mon 4/9/12	
24		Experimental Protocol and Updated PDS	1 day	Mon 4/16/12	Mon 4/16/12	
25		Construct Final Design Assebly for General Testing	15 days	Mon 4/16/12	Fri 5/4/12	22
26		Testing the Thermal Behavior Within the Chamber	7 days	Mon 5/7/12	Tue 5/15/12	25
27		Senior Design Conference	1 day	Thu 5/10/12	Thu 5/10/12	
28		Troubleshooting and Iterating tests for Optimal Heat Loss	7 days	Wed 5/16/12	Thu 5/24/12	26
29		**Data and Results Analysis and Discussion**	**6 days**	**Tue 4/24/12**	**Tue 5/1/12**	**26**
30		Identify Errors in Design and Set Goals for Future	4 days	Thu 4/26/12	Tue 5/1/12	
31		Social and Environmental Impact Report	1 day	Wed 5/16/12	Wed 5/16/12	
32		Thesis draft	1 day	Mon 5/21/12	Mon 5/21/12	
33		Patent Search or Business Plan	11 days	Wed 5/16/12	Wed 5/30/12	
34		Experimental Results	19 days	Wed 5/9/12	Mon 6/4/12	
35		Open House	1 day	Wed 6/6/12	Wed 6/6/12	
36		Final Thesis Due	1 day	Wed 6/13/12	Wed 6/13/12	
37		Travel to Haiti for Field Research and Application Testing (Tentative)	5 days	Tue 6/19/12	Mon 6/25/12	

*Shows dates of completion and measurable goals

5.3. Design Considerations

To allow the product to be easily introduced into developing countries, it had to be designed according to a series of technical considerations generated by the design team. These design considerations were established using the information gathered through research and interviews and helped the design team in the selection of materials and heat exchanger geometries. More specific design considerations were generated for each of the two main structural components; the cylindrical container, and the heat exchanger. It was determined that the PCM container needed to have a circular and scalable geometry to account for radial melting and the implementation into a variety of applications. The container would need to withstand PCM temperatures of up to 80˚C but must be built out of a material that would cheap, widely available, and easy to machine with simple power tools. The heat exchanger would also need to be relatively inexpensive, simple, and widely available. In addition, the material used for the heat exchanger would need to have a high heat transfer rate, low corrosion characteristics, and allow for the construction of a straight tube, single flow heat exchanger geometry. While initial designs utilized tube in tube heat exchangers, such geometries proved to be too complex and expensive for the range of applications being designed for.

For the PCM container, we chose ABS piping mainly because it is a material that is cheap and widely available in developing countries since it is the primary material used for plumbing. It allows for easily scalable storage systems since multiple units would be able to connect in series and the operating temperature of our system is within the temperature limits indicated by the manufacturer. The circular shape allows for all of the wax to be utilized and the variation in available diameters enables us to match the effective diameter determined through visible melting tests. Shown below in 15 are examples of a 4” ABS pipe and cap, along with the configuration of this component into our final design.

Figure 15: ABS piping and end caps used in final design

For the storage tank we chose a straight tube heat exchanger with copper pipe. Copper is a good material choice because it has a high thermal conductivity and much thinner walls than other types of pipes such as galvanized steel. While it was initially believed that copper would actually cost more to use than galvanized steel, due to the simple geometry and range of applications, it is actually cheaper. The benefits of copper piper over galvanized make it the clear material choice. The high thermal conductivity and thin pipe wall relative to galvanized steel mean that the use of copper pipe can allow for almost 30 times the heat to be transferred through the pipe wall in a given amount of time. Shown below in figure 16 are examples of 0.5" Copper pipe and fittings along with a SolidWorks screenshot of the heat exchanger geometry.

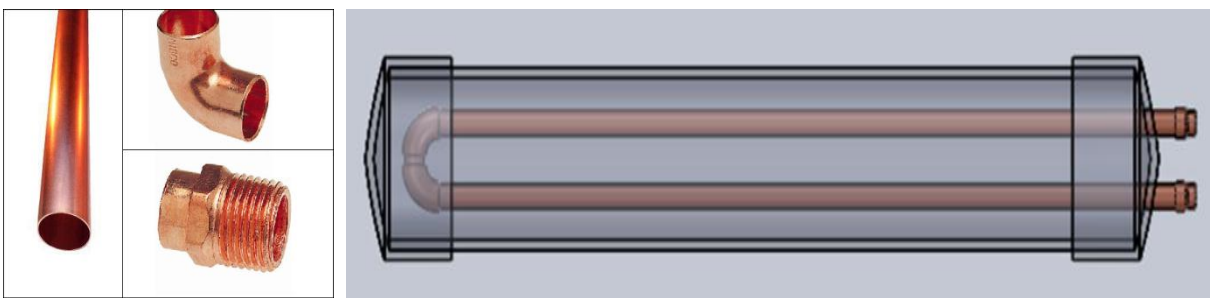


Figure 16: Example of copper fittings and copper piping with sample column

This simple geometry allows for the unit to be easily assembled and solves many of the leakage problems associated with sealing the container by placing the entry and exit points on the same side of the unit and standing it up vertically.

5.4. Design Process

To solve the issues relating to heat storage in developing countries, Project Omoverhi designed a thermal storage unit that needed to be cheap, scalable, and simple. The idea of applying strictly materials that can be found all over the world combined with storing the heat in a phase change material is the basis behind the team's design. The initial design steps were to perform the calculations to determine thermal system size and amount of wax necessary to store the heat required to provide constant heat for a given duration, in this case three days. The calculations provided the ground work necessary to brainstorm and build a prototype. The initial prototyping phase first included a build of the design following the specifications calculated. Testing of the initial prototype was then conducted to determine the thermal efficiency of the design. This design was subject to issues such as hot spots within the wax, expansion and contraction of the wax, long manufacturing time, as well as melting temperature. It also brought up some other issues with the design such as cost versus benefit. A final design prototype was reconstructed to solve these issues encountered during the initial prototype testing stage. At this stage, the design was changed from a straight pipe going in one end of the column and out the other, to a u-shaped pipe entering and exiting from the top. This change saved cost, time of manufacturing, simplicity of the product, and scalability. Additionally, the design was beginning to make sense economically. With a final change from galvanized to copper piping, the design was approaching completion. Further testing and analysis of this prototype with the incorporation of the new design changes demonstrated the success of the final design. Testing also showed other possible areas for future improvements such as further increasing the thermal conductivity of the wax or increasing the effective diameter within the column.

5.5. Business Plan

5.5.1. Abstract

Project Omoverhi is a simple, scalable, and cost effective thermal energy storage solution for implementation in developing countries. Because the design is basic and easy to construct, it makes it appealing for local communities worldwide. The total cost of the heat storage unit is dependent on the heat load size of the application and the duration of time the customer wishes to sustain a constant heat source. Due to the scalable design it is easy to change the size if the customer's needs change. Through a non-profit merger or venture philanthropy support, this product could be used in a variety of applications in developing communities.

5.5.2. Background

Many countries are implementing a wide variety of clean, solar thermal energy solutions. Applications include: Neonatal Transport Incubators (NTI) for use in Nigeria, chicken brooders in Haiti, and residential hot water and absorption chiller systems. However, one major issue with most of these solutions is that the only options available for thermal energy storage are inefficient and costly. For this reason, if the region was to experience a few days of zero sunlight, the babies in the incubators and the chicks in brooders would likely not survive. The ability to store energy for days as opposed to hours not only allows for extended product use, but it can be applied to many other current and future problems that need thermal storage solutions to operate.

Our product explores thermal energy storage using phase change materials and a simple design. By incorporating locally available materials, the design is low cost, easy to assemble, and requires low maintenance, enabling an easy implementation in a developing community.

5.5.3. Goals and Objectives

Project Omoverhi has several viable options for future business opportunities. One option is to sell the product through an existing non-profit organization. For example, the product could be sold through Project Embrace, which is a national organization that focuses on improving the health of people worldwide. If this were to happen, one advantage would be that funding will be readily available from the existing non-profit. Another is that Project Omoverhi can build off the existing non-profit's brand name, which will encourage customers to be more open to purchasing the group’s product. However, one disadvantage is the possible loss of control over managing the product because experts from the existing non-profit might detract from the mission and goals of Project Omoverhi. Another disadvantage is the allocation of funding; by going through another non-profit, Project Omoverhi might have to compete with the existing organization's other products for resources, thus slowing down the process.

Another possible business opportunity for Project Omoverhi is to start a new non-profit organization, which would require the team to obtain funding. Aside from applying for grants, Project Omoverhi can take advantage of a recent trend in venture capital investing called Venture Philanthropy, which provides start-ups with financial support as well as management assistance. Venture Philanthropy differs from traditional VC investing in that it provides "outcome-based" funding. Instead of measuring an organization's success through financial measures like ROI or EPS, they are more interested in how the organization achieves certain social goals. For example, the team's success could be measured by looking at the degree to which infant mortality has decreased in Nigeria as a result of introducing the heat storage system into existing incubators or the number of chickens and eggs being produced in Haiti per year.

5.5.4. Product Description

The Omoverhi thermal storage tank is an easy, affordable way to store energy collected from a solar collector. Solar collectors are currently about four times more efficient than solar panels, but storing the energy for use when the sun is not available is much more difficult. The main application of the Omoverhi thermal storage tank is for neonatal incubators and chicken brooders in developing countries. The Omoverhi design can be constructed using locally parts that are available for free or extremely low prices. By using the Omoverhi thermal storage tank with a solar collector and an incubator the system can work twenty-four hours a day and keep either a prematurely born baby or a group of chickens alive and healthy.

5.5.5. Potential Markets

The goal of the design is to make it so nearly anyone can create and use it, but the main market is for local communities and farmers in Haiti. With the design simplified and the costs driven down to around $3 per column, this system can be a viable thermal energy storage solution for people in the developing world. If the storage system is implemented in a place like Haiti, one chicken brooder in a community can have a drastic effect on the local economy and the health of the people living there. Because the system can provide a constant heat source for up to three days without sunlight the chicken brooder can run 24 hours a day, year-round in Haiti. If a person starts with one hen, that hen will lay one egg and then sit on it for about a month straight until it hatches. Luckily, chickens have the ability to lay one egg every day, so if that hen's eggs were allowed to hatch in a chicken brooder instead, the hen could lay and hatch about 30 eggs in the same amount of time. That could increase chicken reproduction populations by 30 times in a matter of weeks! The kind of economic impact this could have on a developing community is astronomical. The implementation of a constant heat source like this one with chicken brooding is only the beginning of the possibilities. . Other potentially impactful applications include small scale dairy pasteurization and neonatal incubation. With some further research and development this idea can become a reality in places like these.

5.5.6. Competition

No widely available marketable product exists even though similar personal systems have been designed and built. There are many commercially sized and expensive thermal energy storage systems, but not many cheap residential ones available. The heat storage system is not designed to be profitable because it is so easily replicated. It's so simple most people can build it with just a few easy instructions.

5.5.7. Sales and Marketing Strategies

Begin by finding primary local chicken farmers in developing regions and rely on word of mouth to other farmers to incorporate this idea. By getting the word out to local as well as world-wide non-profits and organizations, more people can be shown this simple yet effective design. Another avenue that can be used is talking with international developing country aid societies.

These groups have the most communication and first-hand experience with communities that are in need of heat storage like Project Omoverhi's product can provide.

5.5.8. Manufacturing Plan

The customer can purchase prebuilt columns or disassembled columns with or without wax. Manufacturing would typically be outsourced to local shops in the area**.** The assembly process was designed to be simple. A typical 16 unit system can be built in less than a day**.** Installation would take a few days depending on the size of system, depth buried, weather, available tools, number of people helping and a few other variables. Inventory would consist of individual components but not fully assembled units. The expansion of the product depends on how many communities have the materials necessary to build these heat storage columns.

5.5.9. Service

Because of the nature of this product, no warranty is necessary. No components would typically have a warranty in this design, so it eliminates designating who can fix it and who will pay for it. The main point is that the heat storage device is so simple that any operator can perform maintenance and replacing parts would be as simple as going to a scrap pile.

5.5.10. Financial Plan

There are several philanthropic investors located in the Bay Area. A few include Draper, Richards, Kaplan Foundation and the Omidyar Network. The Draper Richards Kaplan Foundation provides selected social entrepreneurs with funding of $100,000 annually for three years. On the other hand, Omidyar makes initial investments greater than $1 million to start-ups but only to those within their network of contacts. Because of the amount of funding these companies provide, they both implement a rigorous selection process which requires completion of a business plan, reference checks, research and communication with field experts. They also provide guidance by taking an active role as a board member to help the start-up develop into a sustainable business in the long-run.

6. Societal and Environmental Impact

6.1. Ethical Framework

Project Omoverhi is motivated by the belief that every human being, regardless of their location and social standing, has equal human dignity; that every human being has an inherent right to life. An infant's chance for survival or a community's access to healthy food sources is highly dependent on location. Communities that have limited funds and inconsistent grid power are unable to support a premature infant or a chicken brooder through crucial times. The lack of incubators and chicken brooders in developing countries presents inequality. This inequality is the result of inadequate funds, inconsistent grid power and unreliable resources. Project Omoverhi supports the fact that all human beings are to be treated equally and are entitled to the same healthcare privileges no matter their social standing.

6.2. Areas of Impact: Background Information Related to Haiti and Nigeria

Project Omoverhi chose to continue focusing its technology on applications for developing countries. Two specific countries of impact are Nigeria and Haiti. The team continued to focus on Nigeria because of the immediate need for self-sufficient incubators to combat the high premature infant mortality rates. The team from last year's project originally focused on Nigeria because of the personal experience of one of the group members. She was born prematurely in Nigeria and her father had to run with her to a different hospital because the hospital they were in did not have electricity for their incubators. After gathering research specifically from the Center for Science, Technology and Society, the team decided to shift some of its focus to the desperate country of Haiti which still has not recovered from the tsunami that hit in January of 2010.

Nigeria, like many other developing countries, has inconsistent electrical power that can go out very easily. Consistent power is extremely important for incubators because a constant temperature is required to keep the baby warm. The main reason Project Omoverhi started was to help combat Nigeria's high infant death rate which is 14.2 times higher than that of the United States. The death rate for babies in Nigeria is 95.8 per 1000, compared to that of 6.7 per 1000 in the United States. Many of these Nigerian babies die due to a lack of available incubators and the power to run them. Infant mortality rates could be greatly improved if there was a way to run these incubators even if electricity was not available 24 hours a day.

The reason that Haiti was chosen as a focal point for the project was because of the lack of protein being produced in their nation. This lack of protein has resulted in many people being malnourished and therefore leading to sickness and death. Currently, much of the nation is still in ruins from the earthquake and tsunami, which killed more than a quarter of a million people in Haiti. It left buildings in piles and cities and towns in ruins. The disaster destroyed the country and therefore a lot of normal daily routines and lifestyles within it. Even something as basic as eating became very difficult for many people within the nation.

Earlier in the year, The Center of Science, Technology and Society approached Project Omoverhi with this problem of malnutrition and asked if the team thought the project could be used to help alleviate this problem. The use of incubators can greatly increase productivity of all birds and any other animal that lays eggs. Therefore the reproduction of chickens was an obvious choice for the use of this system. The use of the system to power chicken brooders could have both economic and health benefits for a suffering nation.

6.3. Project Assumptions and Scope of Influence

For neonatal incubation in Nigeria, it was assumed that the system would be located in public hospitals. For chicken brooding in Haiti, this would be a community scaled project located on centralized farm land. For both of these applications, it is assumed that the amount of solar resources available will satisfy the minimum requirement. In addition, there would be adequate space to house the incubator, thermal storage tank and solar panels and they would be located within a reasonable distance from each other so that they can easily be connected by plumbing. It is also assumed that there will be technicians available capable of following instructions on how to construct and maintain the thermal storage tanks. Lastly, it is assumed that the materials present in the design can be found locally and that the benefit of the product will be worth more than the product itself so that materials are not stolen.

6.4. Cultural Impact

Project Omoverhi's thermal storage tank and its applications would empower the nation of Haiti by increasing chicken reproduction and thereby expanding the availability of high protein food sources. Given the community has the necessary tools and available resources, a few community members would have ability to improve the lives of many others. Making the intended applications more widely available will also decrease gaps between social classes. Currently, only the families with money have access to hospitals with working incubators whereas poorer families do not have this privilege. If this product was to be implemented in conjunction to an incubator, allowing it to be available in all locations, then the social status that the infant was born into would not play a factor in whether or not the appropriate healthcare was provided. Thus, by decreasing the costs of raising a child, a family would have more resources to spend on other important areas. Essentially, a dead baby is a cheap baby, unless someone spent a lot to get it to a hospital. Parents would be using family funds in hopes of saving the newborn, putting the rest of the family at risk. For the applications discussed in this report, thermal storage in a key component and without it, the systems cannot function.

Providing all hospitals and clinics with affordable thermal storage will make care of premature infants accessible to those in all communities.

Our team also considered the negative impacts of the implementation of the project given change almost always faces opposition. Due to the scale and potential impact of this project, it could easily disrupt traditional lifestyles if it isn't properly implemented. In Haiti for instance, the implementation of a community scaled chicken brooder would put more power in the hands of just a few people. Those not in the position to be making money off of the chickens could potentially become upset with this unbalance. Another problem which could arise would result from the increase in reproduction of chickens. With more chickens and their eggs in circulation, the price of chickens and their eggs would decrease putting pressure on individuals with smaller chicken farms to sell at this lower price even if they cannot afford to.

6.5. Sustainable and Environmental Impact

The Omoverhi thermal storage tank is designed to work as part of a sustainable and independent product, adding to the overall sustainability of the community. The thermal storage tank in particular is designed to make use of local products and is intended to last for many years. All of the parts in the design are easily interchangeable and replaceable. For example, components such as tubing can be replaced by any type of tubing or piping. In addition, the phase change material is paraffin wax and can be replaced by any type of candle wax. The scalable design also allows for the replacement of a single "column" if need be. Because of the simplicity of the design, the wax can easily be melted out and replaced as suggested every two years. This preserves the longevity of the product and allows for easy maintenance. The thermal storage tank is designed with several applications in mind. For neonatal incubation, the main goal is to save infant lives and give babies in poor areas the same opportunity that an infant in a developed country has. A key pillar to the Omoverhi mission is to operate completely from renewable energy. Because of the elimination of this dependency on electricity, carbon emissions would be reduced in comparison to incubators which run on grid power.

6.6. Quantified Impact

Project Omoverhi is a self-sustainable product and adds to the overall sustainability of the community. Donated incubators currently use 200-400 Watts of power which is nearly 4.8Wh per day. Because the incubator has to be powered 24 hours a day for several months at a time this adds up to 1.7 MWh each year Nigeria's grid electricity is produced by coal-powered power plants. Assuming that these power plants produce 0.97 kg of CO_2 emissions for each kWh produced the Omoverhi incubator saves the environment 1,649 kg of CO_2 emissions each year. A lack of funding for hospitals in developing nations is the major reason that incubators are not commonly found. Thermal storage tanks that are currently on the market can cost over $1,500. The Omoverhi thermal storage tank costs about $120 therefore giving these hospitals a more likely chance of purchasing them. For chicken brooding, Project Omoverhi has the potential of drastically increasing the production of hens. A hen has the ability to lay an egg everyday but if it wants that egg to hatch it must continuously sit on that one egg for almost a month. Therefore by taking the egg away and putting it in an incubator chicken reproduction rates can be increased by almost 30 times.

6.7. Manufacturability

The Omoverhi thermal storage tank is designed to be built in developing countries using materials that are readily available. The Omoverhi design uses a phase change material to store heat. Many thermal storage materials were considered, however paraffin wax was chosen because it is cheap, available, and operates within the desired temperature range. It is also commonly used as candle wax which is in abundance given candles are often used as a source of light. To properly install the wax into the thermal chamber it first needs to be melted and then poured into the chamber. For the thermal chamber, ABS piping was selected. ABS piping is commonly used in developing countries for plumbing and is sturdy, cheap, and widely available. The cylindrical shape of piping also allowed the design team to take into account the affected diameter of the wax around the heat exchanger. This improves the performance of the product while keeping the design simple and thus cheap to manufacture. With the wax still melted, the heat exchanger made of copper would be inserted and the top cap would be fitted on. To account for the change in volume of the wax as it changes phases, adequate space should be left to insure it does not over flow. In addition, the wax should be exposed to ambient pressure to insure that the thermal chamber does not become pressurized during phase change. In addition, all components were designed to be easily replaced in the event that a part breaks. This was done by using standard parts and fittings which can be found in scrap piles in the targeted developing nations.

Given the simplicity of the design, Omoverhi believes that someone with minimal technical skills would be capable of building such a product in a timely manner. This reduces cost and increases the likelihood of the product being implemented in the targeted areas. Basic manufacturing techniques such as cutting and soldering would be the only manufacturing skills needed. The intended time to manufacture a single column would take a single person approximately 45 minutes, not including time to allow the wax to melt. With multiple column manufacturing and increased experience, the time to reproduce a column would decrease. Given multiple columns are being built simultaneously; it would take approximately 1.5 hours to make four columns. The most time-consuming part of the process is the soldering of the heat exchanger, therefore if the technician is skilled in this area, the target time to create four columns could be reduced to one hour.

7. Summary

Our project uses solar thermal energy storage to directly address energy storage solutions in Haiti and other countries with similar economic situations through social impact. The project goal is to use materials commonly found in the developing countries to make this product available for construction and maintenance within the region of application. Because the project will be used primarily in underserved countries in remote, off power grid areas, it is very simple to build and operate, and it maintains reliability and durability. The design will contain a rectangular shaped box made of wood to house several “columns” made of standard ABS drain pipe that will hold paraffin wax which has a melting temperature between 50 and 60 degrees Celsius. A copper pipe enters and exits from the top of each column to deliver and absorb energy from the phase change material, depending on available sunlight. The number of columns will depend on the size and necessary amount of time or heat that is needed to be stored. A heat storage system like this can have a major influence on the lives of people in developing communities worldwide. The implementation of a constant heat source like Project Omoverhi’s with chicken brooding is only the beginning to the number applications it can be used for. Other potentially impactful applications include small scale dairy pasteurization and neonatal baby incubation. Further research and development would doubtless turn this simple idea into multiple potentially life-changing ideas.

8. Appendices

A. Product Design Specifications

Project Design Specifications (PDS)		
Omoverhi - A Thermal Storage Solution		
Team: Omoverhi		
Elements/Requirements	Units	Parameter/Value
Thermal Storage Unit		
Volume	in^3	581.5
Diameter ABS column	in	4
Diameter ABS caps	in	4
Diameter copper pipe	in	0.5
Length ABS column	ft	4
Length copper pipe	ft	4
Copper pipe to ABS wall width	in	0.75
Total unit height	in	50
Tube connection length	in	9
Maintenance		
Replace paraffin (if possible)	years	2.5
Check connection tube clamps	months	4

B. Budget

a. Prototype Budget

TESTING PROTOTYPE BUDGET			
Discipline	***Parts/Items***	***Number***	***Cost***
Mechanical Components	2 ft ABS Pipe Section; 4'' dia	1	$ 6.24
	ABS Pipe Caps	2	$ 4.89
	2 ft Copper Pipe Section; 1/2'' dia	2	$ 3.11
	90° Copper Elbow; 1/2'' dia	2	$ 1.12
	Copper Nipple; 1/2'' dia	1	$ 0.49
	Copper Pipe Fitting; 1/2'' slip to threaded adapter	2	$ 1.90
	Push-to-Connect Hose Connector	2	$ 15.86
Phase Change Material	Paraffin 3032 Refined Candlemaking Wax	1	$ 3.86
		TOTAL:	$ 37.47

WHOLESALE PROTOTYPE BUDGET			
Discipline	***Parts/Items***	***Number***	***Cost***
Mechanical Components	2 ft ABS Pipe Section; 4'' dia	1	$ 4.20
	ABS Pipe Caps	2	$ 3.34
	2 ft Copper Pipe Section; 1/2'' dia	2	$ 1.86
	90° Copper Elbow; 1/2'' dia	2	$ 0.68
	Copper Nipple; 1/2'' dia	1	$ 0.12
	Copper Pipe Fitting; 1/2'' slip to threaded adapter	2	$ 0.86
	Standard Hose Connector	2	$ 2.34
Phase Change Material	Paraffin 3032 Refined Candle making Wax	1	$ 2.14
		TOTAL:	$ 15.54

b. Total Budget

FINAL DESIGN BUDGET			
Discipline	***Parts/Items***	***Number***	***Cost***
Mechanical Components	2 ft ABS Pipe Section; 4'' dia	1	$ -
	ABS Pipe Caps	2	$ -
	4 ft Copper Pipe Section; 1/2'' dia	1	$ 1.86
	Hose; 1/2'' dia	2	$ -
	Hose Clamp	2	$ 0.27
	Candlewax	1	$ -
		TOTAL:	$ 2.13

Category	Omoverhi				
Date	19-Apr-12				
INCOME					
Category	**Source**	**Sought**	**Committed**	**Pending**	
Grant	ASME (local section)	$ 500.00	$ 500.00		
	Dean's fund	$ 4,500.00	$ 2,000.00		
	Addt'l Santa Clara Fund	$ 500.00	$ 500.00		
	Dean's travel fund	$ 3,200.00	$ 3,200.00	(fund on hold)	
Fundraising					
					$ 3,000.00
	TOTAL	**$ 8,700.00**	$ 3,000.00	$ -	
EXPENSES					
Category	**Description**	**Estimated**	**Spent**	**Pending**	
Plumbing	CPVC pipes and fittings	$ 200.00	$ 287.00		
	ABS columns and fittings	$ 60.00	$ 170.00		
	Galvanized Pipe (3/4in & 1/2in)	$ 80.00	$ 105.00		
	Flowmeter	$ 140.00	$ 138.00		
	Thermometers	$ 250.00	$ 310.00		
	Push Tube Fittings	$ 100.00	$ 130.00		
	Pump	$ 100.00	$ 137.00		
Heating	Water Heater	$ 600.00	$ 590.00		
	Hard Wiring Cables	$ 40.00	$ 132.00		
Columns	PCM	$ 200.00	$ 180.00		
	Piping	$ 200.00	$ 190.00		
	Acrylic	$ -	$ -		
	Epoxy	$ 50.00	$ 82.00		
Insulation	R19 Insulation	$ 40.00	$ 55.00		
	R13 Insulation	$ 20.00	$ 25.00		
	Insulation Enclosure	$ 20.00	$ 40.00		
	Reflective Insulation Tape	$ 30.00	$ 60.00		
	Gloves	$ 10.00	$ 15.00		
Tools	PVC Saw	$ 15.00	$ 14.00		
	Torch (propane)	$ 60.00	$ 60.00		
	Pipe Wrench	$ 25.00	$ 25.00		
	Misc.	$ 75.00	$ 73.00		
Utilities	Heating/Gas/Electricity	$ 100.00	$ 100.00		
Travel (tentative)	Flights	$ 1,600.00	$ -	on hold	
	Housing	$ 800.00	$ -	on hold	
	Food	$ 400.00	$ -	on hold	
	Guide	$ 400.00	$ -	on hold	
					$ 2,918.00
	TOTAL	**$ 5,615.00**	$ 2,918.00	$ -	
					$ 82.00
	Net Reserve (Deficit)		$ 82.00	$ -	
	*Travel funding not included in calculations. $82 left in our budget.				

c. Concept Scoring Matrix

	TARGET or	DESIGN IDEAS																			
CRITERIA	FACTOR	Baseline		1		2		3		4		5		6		7		8		9	
Time - Design	20	20		40		35		50		40		50		50		50		50		50	
Time - Build	20	20		90		55		100		65		34		40		60		34		90	
Time - Test	100	100		20		15		20		15		65		50		54		43		80	
Time Score	10		10		9.33		13.33		8.24		11.67		9.40		10.00		8.54		11.02		6.36
Cost - Prototype	$ 300	$ 300		$ 200		$ 80		$ 100		$ 90		$ 500		$ 500		$ 500		$ 500		$ 500	
Cost - Production	$ 200	$ 200		$ 400		$ 150		$ 150		$ 165		$ 200		$ 300		$ 150		$ 200		$ 200	
Cost Score	5		5		4.17		10.87		10.00		9.80		3.57		3.13		3.85		3.57		3.57
Size	7	3	5	7	5	7	4	7	5	7	8	7	6	7	7	7	6	7	5	7	9
Weight	7	3	5	7	5	7	4	7	5	7	8	7	4	7	7	7	8	7	5	7	9
Durability	6	3	5	6	6	6	5	6	6	6	8	6	6	6	7	6	8	6	5	6	8
# of parts	4	3	5	4	7	4	6	4	8	4	8	4	6	4	9	4	8	4	5	4	8
Material Availability	3	3	3	3	9	3	3	3	3	3	3	3	5	3	8	3	4	3	8	3	6
Scalability	6	3	9	6	8	6	7	6	6	6	5	6	7	6	8	6	4	6	5	6	8
Efficiency (harnessing)	2		5	2	7	2	3	2	6	2	4	2	8	2	9	2	8	2	6	2	8
Efficiency (Storage time)	2	3	6	2	4	2	4	2	4	2	4	2	8	2	9	2	8	2	8	2	8
	TOTAL		58.0		64.5		60.2		61.2		69.5		63.0		77.1		66.4		61.6		73.9
	RANK																				
	% of MAX		75.2%		83.6%		78.1%		79.4%		90.1%		81.6%		100.0%		86.1%		79.9%		95.9%

C. Other Calculations

a. Heat Exchanger Length

The LMTD method was used to calculate the heat exchanger length for a tube in tube heat exchanger.

$$\Delta t_1 = 80 - 30 = 50^{\circ}C$$

$$\Delta t_2 = 60 - 25 = 35^{\circ}C$$

$$LMTD = \frac{(\Delta t_1 - \Delta t_2)}{\ln\left(\frac{\Delta t_1}{\Delta t_2}\right)} = \frac{(50 - 35)}{\ln\left(\frac{50}{35}\right)} = 42.055^{\circ}C$$

Flow Rate Assumption: 0.2kg/second

$$\left(\frac{0.2}{s}\right)\left(\frac{3600s}{hr}\right) = 720\,\frac{kg}{hr}$$

Heavy Duty Q:

$$Q = mC_p(T_2 - T_1) = (720)(4.187)(50) = 150{,}732\,\frac{kJ}{hr}$$

Cold Water Flow Rate:

$$CWFR = \frac{Q}{C_p(\Delta t_2 - \Delta t_1)} = 1{,}028.6\,\frac{kg}{hr}$$

Velocity:

$$V = \frac{720}{998} = 0.72144\,\frac{m^3}{hr}$$

$$\frac{0.72144}{0.0003683} = 1{,}958.85\,\frac{m}{hr} = 0.54412\,\frac{m}{s}$$

$$Re = \frac{(0.02057)(0.72144)(998)}{(8x10^{-5})} = 185{,}165.259$$

$$Pr = \frac{4.187(998)(8x10^{-5})}{0.623} = 0.53765$$

$$Nu = 0.023Re^{0.8}Pr^{0.3} = \frac{h_i d_i}{k}$$

$$h_i = Nu\left(\frac{k}{d_i}\right) = 9{,}464.43\frac{W}{m^2}{}^{\circ}C$$

Flow Area Annulus =$3.691x10^{-3}m^2$

Wetted Perimeter=$\pi(0.049149) = 0.15441m$

Hydraulic diameter of annulus=$d_h = 4\left(\frac{3.691x10^{-3}}{0.15441}\right) = 0.09516m$

$$A_o = \pi(0.022225)L$$

$$A_i = \pi(0.02057)L$$

$$A_m = \frac{(OD - ID)}{\ln\left(\frac{OD}{ID}\right)} = 0.02139\pi L$$

$$\frac{A_o}{A_m} = 1.0392$$

$$\frac{A_o}{A_i} = 1.0805$$

$$\frac{1}{U_o} = \frac{1}{h_o} + \left(\frac{A_o}{A_m}\right)\left(\frac{r_o - r_i}{kw}\right) + \left(\frac{A_o}{A_i}\right)\left(\frac{1}{h_i}\right)$$

$$\frac{1}{U_o} = \left(\frac{1}{9{,}464.43}\right) + (1.0392)\left(\frac{0.003175}{0.623}\right) + (1.0805)\left(\frac{1}{9{,}464.43}\right) = 0.0040033$$

$$U_o = 249.791\frac{W}{m^2}K$$

$$CWFR = U_o A_o \Delta t_m(0.085422)$$

$$A_o = \frac{1028.6}{(249.791)(42.055)(0.085422)} = 1.1463m^2$$

$$L_{tube} = \frac{A_o}{\pi(0.022225)} = 16.4176m$$

D. Matlab Code

```
%PROJECT OMOVERHI THERMAL ENERGY STORAGE CALCULATIONS


%This analysis will determine the following:
%1. Load supplied by incubator
%2. Storage Capacity
%3. Charge Capacitance
%4. Source Capacity
%From these values the system can be properly sized for certain
%scenarios.
%From the values above, systems will be sized to provide energy
%required
%for 1,2,3,4, and 5 days.
```

a. Load Supplied by Incubator

```
%Calculation of energy required to provide heat to incubator for
%1,2,3,4,and 5 days.

%q_incubator = Heat required to maintain incubator at optimum
%temperature. [W]
%m_dot= Mass flow rate through incubator [kg/s]
%dT= Change in temperature [K]


format('longG')
m_dot_water=0.1265;          %[kg/s] Mass flow rate of water
%through incubator
cp_water=4180;               %[J/kg-K] Specific heat of water
```

```
dT_water=.29;              %[K] Change in temperature of water
%through incubator. Dependent on m_dot.

q_incubator=m_dot_water*cp_water*dT_water;       %Use first law
%of thermodynamics to calculate load supplied by incubator. [W]


%Calulation of energy required to power incubator for specified
%time.

q_oneday= q_incubator*24*3600*1;         %[J] Energy required to
%run incubator for 1 day
q_twoday= q_incubator*24*3600*2;         %[J] Energy required to
%run incubator for 2 days
q_threeday= q_incubator*24*3600*3;       %[J] Energy required to
%run incubator for 3 days
q_fourday= q_incubator*24*3600*4;        %[J] Energy required to
%run incubator for 4 days
q_fiveday= q_incubator*24*3600*5;        %[J] Energy required to
%run incubator for 5 days
```

b. Determining Storage Capacity

```
%Thermal energy can be stored as latent heat + sensible heat.

%q_sensible = Sensible heat stored in the material [J/kg]
%(q_sensible=m*cp*dT)
%q_latent = Latent heat stored in the material [J/kg]
%(q_latent=m*h_sl)

%V = Volume of substance [m^3]
%rho = Density of substance [kg/m^3]
%m = Mass of substance [kg]
%cp = Specific heat capacity of substance [J/kg-C]
%dT = Temperature change [K]
%h_sl = Heat of fusion [kJ/kg]
%h = height [m]

%Calculating volume in a 4 foot 'column'

r_column = 0.0508;      %[m] radius of 'column.' Measured to
%inside edge
r_HEX = 0.009525;       %[m] radius of heat exchanger piping.
%Measured to outside.
```

```
h_column=1.2192;         %[m] height of 'column'
rho_paraffin= 930;       %[kg/m^3] density of parafin wax
%(Approximately. Note: Paraffin wax changes density with
%temperature. Incorporating the change in density of the
%paraffin is beyond the scope of this analysis.)
cp_paraffin=2140;        %[J/kg-K] Specific heat of paraffin wax
dT_paraffin=15;          %[K] Temperature change in paraffin
h_sl= 200000;            %[J/kg] Heat of fusion of paraffin wax
V =(pi*r_column^2*h_column)-(pi*r_HEX^2*h_column);   %Volume of
%substance within 'column'

% Calculating mass of paraffin wax in single 'column'.
m_paraffin = rho_paraffin*V;        %[kg] Mass of substance

%Required storage capacity is equal to the energy required to
%heat incubator
%for specified amount of time. Energy requirements of 1,2,3,4,
%and 5 days
%were considered.
%Total thermal energy stored in a single 'column' is equal to
%the sensible %heat + latent heat.

q_sensible=m_paraffin*cp_paraffin*dT_paraffin;       %[J]
%Sensible heat
q_latent= m_paraffin*h_sl;                           %[J] Latent
%heat

energy_column=q_sensible+q_latent;                   %[J]
%Thermal energy stored in 'column' of specified length

no_columnsoneday = q_oneday/energy_column       %Number of
%columns needed to supply energy for one day
no_columnstwoday = q_twoday/energy_column       %Number of
%columns needed to supply energy for two days
no_columnsthreeday = q_threeday/energy_column   %Number of
%columns needed to supply energy for three days
no_columnsfourday = q_fourday/energy_column     %Number of
%columns needed to supply energy for four days
no_columnsfiveday = q_fiveday/energy_column     %Number of
%columns needed to supply energy for five days

%Calculating volume of wax needed for specified system sizes.
conversion_cubemetertogallon=264.17;    %Conversion from cubic
%meters to gallons

waxneeded_oneday=no_columnsoneday*V*conversion_cubemetertogallon
%Amount of wax needed for system sized for one day
```

```
waxneeded_twoday=no_columnstwoday*V*conversion_cubemetertogallon
%Amount of wax needed for system sized for two days
waxneeded_threeday=no_columnsthreeday*V*conversion_cubemetertoga
llon %Amount of wax needed for system sized for three days
waxneeded_fourday=no_columnsfourday*V*conversion_cubemetertogall
on  %Amount of wax needed for system sized for four days
waxneeded_fiveday=no_columnsfiveday*V*conversion_cubemetertogall
on  %Amount of wax needed for system sized for five days
```

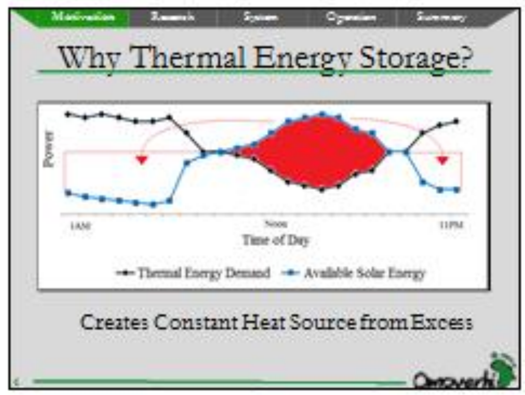
c. Determining Charge Capacity

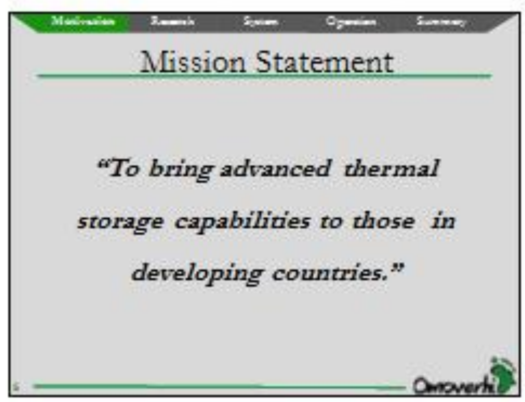
```
dT_column=25;         %Change in temperature of 'column' during
%charging. Assume from room temp (20C) to melted (55C).

charge_cap=m_paraffin*(cp_paraffin*dT_column+h_sl)  %[J] Charge
%capacity for %single 'column'

%Determining power source required to heat 'column' to full
%charge
%capacitance.
hours_exp=8;          %Desired hours until 'column' is fully
%charged.

q_source_singlecolumn=charge_cap/(hours_exp*3600)        %[W]
%Amount of power needed to fully charge one 'column'.

q_sourceoneday=(charge_cap/(hours_exp*3600))*no_columnsoneday
%[W] Amount of power required to fully charge tank sized for one
%day.
q_sourcetwoday=(charge_cap/(hours_exp*3600))*no_columnstwoday
%[W] Amount of power required to fully charge tank sized for two
%days.
q_sourcethreeday=(charge_cap/(hours_exp*3600))*no_columnsthreeda
y   %[W] Amount of power required to fully charge tank sized for
%three days.
q_sourcefourday=(charge_cap/(hours_exp*3600))*no_columnsfourday
%[W] Amount of power required to fully charge tank sized for
%four days.
q_sourcefiveday=(charge_cap/(hours_exp*3600))*no_columnsfiveday
%[W] Amount of power required to fully charge tank sized for
%five days.
```

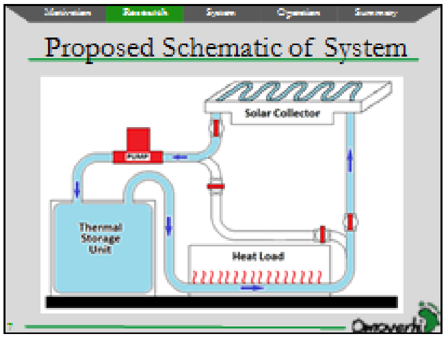
d. Determining Source Capacity

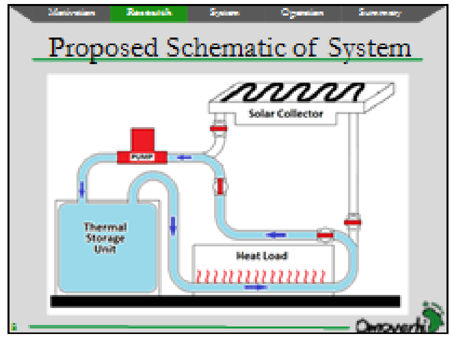
```
q_solar=500;        %[W/m^2] Solar energy provided per square
%meter
A_solar=4.15;       %[m^2] Area of chromasun solar collector
%q_source=1200      %[W] from last years group
eff_collector=.6    %Efficiency of chromasun solar collector at
590 degrees C operating temperature

q_collector=q_solar*A_solar*eff_collector

%Determining number of solar collectors needed for specified
%system size.

no_collectorsoneday=q_sourceoneday/q_collector      %Number of
%collectors needed to provide adequate energy to charge system
%sized for one day.
no_collectorstwoday=q_sourcetwoday/q_collector      %Number of
%collectors needed to provide adequate energy to charge system
%sized for two days.
no_collectorsthreeday=q_sourcethreeday/q_collector  %Number of
%collectors needed to provide adequate energy to charge system
%sized for three days.
no_collectorsfourday=q_sourcefourday/q_collector    %Number of
%collectors needed to provide adequate energy to charge system
%sized for four days.
no_collectorsfiveday=q_sourcefiveday/q_collector    %Number of
%collectors needed to provide adequate energy to charge system
%sized for five days.
```

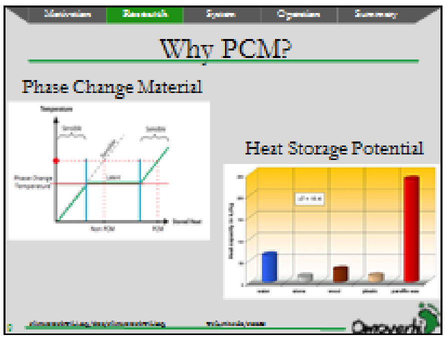
E. Design Conference Presentation Slides

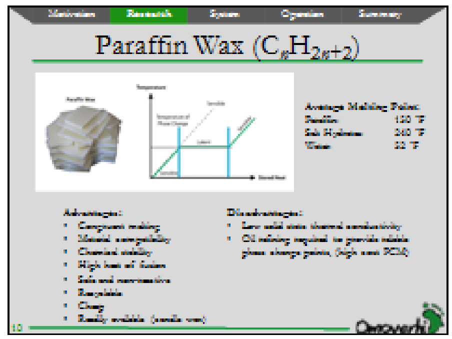


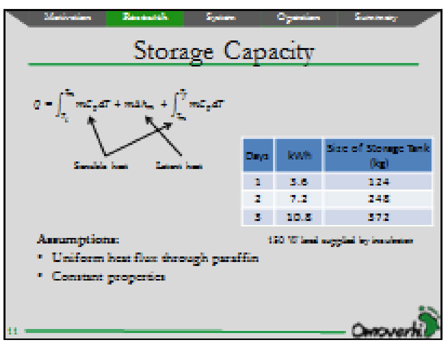


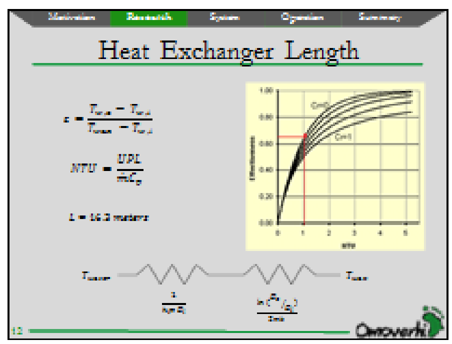

Proposed Schematic of System
Solar Collector
PUMP
Thermal Storage Unit
Heat Load
Omoverhi

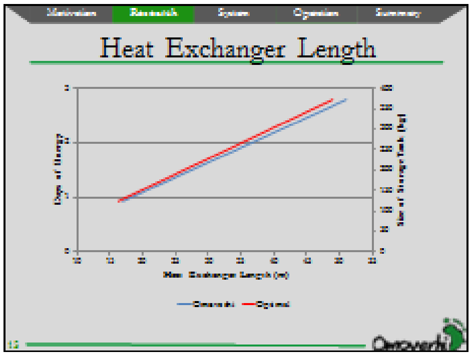

Proposed Schematic of System
Solar Collector
PUMP
Thermal Storage Unit
Heat Load
Omoverhi

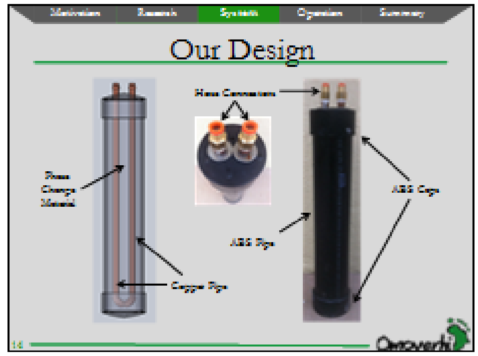

Why PCM?
Phase Change Material
Heat Storage Potential
Omoverhi

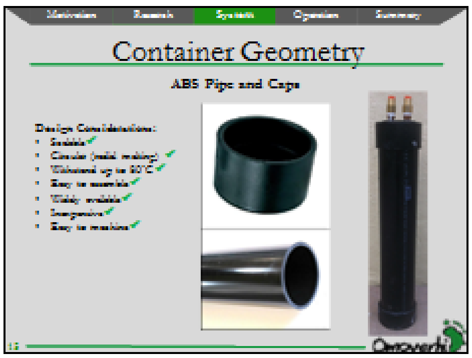

Paraffin Wax (C_nH_{2n+2})
Omoverhi

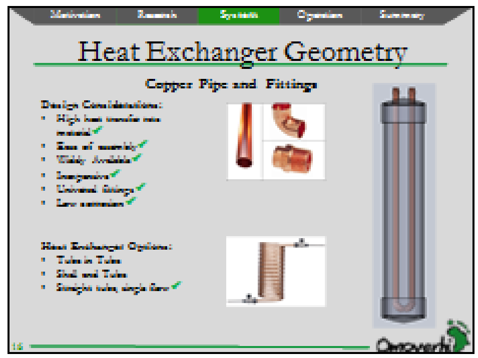

Storage Capacity
Days | kWh | Size of Storage Tank (kg)
1 | 3.6 | 124
2 | 7.2 | 248
3 | 10.8 | 372
Assumptions:
Uniform heat flux through paraffin
Constant properties
Omoverhi

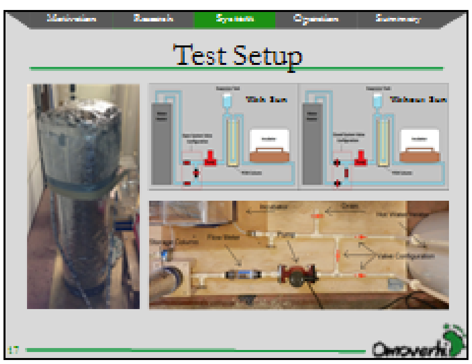

Heat Exchanger Length
Omoverhi


Heat Exchanger Length
Omoverhi


Our Design
Phase Change Material
Copper Pipe
ABS Pipe
ABS Caps
Omoverhi

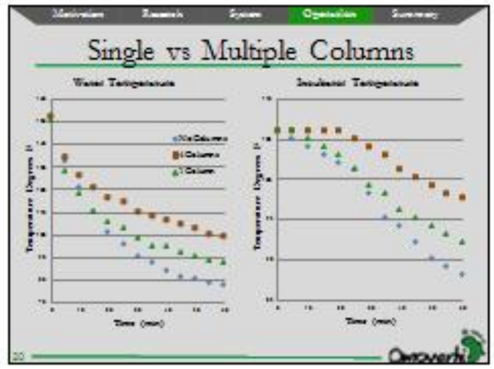

Container Geometry
ABS Pipe and Caps
Design Considerations:
Omoverhi


Heat Exchanger Geometry
Copper Pipe and Fittings
Design Considerations:
Heat Exchanger Options:
Omoverhi

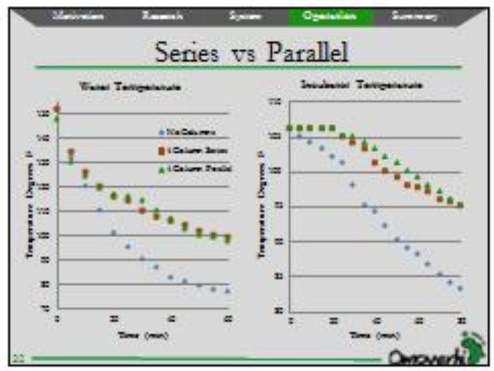

Test Setup
Omoverhi

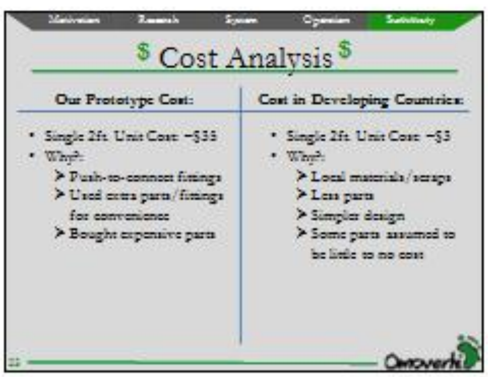

Challenges
Sealing the system
Temperature Resistant Materials
Insulation
Cost vs Effectiveness of Materials
Omoverhi


Series


Single vs Multiple Columns
Time (min)
Time (min)


Parallel


Series vs Parallel
Time (min)
Time (min)


Cost Analysis
Our Prototype Cost:
Single 2ft. Unit Cost ~$35
Why?:
Push-to-connect fittings
Used extra parts/fittings for convenience
Bought expensive parts
Cost in Developing Countries:
Single 2ft. Unit Cost ~$3
Why?:
Local materials/scraps
Less parts
Simpler design
Some parts assumed to be little to no cost


Conclusions
What kind of effects can our heat storage column have?
Provides an affordable solution to a bigger problem
Improves standard of living
Feeds local economy from within


Future Goals
• Try variety of PCM's
• Test with solar collector
• Improve thermal conductivity of wax
• Design optimization
➢ Quicker charge time
➢ Multiple columns
• Devise a manufacturing plan
Omoverhi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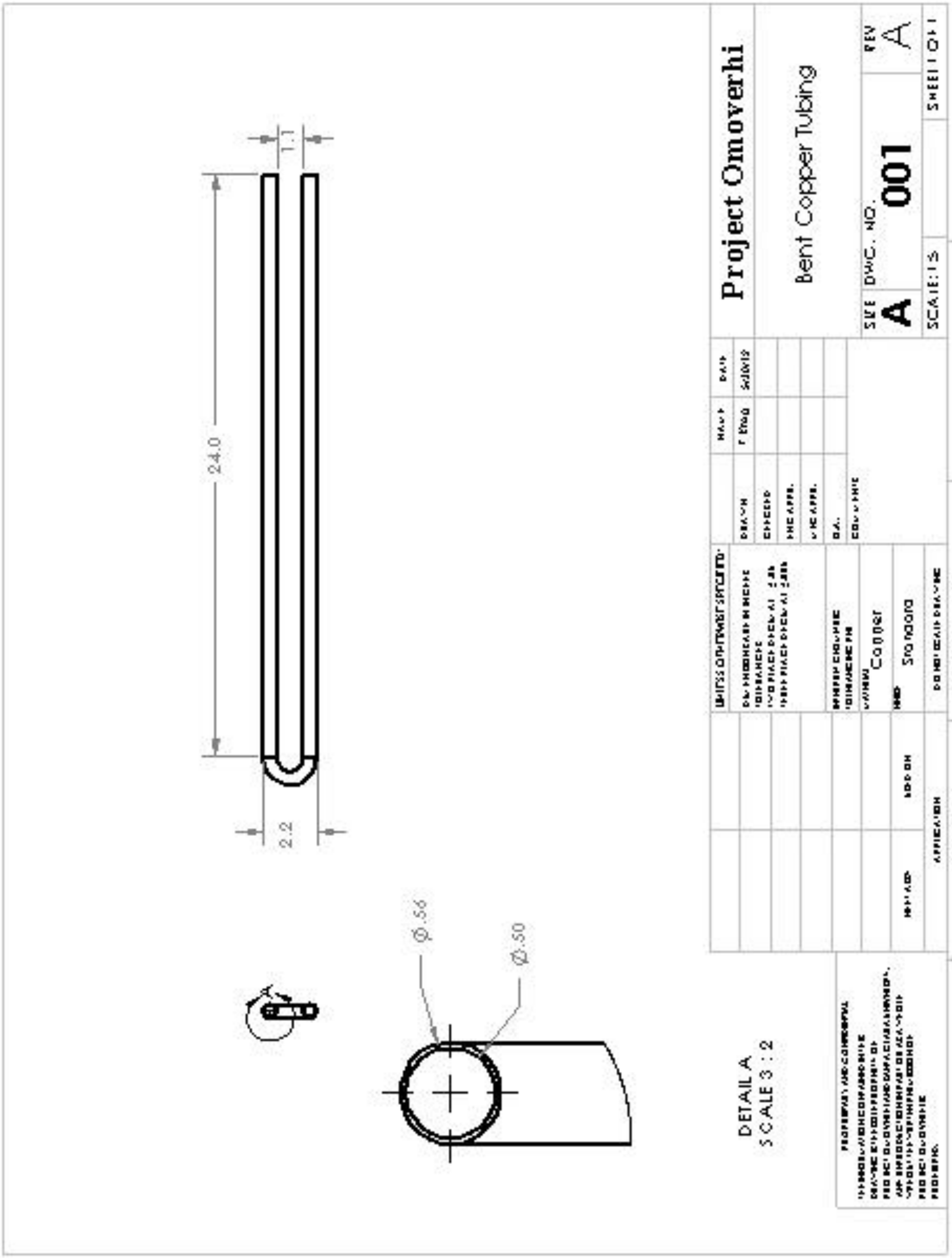
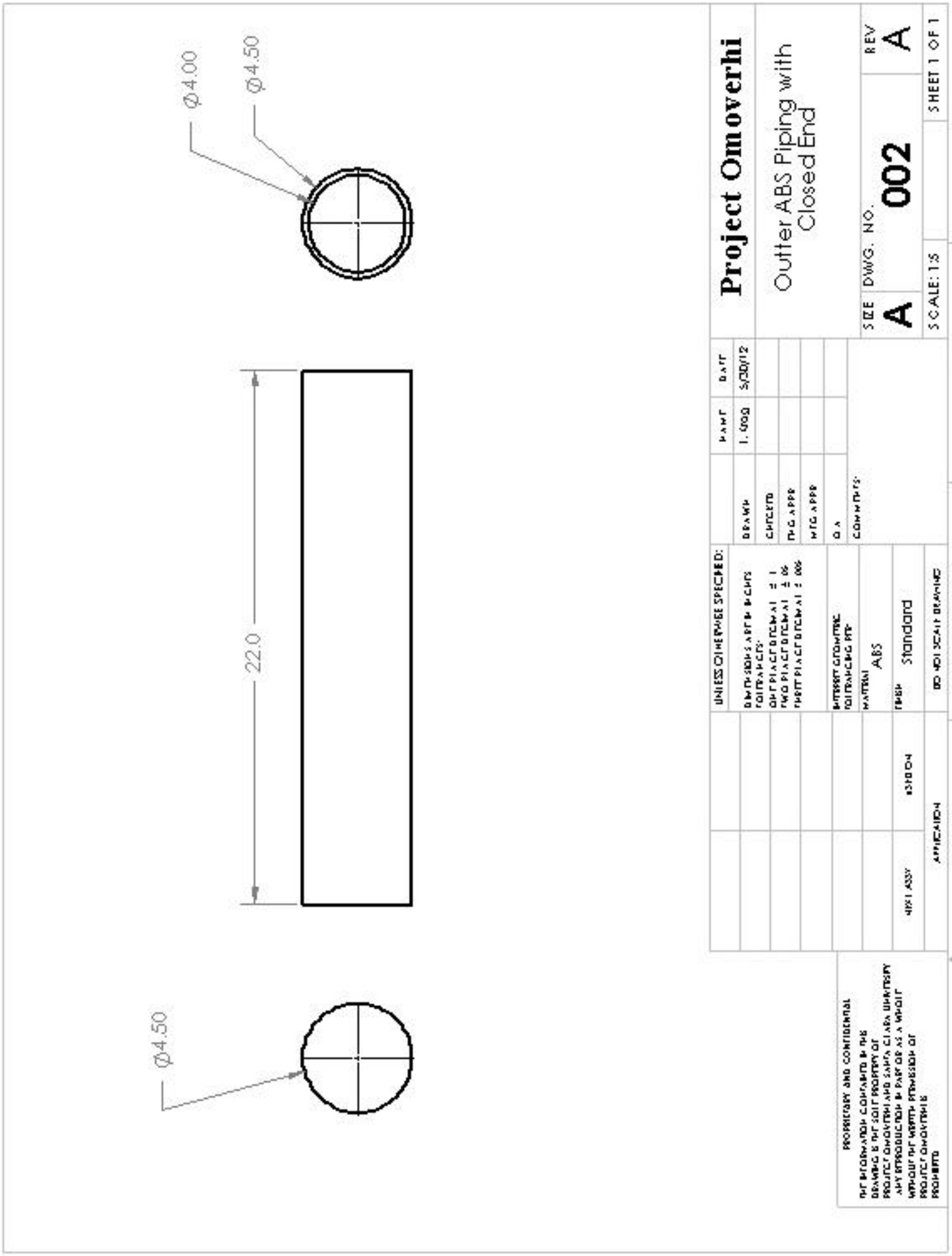
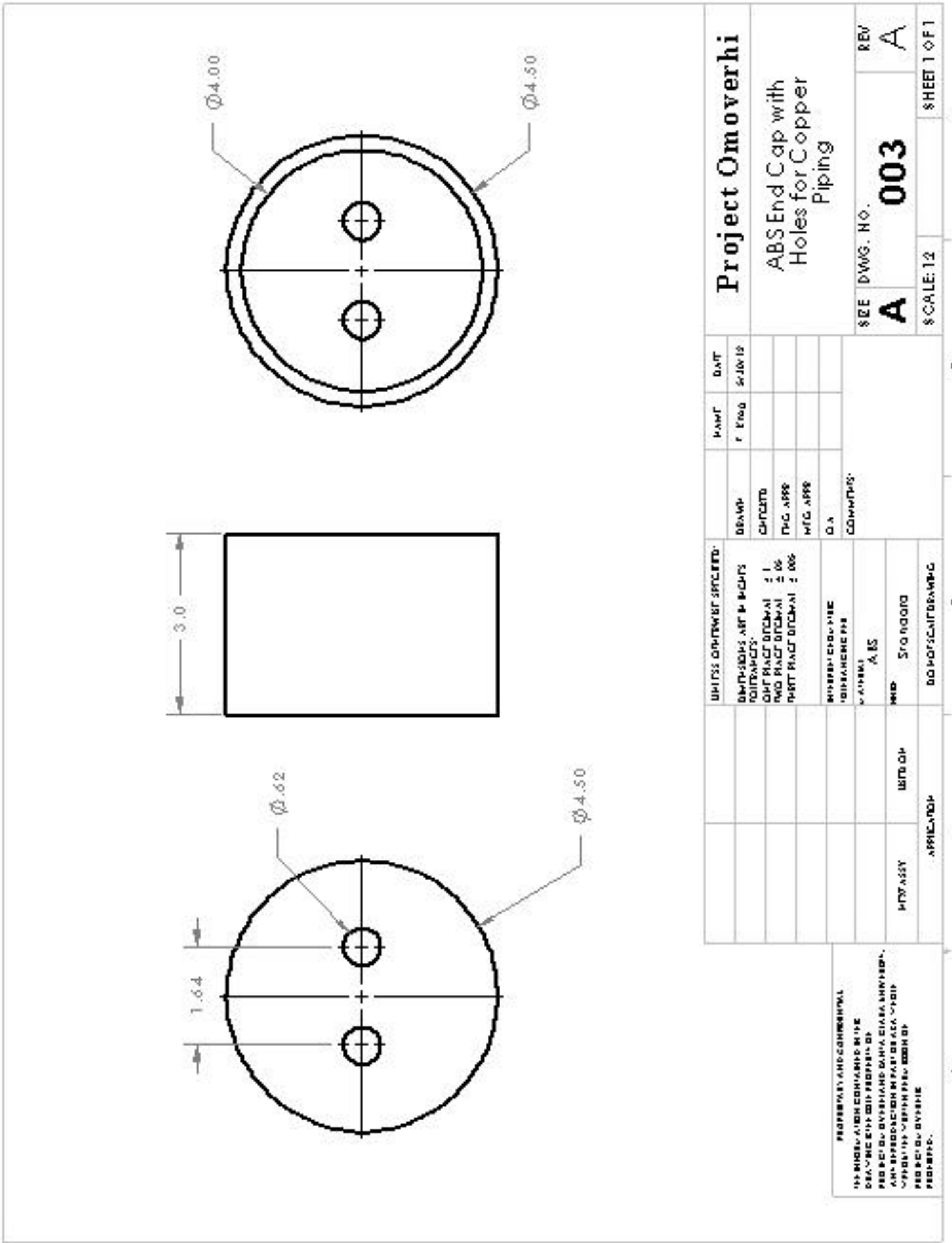
ASME- Santa Clara Valley Section
Dr. Timothy Hight and Dr. Hohyun Lee
2011 Omoverhi Team
Gentlemen of 890 Poplar Street
ASME
100
Omoverhi


Thank you
Omoverhi
100

F. Detailed Drawings




Ø4.00
Ø4.50
22.0
Ø4.50
Project Omoverhi
Outter ABS Piping with Closed End
SIZE A
DWG. NO. 002
REV A
SCALE: 1:5
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED:
DRAWN
CHECKED
MATERIAL ABS
FINISH Standard
DO NOT SCALE DRAWING
APPLICATION
PROPRIETARY AND CONFIDENTIAL


Ø4.00
Ø4.50
3.0
Ø.62
Ø4.50
1.64
Project Omoverhi
ABS End Cap with Holes for Copper Piping
SIZE A
DWG. NO. 003
REV A
SCALE: 1:2
SHEET 1 OF 1
ABS
Standard

G. Manufacturers Information

a. Paraffin Wax Manufacturing Sheet Comparing Different Waxes

Paraffin waxes are available in 10-pound slabs packaged 5 slabs per case. Call for additional information.

3032, 3134 & 4144 are manufactured in compliance with FDA regulations covered under Title 21, sections 172.886 and 178.3710

Paraffin waxes are available in bulk liquid also.

Paraffin Wax

Paraffin	Applications	Melting Point ºF	Penetration	Color Saybolt	Oil Content	Product Data Sheet	MSDS
CF	Container/Jar	122	35	+28	1.5%	PDS	MSDS
3032	Container/Jar/Votive/Hand Dipping	127	17	+30	0.3%	PDS	MSDS
3134	Votive/Novelty/Whipped Wax	131	16	+31	0.4%	PDS	MSDS
4144	Pillar/Taper	141	12	+32	0.3%	PDS	MSDS

Highly Refined Paraffin Wax

These highly refined paraffin waxes are from selected petroleum feedstocks and are white, odorless and all have oil contents less than .5%.

Paraffin	Applications	Melting Point ºF	Penetration	Color Saybolt	Oil Content	Product Data Sheet	MSDS
4045EP	Cut n' carve	142	10	+30	0.18%	PDS	MSDS
5055	Botanical/One Pour Votive	152	11-18	+30	0.33%	PDS	MSDS
5560	One Pour Votive	156.5	11-19	+30	0.12%	PDS	MSDS

5055 exhibits excellent transparency combined with enhanced hardness that makes them suitable for use as the outer shell of botanical candles.

Highly refined paraffin waxes are available only in 10.2-pound slabs packaged 5 per case.

4045 EP, 5055 & 5560 are all manufactured in compliance with FDA regulations.

b. Paraffin 3032 Specifications Sheet

Test Description	ASTM Method	Minimum	Maximum	Typical
Melting Point ˚F / ˚C	D 87	126/52	130/54	127/53
Penetration @ 77˚F/25˚C	D 1321		18	17
Color Saybolt	D 156	+30		+30
Oil Content	D 721		0.5	0.3
Flash, PM ˚F/˚C	D 93	385/196		420/216
Viscosity, SUS, 210˚F/98.9˚C	D 2161	37	39	38
Viscosity, cSt, 210˚F/98.9˚C	D 445	3.3	3.9	3.6
Odor	D 1833		2	1

Recommendations

- Additives are recommended for optimum results.
- Pouring temperature can range fro 170˚ - 190˚ F, depending on application.
- Common additives used in this paraffin wax - Mico 845, Vybar 260, Petrolatum & AstorLite C.
- Always use Ultralight Absorbers to prevent fading.

Packaging

- 3032 is available in 50 lb. cases - 40 cases per pallet (2,000 lbs.) - slab on pallet is 2,100 lbs.
- Available slab on pallet and cases in PA.
- Available in cases only from Chicago, IL.

FDA Status

- 3032 is a food grade paraffin that is manufactured in compliance with FDA regulations covered under Title 21, sections 172.886 and 178.3710.

CANDLEWIC

The Candlewic Company
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H. Applicable Patents

Project Omoverhi did not want to patent parts of this design because it wants others to be able to use it. It isn't necessarily an innovative design, but more of a simple design that can be created with very basic materials. The simplicity makes it more widely applicable.

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