ABSTRACT

Energy storage has been a long-standing issue for solar cookers due to the inability to cook at night. The Solar CookStove is a project that seeks to improve the method of cooking in developing regions of India by using Phase Change Material (PCM) to counter this problem. PCM has a high thermal energy storage capacity, meaning that it stores and releases a large amount of energy while changing from the solid to liquid phase at a particular temperature. The PCM used in this project is Erythritol, due to its high melting point, inexpensive price, and easy availability. Since present cooking methods such as biomass in these regions are inefficient and have health concerns, the Solar CookStove aims to provide an easy, relatively inexpensive and green method of cooking food. The Solar CookStove consists of two major components – a cooking unit and a solar reflector. The cooking unit contains the Phase Change Material (PCM) that can store as well as transfer energy to the cooking surface. The reflector is a parabolic mirror that helps focus the sunlight onto the cooking unit. The Solar CookStove has been designed to be sustainable as well as useful for cooking after sunset.

Based on the energy needed to cook by a family of five, the Solar CookStove will store 8000 kJ of energy. After multiple design iterations, tests and optimizations, the system was able to transfer 275 Watts during the day and 170 Watts after dark out of the system. If produced at source with the help of governmental organizations and donors, the Solar CookStove can prove to be a safe, sustainable, and affordable source of cooking food for families in India.

1. INTRODUCTION AND BACKGROUND

In developing countries, cooking is often done through the burning of biomass such as wood, charcoal, animal, and agricultural waste. The popularity of biomass stems from its affordable price as well as easy availability. Although biomass is popular due to its affordability, it does not convert energy efficiently. The burning of biomass is also harmful for the environment and raises several health concerns such as lung cancer, bronchitis, and severe burns. Burning of biomass is estimated to cause nearly 2 million premature deaths annually [1].

This issue has gained global attention. There are several solutions to this problem in developing countries such as promoting the use of cleaner and more efficient biomass cook stoves that would cost more. Another option would be to promote the use of electricity and fossil fuels as LPG.

However, our team sought to address the problems of biomass using a green source of energy that is inexpensive, sustainable, and easy to construct with materials that are readily available. Solar energy and the concept of solar cookers fit the requirements mentioned above. Several organizations such as the Global Alliance for Clean Cookstoves are attempting to solve the problem of biomass by promoting solar cookers due to their clean nature [2]. There have been several configurations of solar cookers in the form of panel cookers, trough cookers, and box cookers. Solar cookers, however, have not been popular due to the solar energy supply-demand problem. When the sun is shining during the day solar energy is readily available, but the demand for energy during the day is relatively low. Energy is mostly required at night when the sun is down.
However, the supply of energy via the sun is negligible at night. This is why solar cookers have not been a feasible option [3].

**Figure 1 - Solar Funnel Cooker**

Therefore, our solution was to build solar cooker that focused on heat storage. The Solar CookStove looked to counter the energy supply-demand problem by using Phase Change Material (PCM). PCMs have a high heat of fusion resulting in a high thermal energy storage capacity. They store a large amount of energy when changing from the solid to liquid phase at a particular temperature and release this energy when solidifying. The PCM used in this project is Erythritol, selected due to its high melting point of 118°C, inexpensive price, and easy availability. Erythritol provides energy after dark by storing the excess heat during the day, and releasing it during the night.

### 2. CANDIDATE CONCEPTS

We decided to build a family cook stove suitable for 4-6 people. Our team thought of various physical configurations for the Solar CookStove, and narrowed it down to two options: an indirect heating approach and a direct heating option. With the indirect heating system, the sunlight would heat a heat transfer fluid that would in turn heat the PCM above its melting point of 118°C. As shown in an initial prototype in Figure 2, the heat transfer fluid would pass through the pipe and heat the PCM through direct conduction.

**Figure 2 - Indirect Heating Design**

This method, however, was deemed to be very inefficient after testing due to the different layers of heat transfer resistance and large amounts of heat loss that were associated with this design. Moreover, the heat pump system that was needed to make the heat transfer fluid flow made the cook stove very complex. One of the main goals of the Solar CookStove was that it should be sustainable and user friendly. Having such a complicated design made the Solar CookStove difficult to use for the final consumer and inconsistent with our goals.

Therefore, our team decided to adopt a direct heating approach as shown in Figure 3. Using the new design, the solar flux from the sun would be reflected directly on the black conducting plate of the cooking unit that contains the PCM. This design concept removes an extra layer of energy exchange by eliminating the need for the heat transfer fluid and the complications and inefficiencies associated with the piping system.

**Figure 3 - Direct Heating Design**

Since another of our requirements was to make the Solar CookStove easy to assemble and repair, the direct heating approach helped minimize the number of components. Making a system sustainable is easier with a fewer number and easily available components. Hence, simplicity was a key ingredient of this design.
3. DESIGN DESCRIPTION

3.1 Solar Reflector

For our final design we chose a Scheffler-type reflector to concentrate the sunlight. The main advantage of this type of reflector over the other types that we considered (parabolic trough, parabolic dish, and a sun funnel), was the steady daily and seasonal focal point that the shape achieved. The mirror is based off of a section of a 3D parabola, the same as a normal satellite dish. Where the Scheffler-type differs is in the choice of section, instead of a central section it takes an eccentric section, as shown in the diagram below.

Figure 4 - Scheffler Reflector Shape

This shape causes the focal point to be located outside of the reflector, and greatly simplifies our storage unit design. To maintain the focal point during the day, the reflector is rotated about an axis that goes through the focal point and is perpendicular to the plane of the sun path at that time of year. A tracking system, either clockwork or electric, is used to keep the central axis of the parabola pointed directly at the sun during the day. The clockwork mechanism can be built from discarded motorcycle parts, and uses a pendulum to regulate a falling weight that provides the force to turn the reflector. The electronic method uses a motor to turn the motor, and senses the position of the sun using two photovoltaic panels. They are arranged such that when the reflector is pointed directly at the sun, they both receive the same amount of sunlight, but when it is turned one way or another one panel receives more light than the other. Depending on which panel is pointed at the sun, either a positive or negative voltage is produced, driving the motor in the appropriate direction. This method requires the axis to tilt throughout the year, as the sun path changes by ~55 degrees from solstice to solstice. The shape of the parabola must also change throughout the year, the change in inclination produces a different focal point, which is illustrated here.

Figure 5 - Scheffler Reflector Seasonal Changes

[6]

3.2 Cooking Unit

Initially, we planned to build a simple box containing both a cooking section and an energy storage section (see Figure 6). The cooking section sits directly on top of the storage section. On the front of the cooking unit, a sealed glass chamber, similar to a window, is attached. Air is sandwiched between the conducting plate of the cooking unit and the glass to prevent heat loss. This conducting plate is then connected to the heat fin network. The heat fin network is made of multiple straight metal fins, bent on that front to attach to the conducting plate, that run the length of the PCM. This aluminum network is designed to increase the surface area of heat conduction so that the heat can get transferred from the black plate to the PCM quickly and more evenly.

Figure 6 - Final Cooking Unit Design
In terms of the cooking unit, our final prototype was very similar to our final design with a few small changes made after further analysis and manufacturing restrictions. The final prototype still follows our general design of a simple box containing both a cooking section and an energy storage section.

4. PROTOTYPE REALIZATION

The final prototype cooking unit is comprised of five components: an aluminum lid, cooking vessel, cooking plate, fins, and conducting plate. These components are labeled in the picture shown below:

Figure 7 - Exploded View of Cooking Unit (without Insulation)

4.1 Cooking Unit including Aluminum Lid

The cooking unit is an aluminum box with a hinged lid. The overall size is 13 x 13 x 15 inches. The fins have a height of 3.5 inches and a length of just under 13 inches. The PCM is contained within the same area as the fins. The cooking vessel is then placed on top of this energy storage section and contained within the system.

4.2 Conducting Plate

The front of the cooking unit, which faces the reflector during use, is painted with a high temperature thermal paint. This black surface helps the cooking unit absorb and conduct the reflected solar energy from the collector.

4.3 Fins

On the inside of the cooking unit, there are multiple fins attached to the black plate. The fins serve as a heat transfer network that conducts the heat through the PCM. The fins, with their high thermal conductivity, help melt the PCM more quickly by distributing the temperature more evenly through the system. These fins have a 90 degree flange both on the top and the front to provide for good contact with the black plate and a flat for the cooking plate to rest on. The picture below demonstrates the geometry of these fins:
The fins in the final prototype are attached to the cooking unit with thermal adhesive on the front bend. This solution was reached after testing two different methods of attachment on a smaller prototype. The first method involved using fasteners (shown in Figure 9) to attach the fins to the front face of the cooking unit.

This method proved effective in terms of heat transfer; however, PCM started leak out of the holes created by the fasteners after multiple tests. The next method considered was spot welding. This method could work in the future, but was not practical for our prototype because of the geometry of the spot welder. It was possible to attach one fin, but there was not enough room for the welder arm to reach inside of the box to attach more fins.

For future designs, it would be practical to attach the fins using MIG welding. We did not utilize welding because we outsourced the outer box of the cooking unit, and it would not have been possible to attach the fins after the outer box was welded together. If the fins are welded on in the future then they will need to be welded on before the cooking box is fully assembled. The thermal adhesive worked well for testing purposes and could also be used in future prototypes.

The first small prototype only had fins that were bent along the front surface. The second bend, on the top surface, was added during the creation of a second small prototype. This flat was added to aid in testing with the cooking plate. Testing using these fins showed that all of the fins must be of the same height and bent to exactly 90 degrees on both the front and top surfaces. On the small prototype, the fins were uneven in height and each fin was bent to a different angle. This provided very little contact between the fins top surface and the cooking plate. Testing showed that this contact provided for a power transfer from the PCM/fins to the cooking vessel of 21 Watts when the heat lamp was off. This was lower than we wanted and so the contact between the fins and the cooking plate in the final prototype was increased. This was done by manufacturing the fins in a repeatable manner. In this way, the fins would all be the same height and bent to the same angle. Providing more contact area caused the power output to increase by 27% percent.

The fin thickness was 0.063 inches. This thickness was determined based off of ease of manufacturability and analysis. Our analysis (to be described later) dictated that the fins should be thick to make the temperature distribution more even. If the aluminum sheet metal was too thick, however, it would be impossible to bend on the break available to our team. Therefore, we chose the thickest sheet metal that we could while still being able to manufacture relatively easily.

4.4 Cooking Plate

The cooking plate sits directly on top of the fins and acts as a barrier between the cooking vessel section and the energy storage section. This provides the user with protection from the hot PCM as well as keeping food out of the storage unit. The cooking plate is a flat piece of sheet metal and was created using the same material used on the fins.

4.5 Insulation

Since prevention of heat loss is critical, the entire system is covered in insulation. The insulation helps to melt the PCM quickly and to keep the energy stored within the PCM for as long as possible.

During our early prototypes, we used flexible fiberglass insulation wrapped and taped around our system. Through tests with multiple thickness of insulation, we were able to determine how much insulation we would need on the final system. We decided against fiberglass for the final prototype due to irritation it can cause when handled. For the final prototype, we decided to try a new insulation that
we had not tested with. We settled on mineral wool insulation. Mineral wool was chosen because it is inexpensive, has a high thermal resistance similar to fiberglass, can withstand temperatures up to 650°C, and it deemed safe for repeated human contact. Although this is the insulation that we chose and tested, other insulations could be chosen for in-country usage. ASTM standard C411- 11 outlines tests that should be used to evaluate the performance of different thermal insulations when exposed to high temperatures.

To reduce heat loss, the final prototype is fully covered in insulation on all sides. We built a prototype of a box with insulation that the cooking unit could easily be set inside. The full prototype including the exterior insulation box is shown below:

**Figure 10 - Cooking Unit contained in Insulation Box**

The black conducting plate in the front and the top of the lid also has removable insulation so that there is not heat loss from the cooking unit during the night. The insulation on top can be removed for access to the cooking vessel, while the insulation in the front can be removed for solar energy absorption through the black plate. All of the insulation was covered in a cloth that could withstand temperatures of 200°C to keep it from coming into contact with the food and PCM.

There were a few deviations from the original design, but since the cooking unit is a simple design most of the physical attributes stayed the same and all of the functional aspects stayed true to the original. Initially, we had considered placing a thin gasket around the lip to provide for better contact between the lid and the bottom of the cooking unit and to prohibit heat loss. We decided against the lip after building the insulation box that prohibits heat loss through this small gap and through all sides of the cooking unit. The lip around the bottom of the cooking unit was larger than we expected since we outsourced the construction of our final unit. This did not present many problems, but it did require that we make a few fins shorter than 13 inches so that we could fit all of them in during assembly. In the end, we decided not to build the cooking unit with a sealed glass chamber on the front. This was initially in place to prevent heat loss during cooking. As we started to build the final prototype, we realized that constructing this chamber would be difficult. Through our analysis, we saw that the increase in heat loss was minimal and could be countered with removable insulation. These losses were all small changes that did not compromise the function of the Solar CookStove.

### 4.2 Solar Reflector

While the calculated energy needs of our system, at 700 W, required a 1.7 m² reflector, due to constraints of time and space we built a smaller reflector, pictured below, measuring only 0.3 m², to demonstrate the principle behind the design.

**Figure 11 - Small Scale Reflector**

By using the facilities available to us, namely laser cutters, we were able to rapidly and accurately manufacture the demonstration prototype. Since the focus behind the Schreffler design was local manufacture and sustainability, it is usually constructed near the place where local craftsmen will use it. It does not require any exotic materials or tools, only very basic welding and machining operations.
Approximations of the complex parabolas necessary for the reflector are done with simple templates, like the one shown in figure 12. For building the final reflector, we have identified two ASTM standards, E861 – 94 and E782 – 95, to test the durability of both the insulating and cover material on the solar reflector.

Figure 12 - Reflector Template

![Figure 12](image)

The full size Scheffler Reflector is a proven technology. Since 1987 thousands of reflectors have been built, mostly from plans distributed by Solare Brücke [8]. In combination with our thermal storage system, this has the potential to solve many problems in developing countries.

5. EVALUATION AND TESTING

Based on published research data, it is estimated that a family of four to six in India consumes approximately 3 kg of rice, 3 kg of vegetables, and 5 kg of water per day [9], [10]. The energy needed to cook that amount is 8,000 kJ.

With the required energy needed to cook defined, the feasibility of the system was checked. PCM can store energy beyond its critical temperature of 118°C. But, it should be kept below its boiling point of 328°C. Because of PCM’s high latent heat of fusion, the majority of solar energy is stored at the critical temperature point. If the PCM is superheated to 130°C, 68% of the total energy is stored as latent heat. The amount of PCM and the size of the solar reflector were calculated (see Appendix B2) to determine if the values were reasonable.

It is estimated that 36 pounds of PCM is needed, and the solar reflector needs to be 1.667 m². The weight and size are reasonable for the Solar CookStove. The heat loss depends on the solar influx during the day and the temperature of the cooking unit. The average heat loss due to irradiation is 6.3% and 4% for convection losses.

COMSOL, a finite element software, was initially used to analyze the behavior of the PCM. However, several problems were encountered; the phase change process of the PCM could not be modeled and there were difficulties implementing the heat transfer network within the PCM. Therefore, a Matlab program applying the finite difference method was created to solve these problems. The program performs heat transfer analysis of the PCM and fins within the cooking unit during the heating/melting and cooking process.

To simplify the analysis in the Matlab program, a two-dimensional model around a single fin was used. The Matlab program breaks down the PCM and fins into finite elements and applies transient heat equations to the elements. With the known boundary and initial conditions of the cooking unit, the program solves a series of linear equations to output the temperature distribution of the PCM and fins over time. This allowed us to study the behavior of the PCM within the cooking unit for different configurations. Thus, we could optimize the thickness, dimension, and number of fins that are very important to the functionality of the system.

Tests were done on the small and full-scale prototypes. Early tests with the small-scale prototype were done to verify the functionality of the solar cook stove and the Matlab program. We used ASTM Standard C1045-07, as guidance for calculating the thermal transmission properties based off of the data gained from testing. Full-scale prototype testing was done to check whether the cooking unit could heat water and cook food with the stored energy in the cooking unit. The results proved the capability of our solar cook stove to boil water and cook food.

5.1 Test Setup

Solar Energy Source

Due to the lack of sufficient sunlight in Philadelphia and the incomplete reflector in the early stages of testing, we used heat lamps to simulate the solar flux that is concentrated onto the black side of the cooking unit by the reflector. The heat lamp used in testing emits 375 W. We used one heat lamp for the small prototype and two for the full-scale.

To estimate the amount of power received by the cooking unit from the heat lamp, we performed the following steps. We assumed that the light emitted by the heat lamp is spread in a semi-sphere profile (since the lamp housing prevents light from reaching the back of the light bulb). As seen in Figure 13, the point on the virtual semi-sphere, with the bulb as the center, experiences the same light intensity; the intensity is the result of the heat lamp power over the area of this semi-sphere. Then, the power input to the black plate of the cooking unit can be estimated as follows:
Figure 13 - Estimation of Power Input from Heat Lamp to Cooking Unit

\[ \text{Power input} = \text{Light intensity at the black surface} \times \text{Area of black surface} \]

or \[ \text{Power input} = \left( \frac{\text{Power of heat lamp}}{\text{Area of virtual semi-sphere}} \right) \times (h \times w) \]

Where \( h \) is the height of the black surface and \( w \) is the width of the black surface.

The black plate received 46.67% of the light emitted from the heat lamp. The input power per unit area on the black plate for the small-scale prototype is 9,000 W/m². The actual full-scale system, when tested in India, will have a power per unit area of approximately 9,380 W/m².

**Data Collection**

Multiple RTDs and a microcontroller were used to gather real-time temperatures of the PCM, water, and rice. The sensing subsystem was built to automatically record the temperature over time without the use of an extra manual measurement tool. For PCM thermal testing, we utilized ASTM Standard E644-1, which provides uniform methods for resting with RTDs. This method helps produce reliable results.

RTD’s are commonly used in industry due to the wide range of working temperatures, high precision, and excellent linear relationship between the measured temperature and the resistance of the sensor. The RTD we used was PPG102A1 (produced by U.S. Sensor Corp) [11]. It can withstand temperatures up to 500°C, which is beyond the highest possible temperature (around 150°C) we could reach during testing. The flow of the whole real-time sensing and recording system is illustrated in the following diagram:

Figure 14 - Illustration of the Temperature Sensing and Recording System for Testing

5.2 Testing

To replicate the solar flux when testing, we turned on the heat lamp to heat up and melt the PCM. Heating or cooking of water and/or rice can begin before all the PCM has melted, as long as the PCM has reached a high enough temperature of 80°C (according to the FDA, food can be cooked thoroughly at 80°C for safe eating) [12]. This simulates the situation where people cook with the Solar CookStove at noon, when the PCM has not fully melted and is still receiving solar energy from the reflector. It is very difficult to clearly identify which parts of the PCM have melted while it is heating and cooking; the uneven and irregular temperature distribution within the PCM caused by this would make analyzing the testing data complicated. Also, this would lead to unpredictable and uncontrollable initial conditions for testing. To simplify our analysis, we did all our cooking tests after the PCM had entirely melted.

After all the PCM has melted and superheated to around 130°C with the light on, we would place a pot with room-temperature water or rice onto the cooking surface with either the light on or off. Testing with the heat lamp on replicated the scenario of cooking during the daytime. Testing with the light off represented the situation where the sun is down and the reflector is not concentrating light onto the cooking unit; in this case, users are cooking after sunset and using the energy stored by the PCM.

We went through four different types of experiments: (1) boiling water with the light on, (2) boiling water with the light off, (3) cooking rice with the light on, and (4) cooking rice with the light off.

All four tests were run after the PCM was entirely melted and superheated to a temperature of around 130°C. Similar testing was held with both small and full scale prototypes, with some corresponding changes on the size of pot, amount of water and rice, and amount of heat lamps used. For each prototype, we performed 2-3 tests for each type of testing.

5.3 Results

**Small Prototype**

*Heating and Melting:* PCM in the small prototype melted in an average of 3.5 hours. The predicted value was 3.68
hours. As seen in Figures 15, the test data validated the Matlab program. The two graphs show the PCM temperature at different locations within the cooking unit for the same test.

Figure 15 - PCM Temperature (5” distance from plate) versus Time while receiving Power Input from Heat Lamp

Cooking: Testing on a small prototype was performed to determine the average heat transfer coefficient between the PCM storage and cooking vessel; the accurate value could only be obtained by performing cooking tests. The average heat transfer coefficient obtained through testing was 1650 W/m². The coefficient was then used to calculate the average power that could be transferred to the cooking vessel. The estimated power output was used to determine whether or not water could be heated and if rice could be cooked within a reasonable time.

From testing, our small prototype was able to output an average of 34 W with the light on and 21 W with the light off to the cooking vessel.

While outputting the average of 21 W without the heat lamp on, the PCM was able to stay at or above 118 C for 7 hours. The predicted value was 7.48 hours. The PCM behavior was similar to the one predicted by the analysis as shown in Figure 16.

Figure 16 - PCM Temperature over time while outputting 21 W to the Cooking Vessel

Test results from the small-scale prototype validated the Matlab program and helped identify improvements that could be made to the full-scale system. Based on the power output obtained from testing and the cooking surface area, we predicted the power output of the full-scale model to be 120 W with the light off and 200 W with the light on if the configuration of the fins remained exactly the same as the small-scale.

To improve the power output for our full-scale prototype, we optimized the number of fins per unit length; the number of fins was not optimized in the small prototype due to manufacturing difficulties. Having the optimum number of fins would increase the contact surface area between the fins and the cooking plate. In addition, decreasing the depth would improve the heat extraction because of the decrease in the temperature drop over the depth of the cooking unit. Thus, both improvements would increase our predicted power output values by 36% to 163 W and 272 W. This predicted percentage value was derived from the Matlab program.

Full Scale Prototype

PCM in the large prototype melted in an average of 4 hours. The predicted value was 3.7 hours. The average heat transfer coefficient obtained through cooking tests was 2150 W/m². Figure 18 displays tests results from heating water with and without the light on. In addition to boiling water, tests were performed to cook rice. Table 1 lists the summary of the test results.

Figure 17 - Temperature of Water while being heated by the Cooking Unit

<table>
<thead>
<tr>
<th>Water</th>
<th>Light on</th>
<th>Light off</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amount</td>
<td>1 kg</td>
<td>1 kg</td>
</tr>
<tr>
<td>Time</td>
<td>0.833 hour</td>
<td>2 hour</td>
</tr>
<tr>
<td>Rate</td>
<td>1.2 kg/hour</td>
<td>0.5 kg/hour</td>
</tr>
</tbody>
</table>

Table 1 - Full Scale Prototype Predictions and Test Results

<table>
<thead>
<tr>
<th>Rice</th>
<th>Light on</th>
<th>Light off</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amount</td>
<td>1 kg</td>
<td>1 kg</td>
</tr>
</tbody>
</table>
Testing validated the functionality of our Solar CookStove. We were able to heat water and cook rice within a reasonable amount of time.

While outputting an average of 157 W of energy with the heat lamp on, the PCM was able to stay at or above 118°C for 9.2 hours. The predicted value from the Matlab program was 10.4 hours. This showed that our cooking unit can maintain a steady temperature of 118°C long enough to cook meals past sunset. See Figure 18 for PCM behavior during cooking.

Figure 18 - PCM Temperature over time while outputting 157 W to Cooking Vessel

6. DISCUSSION

The Solar CookStove is sustainable and user friendly. The greatest advantage it has over present conventional solar cookers is that it can cook food for several hours past sunset. In addition, PCM in the cooking unit provides a stable heat source for cooking at 118°C.

Although the Solar CookStove helps solve the problem of cooking after sunset, further improvements can be made to our full-scale prototype. Currently, the heat transfer rate is slower than desired making the cooking time long. This is a common problem for solar cookers. The cooking time can be shortened by finding low-cost ways to increase the conductivity of the PCM unit or by reducing the thermal contact resistance between the cooking pot and fins/cooking plate. This could be accomplished by directly attaching the cooking vessel to the cooking plate or by manufacturing fins with perfect 90 degree flanges. The current flanges are very close to perfect, but there is some room for adjustment.

Future plans include testing in India with the cooking unit and the full-scale solar reflector. Getting feedback from the potential users in developing regions of India can help us optimize the Solar CookStove design for the intended users.

Based on research into raw materials in India, the Solar CookStove currently costs $30 per unit. This price is a bit expensive for our targeted users to purchase individually. So to bring it to users, we need to focus on collaborating with NGOs and receiving government funding.

7. CONCLUSIONS AND RECOMMENDATIONS

The Solar CookStove can store approximately 8000 kJ and stay at a temperature at or above 118°C after the sun has gone down for at least 10 hours. It can cook rice at a rate of 1.18 kg/hour during the day and 0.49 kg/hour after the sun has set. While there is room for improvement, the Solar CookStove is readying for testing with users in developing regions and offers a great advantage over current cook stove solutions.

8. ACKNOWLEDGEMENTS

The Solar CookStove team would like to thank our advisor, Dr. Andrew Jackson for his continuous mentoring throughout the project. In particular, his insights from the world of energy have been invaluable. Our team would also express our gratitude to Dr. Robert L. Jeffcoat for his guidance through the term of this project.

We would like to thank our sponsors ASTM International for their generous grant that helped us build the Solar CookStove prototype. Lastly, we’d like to thank students of the senior design class for their suggestions and help during the course of this project.

9. NOMENCLATURE AND DEFINITIONS

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEAM</td>
<td>Mechanical Engineering and Applied Mechanics (Department)</td>
</tr>
<tr>
<td>PCM</td>
<td>Phase Change Material</td>
</tr>
<tr>
<td>LPG</td>
<td>Liquefied Petroleum Gas</td>
</tr>
<tr>
<td>°C</td>
<td>Celsius</td>
</tr>
<tr>
<td>RTD</td>
<td>Resistance Temperature Detector</td>
</tr>
<tr>
<td>W</td>
<td>Watt</td>
</tr>
<tr>
<td>ASTM</td>
<td>American Society for Testing and Materials</td>
</tr>
<tr>
<td>NGO</td>
<td>Non-Governmental Organization</td>
</tr>
</tbody>
</table>
10. REFERENCES

ASTM Standards:
- E782 – 95 Exposure of Cover Materials for Solar Collectors to Natural Weathering Under Conditions Simulating Operational Mode
- E861 – 94 Evaluating Thermal Insulation Materials for Use in Solar Collectors
- F2875-10 Standard Guide for Laboratory Requirements Necessary to Test Commercial Cooking and Warming Appliances
- C1045-07 Standard Practice for Calculating Thermal Transmission Properties Under Steady-State Conditions

Sources:


INTELLECTUAL PROPERTY

This document, in whole or in part, in electronic or other form, may be freely reproduced and modified, without restriction, provided only that the source be properly attributed.

CORRESPONDING AUTHOR

Inquiries should be addressed to Robert Jeffcoat, Department of Mechanical Engineering and Applied Mechanics, Towne 318, The University of Pennsylvania, 220 South 33rd Street, Philadelphia PA 19104-6315 USA; e-mail RLJ@SEAS.upenn.edu
APPENDIX A
MATERIALS AND COST SUMMARY

The materials cost of the building and testing multiple prototypes of the Solar CookStove was approximately $1970. From a MEAM-authorized budget of $1,500 and a $500 grant for ASTM International, this left a surplus of $30.

Table A1 - Embedded, expended, and consumed items and charges

<table>
<thead>
<tr>
<th>Item</th>
<th>Source</th>
<th>Size</th>
<th>Price per unit</th>
<th>Quantity</th>
<th>Other costs</th>
<th>Total Price</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCM</td>
<td><a href="http://www.netitition.com">www.netitition.com</a></td>
<td>1 lb</td>
<td>8.99</td>
<td>5</td>
<td>4.95</td>
<td>49.9</td>
<td>11/22/11</td>
</tr>
<tr>
<td>PCM</td>
<td><a href="http://www.netitition.com">www.netitition.com</a></td>
<td>1 lb</td>
<td>8.99</td>
<td>5</td>
<td>4.95</td>
<td>49.9</td>
<td>11/22/11</td>
</tr>
<tr>
<td>PCM</td>
<td><a href="http://www.netitition.com">www.netitition.com</a></td>
<td>1 lb</td>
<td>8.99</td>
<td>5</td>
<td>4.95</td>
<td>49.9</td>
<td>11/22/11</td>
</tr>
<tr>
<td>PCM</td>
<td><a href="http://www.amazon.com">www.amazon.com</a></td>
<td>1 lb</td>
<td>24.88</td>
<td>3</td>
<td>6.76</td>
<td>31.64</td>
<td>12/9/12</td>
</tr>
<tr>
<td>Insulation</td>
<td><a href="http://www.mcmaster.com">www.mcmaster.com</a></td>
<td>1&quot; by 3&quot; by 25'</td>
<td>6.22</td>
<td>1</td>
<td>4.6</td>
<td>10.82</td>
<td>11/27/11</td>
</tr>
<tr>
<td>Insulation</td>
<td><a href="http://www.mcmaster.com">www.mcmaster.com</a></td>
<td>1&quot; by 3&quot; by 25'</td>
<td>6.45</td>
<td>1</td>
<td>4.8</td>
<td>11.25</td>
<td>12/9/12</td>
</tr>
<tr>
<td>Bulb Holder</td>
<td><a href="http://www.amazon.com">www.amazon.com</a></td>
<td>660 Watt, 125 V</td>
<td>3.54</td>
<td>1</td>
<td>5.02</td>
<td>8.56</td>
<td>12/9/12</td>
</tr>
<tr>
<td>Heat Lamp</td>
<td><a href="http://www.buylighting.com">www.buylighting.com</a></td>
<td>375 Watt R40</td>
<td>19.95</td>
<td>1</td>
<td>7.25</td>
<td>27.2</td>
<td>12/22/12</td>
</tr>
<tr>
<td>Paint</td>
<td><a href="http://www.mcmaster.com">www.mcmaster.com</a></td>
<td>High Temp 1200 F</td>
<td>5.04</td>
<td>1</td>
<td>0</td>
<td>5.04</td>
<td>12/22/12</td>
</tr>
<tr>
<td>Temperature Sensors</td>
<td><a href="http://www.digikey.com">www.digikey.com</a></td>
<td>Sensors</td>
<td>55.5</td>
<td>1</td>
<td>13.46</td>
<td>68.96</td>
<td>12/22/12</td>
</tr>
<tr>
<td>Aluminum</td>
<td><a href="http://www.onlinemets.com">www.onlinemets.com</a></td>
<td>Prototype material</td>
<td>59.61</td>
<td>2</td>
<td>14.76</td>
<td>74.37</td>
<td>11/16/11</td>
</tr>
<tr>
<td>Aluminum Sheet Metal</td>
<td><a href="http://www.mcmaster.com">www.mcmaster.com</a></td>
<td>Sheet metal</td>
<td>19.03</td>
<td>2</td>
<td>4.98</td>
<td>24.01</td>
<td>12/6/12</td>
</tr>
<tr>
<td>Cold Weld</td>
<td><a href="http://www.amazon.com">www.amazon.com</a></td>
<td>8265-5</td>
<td>4.98</td>
<td>1</td>
<td>0</td>
<td>4.98</td>
<td>12/10/12</td>
</tr>
<tr>
<td>Thermometer</td>
<td><a href="http://www.amazon.com">www.amazon.com</a></td>
<td>Taylor 8942</td>
<td>13.98</td>
<td>2</td>
<td>0</td>
<td>27.96</td>
<td>12/30/12</td>
</tr>
<tr>
<td>Aluminum Sheet Metal</td>
<td><a href="http://www.mcmaster.com">www.mcmaster.com</a></td>
<td>Sheet Metal</td>
<td>17.83</td>
<td>2</td>
<td>4.87</td>
<td>22.7</td>
<td>12/31/12</td>
</tr>
<tr>
<td>Aluminum Box</td>
<td>Custom Aluminum Box</td>
<td>12 by 6 by 6</td>
<td>73.99</td>
<td>1</td>
<td>0</td>
<td>73.99</td>
<td>12/11/12</td>
</tr>
<tr>
<td>Temperature Sensors</td>
<td><a href="http://www.digikey.com">www.digikey.com</a></td>
<td>Sensors</td>
<td>55.5</td>
<td>1</td>
<td>13.46</td>
<td>68.96</td>
<td>12/12/12</td>
</tr>
<tr>
<td>Rigid Insulation</td>
<td><a href="http://www.mcmaster.com">www.mcmaster.com</a></td>
<td>1&quot; by 24&quot; by 48'</td>
<td>18.59</td>
<td>1</td>
<td>21.96</td>
<td>40.55</td>
<td>12/2/12</td>
</tr>
<tr>
<td>Thermal HeatSink Adhesive</td>
<td><a href="http://www.amazon.com">www.amazon.com</a></td>
<td>Glue</td>
<td>27.98</td>
<td>1</td>
<td>0</td>
<td>27.98</td>
<td>11/21/12</td>
</tr>
<tr>
<td>PCM</td>
<td><a href="http://www.netitition.com">www.netitition.com</a></td>
<td>1 lb</td>
<td>8.99</td>
<td>5</td>
<td>4.95</td>
<td>49.9</td>
<td>11/19/12</td>
</tr>
<tr>
<td>Temperature Sensors</td>
<td><a href="http://www.digikey.com">www.digikey.com</a></td>
<td>Sensors</td>
<td>18.5</td>
<td>8</td>
<td>148</td>
<td>166.5</td>
<td>11/21/12</td>
</tr>
<tr>
<td>Thermal Tape</td>
<td><a href="http://www.mcmaster.com">www.mcmaster.com</a></td>
<td>Tape</td>
<td>5.22</td>
<td>2</td>
<td>0</td>
<td>10.44</td>
<td>12/12/12</td>
</tr>
<tr>
<td>PCM</td>
<td><a href="http://www.netitition.com">www.netitition.com</a></td>
<td>1 lb</td>
<td>8.99</td>
<td>25</td>
<td>4.95</td>
<td>227.9</td>
<td>12/36/12</td>
</tr>
<tr>
<td>Wool Insulation</td>
<td><a href="http://www.mcmaster.com">www.mcmaster.com</a></td>
<td>1 by 2 by 3</td>
<td>21.08</td>
<td>1</td>
<td>0</td>
<td>21.08</td>
<td>12/36/12</td>
</tr>
<tr>
<td>Thermal Adhesive</td>
<td><a href="http://www.xxolde.com">www.xxolde.com</a></td>
<td></td>
<td>14</td>
<td>6</td>
<td>84</td>
<td>126</td>
<td>12/36/12</td>
</tr>
<tr>
<td>Multipurpose Aluminum (Alloy 6061)</td>
<td><a href="http://www.mcmaster.com">www.mcmaster.com</a></td>
<td>1/2&quot; Square, 6' Length</td>
<td>15.62</td>
<td>5</td>
<td>7.81</td>
<td>83.27</td>
<td>12/27/12</td>
</tr>
<tr>
<td>Grade 5 Zinc-Plated Steel Hex Head Cap Screw</td>
<td><a href="http://www.mcmaster.com">www.mcmaster.com</a></td>
<td>1/4&quot;-20 Thread, 1-1/4&quot; Long, Fully Thrh</td>
<td>14.41</td>
<td>1</td>
<td>14.41</td>
<td>28.82</td>
<td>12/7/12</td>
</tr>
<tr>
<td>Plain Steel Type A USS Flat Washer</td>
<td><a href="http://www.mcmaster.com">www.mcmaster.com</a></td>
<td>1/4&quot; Screw Size, 47/64&quot; OD, 05&quot;-08&quot;</td>
<td>2.52</td>
<td>1</td>
<td>2.52</td>
<td>5.04</td>
<td>3/27/12</td>
</tr>
<tr>
<td>Ultra-Coated Grade 8 Steel Hex Nut</td>
<td><a href="http://www.mcmaster.com">www.mcmaster.com</a></td>
<td>1/4&quot;-20 Thread Size, 7/16&quot; Width, 7/32</td>
<td>6.42</td>
<td>1</td>
<td>6.42</td>
<td>12.84</td>
<td>3/27/12</td>
</tr>
<tr>
<td>Multipurpose Aluminum (Alloy 6061)</td>
<td><a href="http://www.mcmaster.com">www.mcmaster.com</a></td>
<td>1/4&quot; Thick, 24&quot; X 48&quot;</td>
<td>11.77</td>
<td>1</td>
<td>11.77</td>
<td>23.54</td>
<td>3/27/12</td>
</tr>
<tr>
<td>Aluminum</td>
<td><a href="http://www.mcmaster.com">www.mcmaster.com</a></td>
<td>063&quot; Thick, 24&quot; X 48&quot;</td>
<td>63.61</td>
<td>1</td>
<td>63.61</td>
<td>128.22</td>
<td>3/28/12</td>
</tr>
<tr>
<td>Aluminum</td>
<td><a href="http://www.onlinemets.com">www.onlinemets.com</a></td>
<td>Aluminum 5052-H32 Bare</td>
<td>31.33</td>
<td>1</td>
<td>21.44</td>
<td>52.77</td>
<td>3/28/12</td>
</tr>
<tr>
<td>Aluminum Box</td>
<td>Custon Aluminum Box</td>
<td>Full Dimensions</td>
<td>212.34</td>
<td>1</td>
<td>212.34</td>
<td>424.68</td>
<td>3/30/12</td>
</tr>
<tr>
<td>18-8 SS Blind Rivet with 18-8 SS Mandrel Domed</td>
<td><a href="http://www.mcmaster.com">www.mcmaster.com</a></td>
<td>#8 Mirror Finish, .032&quot; Thick, 24&quot; X 24&quot;</td>
<td>40.11</td>
<td>1</td>
<td>40.11</td>
<td>80.22</td>
<td>4/5/12</td>
</tr>
<tr>
<td>Corrosion-Resistant Aluminum (Alloy 5052)</td>
<td><a href="http://www.mcmaster.com">www.mcmaster.com</a></td>
<td>#8 Mirror Finish, 032&quot; Thick, 24&quot; X 24&quot;</td>
<td>40.11</td>
<td>1</td>
<td>40.11</td>
<td>80.22</td>
<td>4/5/12</td>
</tr>
<tr>
<td>PCM</td>
<td><a href="http://www.netitition.com">www.netitition.com</a></td>
<td>1 lb</td>
<td>8.99</td>
<td>8</td>
<td>4.95</td>
<td>49.9</td>
<td>4/5/12</td>
</tr>
<tr>
<td>Heat Lamp</td>
<td><a href="http://www.buylighting.com">www.buylighting.com</a></td>
<td>375 Watt R40</td>
<td>8.85</td>
<td>1</td>
<td>15.95</td>
<td>24.8</td>
<td>4/8/12</td>
</tr>
<tr>
<td>Lamp Holder</td>
<td>Penn Brothers</td>
<td>Blue Clip on Lamp</td>
<td>18.34</td>
<td>1</td>
<td>18.34</td>
<td>18.34</td>
<td>4/15/12</td>
</tr>
</tbody>
</table>
APPENDIX B
MATERIAL PROPERTIES AND CALCULATIONS

The properties of Erythritol helped us choose it as our choice for the PCM while calculations shown below helped determine the size of the solar reflector.

Table B1 – Erythritol Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting temperature (°C)</td>
<td>118</td>
</tr>
<tr>
<td>Latent heat of fusion (kJ/kg)</td>
<td>339.8</td>
</tr>
<tr>
<td>Density in solid phase (kg/m³)</td>
<td>1480</td>
</tr>
<tr>
<td>Density in liquid phase (kg/m³)</td>
<td>1300</td>
</tr>
<tr>
<td>Thermal conductivity in liquid phase (W/m·°C)</td>
<td>0.326</td>
</tr>
<tr>
<td>Thermal conductivity in solid phase (W/m·°C)</td>
<td>0.733</td>
</tr>
<tr>
<td>Specific heat in solid phase (kJ/kg·°C)</td>
<td>1.38</td>
</tr>
<tr>
<td>Specific heat in liquid phase (kJ/kg·°C)</td>
<td>2.76</td>
</tr>
</tbody>
</table>

Section B2 – Calculations for Size of the Solar Reflector

\[
m_{PCM} = \frac{E_{PCM}}{c_{p,solid}(T_c - T_0) + h_f + c_{p,liquid}(T_f - T_c)}
\]

\[
A_{collector} = \frac{E_{PCM}}{(solar\,irradiance\,flux)(time)(efficiency)}
\]

\[E_{PCM} = \text{Energy of PCM needed}\]
\[c_{p,solid} = \text{specific heat of erythritol in solid phase}\]
\[c_{p,liquid} = \text{specific heat of erythritol in liquid phase}\]
\[T_0 = \text{initial temperature of erythritol}\]
\[T_c = \text{critical temperature (melting point) of erythritol}\]
\[T_f = \text{final temperature of erythritol}\]

APPENDIX C
SAMPLE MATLAB MODEL

This model represents the FEA analysis conducted on the system.

\[(q_{in})_{j+3} = \frac{kA}{l}(T_{j+1} - T_{j+3}) + \frac{kA}{l}(T_{j+2} - T_{j+3}) + \frac{kA}{l}(T_{j+5} - T_{j+3})\]

\[\Delta E_{j+3} = mc_p(T_{j+3}(t + \Delta t) - T_{j+3}(t))\]

\[(q_{in})_{j+3} = \Delta E_{j+3}\]

Consider element \(T_{j+3}\) at time, \(t\)