

THE HAWKEYE SOLAR COOKER

*presented by The University of Iowa College of Engineering in conjunction
with The University of California, Berkeley and Climate Healers*

*Mechanical
Engineering Senior
Design Project -
Final Report*

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The Hawkeye Solar Cooker

Introduction

For the past three months, students at the University of Iowa College of Engineering have been working toward providing the native villagers of Rajasthan India with the means to cook food without the use of firewood. Approximately 2 billion people worldwide burn 1.2 billion tons of wood annually. The ecological and sociological impacts of this statistic grow even more apparent as once fertile forests swiftly progress toward barren wastelands (Climate Healers).



Figure 1: Barren hillside in Karech, 2002

The Hawkeye Solar Cooker is the first step toward providing a viable renewable means of cooking, not just in Rajasthan, but in consistently warm regions around the world. The benefits of such a device are many and transcend the technical achievement to provide health, social, and ecological benefits to end-users. In Rajasthan, where collecting fire wood traditionally falls on the matriarch, the ability to cook without firewood can potentially save hours of daily labor once devoted to wood harvesting. As families often cook indoors, smoke inhalation and its related medical concerns can be avoided and reforestation of a region can begin (Rao).

Background & Planning

In December of 2010, nine University of Iowa students along with Prof. H. S. Udaykumar embarked on a trip to the Karech and Mewar regions of Rajasthan, India. Their goal was to collect cultural information regarding the Rajasthani villagers as well as to observe the current implementation

of solar cookers previously provided by the non-governmental organizations, *Climate Healers* and the *Foundation for Ecological Security*.

The existing solar cookers were found to be successful in cooking roti (a flatbread) and other common Indian dishes. However, their inability to conform to traditional cooking and eating practices have led to their abandonment. Figure 2 depicts the *Namaste* solar cooker currently deployed in Rajasthan.



Figure 2: Namaste solar cooker being used to cook roti

The *Namaste* cooker is designed to reach the desired cooking temperatures during peak hours of the day by concentrating solar rays via concave reflectors onto the lower portion of the cooking surface. There were several key issues with its design contributing to its failure with the Mewar and Karech villagers. 1) The cooker required the user to cook standing up. Traditionally, meals are cooked and served from a seated position. 2) The solar cooker possesses no form of energy storage requiring the user to take time away from their daily tasks to monitor cooking progress. 3) On a similar note, the lack of storage prevents users from cooking at the traditional meal times of about 7:00 am and 7:00 pm, India Standard Time.

In addition to evaluating issues with the solar cooker, the Winterim students also conducted surveys to gain a greater understanding of the culture and lifestyle of Rajasthani villagers. Based on their observations, the Mechanical Engineering Design Project (MEDP) Team was provided with valuable information on which to establish constraints for the project.

Two meals a day are served in Mewar and Karech; each at the previously mention times. One meal consists of roti (almost daily), while the other is typically composed of vegetables. The average family size in the region is 6.2 with over 300 families between the two villages. Each family harvests approximately 5-10 bundles of wood each week (a bundle weights about 20 kg). What firewood that

isn't used is sold to market; incentivizing the cutting of additional wood from the surrounding forests (University of Iowa India Winterim Team).

From a cultural perspective the villagers of Rajasthan subscribe to a matriarchal family system. The women perform nearly all of the daily tasks including cooking, firewood collection, and childcare. Based on this information, it was the Winterim Team's observation that successful deployment of future solar cookers in the region rests in the fulfillment of stringent constraints imposed by the primary users; the women of Rajasthan (University of Iowa India Winterim Team).

For planning purposes, the semester was divided into 2 parts: 1) a design phase, and 2) a build phase. For the design phase, the class was divided into five teams, each with their own team leader. An additional coordinating team, comprised of team leaders and three executive officers, was used as a central hub for communication and coordination between groups. Table 1 highlights the team breakdown and organizational structure.

Table 1: MEDP Organizational Structure

| MEDP Organizational | |
|------------------------------|----------------------------|
| Coordinating Team | |
| Chief Operations Officer | |
| Chief Communications Officer | |
| Chief Supplies Officer | |
| Stage 1 | Stage 2 |
| <i>Modeling</i> | <i>Morning Storage</i> |
| <i>Manufacturing</i> | <i>Night Storage</i> |
| <i>Energy Storage</i> | <i>Primary Collector</i> |
| <i>Energy Capture</i> | <i>Secondary Collector</i> |
| <i>Energy Delivery</i> | <i>Mechanics</i> |
| | <i>Modeling</i> |

As the design and build processes progressed these teams morphed to meet the needs of project. Within Stage 1, subgroups were used for to facilitate the creation of conceptual designs. Each of these 5 subgroups (later designated *Designs 1-5*) consisted of members from each of the primary teams listed in Table 1. This ensured that each aspect of solar cooker construction was well represented in each of the conceptual designs. These subgroups reduced in number until the build design was finalized by Prof. Udaykumar and Dr. Sailesh Rao.

As Executive Director of *Climate Healers*, Dr. Rao, was one of the primary instigators of the project and provided valuable feedback and direction regarding designs. He also directed a team from the University of California Berkeley charged with the creation of a heat pipe that could be easily

integrated into MEDP solar cooker. The Berkeley Team's report is forthcoming and their slide presentation can be found in the supplemental information provided with this report.

Stage 1: Design

Research

Between January 21 and March 11, the MEDP students were devoted to researching solar cookers and solar cooker technology. Numerous papers, case studies, instruction manuals, and websites were explored as the teams worked to gather as much information as possible on solar cookers.

In the beginning, Prof. Udaykumar provided the class with several documents and research articles highlighting the basics of solar capture and energy storage methods and materials. As the class became more autonomous and research more extensive, design paradigms and restrictions began to fall into place. Throughout the design process, there arose several reoccurring questions governing the decisions made:

1. Tracking – will the collector actively track the sun throughout the day or passively collect light as the sun progresses through the sky?
2. Collector Shape – should the reflector be a parabolic trough, a dual parabolic trough, or a parabolic dish?
3. Phase Change Material vs. Latent Heat Storage – which of these mediums should be utilized to store the energy collected during the day.
4. Delivery Systems – should heat pipes or conductive heating be employed to deliver heat to the cooking surface?
5. Interface – how will the cooker interface with Rajastani homes?

The final solar cooker design addresses each of these items; though, it should be noted each design selection presented its own tradeoffs according to the “*Cost, Quality, Time*” paradigm.

Constraints

Based on the research conducted by the Winterim and MEDP Teams, the following constraints were imposed for the project:

1. The cooker required a \$250 dollar final production cost. For this prototype, the costs were expectedly higher. Therefore, it was decided that the team should evaluate their selection of materials based on what was considered cheap and available in Rajasthan. Ending cost projections were made based on what the class believed the cost would be to mass produce the cookers in India.

2. The goal temperature for the cook surface was between 150-200 degrees C. This is the cook surface temperature for the cooking of roti.
3. The design needed to be capable of storing 6 kWh of energy to account for losses and to meet the temperature requirements at the traditional cooking times.
4. The cooker should be built using local building materials.
5. The design should be relatively low maintenance. The villager should be able to set the cooker to the appropriate angle and leave it to collect energy throughout the day.
6. Traditional cooking practices, such as seated cooking and cooking times (7:00 am and 7:00 pm), needed to be preserved by the design.
7. Safety was held paramount when designing a cooker meant to operate at high temperatures.

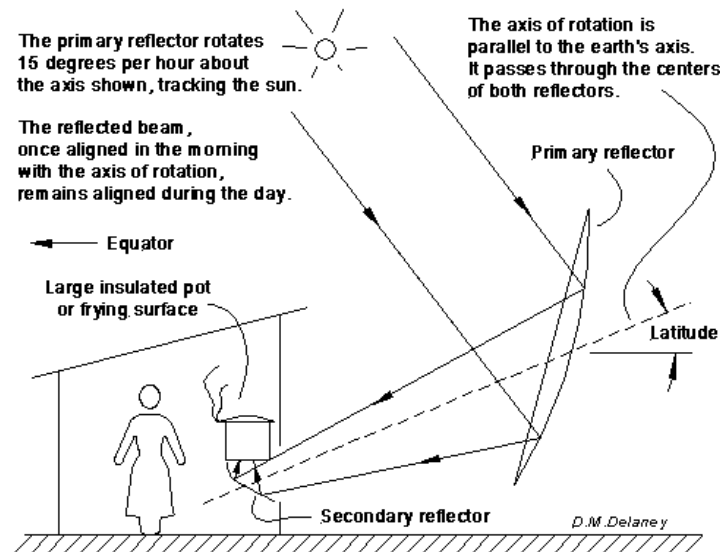
It should be noted that while size was not originally of major concern, it did present itself as the key flaw in the final design. The ending dimensions were based on the assessment of the modeling team regarding how much material would be required to meet the energy needs for cooking. This requires addressing in future design iterations.

Conceptual Designs

After an appropriate amount of knowledge was gained, it was decided that the class should partake in a charette to begin pooling design ideas and solutions. Five designs were initially considered. From these five designs, 3 unique conceptual designs emerged.

The first of the three conceptual designs was the *Scheffler Solar Cooker*. This design draws its inspiration from the *Scheffler Solar Kitchens* found throughout various parts of India and the Middle East. First devised by Wolfgang Scheffler, the *Scheffler Solar Cooker* has been proven to store between 2 and 4 kWh of energy by focusing light via parabolic dish on to a collector plate typically placed 10 – 15 feet away.

Figure 3 depicts the basic positioning and overall concept for the Scheffler cooker. The primary issues with this design lay in its manufacture and assembly. The tolerances associated with the construction of the dish posed many technical difficulties. The dish needed to be constructed with extreme accuracy to ensure maximum concentration of light on the collector surface. It was questionable whether or not the students had the proper resources, training, and time to complete such a task. The storage method was also deemed extremely costly. The Scheffler cooker uses latent heat for storage in the form of four 100 kilogram steel cylinders surrounded by fiberglass insulation within a steel drum. Steel in that amount could potentially cost between \$500-\$1000 dollars depending on bulk pricing and the type of steel used. The design also addresses tracking through a gear system that adjusts the reflector's position throughout the day. It is highly recommended that a design of this nature be revisited in future iterations.



How a Scheffler reflector used for cooking keeps its focus on the cooking place as the sun moves.

Figure 3: Basic Scheffler Solar Kitchen Concept

The second of the three conceptual designs was the "Rose Bud" solar cooker. Aply named for its shape (see Figure 4), this cooker employees a series of flat reflective plates positioned to compose a dish, thus increasing the amount of focused light. A lens is used at the base of the cooker to further focus light to a point and to seal the interior from heat losses. At the focal point, temperatures have been found to reach upwards of 800 degrees C in some studies. The storage medium utilized by this design was latent heat, though a particular material was never fully investigated. The collector dish also rests on a track that allows it rotate to follow the sun throughout the day.



Figure 4: "Rose Bud" Solar Cooker

The last of conceptual designs was the parabolic trough. This design can be approached multiple ways. Figure 5 shows a receiver pipe filled with a fluid that is heated by the reflected light rays. A trough similar to this was utilized in the final design. The preliminary design utilizes a secondary reflector to further concentrate light, further demonstrating the many variations of trough design.

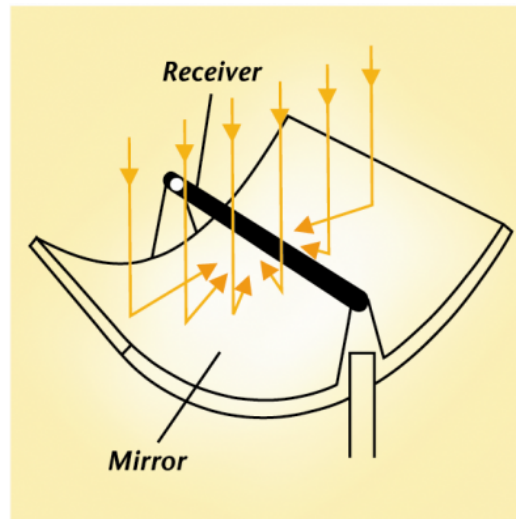


Figure 5: Parabolic Trough Design Overview

The parabolic trough provides for tracking its orientation. When positioned in an east west manor, the trough collects light throughout the day as the sun moves across the sky. Efficiencies, as result, are lower in the morning and night and peak during the day when the maximum light concentration is achieved. This is a passive method of solar collection.

A number of storage mediums can be utilized when employing the parabolic trough. The collection method is primarily what set this design apart from the previously mentioned designs.

Preliminary Design

After reviewing the conceptual designs, Prof. Udaykumar and Dr. Rao determined that the final solar cooker prototype should incorporate the best aspects from each of the concepts. In the interest of time, the concept designs were combined into a preliminary design by the class supervisors. The goal was to quickly select a direction in which the class should proceed. Preliminary design aspects were selected based on what the supervisors believed the class could feasibly complete given the time and resources remaining in the semester.

Figure 6 highlights the overall preliminary design for the Hawkeye Solar Cooker. A parabolic trough design was chosen for its simple construction and ability to track with little to no effort on the part of the user. The preliminary design also utilizes a secondary reflector, however, this design aspect was later scrapped in an attempt to reduce the overall weight and complexity of the assembly.

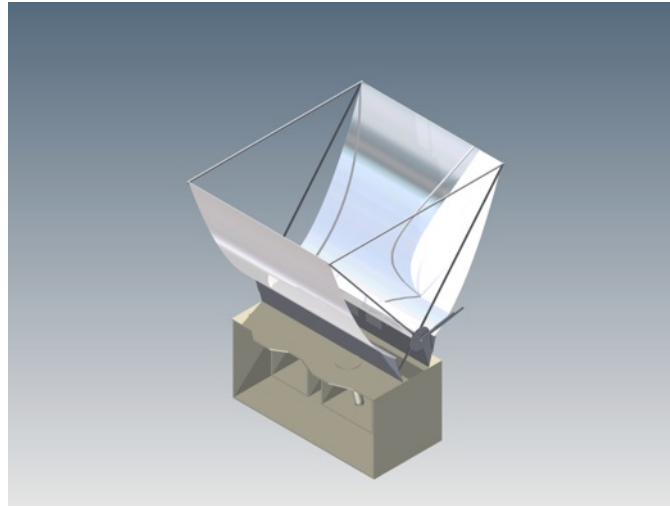


Figure 6: Preliminary Design CAD Assembly

An aluminum fin array surrounded by sand was decided upon for the storage medium. Aluminum is readily available in the form of pop cans that can be cut and fashioned into fin arrays. Sand is also readily available given the proximity of desert sand. Together these materials possessed the desired thermal properties for solar cooking. The foreseeable issue in using sand and aluminum stems from the quantity required for successful energy storage.

Figure 7 shows a cross-sectional view of the proposed assembly. The collector rests and rotates about its own framework while the storage box rests upon a rail system designed to move the cooking apparatus to and from the home. In order to track the sun year round using a trough design, a bi-weekly adjustment was proposed and built into the collector framework. The preliminary design also utilized a heat pipe to be manufactured by the Berkeley Team for heat delivery to the cooking surface.

Figure 8 shows a closer view of funnel assembly designed to prevent light rays from escaping once they have been directed toward the absorber plate. A glass lens/plate was used to prevent the loss of radiative heat out of the absorber area. The absorber plate is attached to the fin array to aid in the spreading of heat throughout the storage box.

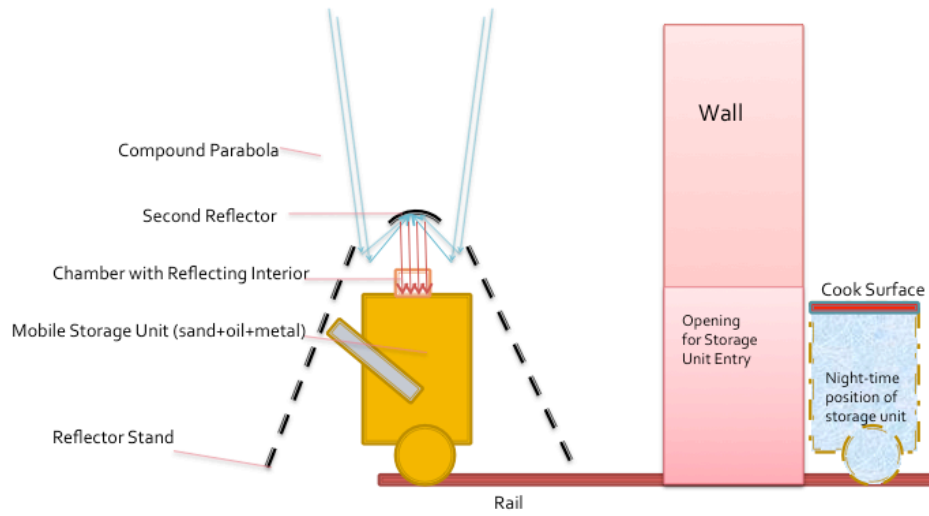


Figure 7: Side View Preliminary Design Overview

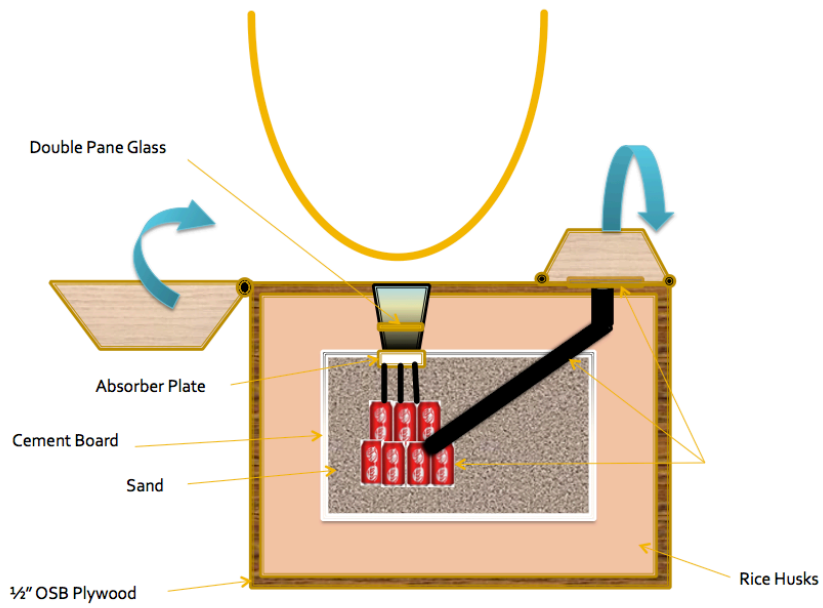


Figure 8: Preliminary Design Interior Overview

Stage 2: Final Design & Construction

The following sections have been compiled by the Stage 2 build teams (Table 1) and highlight their work and recommendations moving forward. Additional supplemental information is forthcoming and can be acquired by accessing the MEDP Google Gmail/Google Docs account with the username *medp.uiowa* and password *slowcooker*. The Organizational Team is in the process of compiling information collected over the course of the semester.

Collector

Design

The design of the outward facing trough solar concentrator incorporated a compound parabola to allow for a 16 degree acceptance angle. The shape of the collector was selected to reduce the focal plane as close to the storage absorber plate as possible while using as little material as possible. From the modeling team, it was determined that there must be an aperture area of approximately 2 square meters to obtain the necessary amount of energy. The storage team also needed to have as short of a collection length as possible so that the energy could be concentrated to the center storage boxes. With these considerations, the team determined the following parameters of the parabola:

$$y = ax^2 + bx + c$$

$$\text{with } a = 0.035, b = 0.3, c = 1.7$$

Eq. 1

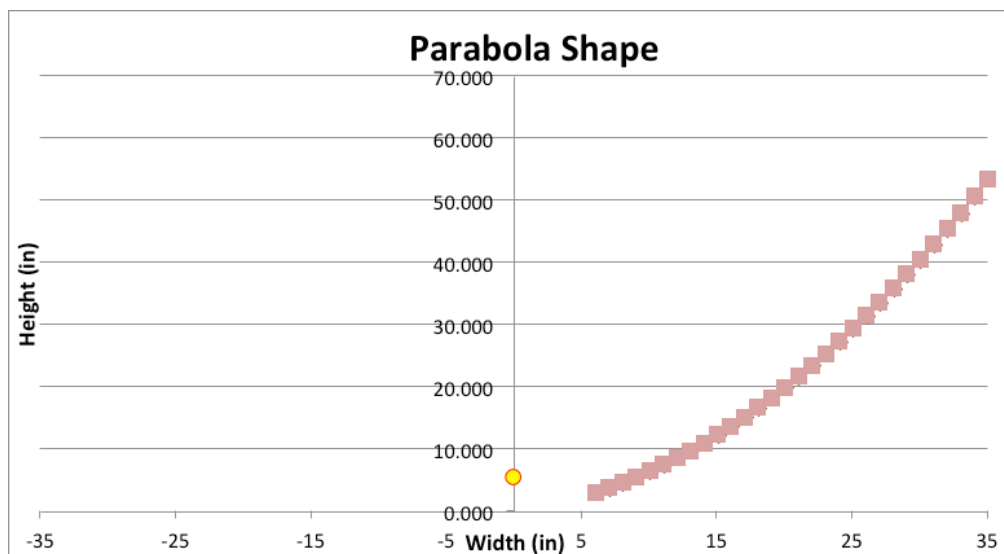


Figure 9: Collector Shape Calculation

Once the shape of the parabola was determined, the team imported the points into *Autodesk Inventor* to create a 3-D model. The parabola was extruded and mirrored to obtain two sides. Each side was then moved 7 inches towards the center and rotated inward 8 degrees. This created a focal plane just below the bottom opening of the parabola.

Fabrication & Assembly

The team began by acquiring three 4' x 8' sheets, *Mother's Polishing Compound*, polishing pads, and an industrial polisher. The sheets were polished by sanding with 600, 1000 and finally 2000 grit sand paper in order from coarse to fine and then using the polishing compound to obtain a final shine. For future reference, this method proved to be slow and didn't provide the desired shine. The team experimented with several different polishing options using the polisher and angle grinder. The best combination found was to use the industrial polisher with a cloth foam pad stuck to the Velcro attachment.

The next step was to start on the framing for the parabola. To accomplish this, the group created a template out of 1/4" plywood. The template was made by placing reference points along the plywood sheet according to the parabolic curve previously established. A finishing nail was put at each reference point and an aluminum drywall ruler was bent along the reference points establishing the curve. The curve was marked and cut out with a jigsaw. This template was then used to mark all six vertical ribs. Each of the vertical ribs were cut with the band saw. The horizontal ribs were measured from the assembly CAD drawings (attached in the supplemental material) and cut with a miter saw. The assembly was put together using 3" screws.

The group then created brackets for the interface piece that maintains a reflective surface along the distance between collection and storage. The brackets were constructed from square aluminum tubing. First, the team cut one end off of the tubing using a band saw. Second, the brackets were cut to 8" with a 45 degree cut on one end to allow for rotation. A hinge was mounted the top of the bracket using 1/4-20 nuts and bolts. Finally, a sheet of polished aluminum was adhered to the top interface section using an industrial tape. The bottom section was then installed into the cavity of the two channels. Stops were used at each end to contain the bottom interface section. Similarly, an industrial tape was used to fasten the polished aluminum to the front of the sub-assembly.

The collector framing was constructed using 2"x 4" wood boards. The overall dimensions of the frame were 6' wide x 8' deep x 9' tall when the collector was attached to the frame. Quick analysis concluded that the overall depth of the framing needed to be about 7.5 feet to enable the collector and framing to withstand a 25 MPH wind and not be blown over. This analysis was also conducted with "worst case scenario" assumptions to account for potential gust conditions.

Attached to the framing was a detent plate that enabled the collector to be adjusted for seasonal changes in the sun's alignment with the collector. The detent plate was made using an aluminum plate with groves for two spring-actuated pins to follow in. The spring-actuated pins were attached to the detent plate so that the seasonal adjustments could be made with little effort from the

user. Every couple of weeks one pin would be retracted and other pin would snap into one of fourteen 1/4" holes allowing for the collector to be adjusted 3.6 degrees.

Recommendations

In the future it would be very beneficial to determine how Mylar could be effectively used in the collector. The aluminum was not well polished meaning the reflectivity was not nearly that of Mylar. If the issues of air bubbles and tearing could be solved, Mylar would prove to be a much better material due to its high reflectivity. Also, it would be very useful to have ray-tracing software that allows for the importing of 3-D CAD models. This would allow the testing of many different reflectors without construction. Finally, there was some concern regarding the detent plate. Each angle should utilize dual pins to secure the collector rather than the single pin system currently employed.

Storage

Medium

Many thermal storage mediums were researched and considered during the design process. Constraints on thermal storage mediums were cost and availability. Ultimately sand was selected because of its availability in the region. Sand was also chosen as the thermal storage medium because of its high energy capacity, about 0.83 W/g*K, and its low thermal conductivity, about .2 W/m*K. This allows sand to store large amounts of heat without losses from conduction.

The type of sand used in the prototype was playground sand of medium coarseness. The amount of sand needed to store the appropriate energy was calculated based on volume and mass. The evening storage unit was tightly packed with 62.1 kg of sand around the aluminum arrays (discusses later). The morning storage unit required 86.8 kg of sand. The total amount of sand used was 148.7 kg. It should be noted that the sand was slightly moist when packed into the storage units, which have affected the performance of the storage device.

Insulation

Many insulation solutions were evaluated during the design process. Ultimately, an inexpensive insulation that could drastically reduce heat loss while resisting heat and flame was desired. These requirements led to the selection of rice hulls for insulation between the inner and outer boxes. Rice hulls have a very low thermal conductivity (approximately 0.07 W/m*K) and do not burn in high heat. Rice hulls could also be found locally in India at very low cost. The Iowa prototype received their rice hulls for free through a donation from *Rice Harvesters Inc.*

Even with favorable insulation properties, modeling calculations suggested that a large volume of rice hulls would still be required; an approximate mass of 168.3 kg of rice hulls was used in the final build. The inner storage boxes were surrounded by .254 m of rice hulls on all six sides within the larger outer box. The rice hulls were not tightly packed as it was suggested small air pockets throughout the rice hulls would provide favorable insulation properties.

Inner Storage Boxes

The inner storage boxes were designed to hold all of the energy collected from the absorber plate at the bottom of the light funnel. Two inner storage boxes were created to allow the cooker to store sufficient energy for evening and morning meals. The inner storage boxes consisted of sand and aluminum for a storage medium. The material properties of these items, which are previously mentioned, ideally created a hybrid material which could store and deliver heat energy. The size of the morning and evening storage boxes was calculated based on the volume of sand and aluminum needed to store the 3.5 kWh and 2.5 kWh, respectively. Therefore, the morning storage box was larger than the evening storage box. Additionally, the sand to aluminum ratio within the boxes was estimated based on the energy storage length of time and energy delivery rate required from each box. The morning storage box contained a 15.5:1 sand to aluminum ratio, while the evening box contained a 10.4:1 ratio. Figure 10 and Figure 11 show the morning and evening storage boxes dimensions in mm.

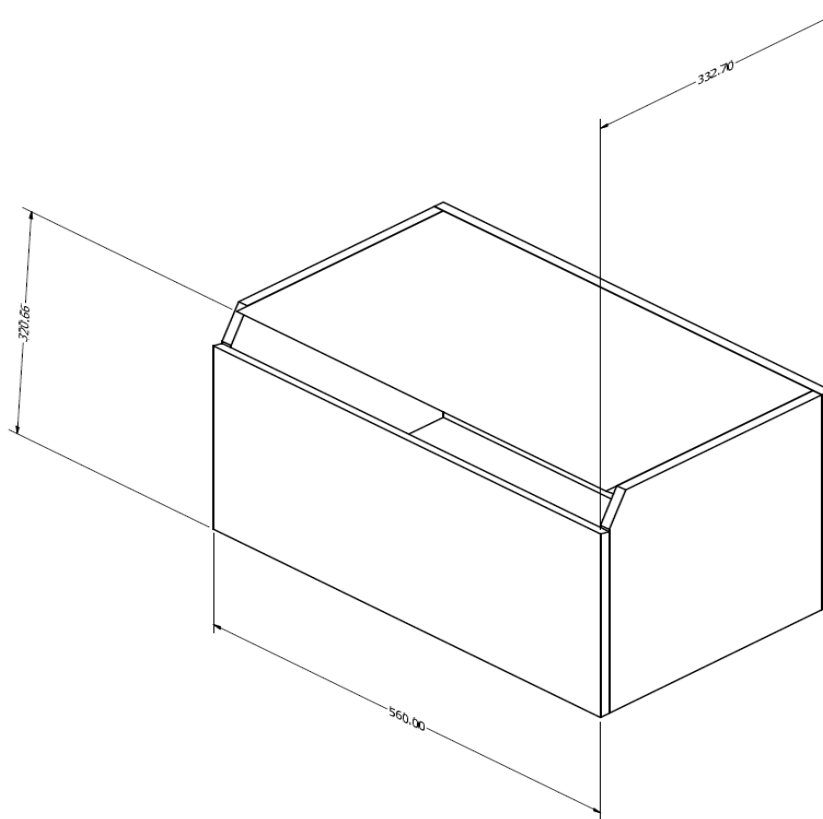


Figure 10: Internal Storage Box, Morning Cooking

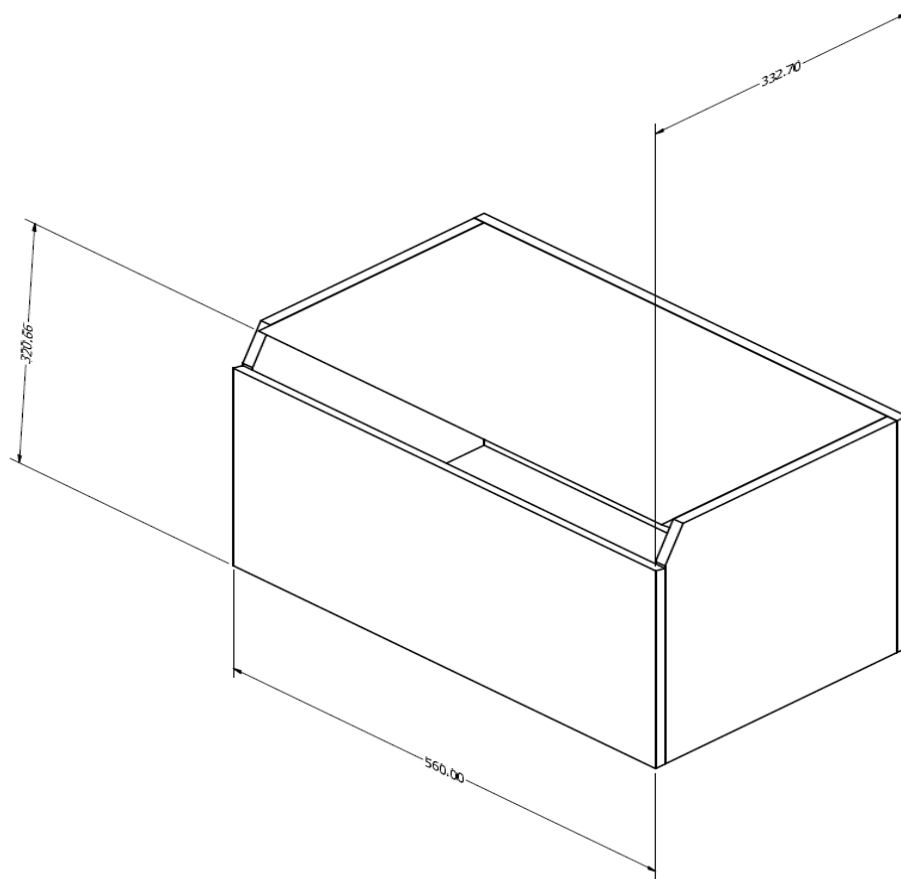


Figure 11: Internal Storage Box, Night Cooking

The boxes were constructed out of 0.0127 [m] thick cement board and aluminum brackets. Durable, heat resistant cinder blocks were used to support the internal storage structures within the outer storage box.

Outer Storage Box

The outer box, which contains all of the components of the storage design, was constructed using 0.0127 m thick plywood with 2" x 4" wood for support framing. The extra framing support was crucial because of the storage unit's mass. Wood was chosen as the building material because of its considerable durability, low cost, availability, and machinability. The final dimensions (in mm) of the outer box are shown in Figure 12. The outer storage box was also painted black with weather resistant paint, the purpose of this color was to collect as much radiant heat as possible from the sun.

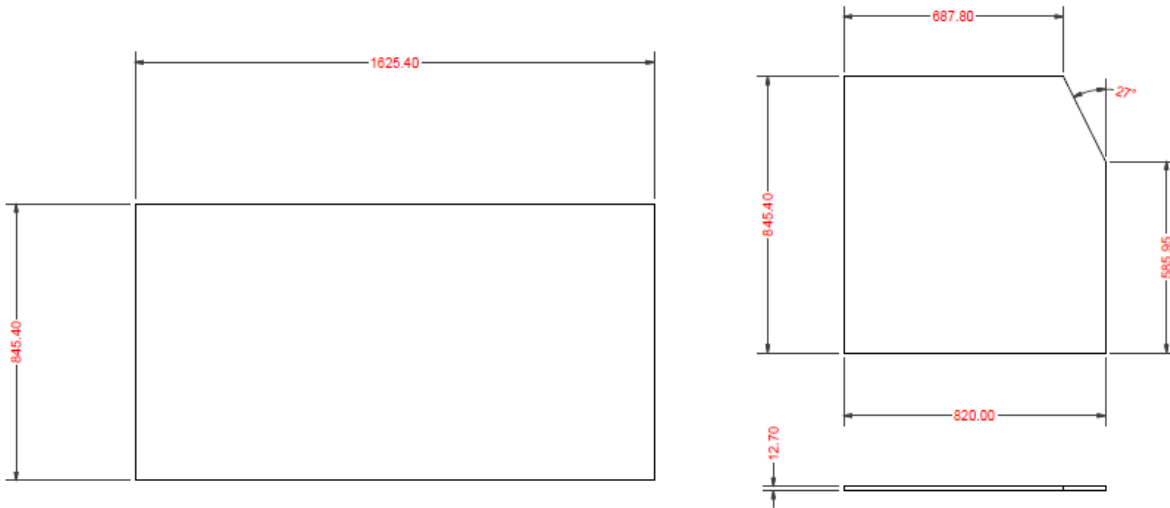


Figure 12: Outer Storage Box Assembly Drawing

Can Arrays

Two separate aluminum arrays were constructed and placed within the sand heat storage medium to increase heat transfer from the collection plate to the heat pipe connected to the cook surface. One array design was built for night storage and a separate design was used for the morning storage. The night storage array was designed to allow maximum heat transfer to the cook surface by using a more concentrated aluminum matrix while the morning array was designed to transfer heat more conservatively in order to reduce heat losses from the relatively long term storage box. The arrays varied in the amount of aluminum used, their overall geometry, and how they were positioned within the cement board sand storage boxes. Because of the difficulty of mathematically modeling the complex geometry required for the arrays, two array designs were chosen to be built for the prototype.

Both array designs consist of two 1/4" thick aluminum plates bent in such a way that there is direct contact with the anodized aluminum collector surface along the entire length of the storage box. Countersunk bolts press fit the plates into the collector surface to ensure proper thermal contact. The 1/4" plates extend from the collector surface to the bottom of the storage box. A hole was drilled in the center of each plate so that a long bolt could connect the plates to the rest of the array. The arrays consist of 4" x 8" pieces of aluminum sheeting stacked along the long bolt in such a way that the aluminum would create a sand-metal matrix within the sand. This matrix allows heat collected from the collection plate to be conducted sufficiently to the entire volume of sand in order to maximize heat storage capability. The bolt runs across the box and connects to another aluminum plate which mates with the heat pipe used for transferring heat to the cook surface. Washers were affixed to each end of the long bolt and tightened so that the array was pressure fit to reduce thermal resistances as heat is transferred through the array.

The array for night storage consists of a cross design. One 4" x 8" sheet was positioned vertically and another horizontally forming a cross. A hole was drilled in the center of the sheets, and they were slid onto the long connecting bolt. Between each cross, a 1" diameter, 1/2" thick aluminum rod spacer was slid onto the bolt. The spacer provides adequate means for heat to transfer horizontally through the array, while the crosses provide a method of heat transfer in the other two dimensions. An illustration of the night storage array can be seen in Figure 13. This design consists of a robust amount of aluminum to readily transfer heat to the cook surface. Due to the fact that the night storage box only needs to store heat for a short amount of time, heat losses caused by the addition of this array wasn't an inhibitor in the design.

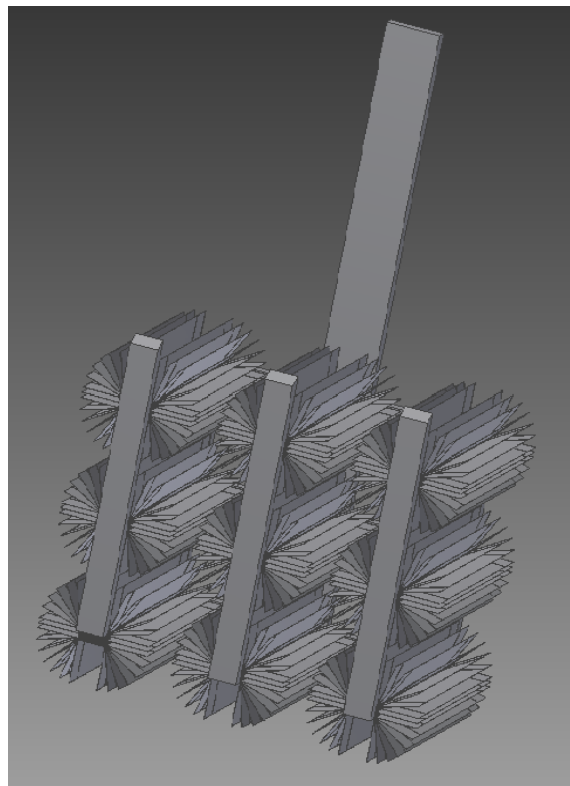


Figure 13: Night Storage Aluminum Array

The array for morning storage consists of a fanned design in which a stack of the 4" x 8" sheets were press fit together in the center and then fanned out along the long side to create a fanned effect so that if viewed from the side, it looks like the spokes of a wheel. This design consists of less aluminum in a less concentrated help eliminate heat losses and increase heat storage potential. Figures of the morning storage array can be seen in Figure 14.

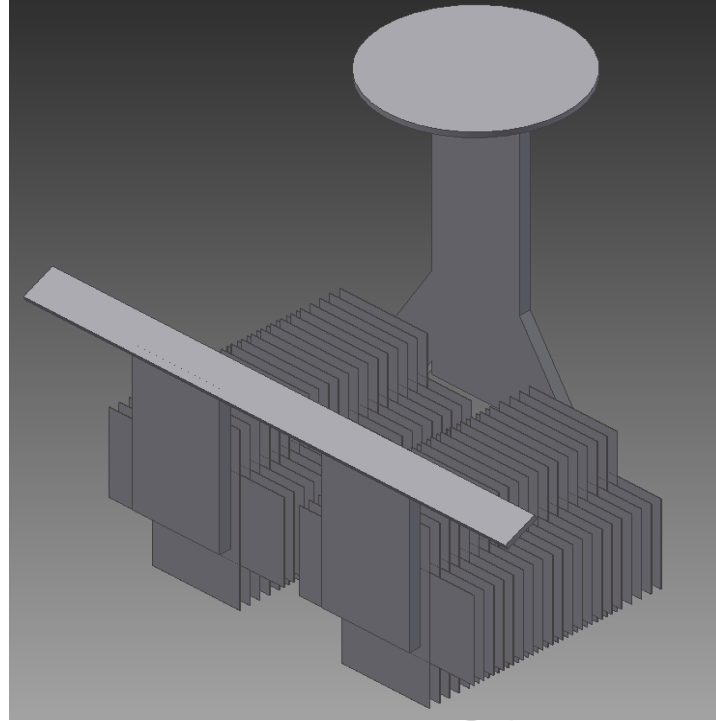


Figure 14: Morning Cooking Aluminum Array

Delivery

The Hawkeye Solar cooker was fabricated for the eventual insertion of the heat pipes from the team at California Berkeley. Because semester schedules between the two teams did not coincide, the MEDP Team did not receive the finished heat pipes in time. The team decided to use a 1" solid aluminum rod to conduct the heat up to the cooking surface through convection. On both the nighttime and morning aluminum conducting rods, an 8" inch diameter cook top was attached. The team decided to go with an 8" cook top to try and stay consistent with the size that they are used to cooking on in rural India. This is intended to be a temporary fix until the heat pipes are received from California Berkeley. At the top of the box a larger than 1" diameter square was cut out so the hot aluminum rod would not come in contact with the box. A piece of tile was cut and placed around the rod to ensure that the aluminum would not come in contact with the wood of the outer box. The solar cooker was fabricated with two lids to cover the cook surfaces when they are not in use. The evening cook lid was made smaller than the morning cook lid because it did not need to insulate as well. It was made smaller to cut costs and minimize weight. The morning cook lid was larger and had more rice husks inside of it to insulate better. The lids were attached by hinges to the main box to ease with opening and closing of them. The morning lid would cover the cook plate on the right with more insulation. However these lids were unnecessary because the Hawkeye Solar Cooker did not work as planned and the cook tops never got hot.

Light Funnel

The funnel design was one of the more complicated processes presented to the storage team. The beam of light had to travel along the funnel without incurring too many losses along the way. Some of the main losses that would occur would be for the light to be reflected back outside the funnel system into the atmosphere. From the onset of the final design it was decided that the solar reflector would be the same length as the total storage box. The storage box would have all of the insulation, morning and evening storage units inside. Ideally the approach would be to funnel the light from the focus line to the absorber plates as if they were one continuous plate. However more complex geometry was introduced.

Figure 15 shows the geometry from a side perspective of the funnel system. The solar collector and modeling teams found that the ideal angle of declination was to be 27 degrees from the horizontal plane. This was due to the latitude in Rajasthan. This was the base point for the funnel system because the absorber plate was to be orientated at the 27 degree inclination. This would be ideal for spring and fall declination angles. Ideally the absorber would be adjusted to the same angle to that of the collector but this was just not feasible. The modeling team decided that an ideal funnel angle to be at 75 degree angle from the absorber plate to avoid scattering effects. However this set the opening of the collector to be set at 30.4cm wide that needed to be absorbed at only 3.84 cm.

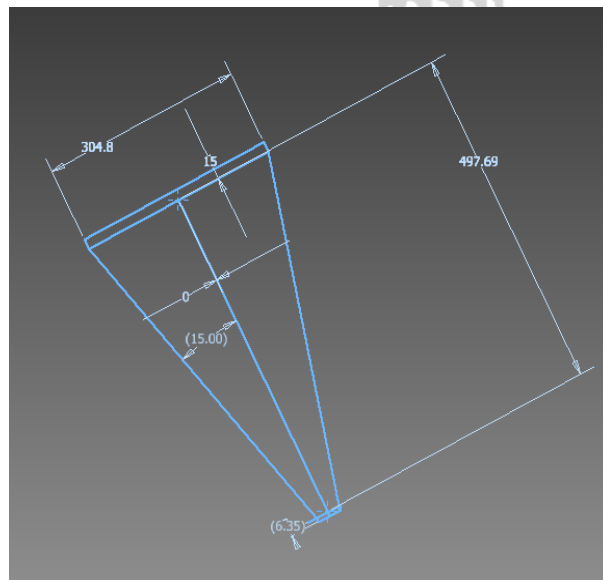


Figure 15: Light Funnel Construction Blueprint

With these two angles set the optimal distance for the opening of the collector could be determined. It should be noted that Figure 6 is from the side perspective of the entire system. The dimensions were communicated back to the collector team so that the additional space could be accounted for in the design of the interface system. The distance between the storage box to the

collector was around 23.0 cm. If the storage box did not have two separate absorber plates then this would have been the only angles that would have been necessary. The absorber plates had lengths of 53.4 and 37.4 cm for the morning and evening storages respectively. This meant that only 55% of the beam would be reflected in an ideal state reflected in the side view.

Figure 16 shows the focus beams as they reached the funnel system. Notice how the beams at the two ends of the box do not make it to the storage device at all. This was due to the length of the absorber plates being shorter than length of the focus beam. The next conundrum was trying to collect as much as the focus length as possible. This meant for the angles going out towards the side of the box the angles would be less than the ideal 75 degrees. The path that was decided upon was to accept those losses and geometrically link the ends of the absorber plates and link them to the end of the collector. This was set for roughly 45 degrees

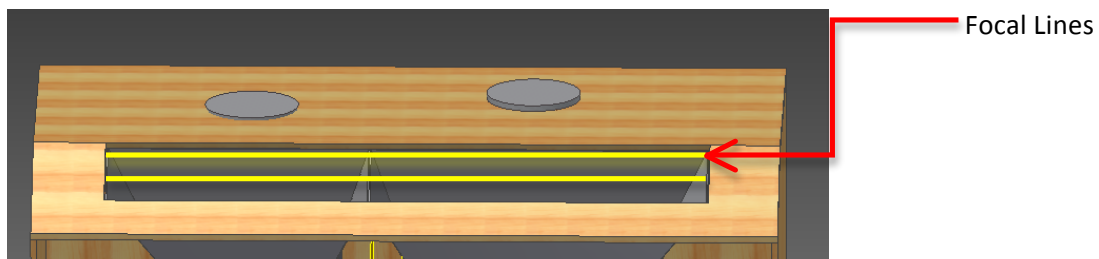


Figure 16: Light Funnel with Focal Beams Shown

The next problem was to decide on the funnel angles between the two storage boxes. The ideal storage insulation dimensions were to set the distances between the storage boxes at 14 cm to prevent thermal losses. This in turn created another level of difficulty to connect the two funnel system to accept the focus line. Figure 17 shows the dimensions of the large morning funnel part. Notice that the angles at both ends are not the same. Essential the angle at the left side of the morning funnel would match that of the right side of evenings. However bother of these angles are still not at the ideal 75 degree declination.

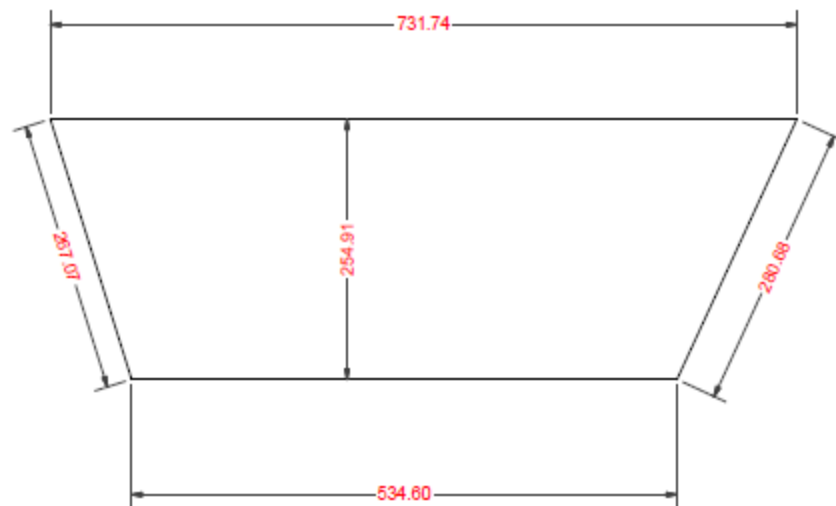


Figure 17: Morning Funnel Dimensions

In general, most of the distances and angles for the morning storage system were already set because of other corresponding dimensions. This limited an efficient design of the funnel system for both the morning and the evening systems. Dimensions were not the only problem for the funnel system. Designing for manufacturability proved to be a harder task. Originally it was thought that there would be more than enough of the polished aluminum for the funnels. Budget constraints and time over rode the decision to use aluminum, so a glass mirror system was to be used. Attaching the mirrors to the system proved to be most difficult because there were not readily available bracketing system for attaching everything given the complex geometry.

Recommendations

Much was learned though the planning and construction of the internal storage boxes, light funnel system, insulation, and external storage box. The size and weight of the storage systems must be changed in future designs. With the current prototype, a woman would not be able to easily maneuver the storage unit in and out of the house two times a day. There are currently 148.9 kg of sand, 172 kg of rice hulls, and additional weight of aluminum and plywood. In future designs, changing the storage material would decrease the weight and size of the overall unit.

The glass elements of the storage unit can be redesigned to provide greater structural strength. The current design of the light funnel was not sturdy enough to survive the transportation from the construction area to the testing grounds. By using a stronger, thicker glass and introducing back supports would increase the durability of the light funnel. With more accurate cuts and proper tooling, they would allow for more precise cuts and better construction.

Computer software should be a significant part in the design of the storage unit. With the lack of knowledge of computer aided engineering analysis software, the current can arrays and delivery system

have not been tested or modeled. With increased knowledge of such computer software, these systems could be modeled properly and modified to maximize output. With more efficient designs, the weight issue would continue to be addressed, hopefully decreasing the total weight and size of the unit. From the data collected for the computer analysis, fewer prototypes would have to be constructed and the number of tests would decrease allowing for quicker implementation of the device to India and other developing regions.

Mechanics

Design

Given that the combination of materials for the collection and storage device totals approximately 800 lbs, the task of the mechanics group was to develop a feasible way to transport the device, as a whole, between the indoor cooking and outdoor collecting positions. The most cost efficient method of moving the cooker was to rest the collector and storage device on a metal frame with four castors. Handles were then attached to the sides of the storage assembly to aid in the movement of the cooker. Due to time constraints, it was decided that the frame sections would be joined through welding. A steel track was also designed to move the storage container into the homes in India though due to budget concerns this piece was never fabricated. The track utilizes two rails approximately 60 ½" apart with an open C-channel design to prevent debris from building up in the channel. The overall length of the track is dependent on the distance between the collection site and the cooking site, which will vary from home to home.

Fabrication & Assembly

The initial design of the cooker assembly was expected to total approximately 600 lbs, although after continued optimization, the final weight rose to approximately 800 lbs. Considering the possibility of further increases in weight, the cart for the assembly was designed to withstand approximately 1200 lbs of force. To withstand this force, 2" x 2" x 3/16" steel angle iron was used in the construction of the bottom frame. The dimensions of the frame were dependent upon the final measurements of the bottom of the storage box. Once the box was constructed, the measurements were found to be 64 ¼" x 33 ¼". To provide enough clearance for the collector, the cart was built to be 64 ½" x 33 ½" with two additional 33 ½" angle iron runners in the middle to further support the assembly.

The outer pieces of angle iron were first measured to specification and then cut on a 45 degree angle to create a mitered joint. These miter cuts allow for easier welding and cleaner joining of the separate pieces. A tungsten inert gas (TIG) welder was used to join the pieces of angle iron together. Welds were placed on the inside horizontal and vertical lengths of the joint as seen in Figure 18.



Figure 18: Miter welds

The two center support lengths of angle iron were then measured to run widthwise inside of the outer frame acting as additional support for the center of the storage container. These supports ensure that the weight of the internal storage components do not warp the box thus weakening the plywood exterior. Additionally, these center runners help to relieve a portion of the weight on the perimeter frame thus reducing deflection in the steel. Since angle iron was used in the construction of the center supporting beams, part of the vertical section of the angle iron was cut to produce notch joints, allowing the beams to be joined to the existing frame. Additional welds were used to join the beams to the frame as depicted in Figure 19.



Figure 19: Center support welds

Steel castors were procured for the frame. Upon further inspection of the casters, it was found that the top plates were composed of galvanized steel. Originally, it was thought that the castors would be welded directly to the frame. At the temperatures required to weld the castors to the frame, the zinc in the galvanized protective coating would have vaporized thus posing a serious health risk. To circumvent this hazard and still effectively join the castors to the frame, intermediate plates were used. Four 3" x 5" steel plates were welded to the four corners of the frame. Four 5/16" holes were drilled in these connecting plates. Figure 20 illustrates the connecting plates welded to the primary support frame.



Figure 20: Welded caster attachment plate

After the plates were welded to the frame, a drill was used to bore through the steel frame, allowing the castors to be secured using 5/16" bolts. Once connected, the bolts were filed down on the two swivel castors to allow for full rotation of the wheels. It is important here to note the swivel casters were used for prototype purposes and will be replaced with straight casters in the final design.



Figure 21: Completed frame with casters

Recommendations

For shipping purposes, it is recommended that the frame be redesigned without welds. Ideally the frame would bolt together making it easier to ship and easier to assemble in Rajasthan.

Assuming that the new frame relies on bolt connections rather than welds, it would also be prudent to galvanize the steel. Despite the fact that the climate in question is semi-arid, it is still important to ensure that the primary source of mobility in the assembly will not succumb to degradation via rust. If galvanized steel is not used, then periodic checkups will be necessary by individuals knowledgeable about the operation of the device.

Modeling

Considerations

The first step in creating a 0-D model was to develop an equation that would best simulate the solar cooker in its projected working environment. The storage team started with the overall energy equation. This equation then had to be modified to incorporate the total energy stored in the morning and night cooking boxes. Equation 2 below depicts the result of the modified total energy equation.

$$mC_p \frac{\partial T}{\partial t} = \eta q_s'' A_{cr} - UA(T_s - T_\infty) - \frac{q_c}{\eta_c}$$

Eq. 2

On the right side of the equation, the first term evaluated was the total solar energy entering the thermal storage box; dependent on the solar flux, the collector plate area, and an efficiency factor. The next term accounts for any losses through the walls of the storage box. This was accomplished by finding the overall heat transfer coefficient, or U , through the walls of the box. The last term represents the energy used in cooking which was assumed to be extracted over a two hour time period per meal, two meals a day. In the equation, m is the mass of the storage box, C_p is the specific heat of the storage box, $\frac{\partial T}{\partial t}$ is the change in temperature between the inside and the outside of the box with respect to time, η is the efficiency of the collector, q_s'' is the solar flux from the sun, A_{cr} is the area of the collector, U is the overall heat transfer coefficient through the walls of the box, A is the area of the storage box collector, T_s is the temperature of the storage box, T_∞ is the temperature of the ambient air surrounding the box, q_c is the energy used to cook, and η_c is the cooking efficiency.

The 0-D equation, after establishing all of its necessary components, was integrated with respect to time and temperature to find the internal storage temperature at six minute time steps. The final integrated solution was then transferred into Microsoft Excel to solve over the specified time intervals. The first step in calculating the energy and temperatures available for cooking after a period of storage was to find the solar influx during the collection time period. This involved finding the angles of incident light from the sun which changes daily with the Earth's rotation and annually with the revolution around the sun. The total offset was calculated to be 23.44 degrees between the Earth's rotational axis and its orbital plane (Wikipedia). The angle and compass orientation of the collector surface also had to be taken into account as well as the latitude of the device. The solar flux, or solar power received per area, can be calculated by taking the solar constant just above the earth's atmosphere and then subtracting off the efficiency losses due to atmospheric effects, which is partially a function of cooker altitude, but is also dependent upon local atmospheric effects such as smog. A small amount of background sky radiation also adds to the total solar flux. This term was not calculated but rather taken from known engineering standards tables. The total energy into the aperture of the collector was then reduced by an efficiency factor to account for the scattering of light and the overall design of the collection, transfer, and absorption components.

For simplicity, a National Oceanic and Atmospheric Administration (NOAA) calculator was downloaded off the NOAA website and inserted directly into the Excel spreadsheets used for the 0-D model. This calculator allowed the user to enter the date, latitude, longitude, and time zone of interest and subsequently be provided specific solar position data on a six-minute time basis for a given 24-hour period. Of particular interest for this project were the hour angle, sun declination, solar elevation (corrected for atmospheric refraction), and the solar azimuth angle at each six-minute increment. Figure 22 shows a partial picture of the Excel spreadsheet used to determine these values. With this information the solar position could be determined to within a reasonable degree of accuracy. Solar position was used in conjunction with collector orientation and tilt angles to calculate the angle of incidence between the sun and the collector.

NOAA Solar Calculations - Change any of the highlighted cells to get solar position data for that location and date.

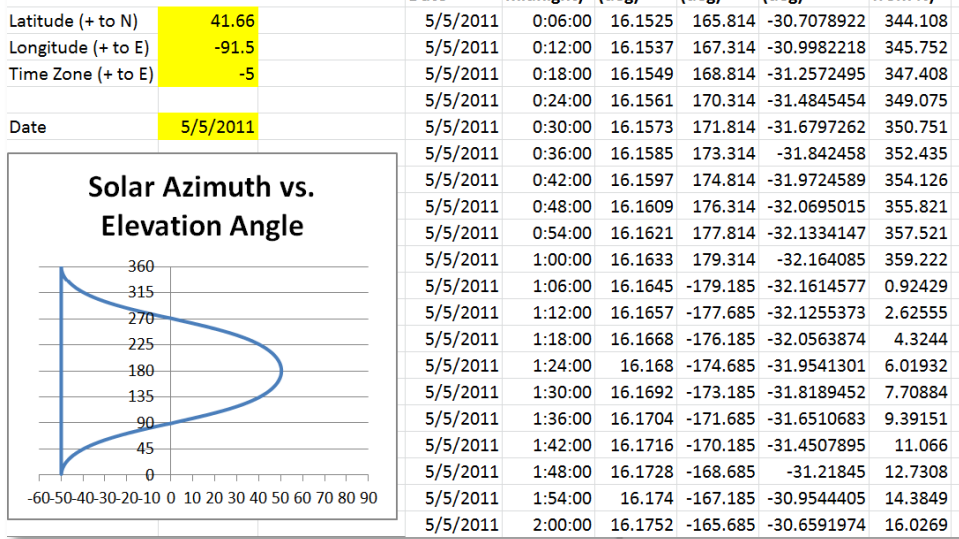


Figure 22: NOAA Solar Calculator (partial view) displaying various relevant solar angles on a six minute time-step based on: latitude, longitude, time-zone, and date.

The next piece of information required was the solar flux for the location at which the solar cooker would be used. Rather than calculate this figure based on estimations, experimental data was sought. The ANSI/ASHRAE Standard 93-2003 was used to acquire data for both 27 degrees north latitude (Rajasthan, India) and 40 degrees north latitude (Iowa City). The 27 degrees north data, converted to metric equivalents and shown below in Figure 23 matched up well with the locations of interest in Rajasthan. Iowa City is actually closer to 42 degrees north rather than 40 degrees north. The difference was small enough to not create significant errors in the preliminary model. The information found in these standards showed hourly averages for the solar flux to a flat surface normal to the incoming light on a month by month basis (ANSI/ASHRAE). In order to make this data compatible with the six minute increments used for the solar angle data, a sixth degree polynomial approximation was created for each month which gave the solar flux on a continuous curve within the period of sun-up to sun-down, an example of which is given for the month of May at 40 degrees north latitude (Figure 24).

The time of day could then be entered into these equations to provide the solar flux for any tenth of an hour point over the course of a day for any month of the year. It is important to note that while these polynomials corrected for daily stepping in the data, the flux used in the final model was still based only on monthly averages. In other words, the model falsely shows solar insolation varying significantly from the 30th the 1st of every month. Since the final output of this model was designed to look mostly at year-

long trends, this was deemed a valid approach. Care must be taken when determining data that span between two months; mid-month findings are considered to be most accurate.

| Month | Time | | | | | | | | | | | | Average | |
|-----------|------|-----|-----|-----|-----|------|------|------|-----|-----|-----|-----|---------|-----|
| | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 1 | 2 | 3 | 4 | 5 | | |
| January | 0 | 224 | 753 | 908 | 971 | 999 | 1009 | 999 | 971 | 908 | 753 | 224 | 0 | 671 |
| February | 0 | 498 | 829 | 939 | 990 | 1012 | 1021 | 1012 | 990 | 939 | 829 | 498 | 0 | 735 |
| March | 0 | 612 | 842 | 930 | 974 | 993 | 999 | 993 | 974 | 930 | 842 | 612 | 0 | 746 |
| April | 126 | 640 | 807 | 883 | 921 | 939 | 943 | 939 | 921 | 883 | 807 | 640 | 126 | 736 |
| May | 271 | 640 | 782 | 848 | 883 | 902 | 908 | 902 | 883 | 848 | 782 | 640 | 271 | 735 |
| June | 306 | 634 | 763 | 829 | 864 | 880 | 886 | 880 | 864 | 829 | 763 | 634 | 306 | 726 |
| July | 255 | 615 | 753 | 823 | 857 | 876 | 883 | 876 | 857 | 823 | 753 | 615 | 255 | 711 |
| August | 110 | 586 | 760 | 835 | 876 | 895 | 902 | 895 | 876 | 835 | 760 | 586 | 110 | 695 |
| September | 0 | 545 | 782 | 876 | 921 | 943 | 949 | 943 | 921 | 876 | 782 | 545 | 0 | 699 |
| October | 0 | 435 | 779 | 895 | 949 | 974 | 980 | 974 | 949 | 895 | 779 | 435 | 0 | 696 |
| November | 0 | 211 | 731 | 889 | 955 | 984 | 993 | 984 | 955 | 889 | 731 | 211 | 0 | 656 |
| December | 0 | 95 | 709 | 886 | 958 | 990 | 999 | 990 | 958 | 886 | 709 | 95 | 0 | 637 |

Figure 23: Clear sky solar insolation [W/m²] at different times of the year for 27 degrees N. latitude

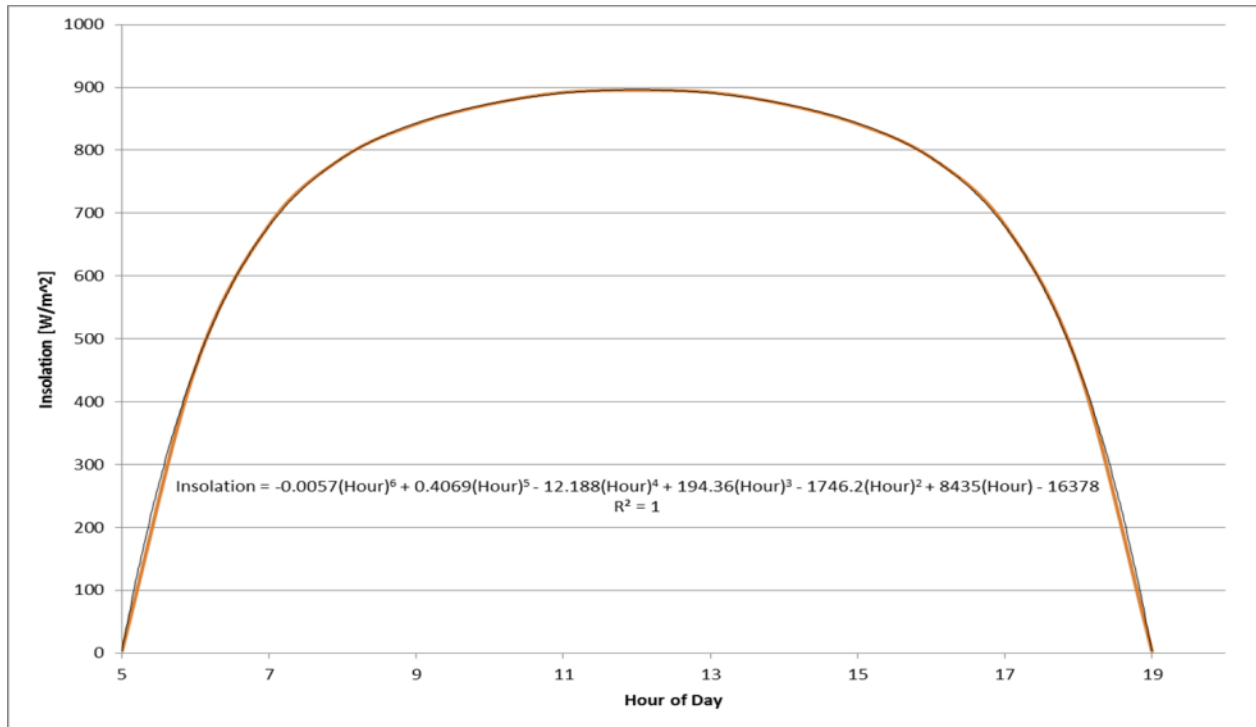


Figure 24: ANSI/ASHRAE curve for May solar insolation at 40 degrees N. latitude (orange) and the sixth degree polynomial approximation (black)

The angle of insolation will lessen the intensity of the incoming light rays. For example, a one meter square area that is receiving perpendicular to the sun having a flux of 500 watts per square meter will have an insolation of 500 watts. However, if that area is 60 degrees from the perpendicular, its view factor is such that the projected area normal to the incoming light will be only half of its full area. This

results in an insolation value of only 250 watts. Thus the model was setup to account for these angles and reduce the incoming solar flux into the collector based on the aforementioned solar angular data and the collector orientation and tilt. The orientation was assumed to be due south, and the tilt was modeled with a step equation that adjusted the collector tilt by 3.6 degrees every two weeks in order to compensate for seasonal shifts in solar declination.

With the energy into the collector in hand, inefficiencies from the collector itself could be used to find final energy into the storage device. First, the reflectivity of the polished aluminum surfaces was assumed to be 96%; the rest was lost to scattering. Multiplying the insolation data by the reflectivity raised to the power of the number of average bounces light rays make on their way to the absorption plate gave the total efficiency of the collector. Additionally, losses due to the glass containment barrier and the absorber plate absorptivity were also considered. However, based on a large number of unknowns, especially concerning the ray paths through the device, a rough estimate of 60% efficiency was used in an attempt to account for additional losses. Thus, the final energy into the device was found by multiplying the solar insolation by the aperture area of the collector and by the 60% efficiency estimate for each time-step considered.

Next, the total cooking time for Roti was determined. At the beginning it was assumed that cooking required 1000 watts of energy for 2 hours at a time. This was assumed for both morning and night cooking. This portion of the model was later refined to reflect Berkeley's experimental results on roti cooking. Through testing, Berkeley was able to provide the Iowa team with data suggesting 550 watts of energy is used to cook one roti. This value was then imported into our model to provide us with even more accurate results.

Material properties were also incorporated into the mathematical model. Storage, Collector, and Mechanics teams provided the Modeling team with material data and sizing for use in the model. Once imported to Excel, the equations provided an extremely dynamic solver, allowing changes to easily be made to the various design parameters. After all variables were accounted for, Excel was able to produce weekly and yearly graphs of temperature and energy in both the morning and evening cooking storage boxes.

Projected Performance

The following figures show graphs for temperature and total energy stored for both India and Iowa.

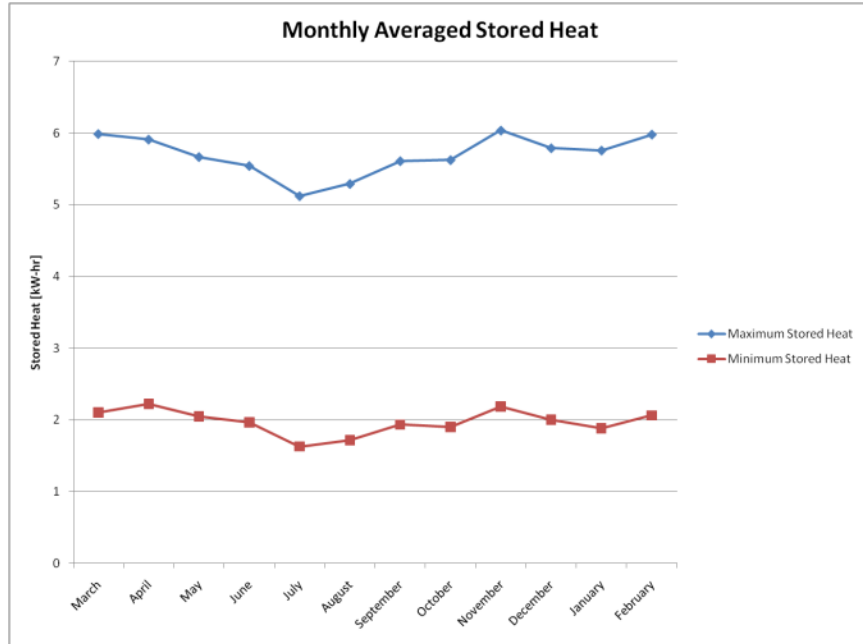


Figure 25: Night Heat Energy Stored, India

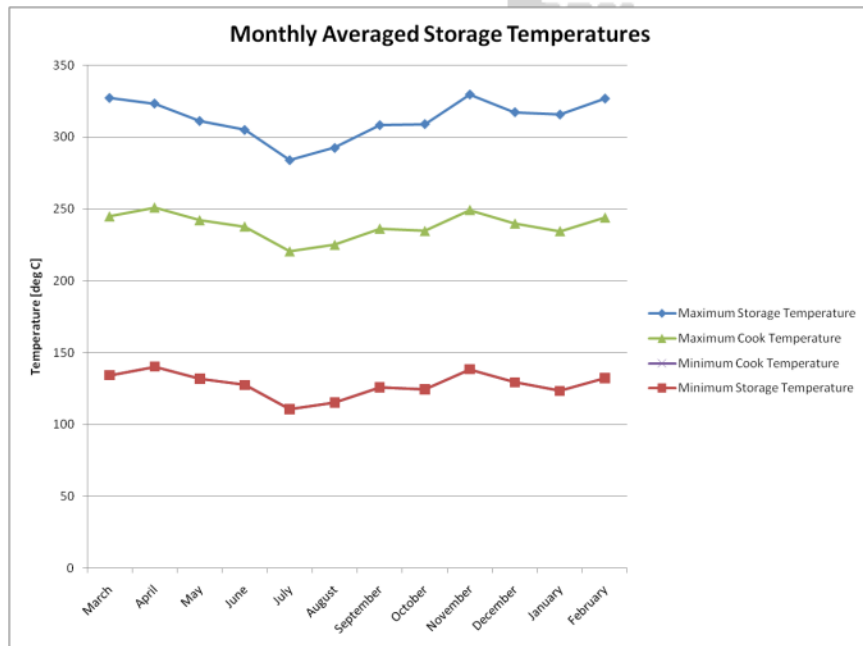


Figure 26: Morning Cooking Temperatures, India

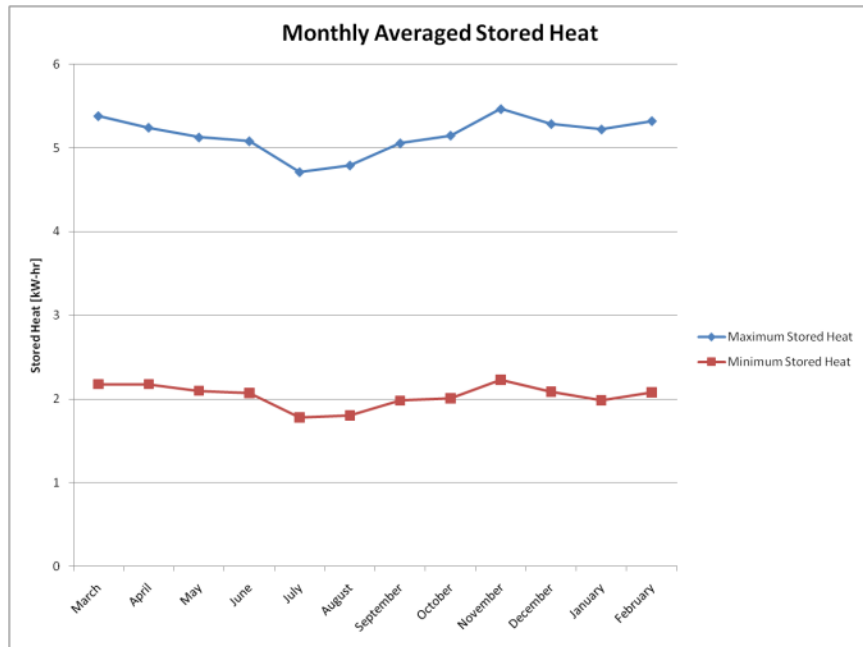


Figure 27: Morning heat energy stored, India

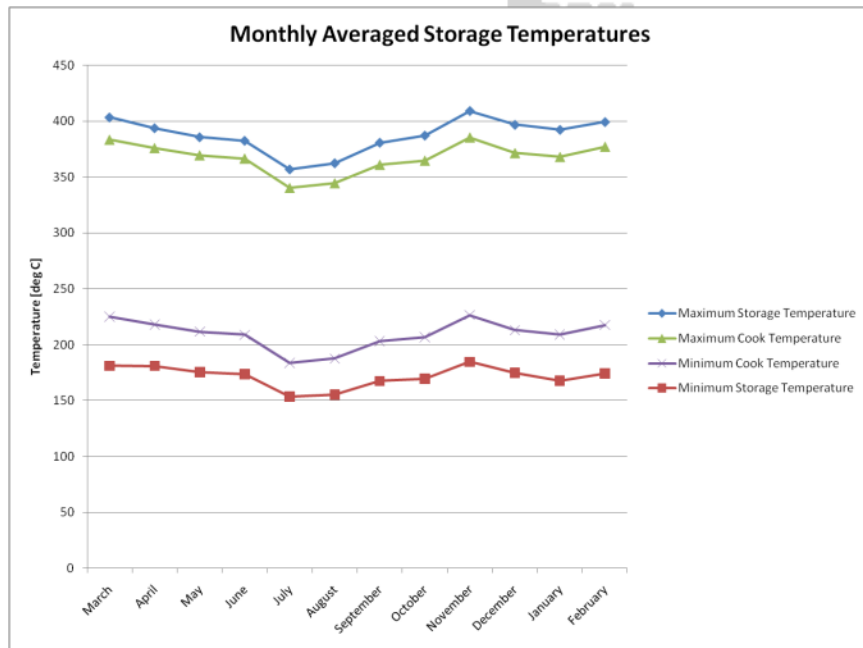


Figure 28: Night cooking temperatures, India

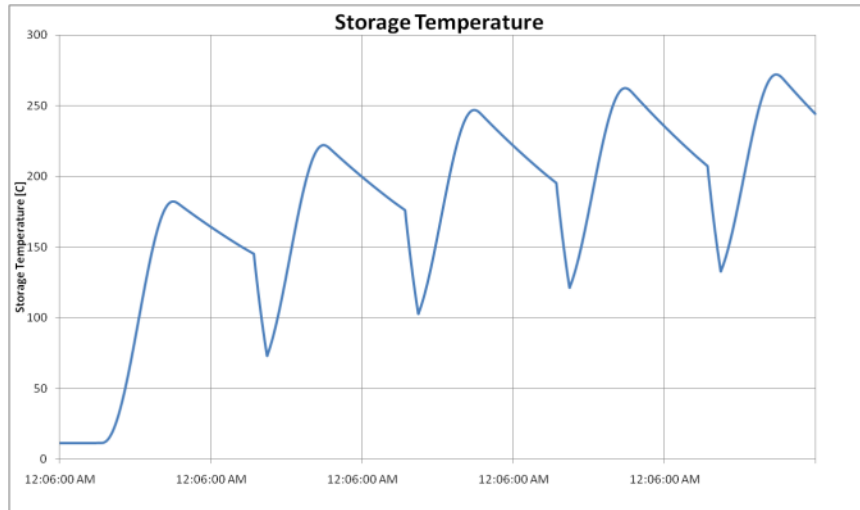


Figure 29: Weekly morning temperatures, Iowa

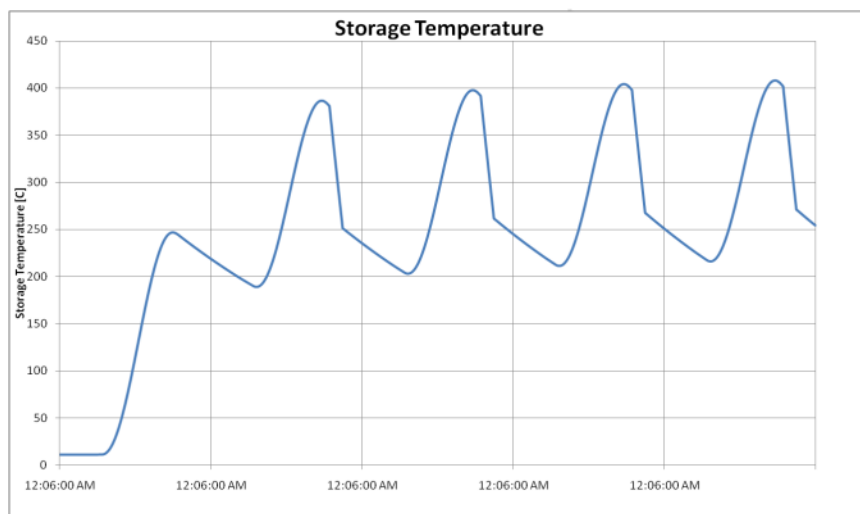


Figure 30: Weekly night temperatures, Iowa

After viewing the heat and temperature graphs for India, it was noted that there is sufficient energy stored with which to cook roti. The morning cooking had a slightly lower cook temperature due to heat losses throughout the night. A more complete picture of how the model projects temperatures in the cooker can be found in the weekly Iowa graphs (Figure 29 and Figure 30). These graphs show that a 1-2 day charging period is required before the cooker is ready for daily use. Extraction of energy due to cooking can be seen in the sharp temperature drops found in the evening and again in the early morning time periods. The slower more exponential drops in temperature are from the heat losses to the surroundings.

Conclusions

Final Recommendations

Ultimately, the class was successful in bringing the final design to prototype. However, there is much work to be completed. Future MEDP classes should be tasked to correct some of the following issues while improving upon the build quality of several key components. The primary recommendation regarding the solar cooker include:

1. Calibration and confirmation of the thermocouple results - The initial test results yielded very little information and a full calibration of the thermocouples was not performed prior to the assembly of the cooker. Before additional data is gathered, calibration of the thermocouples must be performed.
2. Isolation of the interior light funnel from the external assembly - The primary housing and light funnel needs to be assembled separately to prevent cracking that can be caused during the moving of the cooker.
3. A set of experimental evaluation criteria should be established - several suggestions for future work include:
 - a. Gather data on different intervals to obtain a more comprehensive set of performance curves
 - b. Gather data at several collector angles to evaluate performance loss between angle adjustments.
 - c. Prepare hourly note/evaluations for cooker performance. While this might seem excessive, noting little nuances regarding shadow location and light concentration throughout the day will go a long way to aid in the optimization of the cooker.
4. Determine the optimum reflector curvature for practical use.
5. Obtain the heat pipe from the Berkeley Team and incorporate it into the final solar cooker design.
6. Reduce the overall weight of the solar cooker throughout the optimization process.

The major issues at this point in the evaluation process deal with the solar cooker's ability to direct and funnel light to a focal point. It was noted during the two-day test period that light concentrations were off center on the absorber plate. Additionally, the reflector surfaces require additional polishing to increase reflectivity.

It is the Organization Team's suggestion that tests be run on each of the sub components separately. Building and testing the individual parts first will shed more light on proper construction practices and actual performance values prior to future integration between components. In other words, the MEDP groups should get each of the cooker components working separately prior to trying to get them to work together.

It is also recommend that the class be split into two team to divide the work and provide more students with deeper involvement. Thirty students on one project proved to be a bit of a logistical problem at times when opinions got the better of engineering reason. Additionally, there were times when some students were waiting on other groups to complete work, which should be avoided to prevent teams from loosing interest in the project.

Acknowledgements

The Mechanical Engineering Design Project Team would like to give a special thanks to Sailesh Rao and H. S. Udaykumar for inspiring the class to achieve so much in such a short time. The design process was long and arduous. In the words of Prof. Udaykumar, "design is messy; that is just the nature of the process." Moving forward, there is much work to be done. Future groups will need to stay focused and think outside of the box to succeed. This problem won't be solved overnight. Make it a goal to step forward each semester and eventually we will find the solution.

Thank you all for your contribution to our project...

| | |
|------------------------|--|
| Steve Struckman | UI Engineering Shopkeeper – Machining & construction aid |
| Margret Evans | MIE Department Staff – Budget aid |
| Jennifer Rumping | MIE Department Staff – Clerical and office aid |
| Rich Harden | MIE Department Staff – DasyLab aid |
| Dr. Gani Ganapathi | NASA Engineer – Insulation advisor |
| Climate Healers | Information and publicity |
| Engineering for Change | Information and publicity |
| UC Berkeley Team | Advisement and heat pipe design/construction |
| DFM Lab TA's | Machining and construction aid |
| The Mill | Food and meeting room rental |
| Rice Harvesters Inc. | Donation of the rice hulls |

And a very special thanks to the students for sticking with it throughout the semester...

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***Additional information will be provided in the forth coming course packet which will include addition research article, presentation, and the master Excel file used in project calculations.

