Solar cooking: the development of a thermal battery

by

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SUBMITTED TO THE DEPARTMENT OF MECHANICAL ENGINEERING IN
PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE DEGREE OF

BACHELOR OF SCIENCE IN THE MECHANICAL ENGINEERING
AT THE
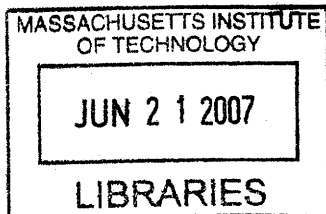MASSACHUSETTS INSTITUTE OF TECHNOLOGY

JUNE 2007

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Abstract

There are many rural area in the world where cooking fuel is very scarce. One solution to this problem is to use solar energy to cook food. However most people around the world like to cook large meals at night, when the sun is not shining. The objective of this thesis was to design and build a thermal battery that could store thermal energy from the sun during the day and retain that heat until it was needed for cooking.

The final battery design was a large block of concrete with a system of copper fins running though it.

Three main tests were conducted. The first two utilized an array of infra red light bulbs to heat up the array, and did store enough energy to cook with. However in the third test the battery was heated using a hot plate, and after the storage period still retained enough heat to boil 20 cups of water. This is enough usable cooking energy to feed most families.

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1. History

In certain areas of Africa cooking fuel is an extreme scarcity. In some tribes it is customary for the female members to collect the daily cooking fuel for the tribe. This task however proves extremely daunting, sometimes requiring these women to travel up to 25 miles per day in search of firewood and animal feces to cook with. In addition to causing extreme physical strain on these women, the search for cooking fuel can be extremely dangerous and is also a major contributor to deforestation in certain areas. A simple solution to these problems is to capture the power of the sun to cook food; and in fact some international aid organizations have introduced solar cookers to these tribes. However even after these solar cookers were introduced the women would still travel to collect cooking fuels, mainly because in these tribes people still prefer to cook and eat their food at night as they have always done. The problem with conventional solar cookers is that you can only cook on them when the sun is shining. The objective of this solar oven is to utilize solar energy to cook at night.

2. Objectives

The specific goals of this solar oven are as follows:
1. Collect 5.4 MJ of energy over a period of 4 hours from a solar array.
2. Store that energy for a period of 4 hours with no more than 10% energy loss
3. After a 4 hour storage period use the stored thermal energy to cook a meal
4. Minimize cost

3. Review of other works

When beginning this thesis there was already a wealth of previous work that had been done on this idea. The basic concept behind this idea is to use a solar array to convert solar energy into thermal energy, then store that thermal energy in a thermal battery and then insulate the thermal battery until it is needed for cooking. A basic schematic of the overall concept is shown in figure 1.
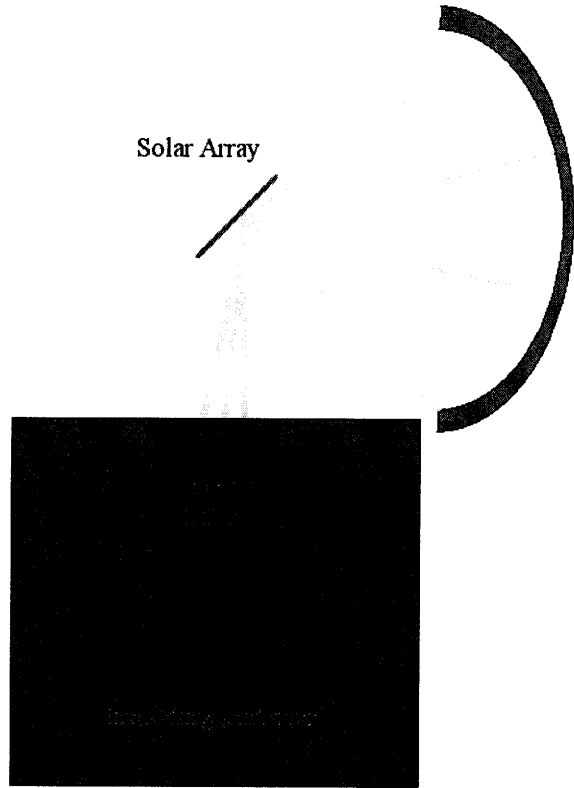
Solar Array

figure 2.

The main difference between the previous work and the design that this thesis is based on, is in the thermal battery. A rough schematic of the previous battery design is in figure 2.

The previous design's main mode of storing thermal energy is through latent heat, the battery that we use here is based on sensible heat. Latent heat is heat that is absorbed and released through a material changing phase, i.e. a phase change material.
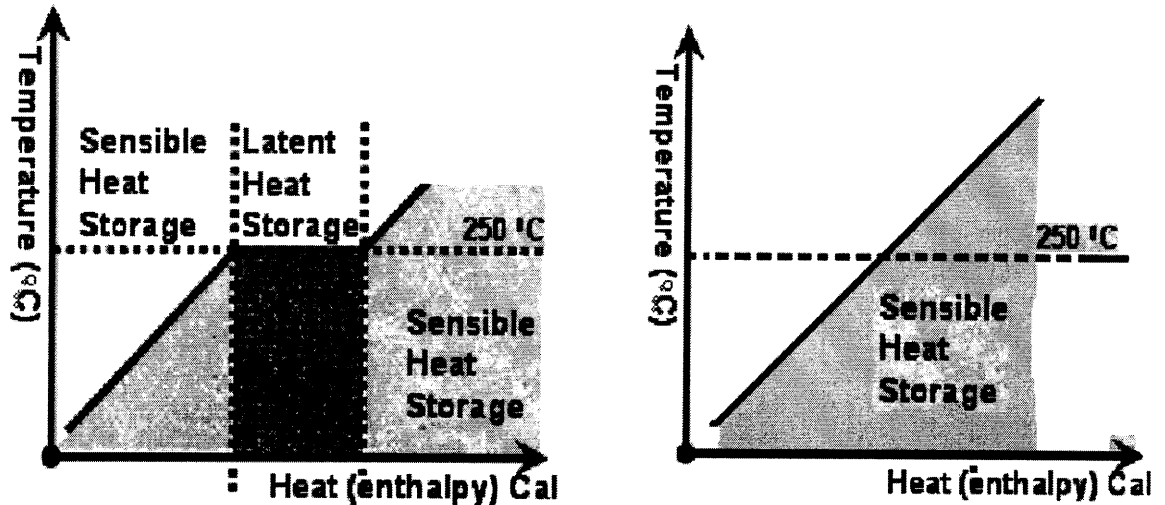
figure 1.

Utilizing latent heat storage for this application has one main advantage. As you can see from figure 2, the temperature required to store the same amount of thermal energy is lower when latent heat is utilized to store thermal energy. This is because at the temperature where the material changes phase, any added thermal energy goes into changing the phase of the material, not increasing the temperature. This results in a large area where energy is stored without raising the temperature of the phase change material. Designing a system that has a lower maximum temperature has many advantages.

A lower maximum temperature of the heating material means that there will be more days in a year that the cooker will have the ability to reach the necessary temperature. This is because due to the weather, on some days the solar irradiance is less than the average, therefore the density of incoming solar energy is less and consequently a given solar array will have a lower maximum temperature.

The other advantage to having a lower maximum temperature is that a lower quality solar array can be used. A solar array works by condensing sun light, this concentrating sunlight will then heat up whatever it is focused on. The more focused the light is the higher the resulting temperature the solar array can attain. However, solar arrays that are capable of higher temperatures are generally more expensive, so if you can design a thermal battery that requires a lower temperature for charging, then the total cost of the system will be lower.

The last main benefit of having a lower maximum temperature is that the rate of heat loss between two bodies is proportional to the temperature difference between those bodies. Applied to our application, the rate at which the

thermal battery loses its energy is proportional to how high its temperature is. Therefore the higher the operating temperature of the battery, the greater the amount of energy is lost during the storage process.

There certainly are great benefits to utilizing latent heat of storage; however, the implementation of it raises many challenges. In P.Femi Akinwale's masters thesis, she conducted an extensive survey of phase-change materials and found that based on latent-heat-storage properties, cost and safety parameters that lithium nitrate was the best choice for a material. One drawback to this solution is that lithium nitrate is expensive; the cost of purchasing enough raw lithium nitrate to store 5.4 MJ of energy through latent heat storage is $ 288.00. However this price would be expected to fall if the product were purchased in large enough quantities.

However more significant of an obstacle for latent-heat storage is the longevity of its ability to perform as a phase-change material. Lithium nitrate has a phase-change temperature of 250° C. It also has a decomposition temperature of 375° C, where it starts to convert into lithium nitrite. Lithium nitrate has very low thermal conductivity of 0.5 $\dfrac{W}{m^2 \cdot K}$. The low thermal conductivity leads to very high temperature gradients forming in the substance when energy is transferred into it. It takes only a very small thickness of lithium nitrate for a very high temperature gradient to form inside. Applying equation 1 to the parameters of the previous design (500 watts of energy transferring through a circular cross section with a diameter of 220 mm) we can see that it takes a thickness of only 5 mm for a temperature gradient to form that is large enough to start to decompose the lithium nitrate. This means that unless all lithium nitrate inside the battery was within 5 mm of a fin or heating surface, the chemical composition of the storage material would begin to degrade. This requirement requires very high machine tolerances and taking the nature and volatility of lithium nitrate into account results in a very difficult assembly procedure.

$$\frac{dE}{dt} = kA\frac{dT}{dx}$$

(1)

Additionally the implementation of such a system could be quite complicated. The previous design called for a system consisting of 8 different thermal batteries that had to be tended to all day by an individual whose sole job it was to move the modules around from their heating position to their storage position and also to adjust the solar collector.
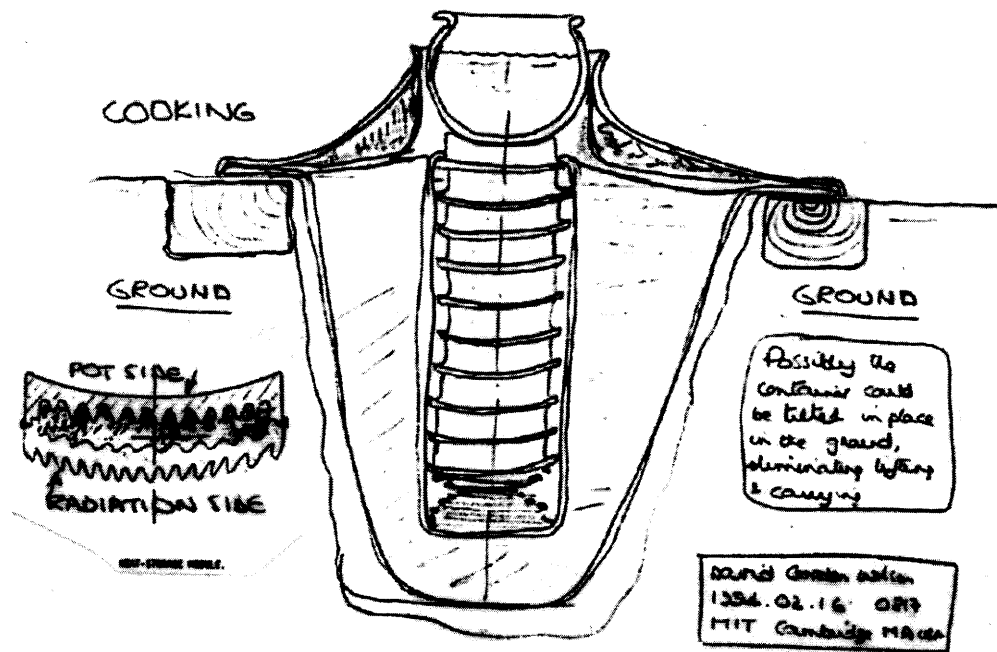
figure 3.

4. Method

The Solar cooker design that we have develop here is based on sensible-heat storage.

The first objective was to find an appropriate material to store the thermal load.

4.1 Material selection

After extensive research we made a list of certain materials that we found to be well suited to store thermal energy. This decision was based on four main criteria; cost, thermal capacitance, thermal conductivity and practicality of implementation.

Practicality of implementation is the common-sense aspect behind a concept. An idea that might look great on paper and is designed to function perfectly might weight 2,000 lbs and be impossible to transport to a remote location. Or if there are very crucial and easily removable parts, the tribes people might remove them for other purposes and never return them.

Thermal capacitance is amount of energy that goes into raising the temperature of the material. This is important because it dictates the mass of

material that is needed to store the necessary amount of energy. Equation 2 relates how much energy is stored in a given mass when its temperature is raised a certain amount. It is important to minimize the mass because the less mass that is used the easier the battery will be to transport. Also, assuming no large variations tin density, a smaller mass translates to a smaller volume. Minimizing the volume will require the heat inside the battery to travel a smaller distance, which means the heat will exit and enter at a faster rate.

$$\Delta E = m \cdot c \cdot \Delta T \tag{2}$$

The thermal conductivity (k) is important because it dictates the rate at which heat enters the battery and also the rate at which heat leaves the battery. This is important because there are only a certain number of hours during the day in which the incoming irradiance is high enough to reach cooking temperatures. So if during that time the heat is not entering the battery fast enough, not enough energy will be stored. As you can see from equation 3 below the greater the conductivity k the longer the shorter the time

$$t_{heat} = \frac{\Delta E}{kA} \frac{dT}{dx} \tag{3}$$

Then there is cost. There are many materials that would be great for this purpose. Copper for example has a very high thermal capacitance and a very high thermal conductance however the cost for that quantity of solid copper would be very high. The lower the cost the more widely available this product could be throughout the developing world. The following are the materials that were considered as the main sensible heat storage units.

1. Copper
2. Iron
3. Aluminum
4. Concrete
5. Sand
6. Saturated Sand

Table 1.1 contains the relevant data on these heat storage materials.

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	thermal conductivity, k $(\frac{W}{m \cdot K})$	thermal capacitance, c $(\frac{J}{Kg \cdot K})$	price (USD) per Kg
Copper	400	380	7.9
Iron	80	449	.5
Aluminum	237	896	2.81
Concrete	1.7	881	0.15
Sand	0.35	1258	free
Saturated Sand	2.7	793	free

Table 1.

In order to apply these variables we first need to quantify what our objectives are.

Using equation 3 we can calculate the mass of each material necessary to store the needed 5.4 MJ of energy. The results are shown in table 2.

	mass required (Kg)	cost of material (USD)
Copper	94	742.6
Iron	80.1	40.05
Aluminum	40.2	112
Concrete	40.9	6.14
Sand	28.6	free
Saturated Sand	45.4	free

Table 2.

From a practical stand point there are certain properties of these materials that can instantly eliminate them as viable options.

The copper block is heavier than most full grown adults and would be very difficult to transport to remote village locations, additionally it is very expensive. The iron is quite inexpensive; however again it is still very heavy and unwieldy, also there would be considerable degradation of performance through rust over time. The aluminum does appear to be a very strong candidate. The mass is heavy but still very manageable and the cost is still reasonable. All of the metals have high enough thermal capacity to store enough energy during the day to supply a meal. The Cement, sand and saturated sand are all extremely inexpensive, however by themselves have thermal conductivities that are too low.

Graph 1 focuses on effects of thermal conductivity on the charging time of a thermal battery. Given initial conditions of a cylindrical battery oriented so that the top surface is receiving the concentrated sunlight, the solar array is maintaining a maximum surface temp of 350° C, the top surface of the battery is circular with a diameter of 220 mm and the battery is 500 mm tall. Under these conditions a thermal battery made entirely out of concrete with a thermal capacitance of, 1.7 $(\frac{W}{m \cdot K})$, it would take the battery 35.7 hours to fully charge. However if the thermal conductivity is increased to 20.5 $(\frac{W}{m \cdot K})$ the charging time decreases to a reasonable 3 hours.

Different wattages are required to maintain the same surface temperature given different thermal conductivities of the battery. In graph 1 the wattage varies between the different thermal conductivities. However a thermal conductivity of 20.5 has an incoming energy of 500 W.

Charging Time vs. Thermal Conductivity
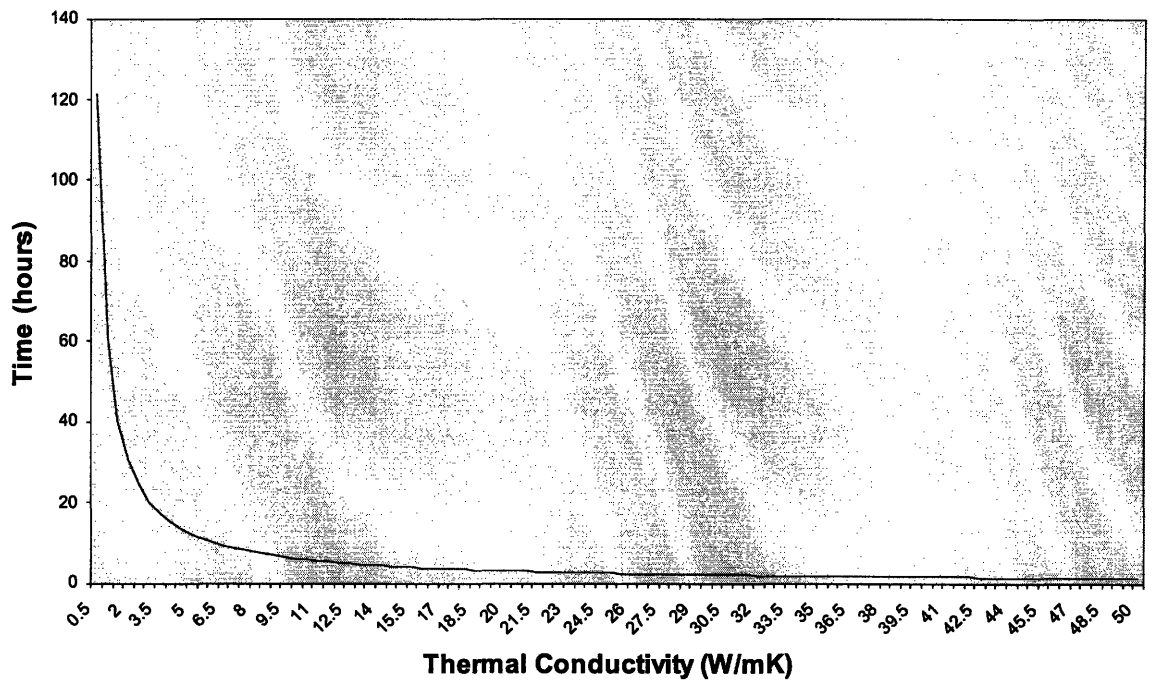
graph 1

       It is very apparent that all of the non-metallic material choices do not have a high enough thermal conductivity to fulfill the heating time requirement on their own. All of the metallic materials introduce other problems such as increased weight, difficulty of transporting, degradation over time and also pose a high likelihood of being stolen or sold for scrap due to their inherent high value. Additionally they also have thermal capacities that are much higher than necessary.

       The solution that we have come up with is to combine the two. We designed a thermal battery that has metallic fins penetrating into a cement block, utilizing the low cost and high thermal capacitance of concrete. To compensate for the low thermal conductivity of the concrete, we are inserting metal fins throughout the concrete mass to facilitate in transferring thermal energy from the heat source to the entire mass on concrete. Copper was chosen for the fin material because of its high thermal conductivity.

4.2 Determining Battery Shape

The first step in designing the fin array was to determine the optimal geometry for the overall battery, and the first step towards that was determining the overall volume of concrete necessary.

Assuming a ΔT of 150°C and using a maximum thermal capacitance for concrete of 881 ($\frac{J}{Kg \cdot K}$), we used equation 2 to find the total mass of concrete necessary to be 45 kg. Next we applied the known density of concrete to the mass and calculated that 0.0187 m^3 is the volume necessary.

The previous work that has been done on this project decided that a circular heating surface area of .22 meters was optimal for our application; we then used a cooking surface of .22 m as a starting point. The ideal shape would keep as much of the heating material as close the heating surface as possible, so that the heat had the smallest distance possible to travel both in for storage and out for cooking.

The rate of heat transfer between two bodies is directly related to the surface area of contact between those two bodies. Therefore reducing the amount of surface area on the outside of the battery will reduce the amount of heat lost during storage.

Another very important criterion is the ease of construction. Whatever is designed will most likely have to be built in rural areas and for very little money. When taking all of these parameters into consideration the two shapes that made the most sense were a cylinder and a half sphere.
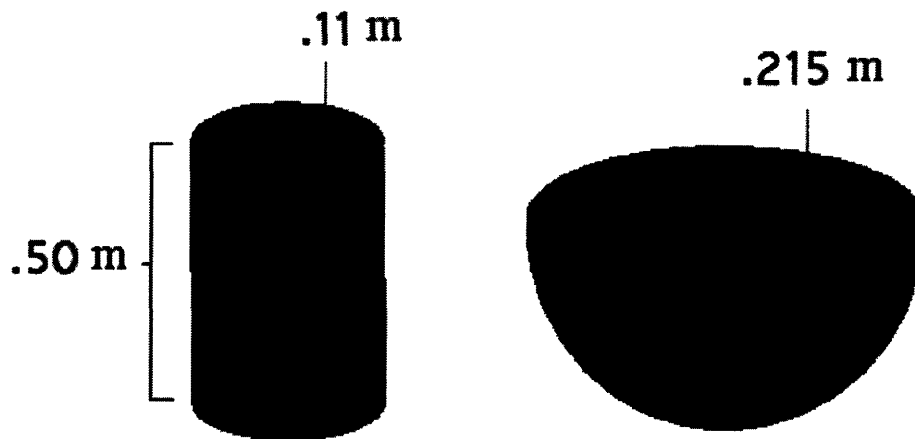

figure 3.

Given the required volume of concrete, the dimensions of the shapes are provided in figure 3. In the half sphere, none of the concrete is further than .215 m from the heating surface, and also the surface area is smaller relative to the surface area of the cylinder. In the cylinder the furthest concrete will be .50 m from the heating surface. If there were no fins involved the half sphere would be the logical choice. However because the radius of the sphere is only .215 it decreases the length and subsequent area of each fin, which has more of a negative impact on the heat transfer rate than the decrease in the distance the heat has to travel. Also the construction of a fin array where the angle of every fin is different and also embedding that fin array into concrete would be a very difficult and potentially expensive to produce. Additionally because the fin array would require all of the fins to be at different angles, there would be pockets of concrete near the perimeter where the fins would be further apart. This would cause areas of relative lower temperatures in the concrete which would slow both the heating and cooling process.

4.3 fin array

Battery Wattage vs. Charging Time
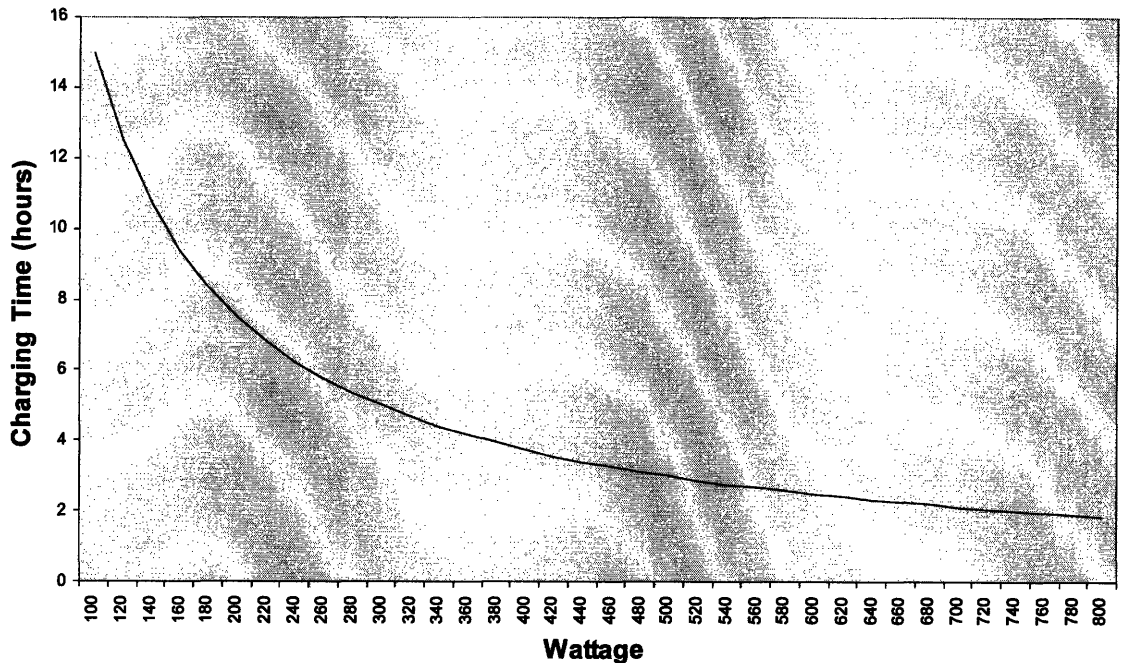
graph 2.

As you can see in graph 2, the number of watts entering the battery also greatly affects how long it will take to fully charge the battery.

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Average solar irradiance in Africa is around $1000 \dfrac{W}{m^2}$.

Our design calls for a solar collector that has a collection surface of 1 m^2. Assuming that the collector has an efficiency of 63% and the surface has an absorption efficiency of 80% there will be at least 500 Watts entering the battery during the heating process. At this energy flow, assuming the heat transfer rate is high enough, it should take about 3 hours to fully charge the battery.

$$\frac{dE}{dt} = 500 \text{ Watts}$$

Because the copper has such a large thermal capacitance compared to that of cement (400 vs. 1.7), we can model the copper block as having no internal temperature gradient. This means we can set the fin temperature equal to the heating surface temperature. We can then set an assumed temperature gradient between the heating surface and the internal temperature of the concrete. In equation 3. dT is the temperature gradient between the fins and the concrete. We will assume a reasonable temperature difference of 200°C.

DT = 200°C

dX = .5 m. because the heat must conduct through the full length, .5 meters, of concrete.

$k = 1.28 \ (\dfrac{W}{m^2 \cdot K})$ the thermal conductivity of concrete is given

The addition of fins effects will affect equation 3 by increasing the area through which heat is conducted from the copper to the concrete; it increases the value of A. When equation 3 is applied to the stated variables above, we find that a total fin area of 1 $(\dfrac{W}{m^2 \cdot K})$ is required to obtain the heat transfer rate into the battery of 500 W.

A = 1 m^2

This is achieved with 3 concentric tubular fins with a length of .5 m. The fins will have radii of .0275 m, .0550 m, and .0825 m. The design is shown below in figure 4.
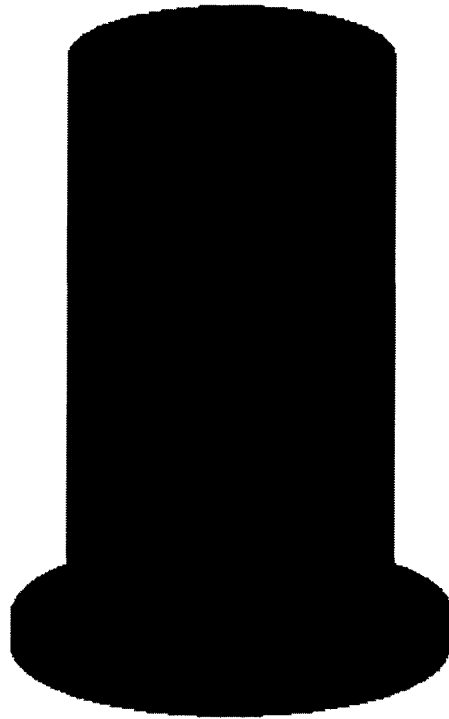
Figure 4.

However due to time constraints and concerns regarding the feasibility of inserting the tubular fin array into a block of concrete, the test apparatus was modified from the original design. Instead of 3 concentric tubular fins, we will now have an array of ¼" rods running the full length of the battery, 60 rods in total at .5 m each. The new fin array gives us a total fin area of .565 m^2.

When we plug this new area into equation 3. we find that in order for the battery to conduct the same 500 Watts, dT = 345.7 °C which is higher than we

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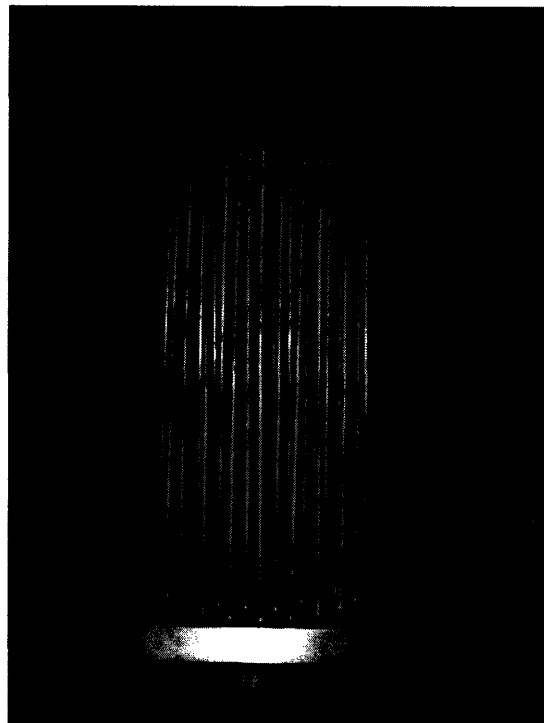
expect to see. This means that in actuality, the rate of energy absorption will be less than the planned 500 Watts. Assuming the original dT = 200 °C we can expect to see around 290 Watts entering our battery.
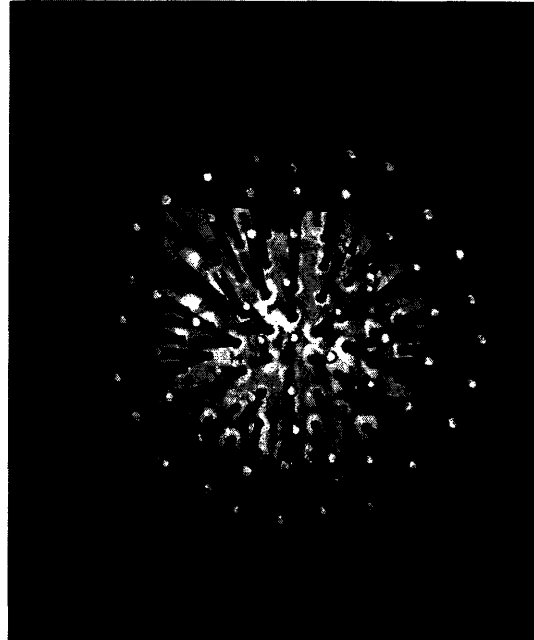
4.4 Insulation

The insulation requirement is that the battery must retain 90% of the original 5.4 MJ stored over a period of 4 hours. Therefore the maximum energy flow rate out of the battery is:

Maximum energy flow rate = (.90*5.4MJ) / (4 hours) => 41.6 Joules /sec

The primary form of heat loss from the battery will be conduction through the insulation. The recommended insulation for this application is Roxul Blanket RW 80 insulation. It is fire proof so that its performance won't degrade with multiple uses, also Roxul insulation has a very low thermal conductivity .03 W/m^2°C at 100°C and .08° $(\frac{W}{m^2 \cdot K})$ at 350°C.

The equation for heat loss through conduction is

$$\frac{dE}{dt} = \frac{K \cdot A \cdot \Delta T}{d}$$

(4)

Where
:

$K = .08$ $(\frac{W}{m^2 \cdot K})$

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A = .422 m^2

ΔT = 375°C

$$\frac{dE}{dt} = 41.6 \text{ W}$$

Plugging these variables into equation 4 we get that d = .304 m. The thickness of insulation during the storage period needs to be .304 m thick at all places around the battery to ensure that 90% of the initial energy is retained.

The final design for implementing the insulation is for the tribes people to dig a large cylindrical hole in the ground that is .630 m in diameter and .804 m deep. This hole will be large enough to fit the battery along with sufficient insulation. On top of the buried apparatus there will be a cover that is the same diameter as the hole and .304 m thick that will insulate the top of the module.

4.5 Solar array

The objectives for the solar array are to condense 1 m^2 of solar radiation on the cooking surface of the thermal battery, with a minimum efficiency of 63%.

The recommended manufacturer for the solar array is Cleardome. They produce a wide array of solar collectors that can attain temperatures above those required for our applications.
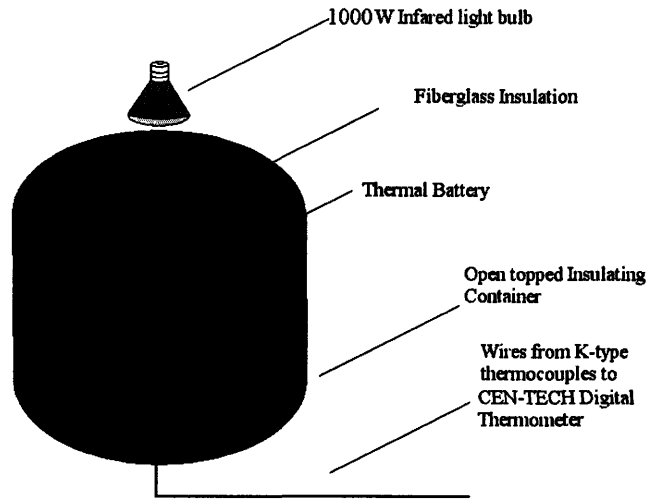
5. Experiment

Materials:
- 10 thermocouples: K-type tp-01 thermocouples with a temperature measurement range from -50°C to 400°C, and an accuracy of ± 1.5°C for temperatures less than 250° C.
- 1 digital thermometer: CEN-TECH model 92242 accuracy ± 1.5°C or .1(Temp in °C) whichever is greater
- Insulation: Pink Panther brand fiberglass insulation R value 30. 34.4 ft^2.
- Trash Can: 1 large trash can with a radius of at least 3 ft.
- 1000 W of IR light bulbs and light fixtures: We used 1 250 W bulb and 6 125W bulbs

- 80 lb. bag of concrete: make sure that it has a fine aggregate.
- 1 copper fin array
- 1 flat bottomed stainless steel cooking pan
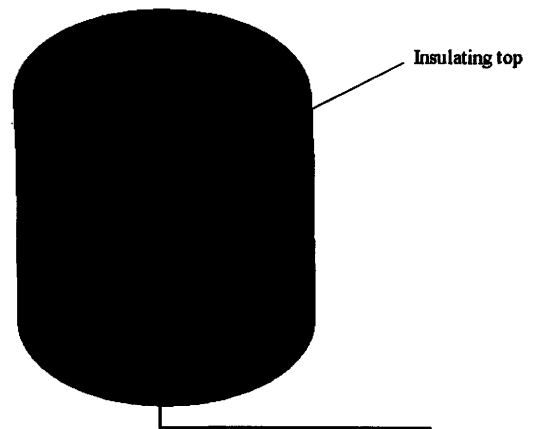- Surface temperature grill thermometer
- Contact cement

1000 W Infared light bulb

Fiberglass Insulation

Thermal Battery

Open topped Insulating Container

Wires from K-type thermocouples to CEN-TECH Digital Thermometer

Phase 1:

Heat the battery using the infra red light.

Phase 2:

Insulate the battery for 4 hours.

Insulating top

Phase 3:
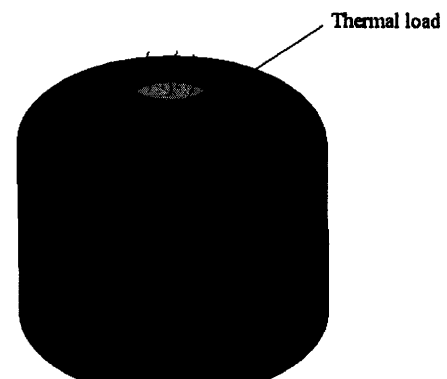
Thermal load

Apply a thermal load and extract heat from the battery.

The first step was to attach thermocouples to the fin array at various locations. This is important because it enabled us to measure the internal temperature of the battery at multiple points, which gave us a good idea of how well the heat was transferring to the different locations inside the battery. We attached the thermocouples using contact cement. There were 9 thermocouples total implanted on the fin array. We selected 3 individual fins to implant the thermocouples on, one in the very middle of the array, one at half the radius, and one at the very outer edge of the array. On each of the fins we attached a thermocouple at the base, half way down and on the tip.
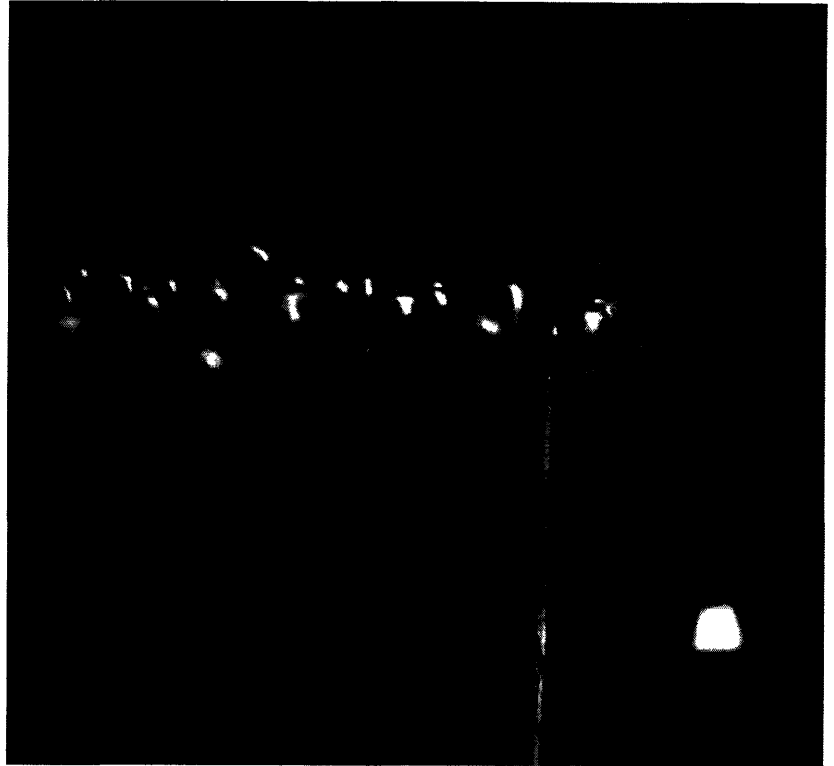
After the thermocouples were attached to the fin array we inserted the fin array into a concrete block. To accomplish this we found a cylindrical concrete column form with a diameter of 8.5" and we cut the form so that it was .51 meters tall. Next we attached the form to a board using tape and filled the form with concrete. Once the form was filled with concrete, we inserted the fin array into it. This process was however very difficult. The concrete was quick drying (setting time around 1 hour) and because we did not have access to a mixer, the mixing had to be done by hand, which took time. Also the aggregate in the
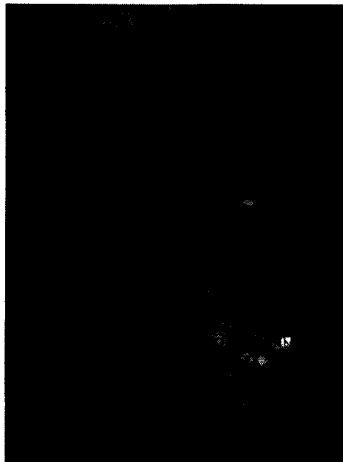
concrete, even though it was small for concrete aggregate, still caused a significant problem during the insertion process. These conditions made it difficult to insert the fin array. What we ended up doing was inserting the fin array until it was about 4 inches from fully inserted, and then we flipped the apparatus upside down. When we did this the weight of the concrete pulled it down the rest of the way. When the array was fully inserted we removed some of the concrete to inspect the fin tips. When we did this all of the thermocouples that had been attached to the fin tips were not there. They had become dislodged from their initial location during insertion and were somewhere else in the concrete mass.
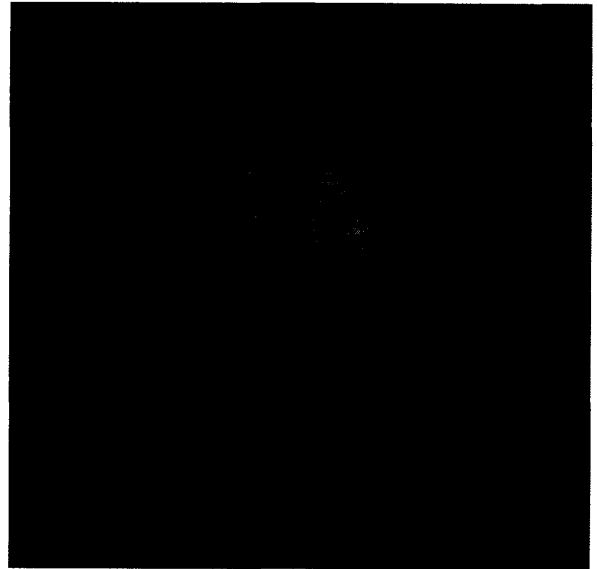
Once the fin array was inserted into the concrete, we had to let the concrete cure for at least 5 days. We waited 6 days and then commenced with the experiment.

The first step in the setup was to secure the insulation. We built a 3 point wooden block and inserted in on the bottom of the plastic container. The wooden block is to support the battery's weight when it is inside the vessel. Once the wooden block was in place we filled the rest of the plastic container with Fiberglass insulation, including a thick layer on the bottom. Once the insulation was in place we inserted the battery into the insulated container.

The next step was to set up the lighting array. We accomplished this by hanging a large dowel horizontally above the top surface of the battery and attaching all of the lights to this dowel. To eliminate as much of the light scattering as possible, we set up reflective aluminum around the outside of the lighting array and also around the base of the copper surface of the battery.

Additionally to increase the absorption of incident light we dyed the top surface of the copper array black.

After the battery was all set up, we put the lights directly above the battery and turned on the lights. This phase of the experiment is to simulate a solar array reflecting condensed sunlight onto the thermal battery. For our first experiment we heated the battery for 6 hours. After this initial heating period, the heating array was removed and a cover above the copper heating surface to further insulate it. After a period of 4 hours the top was removed and a thermal

load was placed on the heating surface of the battery. For our experiment we used a flat bottomed stainless steel pot with water inside. The fact that it is flat bottomed is important because the copper surface is flat and the more surface contact that occurs between these two surfaces the more heat transfer will occur

6. Results

Time vs Temp
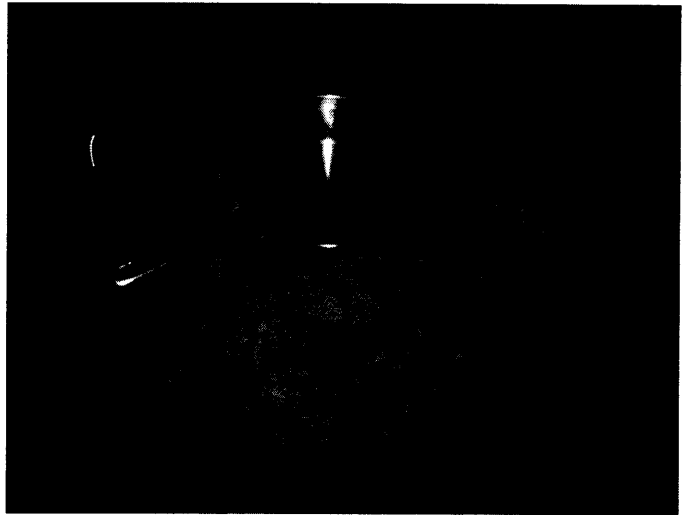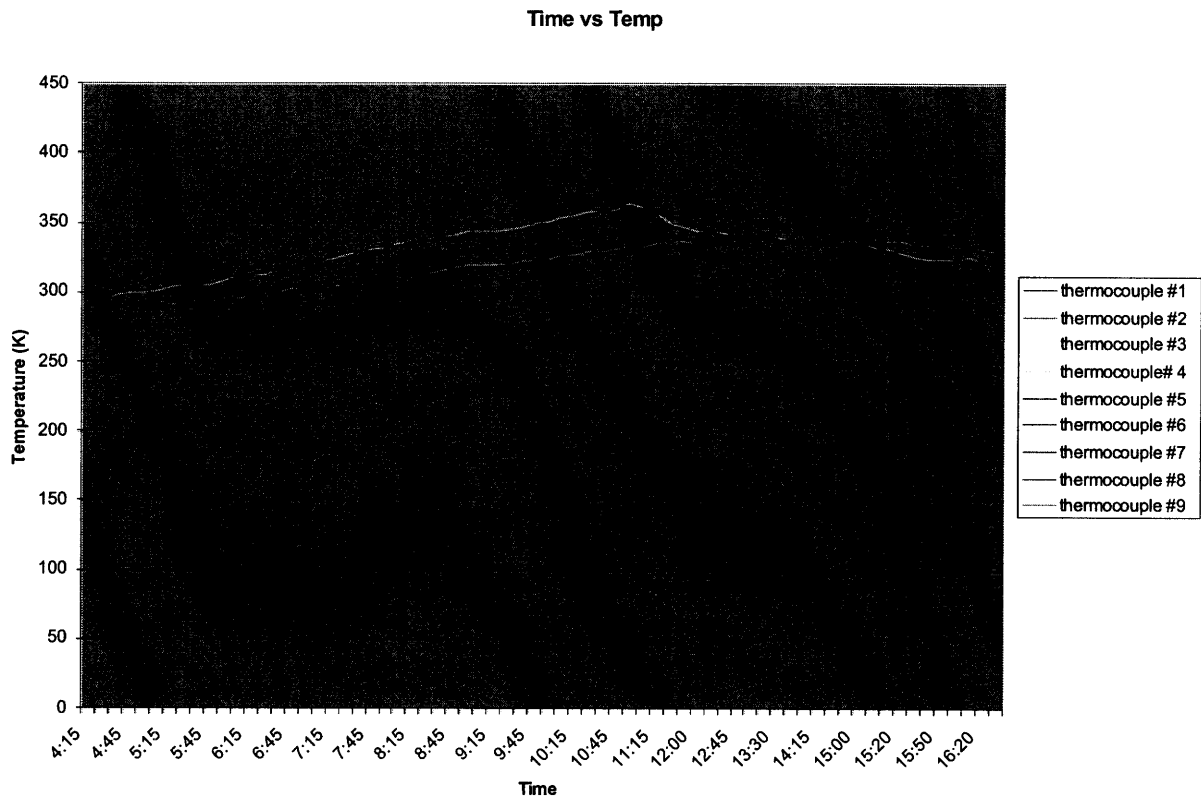
The graph above shows the results of the first
experiment. During the time period from 415 – 1055
the battery was charging under 1000 W of infra red
light. After 10:55 the lights were turned off and an
insulation layer was placed over the top of the battery
for a period of 4:05 hours. Then at 3:00, the top
insulation layer was removed and a thermal load was
applied. Figure 5. is a diagram showing where each of
the thermocouples was placed inside the battery.
Thermocouple # 9 was embedded into the thermal load,
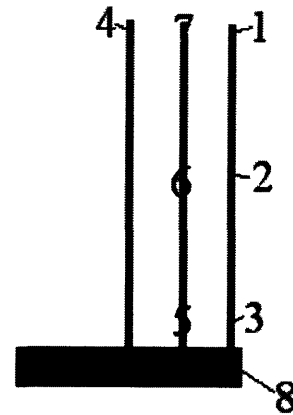which is why it appears later on in the experiment.

Figure 5.

The design parameters call for 45 kg of Concrete and 9.25 kg of
Copper for the battery construction. From this we can calculate the total thermal
capacitance of the system

Thermal capacitance of concrete = 45Kg* 881 J/Kg*K = 39,655 J/°K
Thermal capacitance of copper = 9.25Kg*380 J/Kg*K = 3,515 J/°K
Total thermal capacitance = 43,170 J/°K
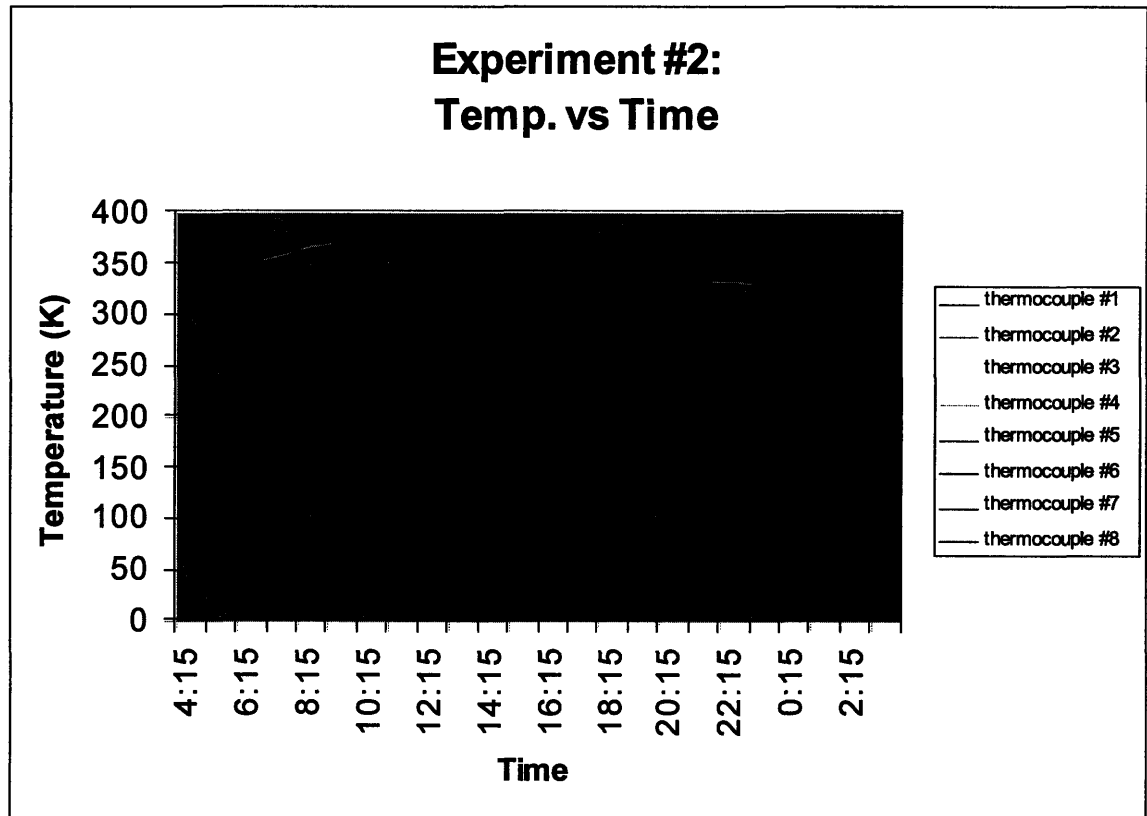
8.2 % from copper
91.8 % from concrete

Once the heating phase of the experiment was over and the storage
phase began, the temperature profiles inside the battery changed dramatically.
While the battery was being heated there needs to be a temperature gradient for
the heat to flow throughout the battery. However when the addition of heat is
removed, all of the internal temperatures converge to a mean temperature.
Thermocouples 3, 6 and 9 were attached to the copper block, while thermocouples
1, 2, 4, 5, 7 and 8 were attached along the fins and measured mainly the
temperature of the concrete. When we take a weighted average of the average
temperature of the copper and the concrete, we find that at the instant the heat was
removed, the convergence temperature was 358° K.

We can calculate the energy at the final state and initial state from
equation 2. Subtracting those values and dividing by the total time that energy
entered the battery gives us an average energy flow rate into the battery of 132
Watts.

This is significantly less than expected. There was a total of 1000 W of incident light hitting the surface. Assuming 70 % of the light emitted struck the battery surface, only 18.9% of the light energy was absorbed.

At the end of the storage period all of the internal temperature had converged to 336° K. We calculated that the average heat loss during storage was 66 W. This is also higher than expected, our parameters set that the heat loss ratio during the storage period could not have a higher than 42 W. This is most likely due to a large transition time between the heating phase and storage time.

When we applied the heating load to the surface of the battery, the surface temperature was insufficient to boil the water. We succeeded in heating a 6 cup sample of water from 288° K to 317° K. When we apply equation 2 to this data we see that the total amount of heat the thermal load extracted was 84 KJ. This is a very small amount of energy extracted compared to that needed to cooking a full meal. More energy certainly could have been extracted from the battery, however because the energy was being extracted at a temperature below that necessary for cooking food, we deemed it unnecessary.

Experiment #2:
Temp. vs Time

Temperature (K) vs *Time*

thermocouple #1
thermocouple #2
thermocouple #3
thermocouple #4
thermocouple #5
thermocouple #6
thermocouple #7
thermocouple #8

Experiment # 2 started 23.75 hours after the start of experiment #1. In that 24 hour period between the start of the cooking sessions, the battery did not cool down to a steady state temperature. The temperature at the start of experiment # 2 was actually 17°C above the start of experiment #1. 24 hours after Experiment #3 started, the convergence temperature of the battery was at 348° K, a higher convergence temperature than either of the first two experiments reached. The result of the increased starting temperature of experiment #2 is that the battery reached a very similar maximum temperature with 4 hours less of heating time. 24 hours after Experiment #3 the convergence temperature was still at 348° K.

For experiment #2, the instant the heat was removed, the convergence temperature was 346° K, resulting in a temperature change of 41°C which corresponds to 1.8 MJ of energy stored. Taking into account the 4 hour heating period this gives us an average energy flow rate into the battery of 122.9 W., which is less than the energy flow rate in of the first experiment.

Experiment #2 focused on the heat storage phase of the design. The battery was stored for a period of 18 hours. During this time the temperature dropped from the convergence temperature of 346° K to a temperature of 322° K. When we apply equation 2, this temperature drop corresponds to a total heat loss of 1.03 MJ. This means that the average heat loss over the 18 hours was 16.0 Watts. This is significantly below the maximum heat loss of 41 Watts.

Experiment #3
Time vs. Temperatrue
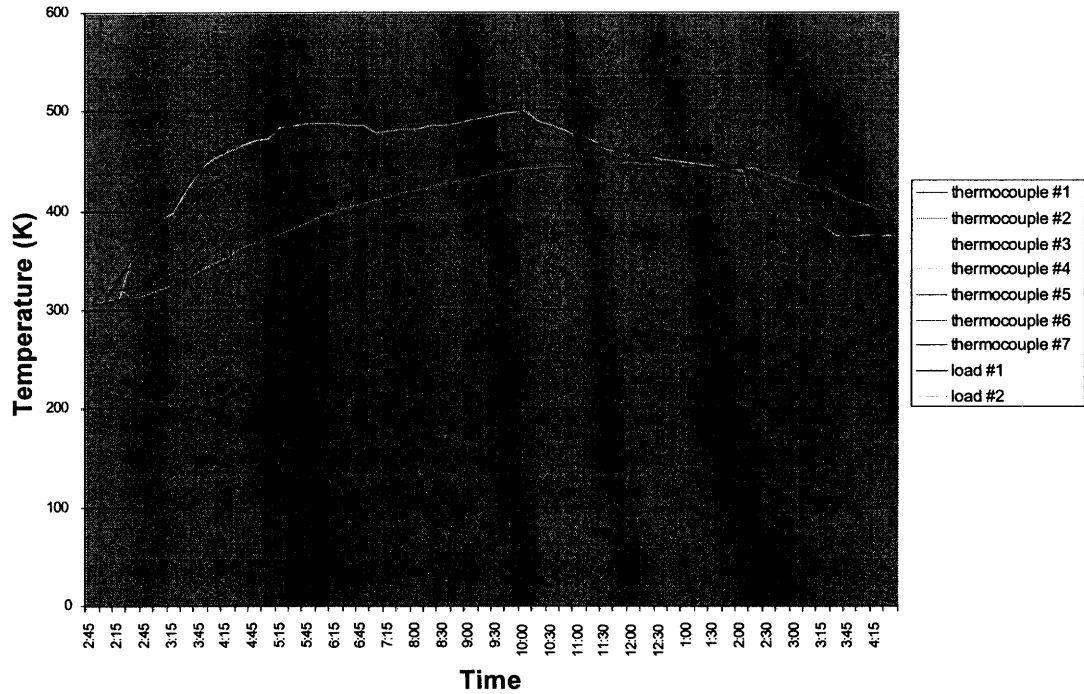
The main difference between Experiment #3 and the previous 2 experiments was the method of heating the thermal battery. In Experiment #3 we heated the battery using an inverted 1000 W hot plate for 7 hours and 45 minutes. Before the hot plate was applied to the battery the average temperature inside the battery was 305° K. At the moment the hot plate was removed from the battery the convergence temperature was 452° K. Applying equation 2, we find that there was a total energy flux in of 6.3 MJ, over the 7.75 hours which translates to an average heat flow in of 228 W.

During the storage portion of the experiment the convergence temperature dropped from 452° K to 442° K. Applying equation 2, this gives us a total energy loss of .43 MJ over the period of 4 hours, which translates to an average energy loss of 31.3 W. This amount of energy loss is again below the design requirement, even though we were working with higher temperatures.

The heating load portion of experiment #3 was very successful. At 2:00 a thermal load of 10 cups of water was placed in a pot and heated using the thermal battery. At 3:05 the water was boiling, and another thermal load of 10 cups water was placed on the battery's heating surface. At 4:15 the second thermal load of 10 cups of water was brought to a boil. Both 10 cup loads started the heating process with an initial temperature of 288° K.

This translates to a 1.7 MJ of usable cooking energy, transferred to the thermal load. This corresponds to an average energy flow rate of 233 Watts.

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7. Recommendations for further progress

Heat transfer rate: the heat transfer rate into and out of the battery was not quite high enough. We want to be able to absorb between 300 - 500 Watts, with the hot plate directly on the thermal battery, the battery was only absorbing 228 W. Also the heating of the thermal load was relatively slow it took around 1 hour to bring the 10 cups of water to a boil and over 1 hour to bring the second cup up to a boil. Recommendations for further progress are to construct the initially designed fin array, which would increase the area of thermal communication between the fin and the concrete form .56 m^2 to over 1 m^2, which would significantly increase the battery's heat transfer rate. Also for ease of construction and compatibility with fin array, instead of concrete investigate the feasibility of cement.

High thermal conductivity concrete: there have been some studies showing that the higher the crystalline structure of a concrete mixture, the higher its thermal conductivity. There have been reports of the thermal conductivity approaching over 20 $\dfrac{W}{m^2 \cdot K}$, as opposed to the standard 1.7 $\dfrac{W}{m^2 \cdot K}$.

Solar array development: finding the right solar array and configuring it to supply the necessary amount of energy to the battery will be paramount to the success of the project.

Absorption/emissivity ratio: the copper surface with black dye was only converting around 18% of the incoming radiation into thermal energy. What needs to be improved is the absorption to emissivity ratio, which is the determining factor for the percentage of light that is converted into thermal energy. Recommendations for improving the design in this area are to fabricate another metal surface that has a very flat surface on one side and a surface on the other side with a very high absorption to emissivity ratio. Also if there is some kind of clamping system, that would help decrease the contact resistance between the surface of the battery and the bottom of the attached plate.

Thermal contact resistance: the thermal contact resistance between the heating surface of the battery and the bottom of the cooking pot was quite low. In the second heating load, the water reached boiling point when the heating surface was only 6° C above the water temperature. Although this is a very good result, one way to eliminate this temperature difference would be to have the liquid heat directly on the surface of the battery heating surface. This could be accomplished by attaching some kind of wall around the outside of the heating surface, creating a pot where the bottom of the pot is the top heating surface. The thermal contact resistance between a metal and a liquid is exceptionally low.

Resources

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