Construction and Improvement of a Scheffler Reflector and Thermal Storage Device

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I. Abstract

We constructed and successfully tested a 2 m^2 parabolic dish solar concentrator (Scheffler Concentrator) to focus sunlight onto a stationary target. Present efforts are to decrease the construction complexity and cost of the concentrator. In order to store solar heat, we also constructed and are testing a thermal storage device made of sand (for thermal mass), and pumice (for insulation). Preliminary tests indicate thermal retention times of many hours. Present efforts are to increase accessible power, and structural integrity.

II. Previous Projects

Our project goal is to develop a convenient solar cooking technology with thermal storage. This may decrease the number of deaths associated with indoor smoke inhalation in developing communities, as well as remove a source of carbon dioxide (a contributor of global warming), and other pollution. Since our goal is to apply this in a developing country where the primary problem is both social and economic, the end result will need to be inexpensive and easy to construct to allow for easy proliferation of the technology.

In the summer of 2009 we designed and built a full-size (2.4m x 3m) parabolic trough reflector to concentrate sunlight onto a pipe. The pipe was to be filled with oil as a thermal transfer fluid, transferring the heat to a thermal storage device, an insulated concrete block (Illustrated in Figure 1 below).

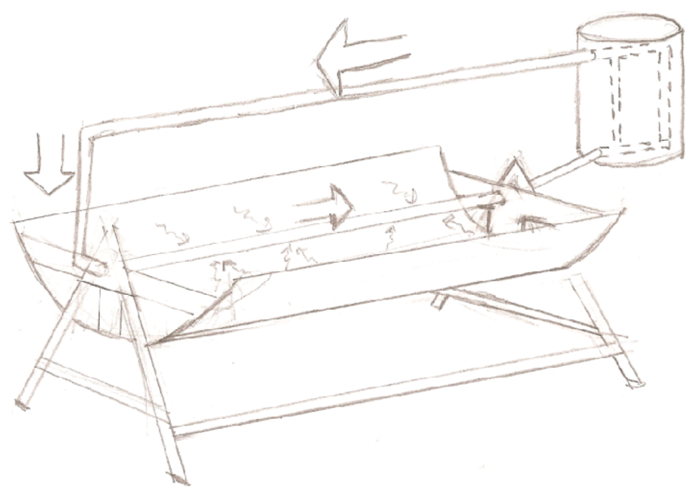

Fig 1: Thermal storage integrated with a solar trough concentrator, constructed in the summer of 2009.

Parabolic Trough Concentrator:

This design was proposed because of the straight forward geometry, single axis tracking, and proven technology. Construction went smoothly, and we had a mostly functional concentrator by the end of summer 2009 (shown in figure 2).

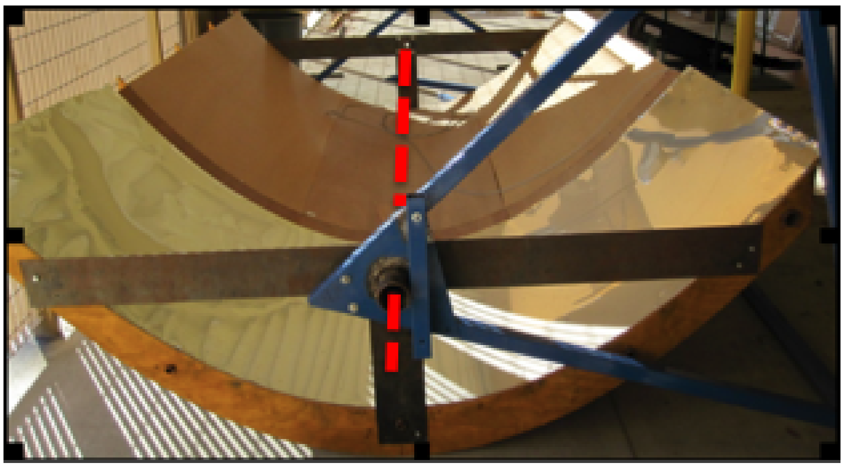

Fig 2: Solar trough near completion. The red dashed line represents the location of the pipe through which the heat transfer fluid would flow in the completed model.

The trough was never connected to the thermal storage device, nor was it tested in sunlight. The reason the trough was never tested in sunlight was due to the lack rigidity to resist torsion in the trough itself. When one end of the trough was turned, the other would remain stationary. This caused the mirror frame to twist, and was the reason the reflective aluminum was never attached, for fear of damaging the material.

Thermal Storage Unit:

The insulated thermal storage device was designed to hold a large amount of heat after the sun goes down allowing cooking in the evening. The original thermal storage design used a pipe system to deliver the heat to the thermal storage from the trough.

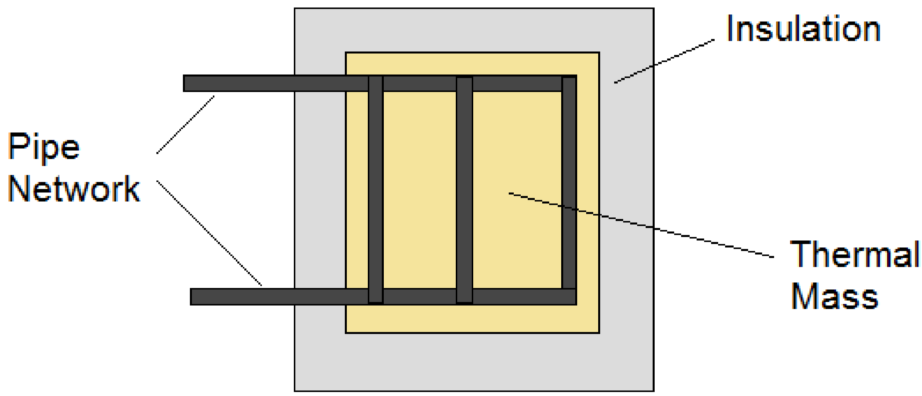

Fig 3: Original thermal storage, showing the pipe network within the thermal storage for heat delivery.

A thermal siphon was planned to drive the motion of the oil (thermal transfer fluid) through the pipes. This takes advantage of the fact that by heating a substance its volume increases, reducing its density. Using the arrangement shown below the power required for the flow rate was calculated.

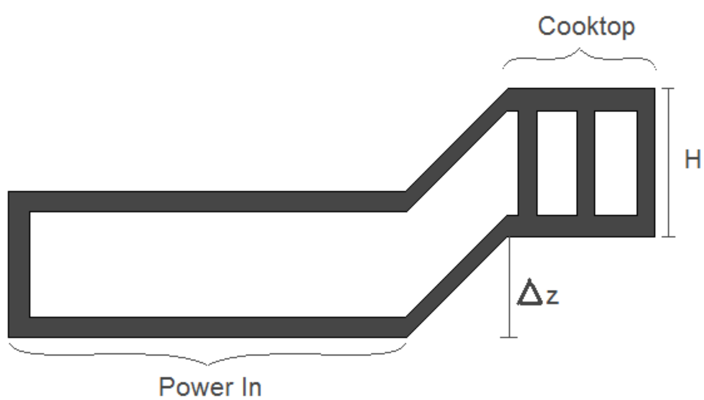

Fig 4: Thermal Storage pipe setup
This flow rate was calculated using the mass flow rate equation:

$$Flow\ rate = \left(\frac{dm}{dt}\right) = \rho_{oil}\left(\frac{dV}{dt}\right)$$

Where dV/dt is given by Poiseuille's equation for fluid flowing through a pipe:

$$\left(\frac{dV}{dt}\right) = \frac{\pi R^4}{8\eta} \cdot \frac{\Delta P}{L}$$

Where R is the inner radius of the pipe, L is the total length of the pipe network, η is the viscosity of the fluid. ΔP is the pressure gradient across the region through which the fluid must flow, caused by the thermal gradient:

$$\Delta P = g\Delta h\Delta\rho$$

The density change here can be found using thermal expansion:

$$\Delta\rho = \beta\Delta T\rho_0$$

The calculations indicated that a 65 Kelvin difference between the top and bottom is necessary to cause the oil to deliver enough energy to adequately cook the food, and to move the oil effectively. This setup was tested, using a hot plate for power (drawing about 1kW of electrical power), using sand as the thermal storage medium (the proposed design used concrete), and using pumice as the thermal insulation. It was found that the energy delivery rate was much lower than was expected, and the device lost heat much faster than predicted. We believe this may have been due to the failure to fully analyze the resistance due to turns in the pipe, and the rate at which the oil lost heat to the earth between the heat source and the thermal storage.

The major lesson we learned from both the concentrator and thermal storage construction is the importance of building something quickly, to learn as much from the process as possible. This allows quicker implementation of improved designs, and brings us faster to a better design.

III. Scheffler Reflector

<u>Design</u>

The Scheffler reflector design is a proven design for concentrating sunlight for the purpose of cooking, used extensively in India, and elsewhere. It concentrates sunlight in two dimensions to a “point” or small area, allowing heat flow without a dedicated mechanism such as transfer fluid.

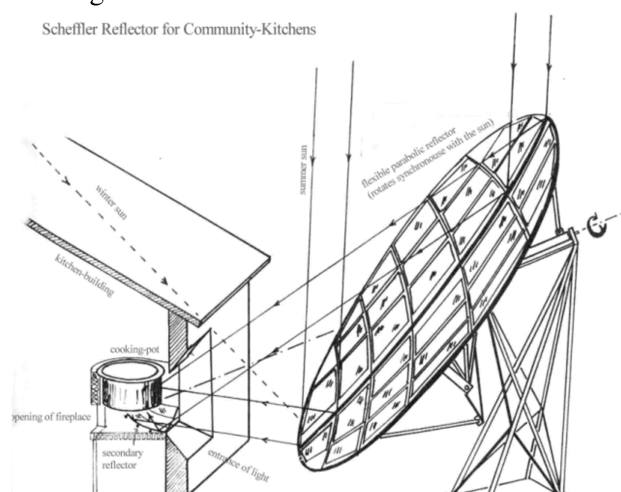

Fig 5: Scheffler reflector diagram showing integration with a cooking area

Our specific goal in investigating the Scheffler Reflector design is for implementation in cooking in developing countries, and for the continuing study of solar energy for multiple purposes.

The Scheffler reflector is based on a similar principle to satellite dishes, using the side of a rotated parabola instead of the bottom (the main difference is that the satellite dish does not need to track, since TV satellites are in geosynchronous orbits). If the reflector is located directly north or south of the focus, the Scheffler can track on a single axis. As is shown in figure 6, the sun's apparent path through the sky defines a series of planes perpendicular to the earth's axis of rotation (the polar axis). These planes shift north and south based on the season. The innovation of the Scheffler is the adaptation to changing seasons: in order to maintain focus the mirror must be adjusted in altitude and its shape must be changed.

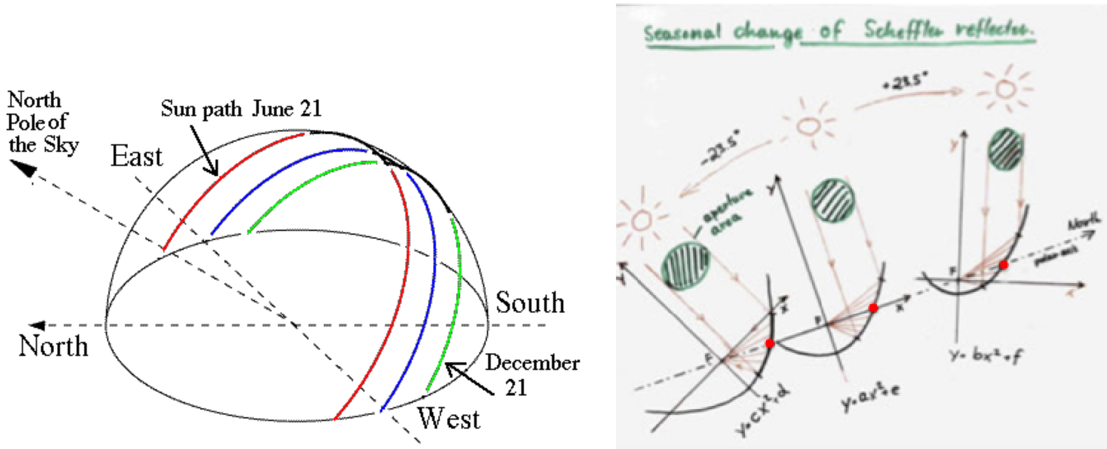

Fig 6: *(Left)* The sun's apparent path across the sky. *(Right)* Depiction of mirror modification by season. The letter "F indicates the focus, where the thermal target is. The darkened portion of the parabolic surface is represents the Scheffler Mirror, the darkened circle above the shape represents the apparent cross sectional area of the reflector, and the dotted line represents the axis of the earth's rotation.

Mathematically, the mirror's shape change is due to the fact that we have two fixed points that define the shape of the parabola: the focal point, and the point where the mirror is held to the frame. Using this, we can figure the correct parabola for the sun's current altitude at any time of the year.

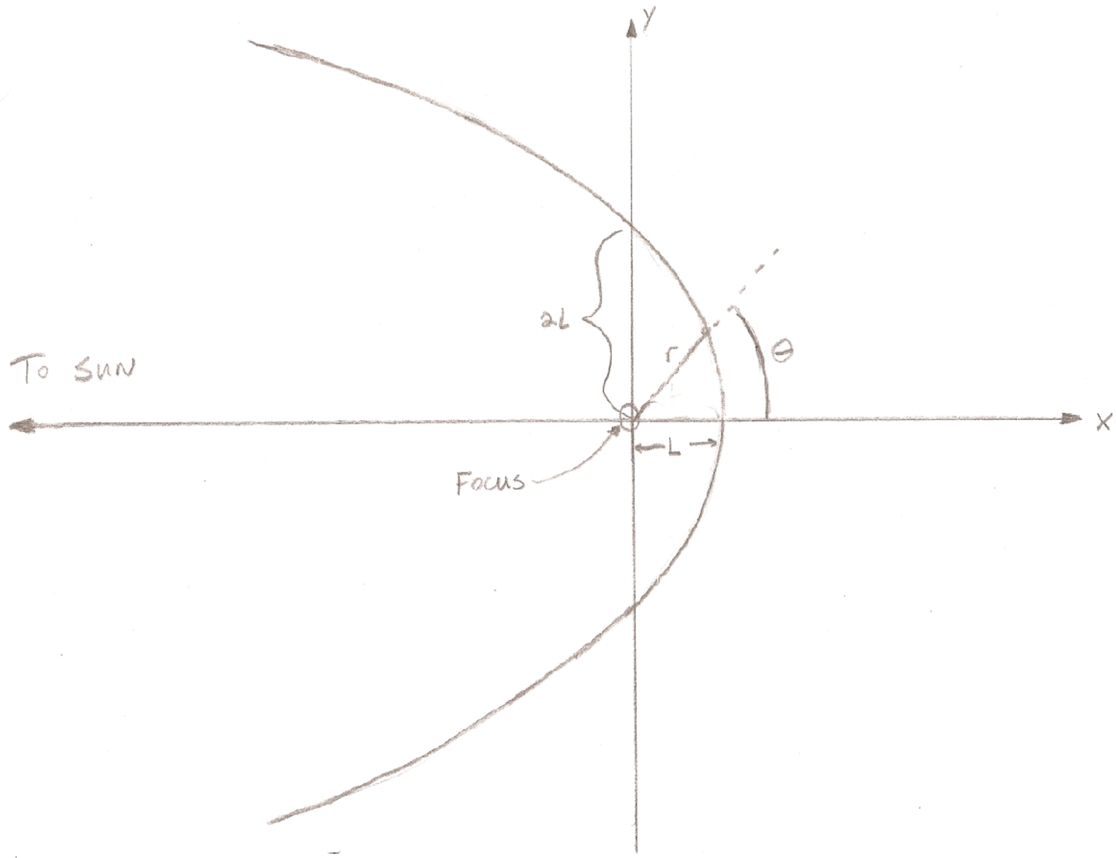

Fig 7: Parabola defined in polar coordinates: $r = L/(1 + \cos\theta)$

The parabola defined in figure 7 is situated with the focus at the origin. “L” is the semilatus rectum, or the distance between the focus and the vertex which need to be constant as the mirror is reshaped: the focus needs to always be at the cooking area, and the mirror’s attachment location is permanent (at least for now). These points, and two such shapes are shown below in figure 8.

The angle θ is measured from the x axis (shown as vertical in figure 8), and r is measured from the origin to the point, as normal.

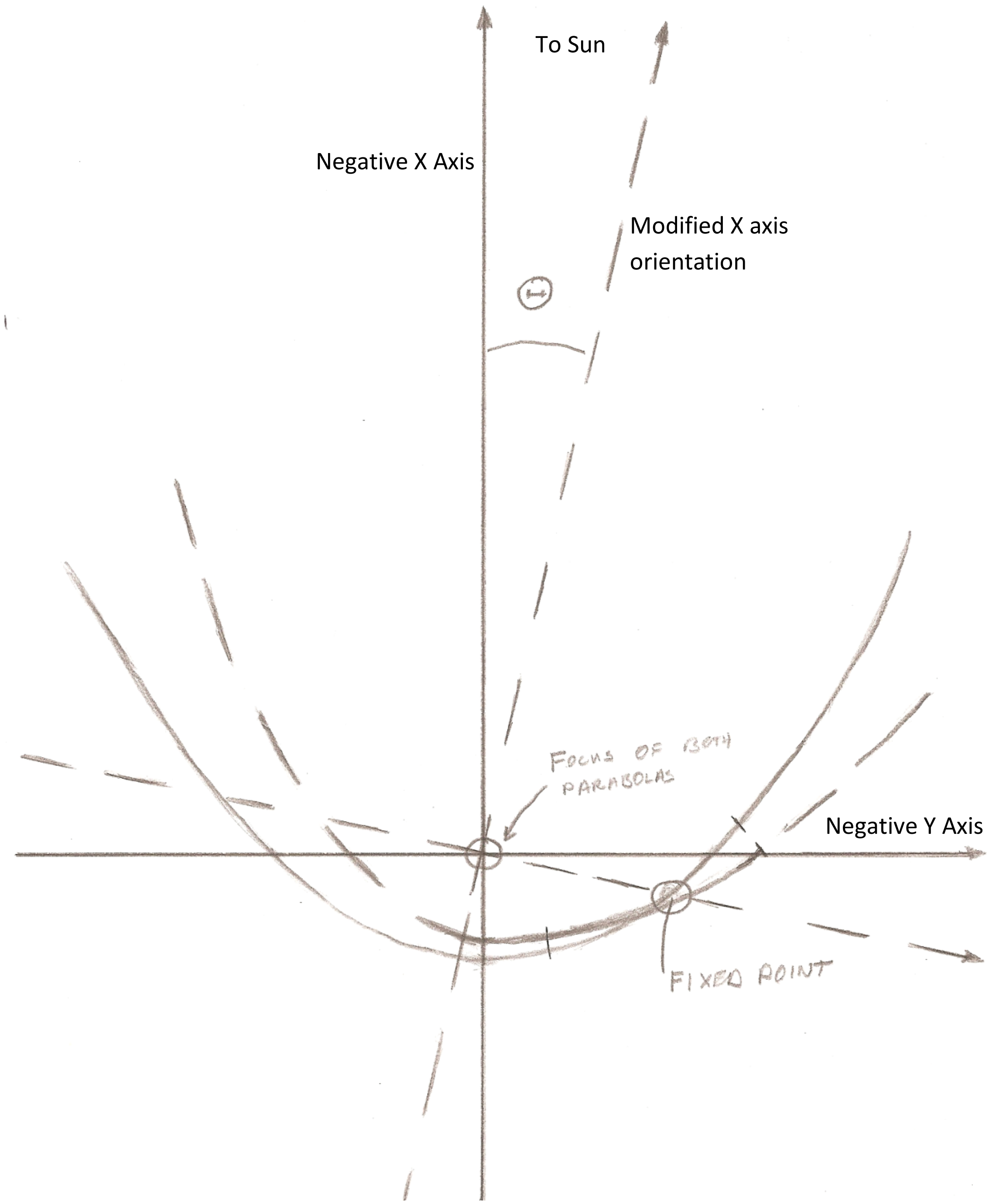

Fig 8: Two example parabolas using the polar definition of a parabola. Between seasons, the sun's position changes from the central default position. This allows us to do single axis tracking, only modifying the shape and orientation of the reflector by season.

The definition of a parabola in polar space puts the focus always at the origin, leaving one fixed point where the mirror is attached to the support. In this case mathematically convenient to reposition the default axes to have the negative x axis point at the sun at all times.

To translate between the two coordinate systems (the neutral position of the sun, and any other time in the year) :

$$r' = r; \;\; \theta' = \theta + \Theta$$

Where Θ is the angle between the two frames, and the primed variable is the second frame (dashed lines in the figure above). Between summer and winter the parabola must change shape, and orientation. Shifting its altitude by Θ to match the displacement of the plane of the sun's motion and changing its shape to properly focus to the cooking area.

Given our two fixed points, and the modification to the axes, the formula for the shape of the mirror is:

$$r = \frac{L}{(1 + \cos\theta)}$$

We are also able to directly find the radius of curvature of the mirror at any point, by directly translating to the y axis (the horizontal axis in the figure above):

$$y = r\sin\theta$$

As the sun's altitude changes from winter to summer, there are two opposite effects to the curvatures in the rotated plane (circular, perpendicular to the axis of symmetry of the parabola) and to the parabola (in a vertical plane). If the parabola is on the sun side of the target, in the summer when the altitude increases the parabola itself becomes larger, but since the attachment point is closer to the vertex the parabolic curvature increases. At the same time the radius in the rotated plane increases. The opposite is true if the mirror is on the shaded side of the target, making it important that between the seasons we have the ability to change the curvatures of the mirror in opposite ways. Recent computer modeling (not discussed in this paper) indicate that a rigid mirror optimized for equinox produces concentrations in summer and winter as low as 70 suns.

Results:

In the summer of 2010 we constructed a Scheffler reflector from a set of plans[1] as a first step. We constructed the Scheffler to ascertain that it worked and that we could build it regardless of issues of access, and cultural acceptance. The second step, once this was completed, was to develop the design with those three criteria in mind to improve it. We built a Scheffler Concentrator, and it worked well: in figure 10 below the Scheffler is shown igniting a piece of wood placed at the focus. We also found some parts that could use improvement, for example we found that the base took a short amount of time, while the mirror structure took much longer, and the entire arrangement cost more money than would be affordable in a developing country.

This gave us 3 goals in our second objective: make it cheaper, make it faster, and improve the performance.

Fig 9: Scheffler Reflector completed according to plans

As shown above (in figure 9) and below (in figure 10), when completed the dish concentrated sunlight well enough to heat water, and to ignite wood placed at the focus. However, the heating was slower than expected when water was placed on the cooking area. The focus spot was about 30cm in diameter, implying a concentration of about 25. We measured this using a large piece of white paper (other paper colors would have absorbed too much light and ignited). As a result we have identified some improvements discussed below.

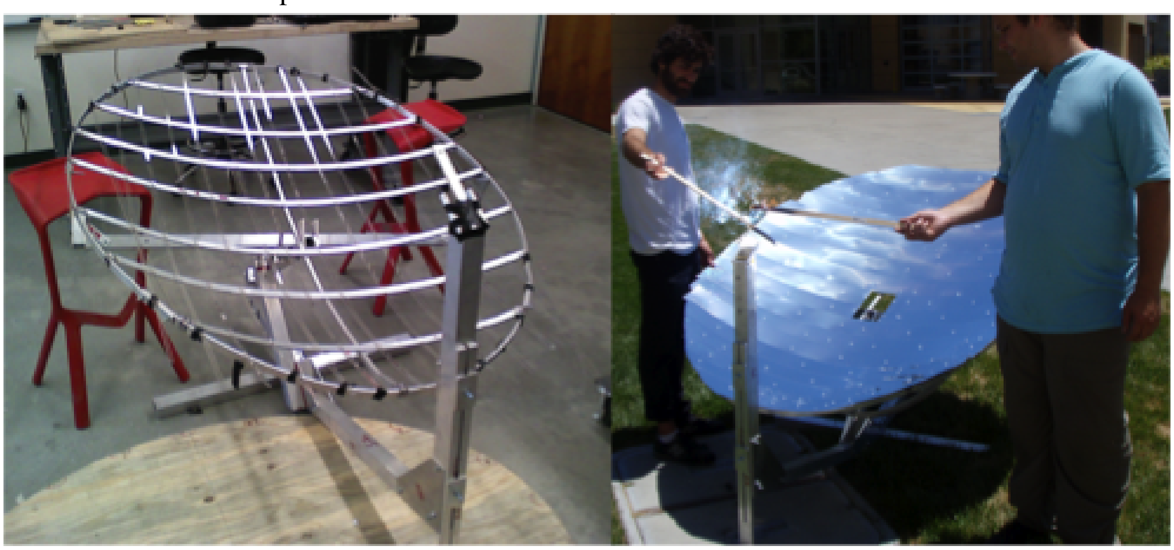

Fig 10: *(Left)* Lexan and aluminum framework support for the reflector. *(Right)* Wood ignited when placed at the focus of the mirror.

The plans originally called for a system of Lexan support ribs (Fig 10, *left*) to which thin sheets of reflective aluminum are riveted. The reflective aluminum (with a thickness of a little under a millimeter) deforms when drilled, and on the edges when cut (due to the method of cutting the reflective aluminum into long strips). The Lexan ribs were also contributors to the deformation, since they had very little strength to hold the correct shape, and when the mirror changed shape, the ribs bow up or down deforming the mirror's attachment points.

We constructed a second mirror with greater surface uniformity eliminating the rivets and drilling from the construction process. This reflector used Lexan tubes (of rectangular cross section) rather than Lexan strips to support the reflective material eliminating the bowing of the Lexan strips. The mirror material was attached with strong double-stick tape, reducing or in some cases eliminating deformation from the attachment process. The only deformation left in the process was due to the method of cutting the reflective mirror, causing slight warping along the short axis of the strips.

This second version of the reflector was significantly improved as far as concentration. Again, we measured the spot size at the focus using a large piece of white paper, yielding an aperture size of 10cm, (consistent with a concentration of over 200), indicating that the deformations due to the riveting process were significant in causing the focal divergence that we observed.

The last part of our research, and part of our ongoing investigation, is to reduce the time it takes to construct the reflector. In the construction of the device we found that the support structure took a fairly small amount of time and could be easily modified to allow multiple constructions per day, but the large portion of our work was in the mirror frame, and reflective surface. In the section on ongoing and future work this we describe efforts to reduce complexity, time, and expense of the mirror construction process.

Tracking Mechanism:

The tracking mechanism is a combination electronic and mechanical design which tracks the sun, Like the mirror, the tracking mechanism must be durable, simple, and inexpensive. The suggested tracking system from the plans used a simple voltage balance where the output of two PV panels worked against each other:

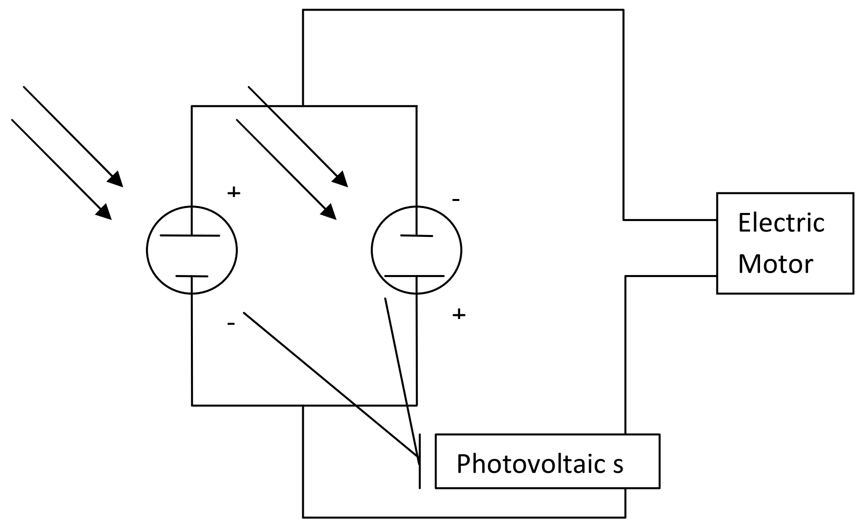

Fig 11: Original circuit design

In the above circuit, the photovoltaics each put out 1V and 100mA, while the motor requires approximately 80mA and 1V to run.

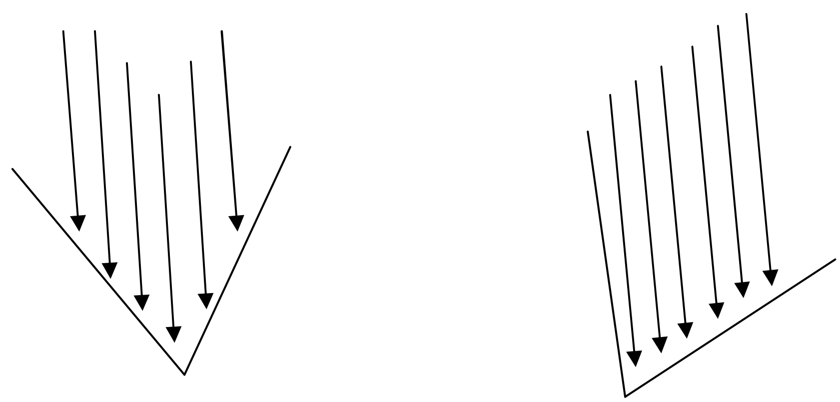

Fig 12: Photovoltaic balancing, *left:* relatively balanced, will not move. *Right:* Imbalanced, will move to correct

This circuit was to work by balancing the two solar cells, set at an angle to each other, when the cells were not pointed at the sun evenly, one cell would have the higher voltage, and power the motor. We found that this arrangement did not provide enough power to properly move the reflector, and would put the motor under constant load from the two photovoltaics. A modified design was needed:

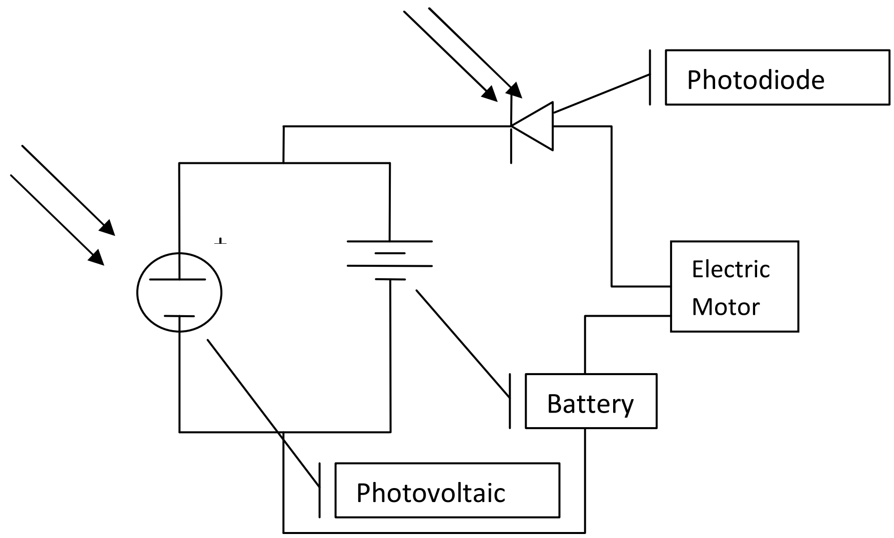

Fig 13: Modified tracking system circuit.
A photovoltaic cell charges a battery to power the motor, controlled by a partially shaded infrared photodiode (Fig 14), where reverse diode current is increased by IR exposure:

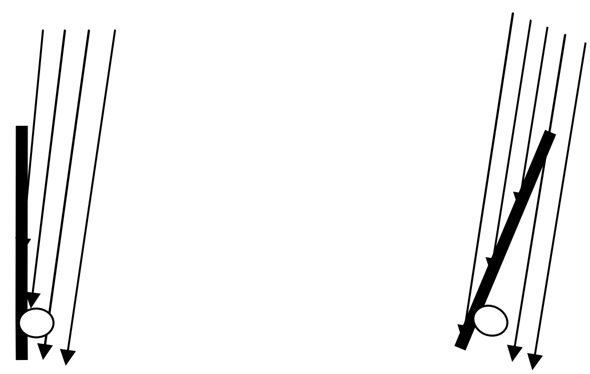

Fig 14: Tracking system arrangement, *left:* light falling on photodiode, allowing current to flow through the motor. *Right:* System rotated to be ahead of the sun again, circuit cut off and battery charging again.

We purchased a diode that promises to allow enough current to power the motor (RKI-1087 from Robokits World). Completion of the working circuit is part of our ongoing work

The plans call for a small motor with a large gear ratio to power the motion of the mirror from a relatively small torque. However, the gear ratio on our motor was insufficient to move the mirror. The remedy being explored involves increasing the gear ratio by using a wheel driven by the motor's shaft, after the motor has already been geared down to a higher torque. This setup is shown in the following figure:

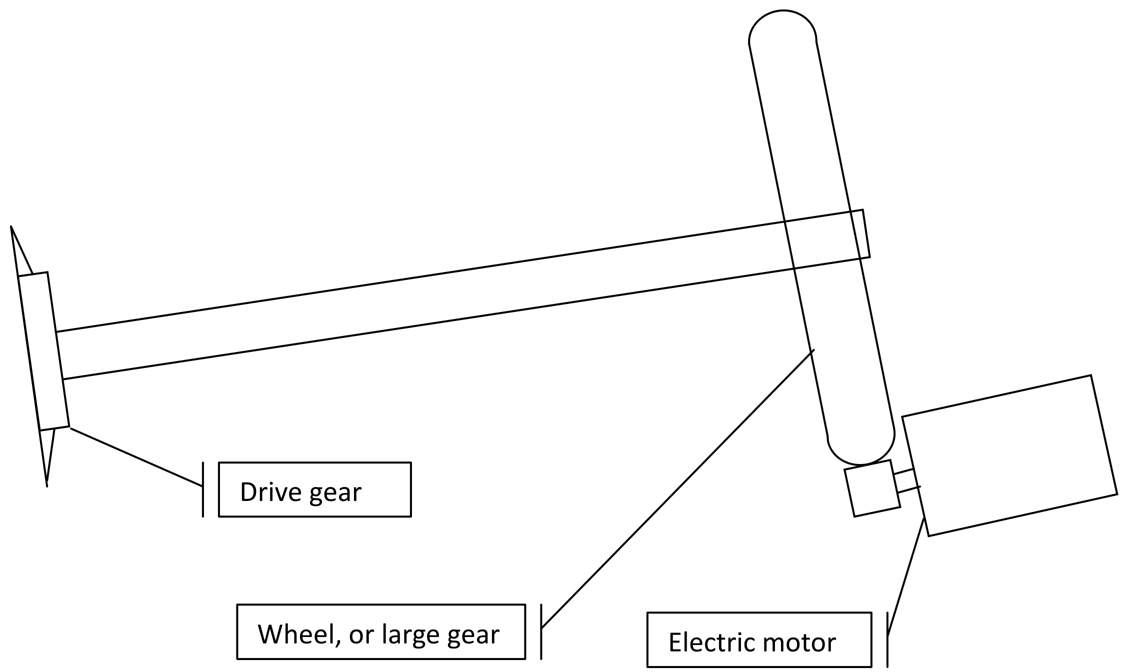

Fig 15: Proposed drive shaft arrangement.
This mechanism is part of our ongoing work.

Outlook and Future Work:
We are exploring fiberglass as a low cost, rapid construction material for the mirror, with application of a reflective material such as aluminum-coated Mylar, glass or. When fabricated, the fiberglass rigidity is determined by the number of layers of fiberglass cloth and type of resin. This will be used to control the mirror rigidity and reduce mirror warping.

We have begun evaluating different types of fiberglass templates, resin and methods of application. The initial results are promising; the fiberglass is strong, but also fairly flexible. Continuing work will investigate methods of molding the fiberglass to allow quick, precise, and inexpensive manufacture of the fiberglass mirrors.

IV. Thermal Storage

<u>Design</u>

Thermal storage provides a means to extend cooking into the evening. Our design has been shown to be a viable solution for this predicament, by physical testing and mathematical modeling.

A simple computer model of a thermal storage device composed of concrete and pumice (for insulation) indicates thermal retention times sufficient for cooking well after sunset, and can be constructed durably and inexpensively using local materials. Additionally, measurements on a physical model support the simulation. The eventual goal is to integrate the thermal storage with the solar concentration device, as shown in the figure below:

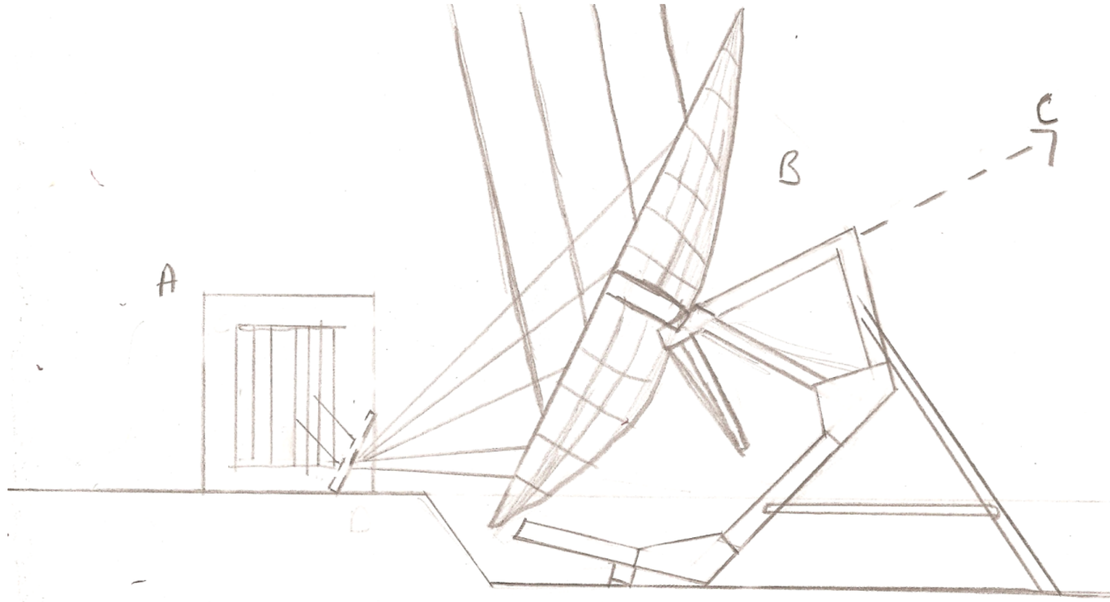

Fig16: Thermal storage and solar concentrator integration diagram.

A) Thermal storage device - Illustrated in detail below in figure 17
B) Scheffler Solar Concentrator - in our project this is the $2m^2$ design, modified for the "away from the sun" side of the kitchen.
C) Polar axis - the Scheffler rotates about the same axis as the earth, countering the earth's rotation, as to always track the sun.

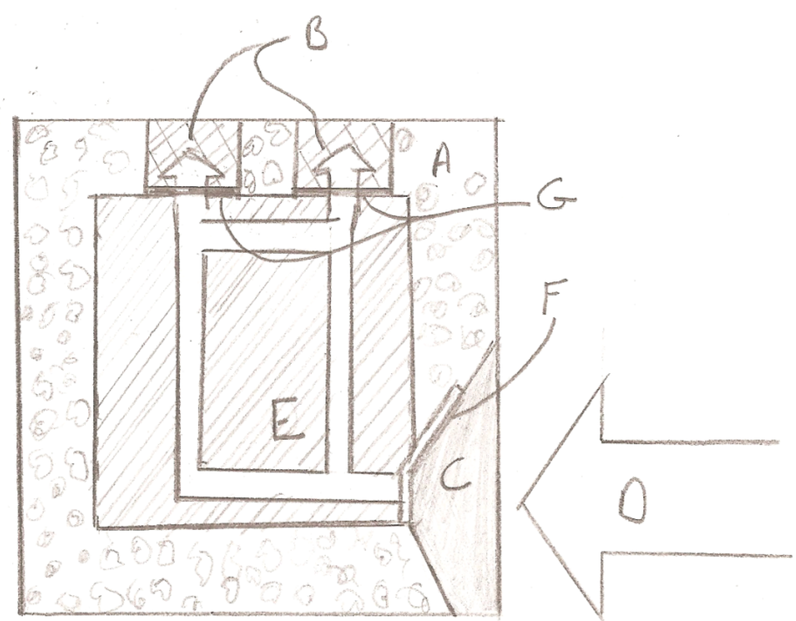

Fig 17: Thermal storage diagram, the thermal storage test model is about 1m in diameter, and 1m tall.

A) Pumice insulation, or other locally available material used for insulation. (This layer is about 4 inches thick, on all sides)
B) Removable insulation plugs - to insulate the cooking plates (G) while not in use to promote retention of heat.
C) Removable heat insulating plug - allows effective heat storage at night, while allowing the sunlight in during the day.
D) Sunlight from reflector
E) Heat distribution and storage system; Present plans uses concrete to store thermal energy with iron bars to distribute heat faster.
F) Absorbing plate, coated in to absorb as concentrated sunlight, directly connected to the metal bars on the interior of the device.
G) Metal cooking plates, directly connected to the metal conduits on the interior of the device, allowing quick transfer of heat out of the thermal storage.

Fig18: Thermal storage device test model

Shown in the above figure, we constructed a model of the proposed thermal storage device, using sand as the storage medium, and pumice as insulation. This allowed us to approximate the thermal properties of using a solid concrete block, and still be able to it. The experimental test model was heated from the interior (close to the bottom) with an electrical heater which supplied about 1.2kW of heat to the device. For measurement we placed several heat sensors (thermocouples) at locations within the device. These locations were not recorded when the device was constructed, and will be included in future tests.

The model was simplified into a multi-layer cylinder[2].

$$\dot{Q} = \frac{2\pi L(T_1 - T_2)}{\frac{\ln\left(\frac{r_2}{r_1}\right)}{k_1} + \frac{\ln\left(\frac{r_3}{r_2}\right)}{k_2} + \cdots}$$

Where T_1 is the exterior temperature, T_2 is the interior temperature, the radii define internal layers, r_1 being the radius of the core of the thermal storage. L is the height of the cylinder, and k_1, k_2, etc are the respective thermal conductivities of each material.

The specific heat equation is:

$$Q = mc\Delta T$$

And mass is the product of density and volume:

$$m = \rho L\pi r^2$$

Taking the time derivative:

$$\dot{Q} = mc\dot{\Delta T}$$

$$\dot{Q} = \rho L\pi r^2 c\dot{\Delta T}$$

To solve for the rate of temperature change, we insert this for $\dot{Q}$ above, and solve for $\dot{\Delta T}$:

$$\dot{\Delta T} = \frac{\frac{2}{\rho r^2 c}(T_1 - T_2)}{\frac{\ln\left(\frac{r_2}{r_1}\right)}{k_1} + \frac{\ln\left(\frac{r_3}{r_2}\right)}{k_2} + \cdots}$$

This equation is independent of the length of the cylinder, and in fact represents only a slice of the thermal storage, and horizontal radiation. Given a specific internal temperature within some core radius "r_1", and the radii of the layers, this equation will give you the rate at which heat leaves that segment of the cylinder. This model can be expanded to model the thermal storage as a set of multiple layers, each modeled as one of these slices. As is there is some question to the validity of this model, and the model's output number may be off by about 30% from the actual value (estimated using the surface area of the sides, versus the surface area of the top and bottom)

The computer model results are compared to the experimental results below.

Inside radius of the insulation layer was about 0.45m, and the core radius "r_1" (the region losing heat in the model) was estimated to be 10cm.

Material	K (W/mK)	C (kJ/kgK)	ρ (g/cm^3)	Cost
Concrete, light	0.42	0.75	1.1	~70$/m^3$
Concrete, stone	1.7	0.75	1.9	
Sand (dry)	0.15 - 0.25	0.83	1.78	45-60$/m^3$
Sand (moist)	0.25 – 2.0	0.8	1.92	
Pumice	0.43	0.7	0.25	Varies
Iron	80	0.46	7.9	0.24$/lb
Aluminum	250	0.87	2.7	1.2$/ft

Table 1: Thermal properties and other properties of construction materials used in the project.

Test and modeling results:

In the experiment carried out, the thermal storage device was heated for about 9 hours, and let cool for about 14 hours. The individual lines in figure 19 correspond to a thermocouple placed at a unique position in the thermal storage. Specific locations for the thermocouples are not known, but we can fairly accurately assume that the hottest thermocouple lines correspond to the locations closest to the hot-plate.

The delay time between when the heating element is shut off (t=0hrs) and when each thermocouple begins to show cooling should increase with distance from the core.

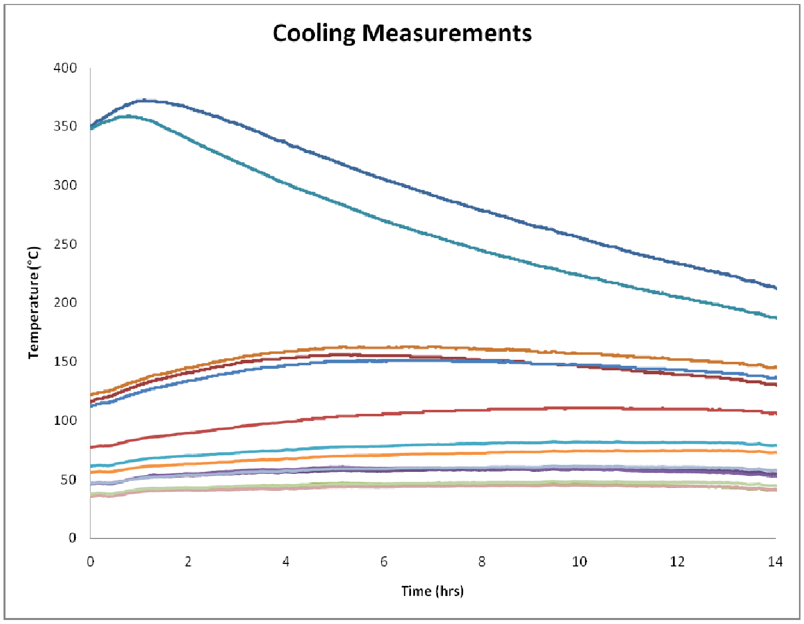

Fig 19: Experimental data from the cooling of the thermal storage. Each line represents an individual thermocouple's data for the duration of the cooling.

The temperature should be a complicated function of time. However, we did a linear fit where the temperature exhibited a maximum rate of cooling. For the higher temperatures (around 375°C peak) the cooling rate measured was 14°C per hour, while the model gave a value of 15°C per hour. In the lower temperature range (around 150°C peak), the data showed a cooling rate of 3 °C per hour, while the model predicted 5.5°C per hour. As noted previously the uncertainty in these measurements is fairly high. However, experimental and computer modeling results indicate thermal storage is possible with this device.

Using this as a framework, we will predict the performance of future designs.

Note that in the above figure there is a large difference between the temperature of the thermocouples near the heat source and the thermocouples distributed through the rest of the device. Future work will use a thermal conduit, in the center of the device to distribute heat quicker and more uniformly.

Fig 20: Inserting the aluminum bar into the thermal storage to more quickly equilibrate the temperature within the thermal storage and increase power to the cooking surface.

To get the aluminum bar into the pre-existing storage device we used a sledge hammer to pound it in, which disoriented the sensors and damaged the heat source. We dismantled the thermal storage device; rebuilding it with the aluminum bar and plan to measure the heating and cooling profiles with the bar in place.

Outlook and Future Work on Thermal Storage:

Future goals address distributing and storing large amounts of heat through the thermal storage device. An interesting problem is how to minimize heat loss when there is no cooking, but maximize heat transfer when cooking is in progress.

To this end, we will construct several computer and physical models.

V. Conclusions

A working Scheffler Concentrator consistent with the design provided by Solare Brücke was constructed, and met expectations, providing concentrations better than 200 suns. We are continuing to explore methods to increase concentration, and reduce the cost and construction time associated with the device. A thermal storage device was also successfully constructed and tested indicating thermal retention times sufficient for cooking into the evening. The tests agreed with a simple computer model providing validation for the performance of future models. Future improvements include using a thermal conduit to increase thermal storage capacity (by increasing access to the thermal core) and heat delivery rate. Additionally, the thermal storage device will be modified to accept heat from the Scheffler Reflector as well as decrease the cost and construction time of the reflector itself

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