Project II Final Report – Design, Construction, and Testing of a Solar Water Heater

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Abstract

In order to heat small amounts of water quickly using solar energy, we have designed and implemented a solar heating device. The design concept is to capture and concentrate income solar radiation by using a paraboloid mirror and place the water at its focal point. This solar heating device is designed to fit in a 0.5 m^3 box, and able to heat up 100 ml water by harvesting solar radiation. Based on our analysis and prototype testing, the design should be able to heat water up to a boiling point in about half an hour. Testing of the actual device showed that it is able to heat 100 ml of water approximately 30^{o}C above the ambient temperature. To prevent the heat loss to the environment during the heating process, a well thermal insulated but transparent container will be used to hold the heating fluid. Once implemented, such proposed produce will be able to provide hot water with no negative environmental effects and minimal maintenance requirement. This proposed design will be able to serve a wide range of hot water consumers.

Introduction

A portable solar water heater has many potential markets in the camping, outdoors living, and humanitarian sectors [1]. People interested in any of these activities often need to heat a small amount of water quickly, for drinking or to sanitizing equipment. In such situations, making a fire or using a stove would be cumbersome and impractical, so a simpler, more compact solution is sought. Here, a solar heater presents itself as a strong solution, as solar energy has several advantages applicable to camping and outdoors activities. Firstly, no special equipment is needed to generate solar energy – no wood or gas. Secondly, insolation is very energy-dense, providing 1 KW per square meter on a clear day [2]. Finally, solar energy is available on-demand for an average of 12 hours per day: even on overcast days, 150 W of energy per square meter still hits the Earth's surface at mid-latitudes [3]. All of this makes solar energy a consistent, powerful source of heat.

This solar water heater has two essential requirements: portability and rate of heating. In order to be portable, the heater must fit in a 0.5 m cube. Beyond portability, it must heat 100 ml of water, enough for a small cup of coffee, as quickly as possible. Thus, in designing such a heater, the main challenge is to concentrate solar energy from the 0.25 square meter surface of the heater to a much smaller water container. There are several ways to concentrate solar energy, including solar panels, lenses, and reflectors. For a portable, robust heater, reflectors appear to be the best option.

Background

To design a solar water heater, three theories need to be understood: how much solar energy reaches the Earth, how to focus sunlight to a water container, and how heat escapes the water container.

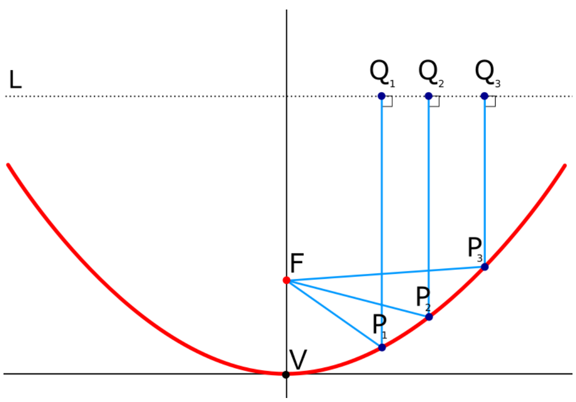

Figure 1 - Focusing property of a parabola. All parallel incident rays are reflected to the same point, called the focus.

In the Boston area, daytime insolation provides a year-round average of 330 W per square meter of exposure. The November average insolation, relevant to the time of testing, is around 210 W per square meter [4].

Assuming that rays of incoming sunlight are essentially parallel over the span of a meter, a parabolic mirror focuses sunlight to a single point. In a 2-dimensional model, if incoming sunlight is parallel to the y-axis, a parabolic mirror in the shape of $y = \frac{x^2}{4a}$ directs all incident rays to the point $(0, a)$ [5]. This is illustrated in figure 1.

For a solar concentrator, a parabola can be generalized to three dimensions, making a paraboloid, which appears as a parabola revolved around its central axis. A paraboloid can receive insolation in two dimensions. Compared to the parabola's single receiving dimension, this makes a paraboloid mirror much more efficient at focusing a large amount of solar energy into a small area [6].

As solar energy makes the water container hotter, heat loss will have a more pronounced effect on temperature. Heat may leave the container in two ways: conduction and radiation, both of which become more marked as the temperature difference between the water and the surroundings increases. The rate of conduction is described by equation 1, if the container can be approximated by a one-dimensional barrier.

$$\frac{dQ}{dt} = \frac{kA\,\Delta T}{\Delta x} \quad (1)$$

A is the surface area of the container, ΔT is the temperature difference, Δx is the barrier thickness, and k is the thermal conductivity of the material, a constant unique to each material. [7]

Radiation is depends on a similar set of variables: its rate is defined by equation 2.

$$\frac{dQ}{dt} = \alpha e(T_{in}^4 - T_{out}^4)A \quad (2)$$

Here, α is the emissivity of the container (an intrinsic property of the material), e is the Stefan-Boltzman constant (5.673×10^{-8} W m^{-2} K^{-4}), and A is the surface area of the container. [8] For the temperature differences experienced in a solar heater, radiative heat loss is not significant.

Methods

Modeling a Parabolic Solar Heater

To predict the effectiveness of a parabolic solar heater, first the heat loss rate of the water container was experimentally measured. An 8 oz plastic water bottle, identical to the one used in the final product, was filled with 100 mL of hot water, and the water temperature was measured over time. The result is shown in figure 2.

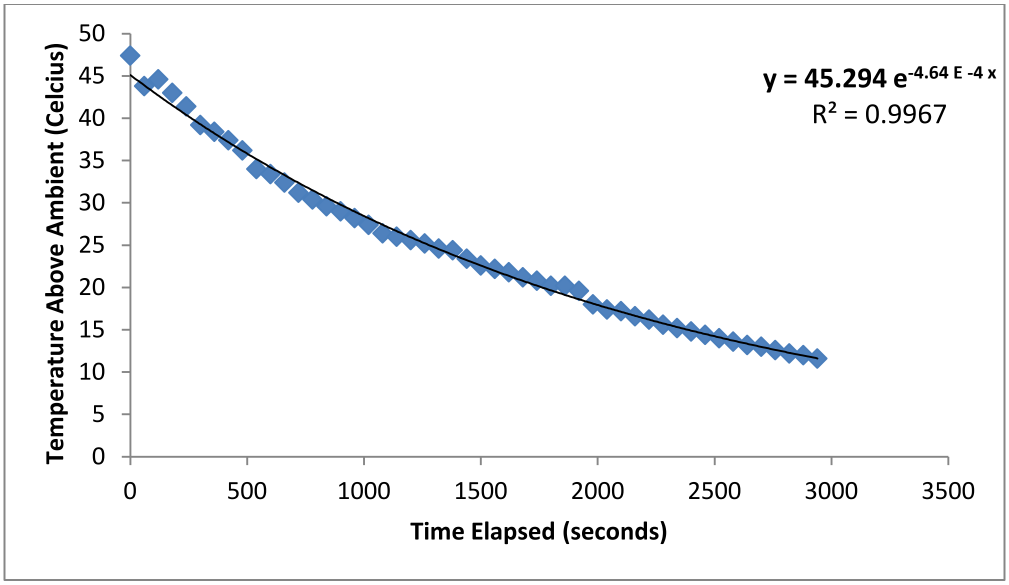

Figure 2 – Experimental temperature of hot water in a plastic bottle over time. These data are used to find the heat loss rate of the plastic bottle.

The rate of heat loss is proportional to the temperature difference, according to equation 1. Therefore, heat loss from this bottle can be modeled by equation 3.

$$\frac{dT}{dt} = -4.64 \cdot 10^{-4}\, \Delta T \qquad (3)$$

Here, ΔT is the temperature of the water in the bottle, minus the ambient temperature. One can verify equation 3 by taking a time derivative of the regression equation. Considering both this model and the heat input calculated earlier, the net temperature equation of the water in the solar heater is given by equation 4.

$$\frac{dT}{dt} = \frac{210\frac{W}{m^2}\cdot A}{418\frac{J}{°C}}(k) - 4.64 \cdot 10^{-4}(T - T_{ext}) \quad (4)$$

In equation 4, A is the surface area of the reflector (0.2 m^2), and k is an efficiency constant that takes into account the reflectivity of the mirrors and the container. For initial calculations, the reflectivity of Mylar, used in the reflectors, is 0.95 [13], and the reflectivity of plastic bottles is 0.40 [14], making $k = 0.57$. With these parameters, the simulated temperature of water over time is shown in figure 3.

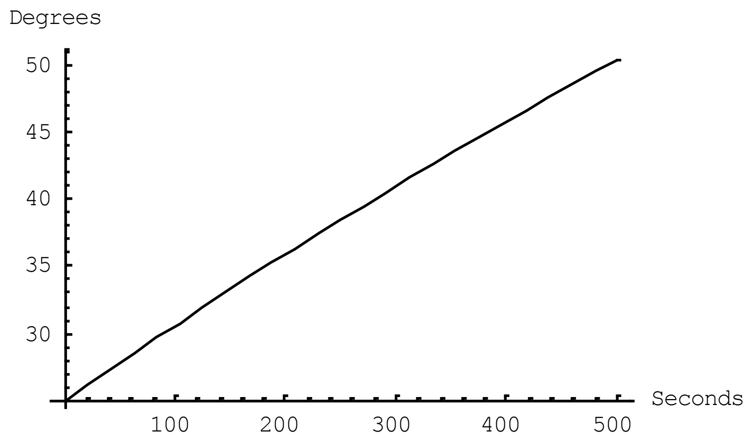

Figure 3 – Simulated temperature of water. The water eventually boils after 33 minutes.

This simulation indicates that water will boil in a relatively short period of time.

Manufacturing

The solar water heater consists of three main components. The first component is the paraboloid mirror, which concentrates solar energy for the device. The second is the support prop, which holds the mirror at the desired angle. The final component is the water container, which holds the water at the focal length of the mirror, and reduces heat loss from the water to the atmosphere.

The paraboloid mirror is constructed out of sheet metal, as shown in Figure 4, cut using a water jet. Solar heater hobbyists have previously used a similar design to some success [15]. Each of the eight fans in the design has slightly curved edges. After cutting, all the fans are folded together so that adjacent edges touch, curving each fan and making a paraboloid shape.

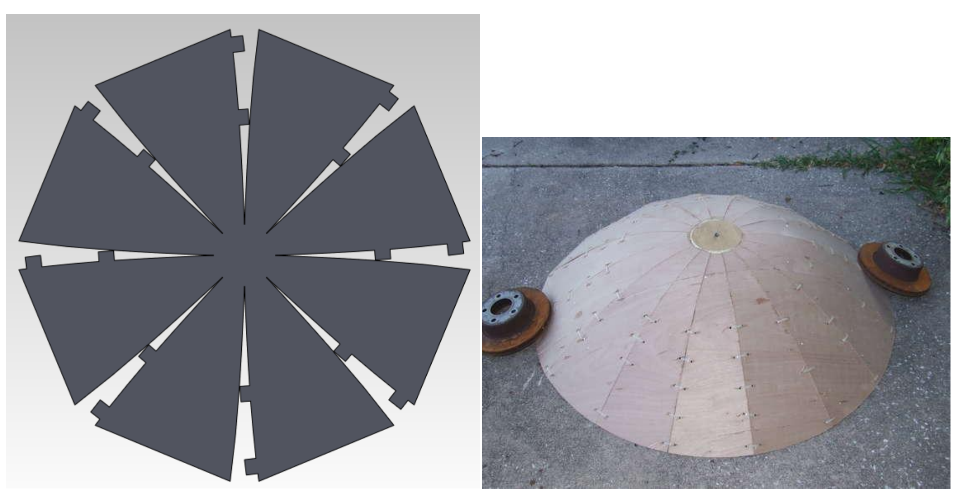

Figure 4 –Left: CAD model of mirror mesh. Right: a similar design made of wood.

The surface of the metal disc is covered with a mylar thermal blanket, which reflects over 95% of incident radiation. The thermal blanket is attached to the surface with spray-on adhesive.

The paraboloid mirror is attached to a stand, shown in figure 5, allowing the mirror to be aimed at the sun. The stand consists of a flat board connected by a door hinge to the center of the mirror, and a rope that fixes the angle between the mirror and the board.

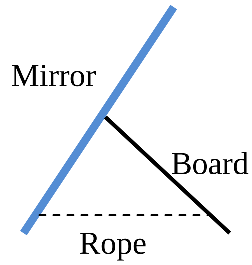

Figure 5 – Supporting stand for water heater.

Water is stored in a small plastic bottle, elevated a few centimeters above the vertex of the mirror. The location of the plastic bottle coincides with the focus of the paraboloid, where all of the incident solar energy is concentrated.

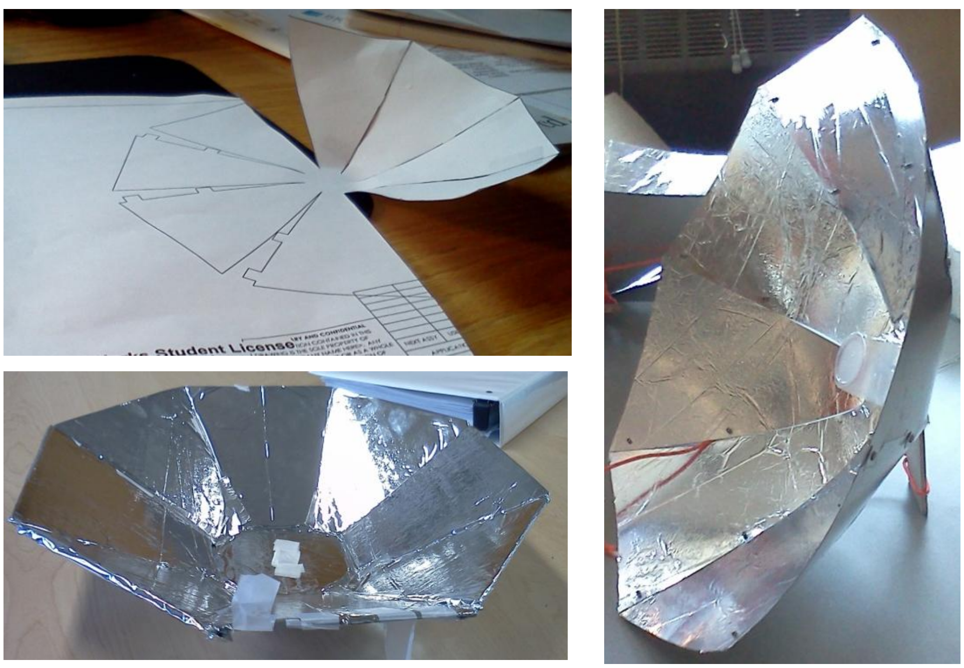

Figure 6 – Progress of the solar heater design. Left above: a scale model of the mirror mesh, used to calculate the dimensions and observe the folding properties of the actual design. Left below: a cardboard prototype of the design. Right: the completed final design.

In all, this design satisfies all fundamental requirements of the project: it fits within a cube with edges of 0.5 m, focuses virtually all incident solar energy into the water, and is easily portable. In addition, the lightweight, simple design should appeal to campers and hikers. The use of recycled materials – the water bottle, door hinge, and scrap wood – sells this design to the environmentally conscious, and makes repairing the product simpler.

Results

The solar heater was tested in two ways. First, a single solar heater was positioned indoors, next to an open window, to measure the effectiveness of the design at room temperature. Next, three copies of the solar heater design were set up outdoors on a chilly November day (air temperature: 9°C). This second test checks the repeatability of the design, as well as its functionality in cold weather. In both tests, the heater consistently raised the temperature of water to 28°C above ambient temperature.

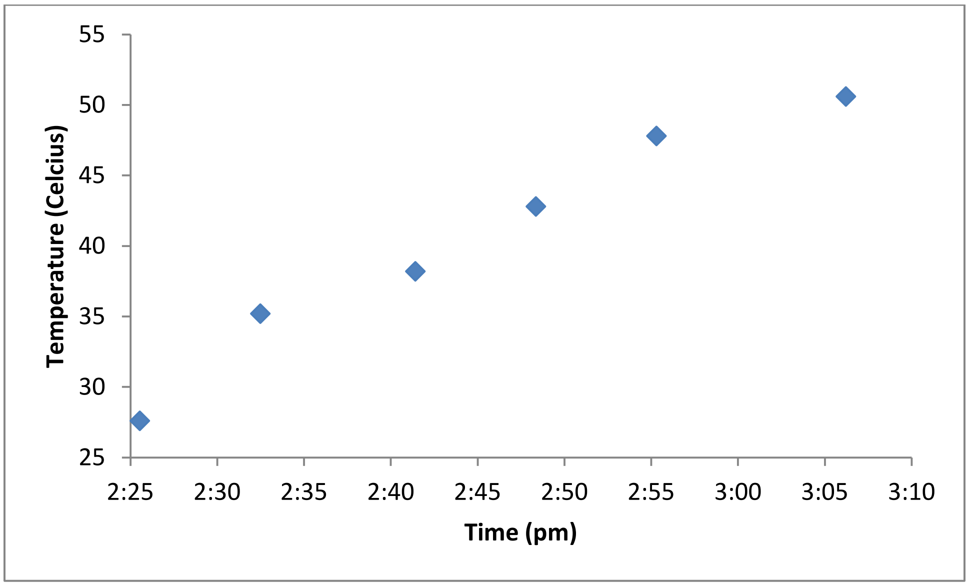

Figure 7 – Room temperature test of single reflector. Ambient temperature was 22°C. Over a half hour, the temperature of the water rose to 50°C.

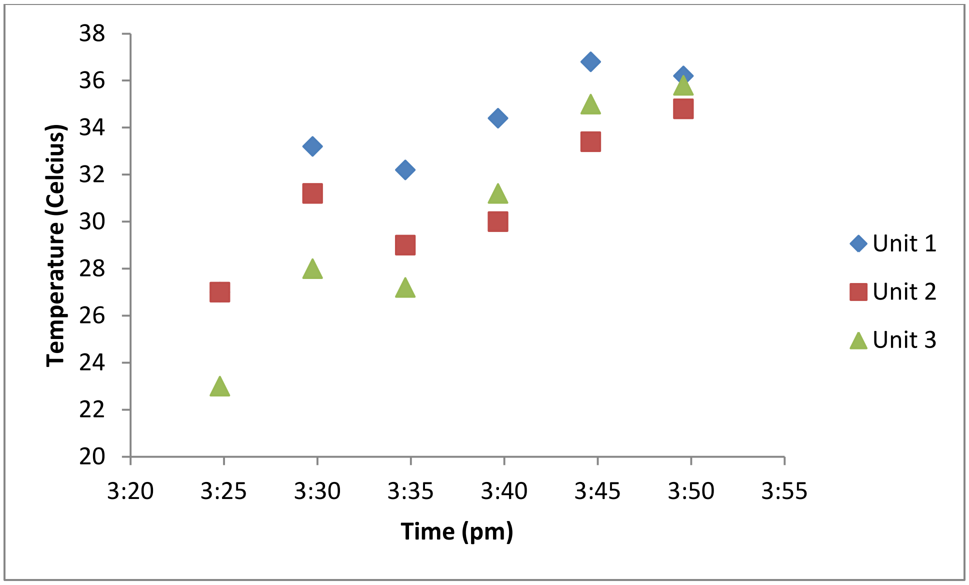

Figure 8 – Cold-weather test of all three solar reflectors. Ambient temperature was 9°C. Despite reflector 3's lower starting temperature, all three reflectors achieved temperatures of ±1°C within the same amount of time.

The second test shows that the design performs consistently across multiple units, which is not surprising, since each unit was precisely cut with a computer-controlled tool.

Analysis

Re-analyzing the Model

Unlike what was initially predicted, the water did not boil, nor did it come close to boiling. To explain the difference in temperature, it is hypothesized that the water did not absorb all incoming radiation, letting much of the solar energy pass through the bottle. Using the first experiment's final temperature, a revised k value of 0.129 can be determined. This k value indicates that the water absorbed only 22.7% of the solar energy it received.

Evaluating the Design

Two important goals should be considered in analyzing the performance of this design: end temperature and time to heat. An ideal solar heater achieves a high temperature quickly.

The end temperature, 50°C is on the borderline between warm and hot, as perceived by most people [9]. This temperature is adequate for showers and dishwashing, but not for making coffee or instant noodles. Likewise, the cold-weather test resulted in water of only 36°C, barely warm enough for a shower. [10] In order to increase the effectiveness of the water heater without expanding its bulk, a better and more specialized water container is needed. The container should be insulated from the inside to trap energy not absorbed by the water, and to prevent heat loss. However, most insulating materials will also block insolation, preventing solar energy from reaching the water in the first place. Designing a container that both insulates and transmits solar energy is the key to good, fast heating; typically, each solar heating company has its own proprietary container formula [11]. Therefore, a better water container will improve the performance of this heater.

A candidate for a better container might be SunMaxx©, by Silicon Solar, which is designed to provide hot water in freezing conditions without a reflective concentrator. SunMaxx has a net heat loss of 0.7 W/m^2°C (compared to 14.9 W/m^2°C in the plastic bottle), and allows water to absorb 92% of solar radiation that it collects (compared to 22.7% in the plastic bottle) [12]. Figure 10 compares simulations of the water heater with a plastic water bottle, and with SunMaxx.

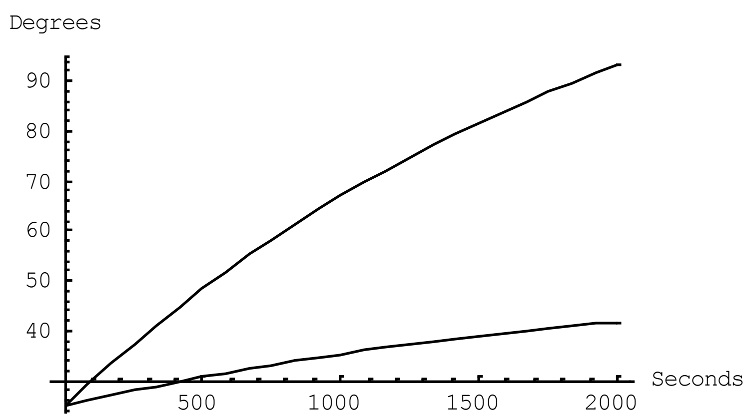

Figure 10 – Simulated temperatures of solar heater with SunMaxx container (top) and plastic bottle (botton). Despite identical sun conditions, SunMaxx vastly outperforms the plastic bottle.

The time required to heat, around a half hour in both tests, is a reasonable length to wait for hot water. During the half hour, testing showed that the heater did not require readjustment, as long as the sun does not set behind an obstacle. A better water container will also decrease the amount of time required to reach any given temperature.

In all, this solar heater achieved usably hot water in a reasonable amount of time, though a better container can significantly improve performance.

Conclusion

The Solar heating device has achieved some level of success. It is able to heat water a substantial amount above the ambient temperature in only half an hour. However, the success of the device is limited in that it was unable to accomplish the goal of reaching a boiling point. Continued experimentation, redesign and reimplementation of different containers will lead to an even better device to heat water.

Bibliography

[1] "Camping Checklist." http://www.lovetheoutdoors.com/camping/checklists.htm.

[2] Wikipedia. "Insolation." 2011, http://en.wikipedia.org/wiki/Insolation

[3] W. Stine and M. Geyer. "The Sun's Energy." 2001, http://www.powerfromthesun.net/Book/chapter02/chapter02.html

[4] National Renewable Energy Laboratory. "Solar Maps." 2011, http://www.nrel.gov/gis/solar.html

[5] Wikipedia. "Parabolic Reflector." 2011, http://en.wikipedia.org/wiki/Parabolic_reflector

[6] Radio-Electronics.com. "Parabolic Reflector Antenna". http://www.radio-electronics.com/info/antennas/parabolic/parabolic_reflector.php

[7] C. Nave. "Heat Transfer." http://hyperphysics.phy-astr.gsu.edu/hbase/thermo/heatra.html

[8] R. Beardmore. "Thermodynamics Heat Transfer." 2011, http://www.roymech.co.uk/Related/Thermos/Thermos_HeatTransfer.html

[9] F. Sun. "Final Report: Cardboard Coffee Insulator." October 2011.

[10] Wikipedia. "Water Heating." 2011, http://en.wikipedia.org/wiki/Water_heating#Tankless_heaters

[11] Industrial Nanotech, Inc. "Nansulate Insulation." 2011, http://www.nansulate.com/nansulate_solar_thermal_insulation.htm

[12] Silicon Solar. "Evacuated Tube Collector." 2010, http://www.siliconsolar.com/20-evacuated-tube-collector-p-16145.html

[13] HTG Supply. "Reflective Mylar." 2011, http://www.htgsupply.com/Category-Reflective-Mylar.asp

[14] PLCER. "Table of Reflectivity Values for Different Materials." 2008, http://www.plcer.net/Fundamental/Table_of_Reflectivity_Values_for_Different_Materials_169.html

[15] 'Tool Using Animal' (Username). "How to build a parabolic solar reflector." 2006, http://www.instructables.com/id/How-to-build-a-strikeheliostatstrike-paraboli/