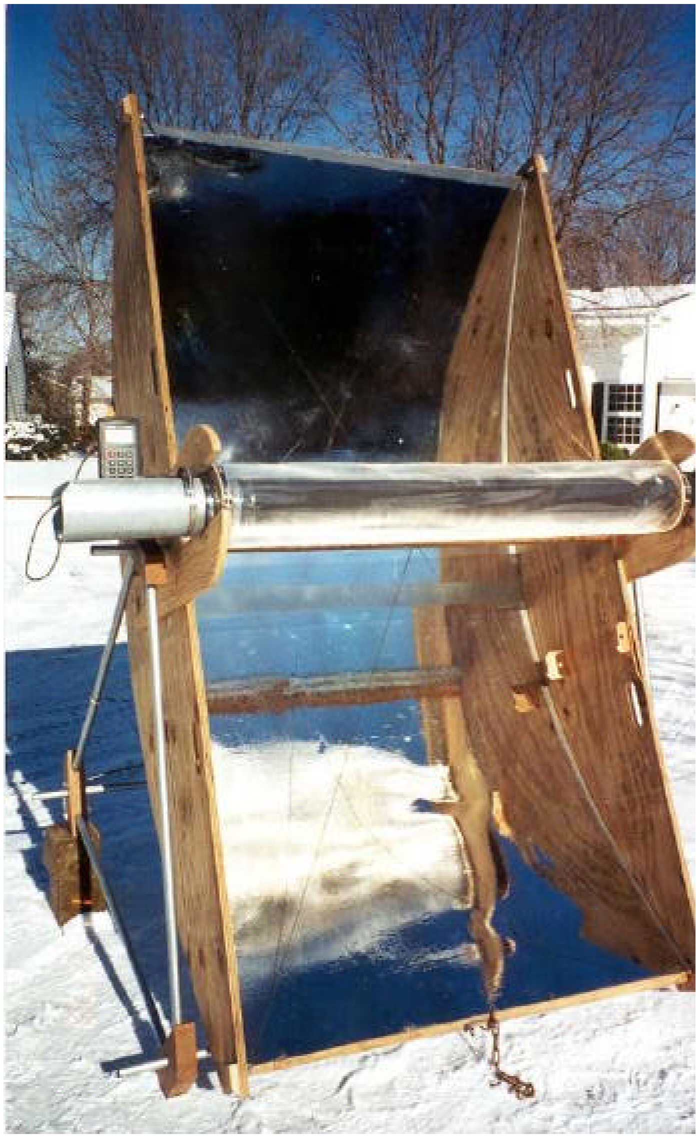
Performance and Design of the CTI Solar Oven

A Parabolic Trough Solar Concentrator



Overview

This paper describes how to measure performance of a parabolic trough solar concentrator and gives preliminary results from the CTI Solar Oven. It also describes the rationale for several of the design decisions and gives guidance to designers who are considering changes. To understand this paper, readers should first read an overview article, “The CTI Solar Oven.”

We conducted most of the tests on an oven with an area of 2.735 square meters exposed to the sun. It has a roasting tube with a 127 mm diameter (5 inches) and length of 1219 mm (4 feet), giving it a volume of over 15 liters (4 gallons). It reaches temperatures of 150-260 degrees Celsius (300-500ºF). The effective power transferred to the food is approximately 1100 watts in a temperate climate (Minnesota), which represents efficiency in excess of 50%.

PHOTO: A PARABOLIC TROUGH SOLAR CONCENTRATOR CONFIGURED TO ROAST PEANUTS

PURPOSE OF THIS AND RELATED DOCUMENTS

This is one of several related documents describing parabolic trough solar concentrators. The first, “The CTI Solar Oven,” is an overview of the purposes, design, and usage of these ovens. The second, a collection entitled “How to Build the CTI Solar Oven,” includes instructions, drawings, parts list, etc. The last, a paper entitled “Performance and Design of the CTI Solar Oven,” is a discussion of factors that should be considered when modifying the design of these devices or predicting their performance under various conditions. These are minor revisions of documents originally written in March 2001.

Oven Performance

The experiments that were conducted to get the following data were performed in the St Paul, Minnesota, area, which is at approximately 45ºN latitude. They were conducted on clear days during which direct solar radiation had a strength of about 700 watts per square meter. All experiments used a 1219 by 2438 mm reflector with 750 mm focal length, an aperture size of 2.735 square meters, and a surface area of 2.97 square meters. Roasting tubes were nominally 1219 mm long.

Heat Energy Available

The rate at which solar energy hits the earth at the edge of space is nearly constant, 1370 watts per square meter. However, the atmosphere (especially clouds or haze) absorbs some of this energy and some is diffused before getting to ground level. The parabolic trough solar concentrators described here can only make use of direct beam radiation, i.e., that energy that radiates straight from the sun. Radiation arriving from other angles will not be reflected to the focal line. The amount of direct beam radiation energy that actually reaches the surface of the earth depends upon the elevation, climate, weather, season, time of day, etc., but it has been recorded for many places on earth (e.g., Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors, http://rredc.nrel.gov/solar/pubs/redbook/preface.html). In Minnesota, a typical rate of direct beam energy available at ground level on a sunny day is about 704 watts per square meter. (978 watts total measured radiation, 72% of which is estimated to be direct beam. 72% is the ratio of average maximum direct beam radiation to average maximum flat plate radiation for a typical month in Minneapolis, taken from the data referenced above.)

Heat Energy Absorbed

To determine the average heat absorbed by the tube, the tube is partially filled with water and both ends are sealed except for a small tube leading to a condenser. The oven is operated until the configuration reaches steady state, characterized by water boiling in the tube, steam flowing to the condenser, and a steady stream of condensed steam dripping into a measuring cup. The amount of condensed steam is measured for a specific time interval. Since the amount of heat needed to create steam is known (539 calories per gram of water), it is possible to compute how much heat was absorbed per unit time.

> Using the 115 mm (4.5 inch) conduit roasting tube, 875 ml of condensed steam was measured in 30 minutes.
>
> If: S = amount of condensed steam in ml = 875, and
> T = time during which condensed steam was measured in min = 30, then
>
> Avg absorbed power = [S ml / T min] [539 calories / ml]
>
> = 15,721 calories / min
>
> = [15,721 calories / min] [1 min / 60 sec]
> [4.186 joules / calorie] [watt / (joule / sec)]
>
> = 1097 watts

PHOTO: STEAM CONDENSER TO MEASURE ABSORBED HEAT

Efficiency

The efficiency of the oven is the ratio of the energy actually absorbed by the food divided by the energy available at the reflector. The energy absorbed by the food was calculated by measuring condensed steam as described above. The energy available to the reflector was calculated by measuring the power per unit area of direct beam solar radiation using a calibrated instrument, and multiplying that reading by the area of the reflector and the time period of collection. Preliminary results indicate efficiency in excess of 50%. The causes of inefficiency include radiation losses in reflection, radiation losses in the jacket, radiation reflections off the tube, and heat losses (convection, conduction, and radiation) from the tube.

Power measured = [310 BTU / sqft-hr] [watt / [3.412 BTU / hr] [10.764 sqft / sqm]

= 978 watts / sqm

Direct beam power = [978 watts / sqm] [.72] = 704 watts / sqm

Power available = [704 watts / sqm] [2.735 sqm] = 1925 watts

Efficiency = [power absorbed] / [power available]

= 1097 / 1925 = .57

Roasting Time

It is possible to estimate the roasting time for peanuts (or similar tasks) by adding up the amount of heat (calories) needed to accomplish each step of the roasting, and dividing the sum by the roaster power in calories/min. For example, to roast 2.5 kg of peanuts at 163 degrees Celsius (325ºF), starting from 24 degrees Celsius (75ºF) until their moisture content goes from 10% to 2% requires both raising the nuts to the roasting temperature and also evaporating off the excess moisture.

Heat to raise temp = [mass of peanuts] [specific heat of peanuts] [temperature rise]

= [2500 grams] [0.5 Calories / gram-deg C] [(163 - 24) deg C]

= 173,750 calories

Heat to evaporate = [mass of peanuts] [heat of evaporation] [% moisture change]

= [2500 grams] [539 calories / gram] [.10 - .02]

= 107,800 calories

Time to roast = [heat to raise temp + heat to evaporate] / [heat available / min]

= [(173,750 + 107,800) calories] / [15,721 calories / min]

= 17.9 min

To summarize, it will take longer to roast a batch of food if the solar radiation is weaker or is interrupted by clouds, if the reflector or jacket are dirty or distorted, if the aiming is improper, if there are excessive heat losses out the ends of the tube, or if the mass of food is larger. It will take less time if the food is preheated or pre-dried. These calculations also make it clear that if the reflector is twice as big, it only takes half the time to roast, etc. These are all theoretical calculations, which may not be accurate in actual practice.

Temperature

Temperature is a critical parameter for some applications, such as baking bread. Experiments were conducted to characterize the effect of the roasting tube size and of food mass on the absorber temperature. The results show trends, but the actual readings are not yet reliable for several reasons. Air temperature inside the roaster varies significantly, depending upon the exact location within the tube. Even light breezes cause rapid heat loss, especially if there is no jacket surrounding the roasting tube. The temperature inside the tube is affected by phase changes when the tube contains food. Boiling off moisture absorbs a lot of energy and prevents the temperature from rising. At this time we have not completed enough experimentation to quantitatively characterize temperature performance. (Table 1, below, is not yet complete.)

Preliminary observations indicate that maximum tube temperatures are higher when the tube size is smaller, as expected. Maximum tube temperatures are higher with a jacket installed, as expected. Tube temperature stays near the boiling point when water or significant moisture is in the tube. No conclusions have yet been drawn regarding the mass of the tubes.

TABLE 1. TUBE TEMPERATURES ACHIEVED UNDER VARIOUS CONDITIIONS

Tube type	Tube Mass	Inside Diameter	Volume	Contents	Food Mass	Max temp, no jacket	Max temp, with jacket
5” air duct	2.3 kg	12.7 cm	15.4 liter	Air	N.A.		
4.5” conduit	8.6 kg	11.0 cm	11.5 liter	Air	N.A.		
3” air duct	1.6 kg	7.7 cm	5.7 liter	Air	N.A.		
2 3/8” post	2.7 kg	5.7 cm	3.1 liter	Air	N.A.		
5” air duct	2.3 kg	12.7 cm	15.4 liter	Peanuts			
5” air duct	2.3 kg	12.7 cm	15.4 liter	Bread			
5” air duct	2.3 kg	12.7 cm	15.4 liter	Potatoes			
4.5” conduit	8.6 kg	11.0 cm	11.5 liter	Water			

Critical design issues

The builder of a parabolic trough solar oven may want to adapt the design to different materials, foods, or other special needs. Some of the most important design issues are not unique to parabolic trough solar ovens; they apply to all appropriate technology designs. Overall cost, weight, availability of materials and processes, skills of builders and operators, safety, and compatibility with the social and physical environment are indeed critical issues, but are not addressed here. In addition to these generic issues, the following oven-unique issues should be considered.

Size and Weight

The tested oven is approximately 1.5 m high, 2.5 m wide, and 1.5 m long when aimed straight up. With a redesigned support frame the reflector assembly could be rotated to vertical, providing a smaller footprint. Storage size could then be 2.5 m high, 1.5 m wide, and 1.5 m long.

The tested oven weighs approximately 59 kg (130 lb) with no food in the tube. With wheels on one side, half the weight must be borne by an operator lifting the other side while changing azimuth or moving the unit. While this has not been a problem, it could be awkward for small operators. Adding pivoting casters on the second side of the frame would solve this problem.

The oven is designed with the same effective tube length and trough length (tube is a bit longer, but no energy is reflected onto its ends). If the two lengths are increased, the maximum temperatures, efficiencies, and concentration factors remain the same. The effective power delivered to the tube would increase, but the volume of the tube (food capacity) would increase by the same percentage. Therefore, increasing the length of a parabolic trough solar concentrator is not likely to change its performance, only its capacity.

Reflector size and geometry

The size of the reflector determines the maximum amount of solar energy available for heating the absorber. More specifically, the area of an imaginary plane perpendicular to the sun's rays that casts a shadow on the entire reflector determines the effective amount of available energy. This area is sometimes called the aperture area. The accuracy of the parabolic shape, along with several other issues, determines how much of the available energy gets transferred to the roasting tube. The design challenge is to make the aperture area as large as possible, while maintaining the necessary accuracy, ease of operation, and safety.

The focal length of the parabola may be changed to increase the effective area of the reflector. The focal length is the distance from the center of the trough (vertex) to the center of the roasting tube. A longer focal length results in a flatter reflector which collects more solar energy for a given reflector surface area. On the other hand, a longer focal length means that the roasting tube will be higher and possibly harder to reach. Increasing the focal length also makes aiming more critical and requires a more accurately shaped trough and smoother reflector material. The aiming range is the amount of aiming error that can be tolerated while still reflecting all direct beam radiation to the absorber tube. Aiming is discussed later in this paper.

Table 2 illustrates three reflector sizes, each with three different focal lengths. Note that the longer focal lengths provide more available heat, but have a smaller aiming range.

TABLE 2. INFLUENCE OF REFLECTOR SIZE AND FOCAL LENGTH ON AIMING RANGE AND AVAILABLE HEAT

Reflector size	Focal length	Aperture area	Aiming range *	Avail. heat **
1219 x 1219 mm (**4 x 4** foot)	**250** mm	1219 x 1050 = **1.280 sq meter**	+/- 6.9 degrees	1024 watts
1219 x 1219 mm (**4 x 4** foot)	**500** mm	1219 x 1158 = **1.412 sq meter**	+/- 5.46 degrees	1130 watts
1219 x 1219 mm (**4 x 4** foot)	**750** mm	1219 x 1189 = **1.449 sq meter**	+/- 4.20 degrees	1159 watts
1219 x 2438 mm (**4 x 8** foot)	**250** mm	1219 x 1755.9 = **2.14 sq meter**	+/- 3.59 degrees	1712 watts
1219 x 2438 mm (**4 x 8** foot)	**500** mm	1219 x 2100 = **2.56 sq meter**	+/- 3.47 degrees	2048 watts
1219 x 2438 mm (**4 x 8** foot)	**750** mm	1219 x 2244 = **2.735 sq meter**	+/- 3.12 degrees	2188 watts
2438 x 2438 mm (**8 x 8** foot)	**250** mm	2438 x 1755.9 = **4.281 sq meter**	+/- 3.59 degrees	3425 watts
2438 x 2438 mm (**8 x 8** foot)	**500** mm	2438 x 2100 = **5.12 sq meter**	+/- 3.47 degrees	4096 watts
2438 x 2438 mm (**8 x 8** foot)	**750** mm	2438 x 2244 = **5.47 sq meter**	+/- 3.12 degrees	4376 watts

* Assumes 127 mm (5 in.) diameter roasting tube

** Assumes 800 watts/square-meter radiation. This varies with location and weather.

Reflective material

The reflective material that lines the parabolic trough must have the same properties as a good mirror. It must reflect most (80-85%) of the sun's energy back to the roasting tube. It must also be so smooth that the reflected energy is not diffused, causing it to miss the tube. Additionally, the reflector should be durable, easy to clean, easy to polish or replace, and should not degrade in the expected weather. Ideally, the reflective material would be the trough surface, but we did not find any such material that also met our cost and weight criteria.

The reflector for the oven shown here is a 2-mil, weather protected polyester film covered with an aluminum layer and an acrylic coating to prevent oxidation of the aluminum. The film was applied to the parabolic trough (see sidebar). The film was developed by 3M corporation, but is not currently in production. Small quantities of the film may be obtained directly from CTI. We are not aware of reasonably priced commercial equivalents.

This reflective film is critical to the performance of the reflector assembly. Other materials were tried, but many of them are not as reflective as they appear or they diffuse the light. A good way to test the diffusion is to shine a laser pointer at the reflector and see if the reflected beam is distorted or fuzzy when it hits a surface 3-4 meters away. Finding a durable alternative material is a topic of continuing investigation by CTI engineers.

APPLYING THE REFLECTIVE FILM

The reflective film must be applied to a very smooth surface. Any bumps or ripples will change the direction of light reflection, possibly causing it to miss the tube. Two types of backing were tried, wood based (plywood, masonite) and metal (galvanized steel, aluminum). Metal backings work well. Wood based backings only work if they are sealed before use with a polyurethane or similar finish. If not sealed, they swell and shrink with changes in humidity, causing ripples in the film. After a few weeks the ripples get so bad that the reflector performance is seriously degraded. Sealed masonite mitigates, but does not completely resolve, this problem.

Film was attached to the backing using two methods. High temperature (low volatile) grease has the advantage that the film may be pealed off if it is damaged or wrinkled, but it must be very carefully applied at the edges or the film may begin to peal off in the wind. Spray adhesive is more secure, but if the film needs to be replaced it will be very difficult to remove. Film carefully applied to galvanized sheet metal with grease has held up very well in all weather.

Tube size and temperature

The size of the roasting tube should be selected while considering food type, desired temperature, and ease of aiming. A larger diameter tube allows more food to be loaded and makes aiming the reflector at the sun less critical. Unfortunately, a larger tube with more food takes longer to roast since the amount of energy available from the sun is limited by the reflector size. A larger roasting tube also seems to lose heat faster than a smaller one, thereby limiting the maximum temperature that can be attained. The section on performance presents experimental data relating tube size and temperature.

CONCENTRATION FACTOR

The advantage of a parabolic trough solar concentrator over a flat solar collector can be conveniently summarized with one parameter, the concentration factor. The concentration factor is the ratio of the opening (aperture) of the parabolic reflector to the area of the tube surface. A concentration factor of 5 means, for example, that five square meters of solar radiation is being reflected onto one square meter of roasting tube surface. More energy per square meter of tube surface implies that the absorber will be hotter, be able to heat more food, or both. The tested ovens had concentration factors of 5 or above. A flat collector has a concentration factor of one. The concentration factor may be increased by either increasing the size of the reflector or by decreasing the diameter of the roasting tube.

Jacket material and design

The jacket material should have some of the same general properties as the reflective material, except that it must be clear. It should be durable, easy to clean, easy to replace, and should not degrade in the expected weather. It must pass most (80-85%) of the sun's reflected energy to the roasting tube. In addition, it must withstand high temperatures and effectively minimize convective heat loss from the tube. A glass cylinder would be ideal, but was considered too expensive and fragile.

The tested oven uses a 4-mil weather-protected polyester film. The film is wrapped around wooden spacers, forming a cylinder that encloses the roasting tube between the yoke pieces. Tape and hose clamps are used to maintain the shape. Since the film is easily crushed, the roasting tube has disks on both ends so that if it is removed from the yoke and set down, the jacket film will not rest on the ground.

Earlier experiments used a much larger jacket that was more like a tent over the roasting tube. While simpler to build, this approach allows more convection currents within the jacket and it is more difficult to clean the reflector.

It is also possible to operate a solar oven without a jacket. This allows a higher heat loss, which reduces the amount of food that can be roasted and reduces the temperature that can be achieved. However, for some roasting there is so much excess heat available that operation without a jacket is feasible. The tested oven achieves a 50-60 degree Celsius lower temperature when operated on a still day with no jacket. Wind would probably cause greater heat loss.

Aiming

The reflector assembly must remain aimed at the sun as it appears to move across the sky. Figure 1, the Sun Path Diagram, illustrates how the sun's apparent azimuth and elevation angles change as a function of time and date for a given latitude. The diagram looks like a tennis net overlaying a spider web. The input parameters, time and date, are plotted on the tennis net. The corresponding output data, azimuth and elevation, are then read off the spider web. A Sun Path Diagram may be computed for any latitude. It allows the designer to predict the operating range needed for the reflector, but is not needed for actual operation.

The sun path diagram illustrates that the sun's apparent azimuth (compass direction) may vary more than 200 degrees from morning to night. Its elevation (angle from the vertical) also varies from zero to 90 degrees, but near the horizon the radiation losses in the atmosphere make operation inefficient. A parabolic trough solar concentrator can be designed with only azimuth adjustment or with only elevation adjustment, but it will not be as efficient as a design that allows both to be adjusted. The design of the support assembly should provide azimuth and elevation adjustments that can be easily performed by an operator every five or ten minutes.

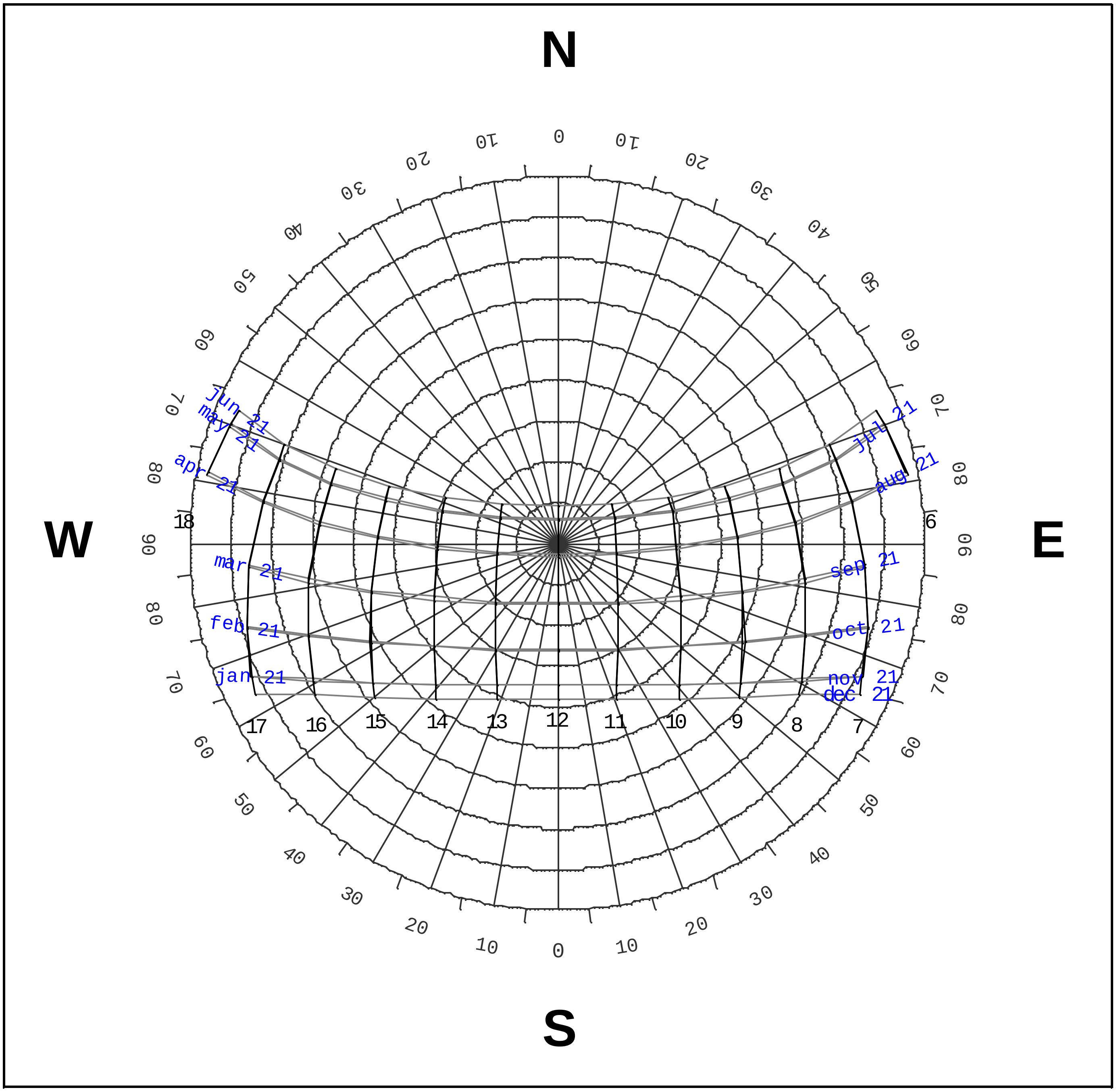


FIGURE 1. SUN PATH DIAGRAM FOR JALAPA, GUATEMALA, 14.5 DEGREES NORTH LATITUDE

The tested oven provides azimuth adjustments by turning the entire support frame on a flat surface. The frame has two wheels; turning it is like turning a two-wheel trailer. Swinging the reflector around its pivot point on the horizontal bar of the frame allows elevation adjustment.

A perfectly constructed and aimed reflector would reflect all available energy to the focal line. In practice, three factors cause the energy to miss the focal line. Inaccuracies in the shape of the parabola, imperfections in the surface of the reflective material, and errors in aiming the reflector at the sun all cause the reflected energy to miss the focal line. Fortunately, the target is bigger than a line. A roasting tube that is a hundred or so millimeters in diameter presents an easy target and compensates for minor construction and aiming errors. As long as most of the sun's energy hits the roasting tube, the oven will work properly.

For our two axis parabolic trough, there are two kinds of aiming errors, azimuth errors and elevation errors. Azimuth errors are fairly benign; they factor the radiation by the cosine of the error angle. For as much as a 45-degree error, the resulting radiation is only reduced to 71% of its ideal value. This is especially good news because it is the azimuth that changes most rapidly during the midday.

Elevation errors are much more serious; they cause a precipitous reduction in the radiation when they are outside of rather narrow limits. For a given reflector, the diameter of the roasting tube determines how much elevation error is possible. Table 3 shows the percentage of solar energy that will hit various sized tubes for different elevation angle errors.

TABLE 3. THEORTICAL (CALCULATED) INFLUENCE OF TUBE SIZE AND ELEVATION ANGLE ERROR ON THE PERCENTAGE OF ENERGY HITTING THE TUBE

Tube diameter	152.4 mm (6")	127 mm (5")	101.6 mm (4")	76.2 mm (3")
Concentration Factor	5.09	6.11	7.64	10.2
Elevation angle error (degrees)	**Percentage of energy**	**Percentage of energy**	**Percentage of energy**	**Percentage of energy**
1.0	100	100	100	100
1.5	100	100	100	100
2.0	100	100	100	83
2.5	100	100	92	52
3.0	100	100	69	0
3.5	100	77	42	0
4.0	83	58	0	0
4.5	65	35	0	0
5.0	49	0	0	0
5.5	31	0	0	0
6.0	0	0	0	0

These small changes in elevation angle can be easily measured with shadow blocks, which are two small blocks attached to the side of the trough along a line parallel to the axis, one near the top and one near the bottom of the trough. The top block has a hole drilled through it and the bottom block has a circle of the same size drawn on it, but not drilled. With the reflector aimed directly at the sun, a small beam of light should go through the hole in the top block and illuminate the circle on the bottom block. If the reflector elevation is changed slightly, the spot of light will miss the circle or illuminate only part of it (see Figure 2). The amount of shift equals the sine of the error angle times the distance between blocks. If the blocks are 120 mm apart, have 6 mm hole and circle, and the bright spot just misses the circle, then the error angle is about 3 degrees, which would be satisfactory for the 127 and 152 mm (5 and 6 inch) tubes described in the table. Similarly, if the blocks are 240 mm apart and the bright spot just misses the circle, the error angle is about 1.5 degrees, suitable for the 76 and 102 mm (3 and 4 inch) tubes. This makes aiming quite easy. If the operator keeps at least part of the bright spot in the circle then the reflector will operate at maximum efficiency.

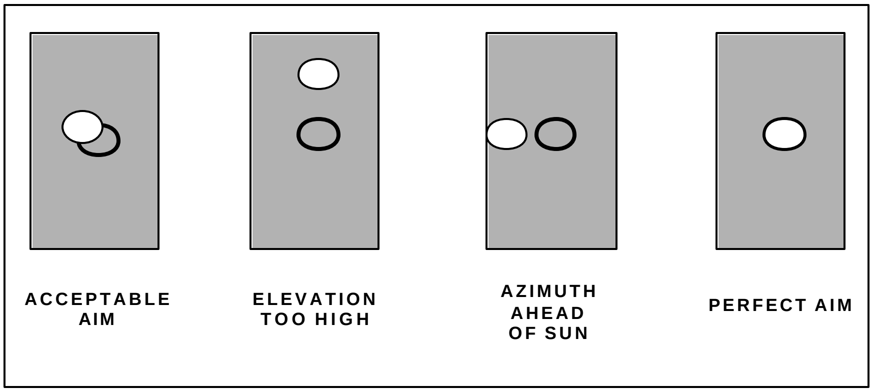


FIGURE 2. TYPICAL AIMING INDICATIONS ON SHADOW BLOCK

Pivot point and frame height

The center of mass of a rigid body, such as the combined reflector and absorber assemblies, is the point at which gravity seems to exert its force on the body as a whole. The pivot point is the location of holes drilled through the yoke pieces for the horizontal support bar. The support bar allows the reflector and absorber assemblies to swing to a desired elevation angle. If the center of mass is directly below the pivot point, the assemblies will hang still (see Figure 3). If it is to the right or left of the pivot point, then the assemblies will tend to swing around the bar unless they are prevented from doing so by a stick, strap, or chain. A pivot point higher on the yoke means that the reflector and absorber assemblies will be more stable and the roasting tube will be lower and easier to load or agitate. But a higher pivot point will require more force to adjust and maintain the desired elevation angle. A pivot point lower than the center of mass of a fully loaded absorber will allow the reflector assembly to tip over by itself (see Figure 4). A fully loaded absorber tube raises the center of mass.

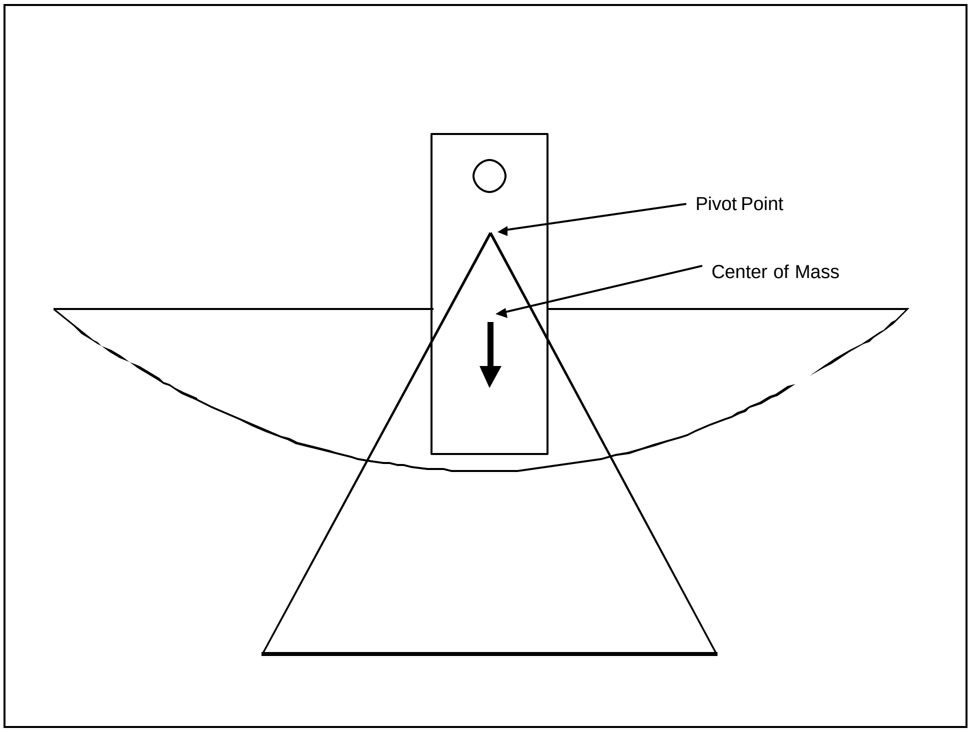


FIGURE 3. TABLE GEOMETRY WITH CENTER OF MASS BELOW PIVOT POINT

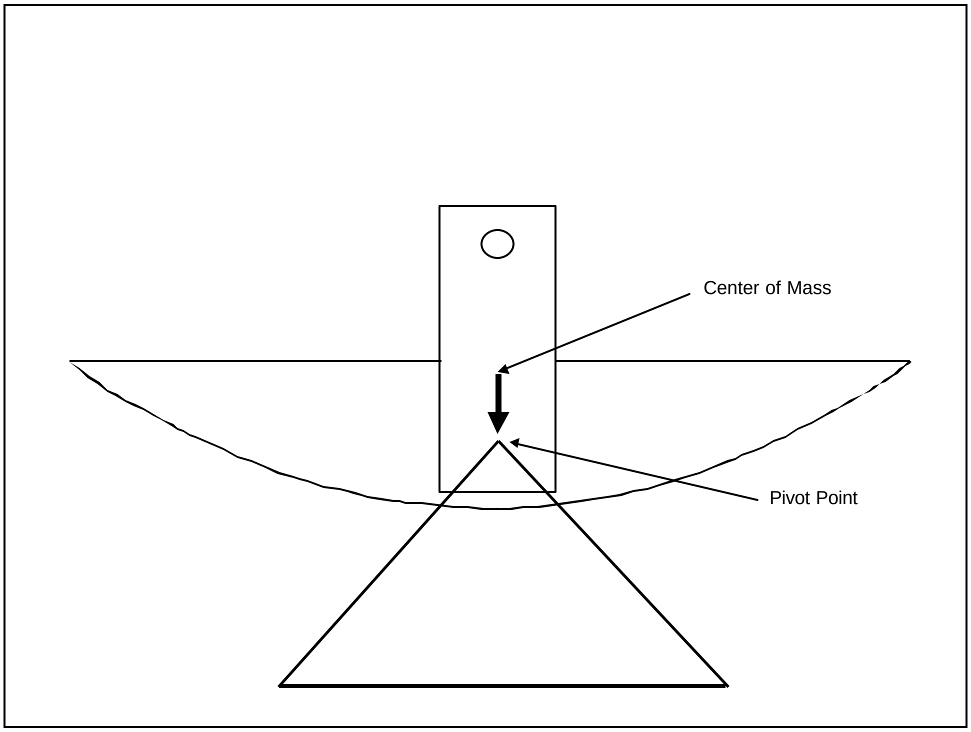


FIGURE 4. UNSTABLE GEOMETRY WITH CENTER OF MASS ABOVE PIVOT POINT

The frame may be built to any design that provides stability while allowing the range of elevation needed for operation. The height of the horizontal bar that supports the reflector and absorber assemblies is a critical parameter. A lower bar makes it easier for a short operator to load, unload, agitate, inspect, and clean the tube (see Figure 5). A higher bar allows a greater range of elevation, up to a full 90 degrees from vertical (see Figure 6).

In summary, the pivot point should first be chosen as high on the yoke as possible without interfering with the absorber assembly or requiring too much force to adjust the elevation. Then the horizontal bar should be designed high enough (by selecting the support frame leg length) to allow the reflector to be adjusted to 30 degrees (or less) elevation from the horizon. The tested oven used a pivot point 1090 mm from the ground with a reflector whose maximum extension from the pivot point was 1240 mm. It was not adequate for low sun angles experienced in Minnesota in November.

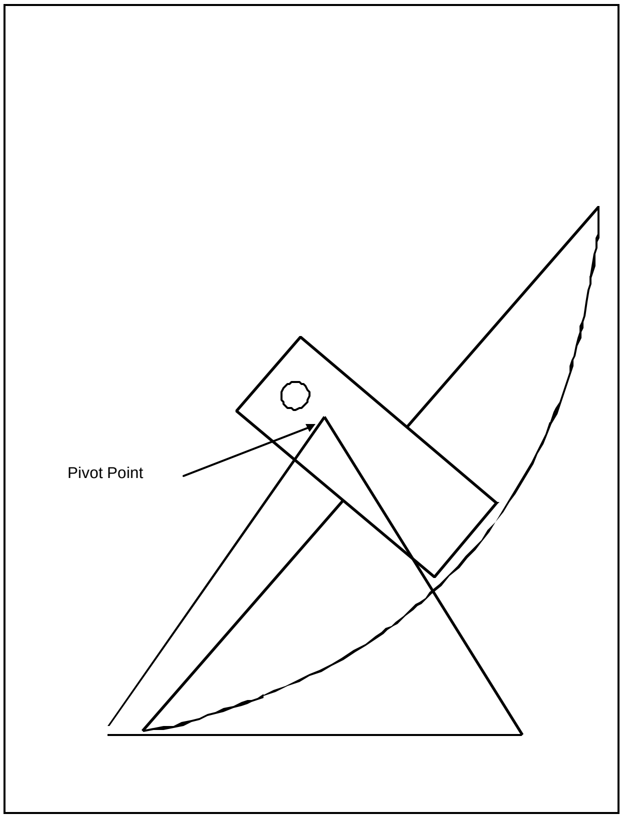


FIGURE 5. SHORT SUPPORT ASSEMBLY IS EASIER TO LOAD AND OPERATE

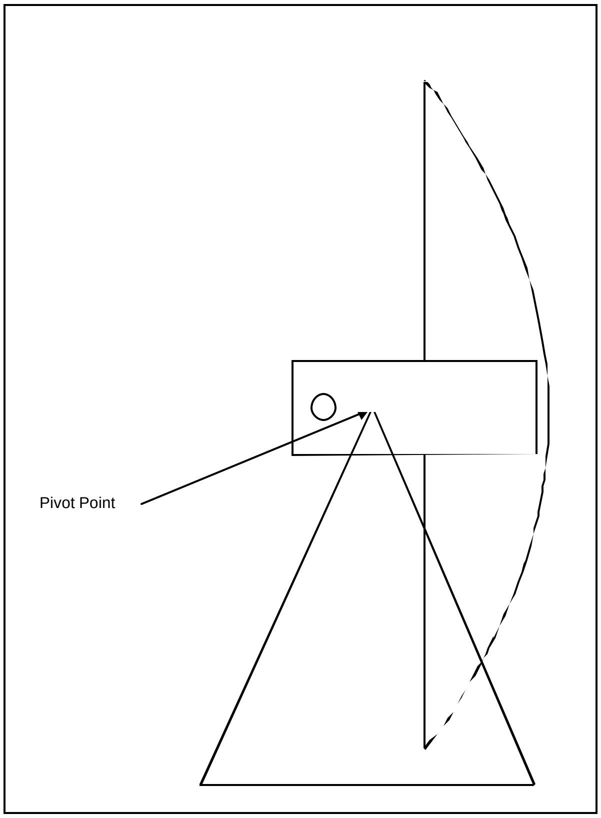


FIGURE 6. TALL SUPPORT ASSEMBLY ALLOWS FULL RANGE OF ELEVATION

Continuous vs. batch roasting

"Batch processing" means loading the tube with product, heating until it is done, removing the product, and then repeating the sequence. "Continuous processing" means continuously adding product, and after some period of roasting, continuously removing that which is done. The cylindrical roasting tube, with two open ends, lends itself to either method. Continuous processing would be more difficult using most other solar cooking geometries.

Our limited experiments with continuous processing so far have not been very successful except for boiling water. The output product has not been uniformly "done". This is probably due to variations in aiming accuracy and inadequate stirring or agitation of the product. Since we expect control of these factors will get better through practice, and with an improved agitator, we consider it wise to maintain clearance at the two open ends of the roasting tube so that continuous roasting can be tried in the future.

Modularity

Each assembly (reflector, absorber, and support) should be designed to be compatible with variations of the other two. This allows changes to the design of any one of the assemblies without affecting the design of the others. For example, different absorber assemblies should be usable with the same reflector and support assemblies. The builder of an oven should consider this before changing the methods by which the assemblies attach to each other. The tested oven achieves this by the design of the yoke. The yoke pieces provide two secure supports for a large diameter tube (130 mm). Smaller diameter tubes are easily accommodated with screw-on plates. Similarly, the yoke pieces, which are attached to the parabolic trough, provide for simple attachment to the support assembly, i.e., the horizontal bar of the support assembly frame goes through 24 mm (15/16") holes in the two yoke pieces. These modularity conventions have allowed us to test major variations of reflector, absorber, and support assemblies without rebuilding the unaffected assemblies.

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