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Solar Cooker Reflector Optical Evaluation and Design Evolution

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Solar Cooker Reflector Optical Evaluation and Design Evolution

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18 June 2001

The design started out as an elevation angle trackable 1 m^2 spherical mirror hung from a tripod. This was relatively easy to ray trace, producing good images of the convergence of reflected rays onto the cook pot, as shown in Fig.1.

This design was discarded as too complicated and flimsy, due to the need for a tripod to hold both the cook pot and the spherical reflector, and a slot in the reflector for one leg of the tripod. Also, it was felt that tracking the mirror would be too difficult and time consuming, detracting from the desired simplicity of a relatively passive solar cooker.

The next design was of a set of planar reflectors that could be folded up for easier portability. The suggested design was something like

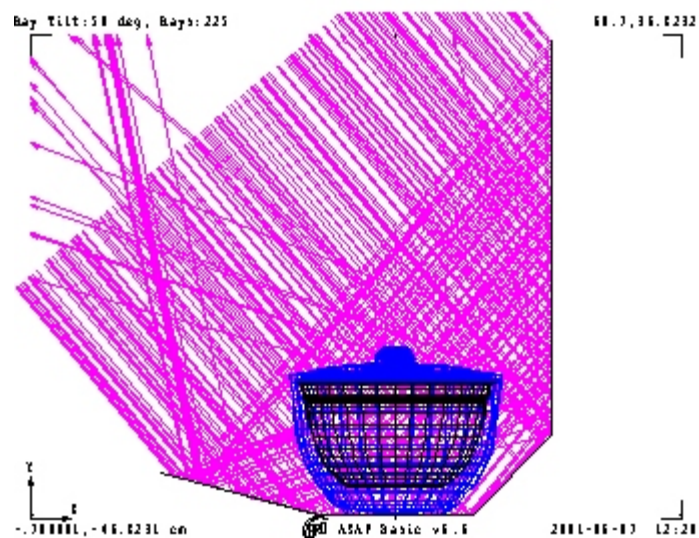


Figure 3. Ray trace for solar altitude angle of 50 degrees of the geometry shown in Fig. 2.

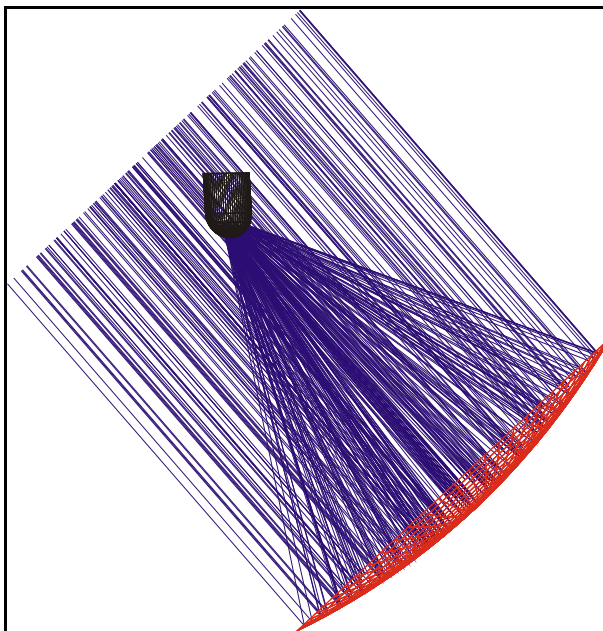


Figure 1. Ray trace of incident solar rays reflected from spherical mirror in red onto cooking pot in black, 40 degree solar altitude angle.

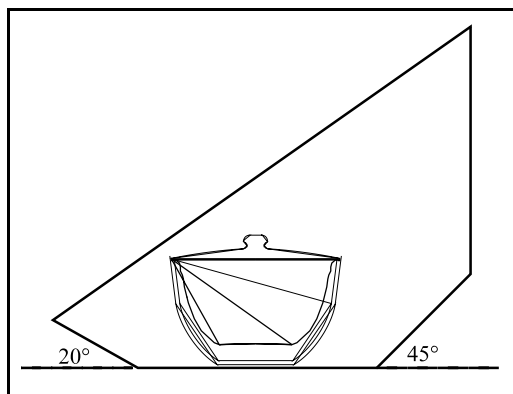


Figure 2. Second geometry of solar cooker cook pot, insulating glass “greenhouse”, and black metal pot.

that shown in Fig. 2.

A sample ray trace of an embodiment of this is shown in Fig. 3. It is seen that a high portion of the incident rays strike the pot. In the X-direction the incident rays

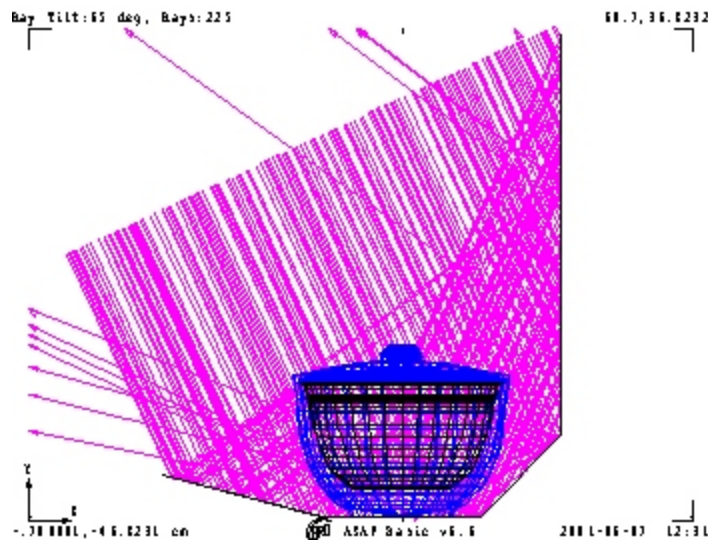


Figure 4. Ray trace of the geometry shown in Fig. 2 for solar angle of 65 degrees.

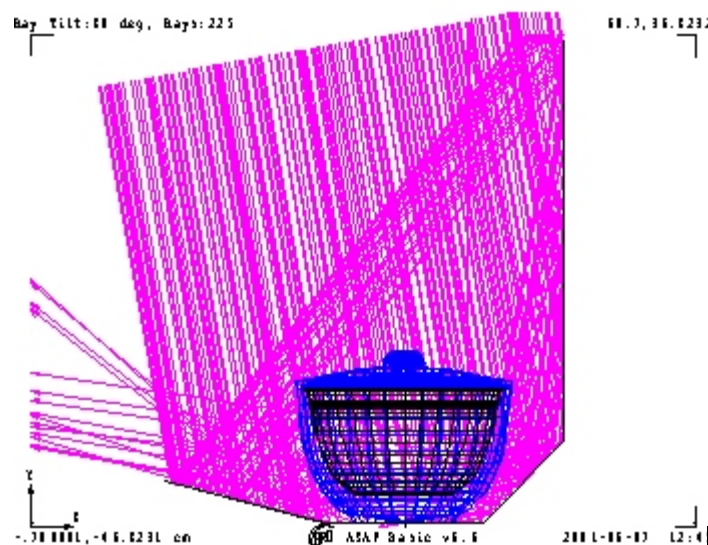


Figure 5. Ray trace of solar cooker for solar altitude angle of 80 degrees.

Solar irradiance is greatest at high sun angles, owing to the smaller atmospheric thickness transited by the rays, so this effect can partially compensate for this loss. There is also, however, a slight reduction in the solar ray acceptance area of this configuration. The direct normal width of the rays accepted by this geometry is tabulated for angles ranging from 40 to 80 degrees.

were made to illuminate an area just about the width of the glass envelope.

Ray traces for 65 degree and 80 degree solar altitude angles are shown in Figures 4 and 5. For the whole range a fairly high fraction of the incident rays are stopped by the solar cooker. Note that this design concentrates only in the plane shown. There is no concentration in the X-direction, perpendicular to the plane of the page. It is felt that this reflector design, or a minor variation of it, is amenable to folding into a compact portable unit.

It would be desirable to see if some version of this basic design approach could be made to provide higher concentration, by picking up rays in the X-direction for concentration as well.

At the 80° extreme angle, it is seen that the concentration has been diminished somewhat, since some of the rays incident on the frontmost reflector facet miss the pot altogether. Perhaps by tilting this facet more, this effect can be reduced, with only modest loss of performance at the 50 degree angle.

Reflector acceptance width	
Solar angle, deg	Width in cm
40	74.3
50	73.7
60	70.8
70	65.8
80	58.8

Collection Efficiency

Next we look at the concepts of efficiency and concentration ratio. Three different figures of merit can be defined:

1. **Concentration ratio** is defined to be the ratio of the entrance aperture area to the absorber area.

2. **Effective concentration ratio.** Considering flux losses, we could define the effective

concentration ratio as the average irradiance on the absorber divided by the average irradiance over the entrance aperture.

3. **Collection efficiency** is the absorbed flux on the receiver divided by the flux entering the entrance aperture.

To be accurate in calculating these, ASAP should be told to reduce the flux in each ray upon reflection or transmission by the appropriate value of the reflectance and transmittance. The transmittance through a transparent medium is the combination of interface transmittance and medium transmittance. ASAP has the ability to follow multiple daughter rays at each ray split at an interface, keeping track of the transmitted ray and the reflected ray, and their subsequent history. It also has a command to stop tracing such rays when their flux level falls below some user-specified small value and another to stop tracing after a specified number of surface intersections.

I don't have time for an advanced simulation, so will ignore any losses within the glass and will keep only parent rays split 2 or fewer times at an interface, plus all their child rays. This will provide a degree of multiple

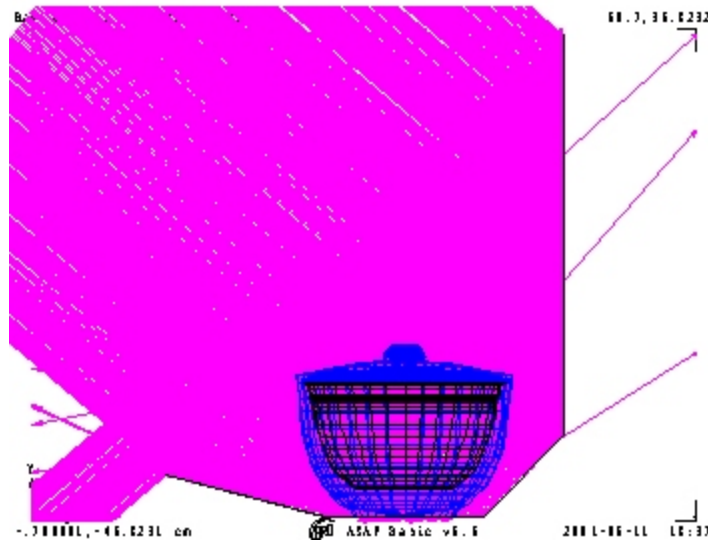


Figure 6. Side view of reflector, cook pot, greenhouse, and ray trace. 1600 source rays, solar angle 40°.

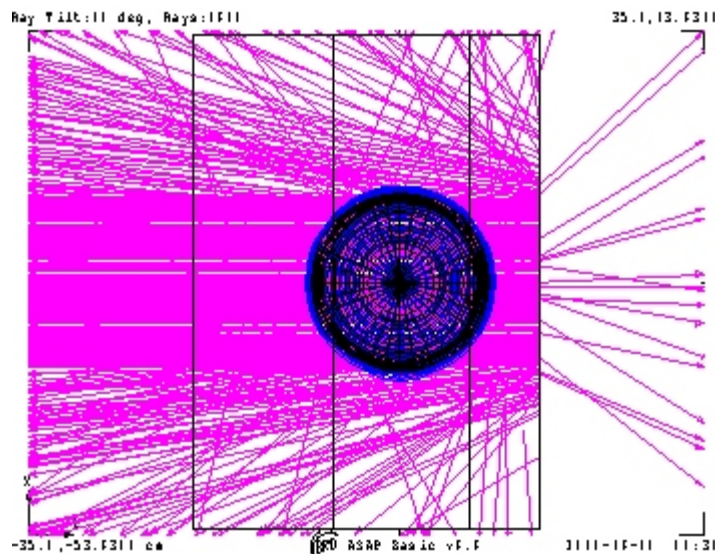


Figure 7. Top view of ray trace shown in Fig.6, without the incident rays, showing only stray rays emerging.

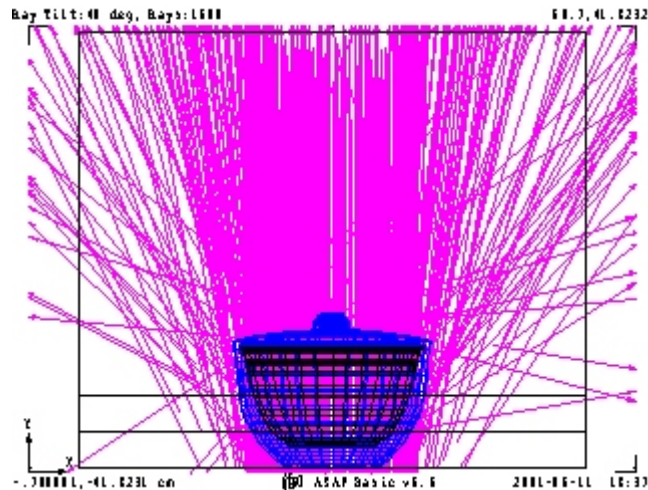


Figure 8. Front view of solar cooker and rays not absorbed by the cook pot.

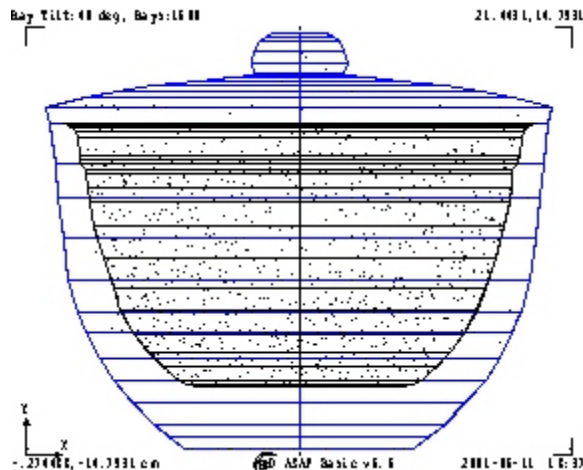


Figure 9. Profile of solar cooker showing a projection of ray intersections with the cook pot.

around the axis. As expected with planar reflectors, the angular range of incident rays on the pot is limited, even though from Fig. 9, it appears that they are well distributed over the pot.

Concentration Ratio

Dividing the total absorbed flux by the incident flux gives the collection efficiency figure of merit for the design, defined above and

reflection between inner and outer surfaces of the glass envelope. The simulations were done for pyrex glass having a refractive index of 1.474.

To show the basic performance of the design, a trace was done with 900 source rays and a solar angle of 40 degrees. Shown in Figs. 6 through 8 are a side view of the trace, a top view, and a front view. Figure 6 shows the projection of all rays onto the Y-Z plane. Figure 7 shows missed rays. The incident rays are just the width of the glass envelope. Fig. 8 shows a front view of the pot and reflector, with reflected rays superimposed on it.

Fig. 9 shows a plot of the linear projection in the z-direction, onto a vertical plane perpendicular to this direction, of the positions of the rays absorbed on the black pot. Superimposed in this “spot diagram” is a profile of the outer glass surface and the black metal pot. Fig. 10 shows an isometric plot of the angular distribution of the flux incident on the cook pot, in angular coordinates. Flux per unit solid angle is plotted versus the angle in degrees from the axis and

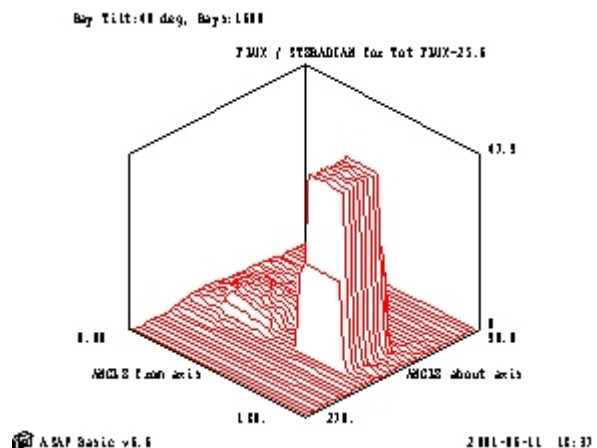


Figure 10. Isometric plot of the flux per unit solid angle impinging on the cook pot, projected onto a plane perpendicular to the Z-axis.

tabulated for the incidence angles shown in the previous table. This is tabulated below, along with the area of the entrance aperture. For comparison purposes, the projected area of the cook pot from AutoCAD is approximately 42.6 cm².

If we divide the aperture area by the cook pot profile area the perfect concentration ratio would be 41½ to 1 for the 50° case. However, many of the rays are not concentrated on the cook pot, and the actual cook pot area is larger than its projected area. The concept of area concentration ratio breaks down for this design.

Aperture area in cm ² and flux efficiency versus solar altitude angle			
Solar altitude	Aperture Height cm	Aperture Area cm ²	Flux efficiency
40°	74.3	1782	25.6%
50°	73.6	1768	33.3%
60°	70.8	1699	33.8%
70°	65.8	1579	24%
80°	58.8	1411	15.6%

Assuming a uniform irradiance E_o over the effective entrance aperture A , the incoming flux would therefore be $E_o A$. If the flux efficiency calculated by ASAP is η , then the absorbed flux will be

$$\Phi = \eta E_o A,$$

with η and A given in the table above. For determining the effectiveness of this design for increasing cooking temperatures, we need to compare the flux received by the pot with the reflector behind it to the flux received by it without a reflector. To do this calculation properly with ASAP, we would need to illuminate the cook pot and greenhouse with rays only incident on it. The projected area of the cooker varies with solar incident angle, however, so this is not an easy calculation to perform with ASAP.

If we assume, for the sake of approximate calculation that the profile area of the cooker is, say, 30% larger than the projected area of the horizontal projection of the cook pot alone, or an area of 1.33 times 42.66 or 56.7 cm². So the cooker without reflector would receive a flux of approximately E_o 56.7 cm². The true flux concentration ratio is therefore approximately the ratio of the actual absorbed flux Φ given by the equation above, to $56.7 E_o$. Calling this flux concentration ratio C_f we have

$$C_f = \eta A / 56.7$$

Choosing 1700 cm^2 as a representative value for the aperture area and the corresponding value of 0.338 for η from the table above, we arrive at an approximate flux concentration ratio for this cooker of approximately 10 to 1, a very respectable value for this design. Losses in a real system, imperfections in the mirror, scattering in the glass envelope, and other factors are likely to reduce the effective flux concentration substantially. However, this 10:1 figure encourages further work with this design, and a possible mock up with it.

The concentration can further be improved by adding side reflectors, gathering flux from the side and directing it onto the cook pot. My feeling is that this is best done with a mock up rather than through further time-consuming ray tracing.

Resizing the Reflector

There is a problem with the current design. The collection area is much smaller at a nominal 1700 cm^2 than the desired $1 \text{ m}^2 = 10,000 \text{ cm}^2$.

If we extend the front and back reflectors to intercept substantially more flux, much of the newly intercepted flux misses the target altogether. So the reflector was redesigned from scratch, in an attempt to increase the size of all four reflectors, to intercept more flux from the sun without having excessive numbers of rays miss the target.

Improved Reflector

In an attempt to improve on the design, the front reflector facet was extended and tilted more. A ray trace result for this is shown in Fig.11 for a 50° sun angle and in Fig. 12 for an 80° angle. In the first case, the ASAP-calculated collection efficiency is 38%, with an aperture height of 65.2 cm and an aperture area of 1565 cm^2 . At the 80° angle, these figures turned out to be

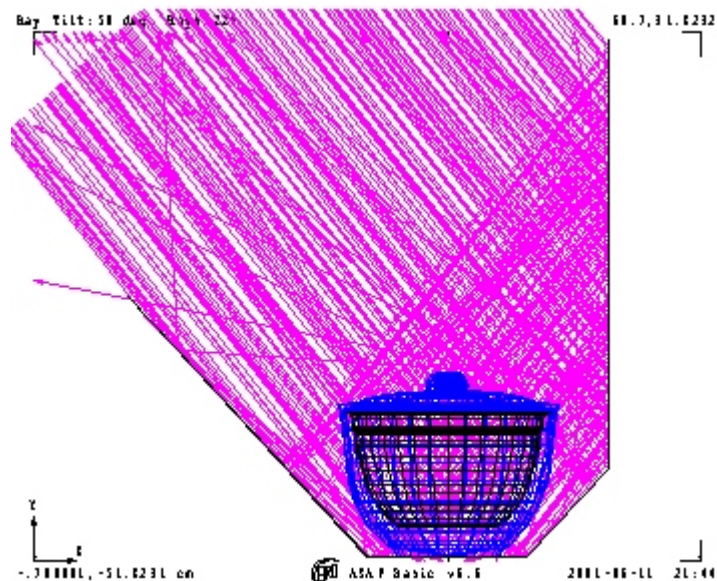


Figure 11. Ray trace of solar cooker with extended and more inclined front reflector facet. Sun angle 50° .

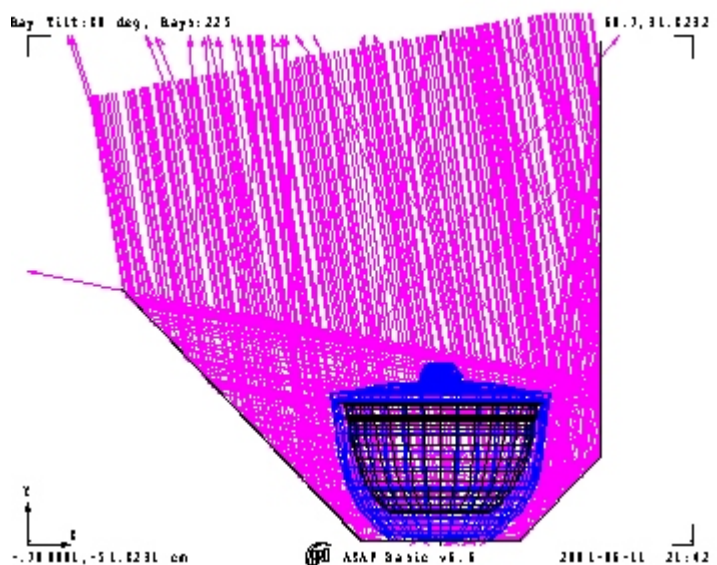


Figure 12. Ray trace of solar cooker with extended and more inclined front reflector facet. Sun angle 80° .

17.7%, 64.3 cm, and 1543 cm², respectively, indicating some improvement in performance at both sun angles.

An AutoCAD drawing of the resulting design is shown in Fig. 13 in cross-section. In order to pick up additional flux from the side, two additional mirrors were also added. Inclined at 20 degrees from the vertical, they should admit solar radiation and reflect it toward the target area over more than a two-hour period. (The Earth turns 15 degrees each hour, so vignetting of the pot by the side mirrors will not occur when the sun is within a little more than an hour away from central incidence on the cooker.)

There was insufficient time to try and design the front, back, and side reflectors so that they come together at the edges of the side mirrors. There is a bit of a gap, therefore, at the edges of the side mirrors. Thus the apparent flux efficiency is lower with this design. However, it does direct more solar flux onto the cook pot. A side view, showing the side reflectors is shown in Fig. 14,

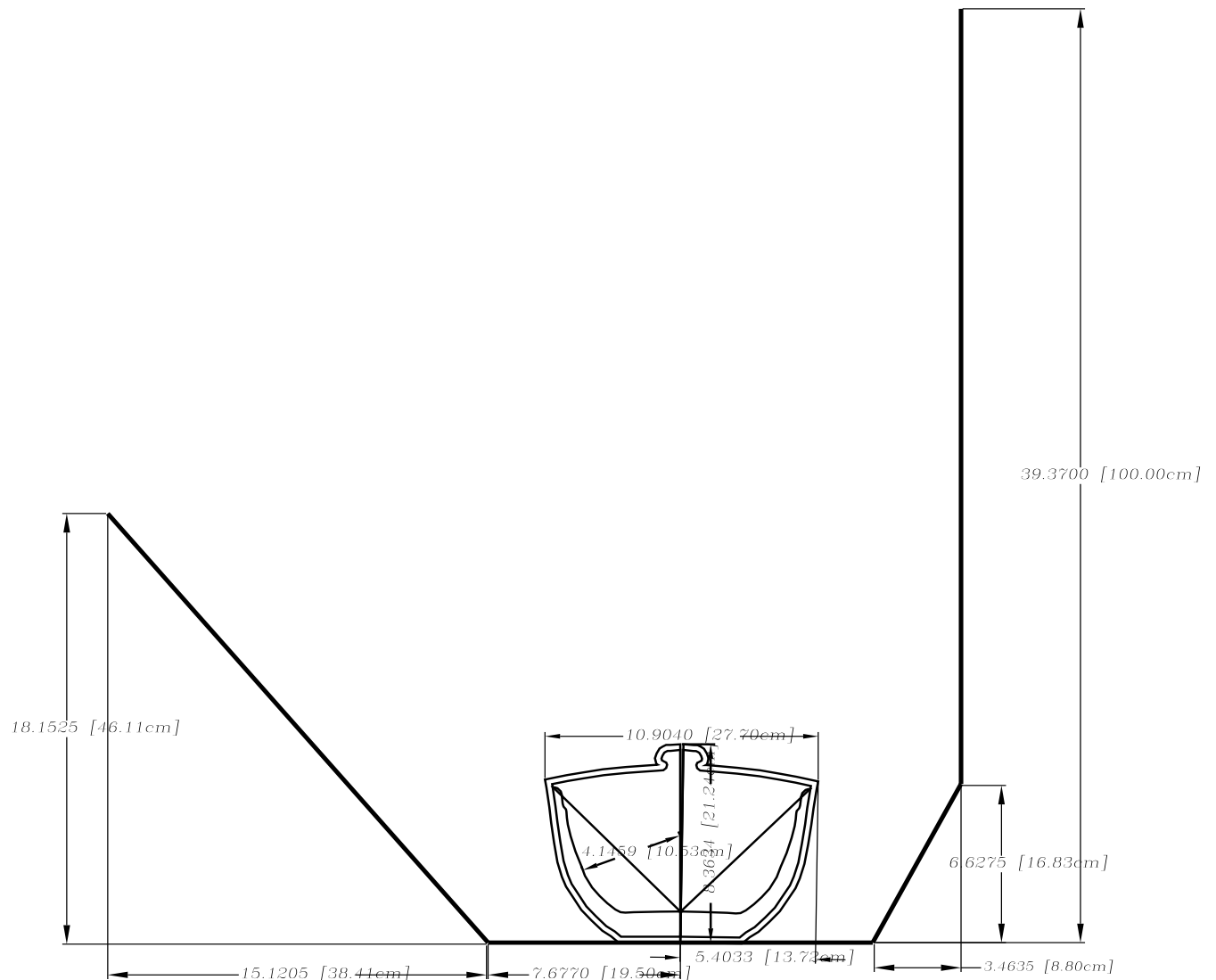


Figure 13. Profile of cooking pot and glass envelope and front and back reflectors.

along with some rays scattered out of the beam and some more that missed the cook pot.

A ray trace of this design is shown in Fig. 14. An algorithm was developed to determine the coordinates of a set of launched rays which, when tilted to the right angle and launched will just fill the front and back mirrors and the side mirrors. In Fig. 14, it appears that some rays are passing through the reflector, but they are, in reality, missing the side reflectors at the front and back. Figure 15 shows a side view of a ray trace for rays incident at a solar altitude angle of 50° . The rays apparently passing through the back reflector are in fact passing by it on the left and right sides. This design can be refined by widening the front and back reflectors at their tops, out to the same 20° angle of tilt of the side reflectors. This would catch most of the missing rays shown in Fig. 15.

Fig. 16 shows an isometric plot of the angular distribution of solar flux over the metal cooking pot. We see that using the larger mirrors and adding the side mirrors, the flux is distributed over a wider range of angles, giving better coverage of the pot and less chance of a hot spot. The angular distribution in this view roughly corresponds to the flux distribution over the approximately hemispherical pot bottom.

For the sun at 80° , the front mirror comes more into play. A ray trace for this angle is shown in Fig. 17. Fig. 18 shows the corresponding isometric plot. Though the flux distribution has shifted, it still covers a relatively large angular range of the cook pot. Fig. 19 shows a spot diagram of ray intersections with the cook pot, projected onto the X-Z plane, for the 50° sun angle.

Fig. 19 gives some confidence that the rays are distributed fairly uniformly over the outside and inside of the metal pot for this sun angle. For the

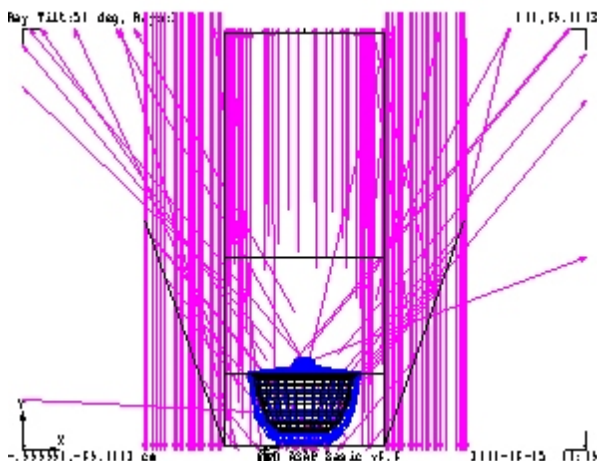


Figure 14. Front view of cooker, with 20° side mirrors.

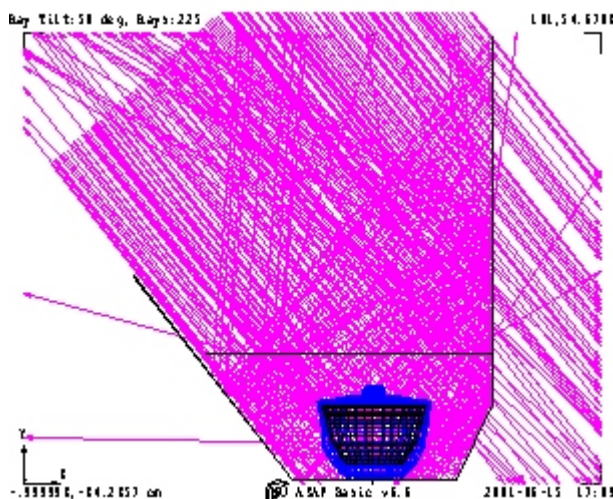


Figure 15. Side view of solar cooker ray trace, rays incident at 50° solar altitude angle.

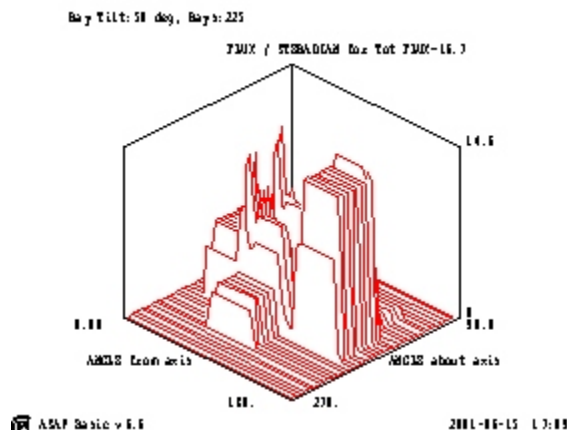


Figure 16. Isometric plot of the angular distribution of rays arriving on the cook pot surface.

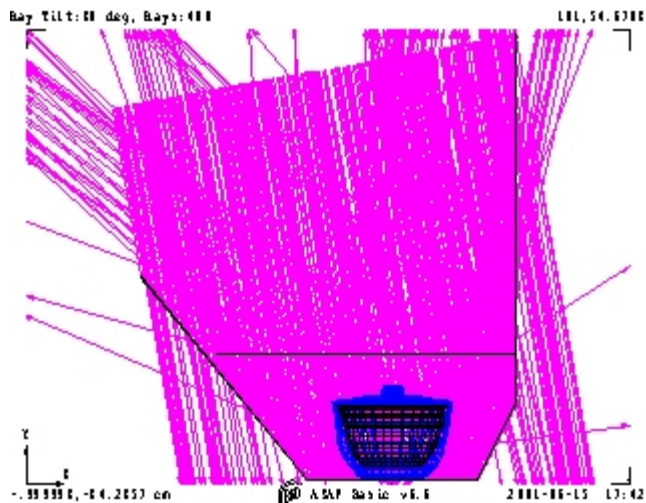


Figure 17. Side view of ray trace for solar altitude angle of 80°.

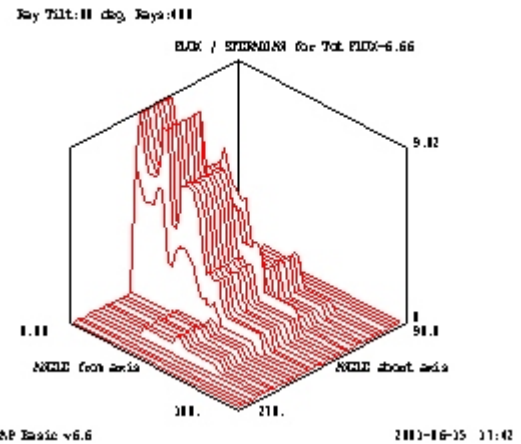


Figure 18. Isometric plot of angular distribution of rays illuminating the metal cook pot for a solar altitude angle of 80°.

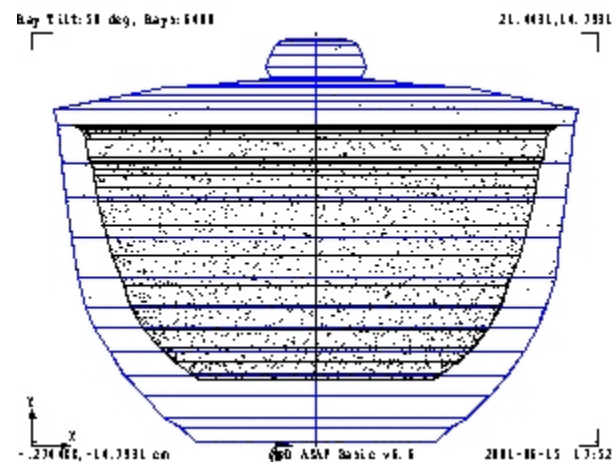


Figure 19. Spot diagram showing projections of ray intersections with cook pot onto the Y-X plane. Solar angle 50°. 80° angle, Fig. 20 shows similar uniformity. Spot projections onto the Y-Z plane are similarly uniform in appearance. A spot diagram for the 50° angle projected onto the X-Z plane is shown in Fig. 21.

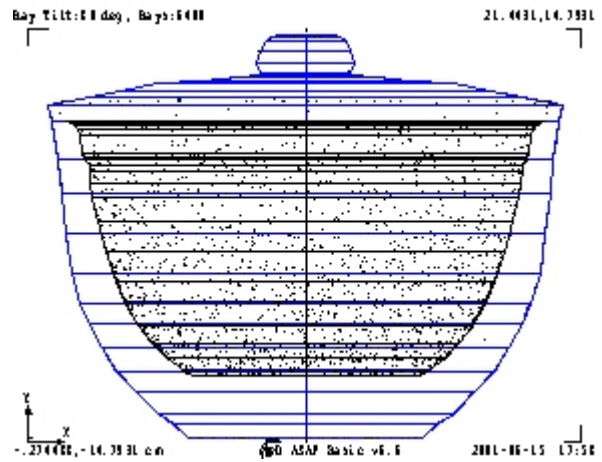


Figure 20. Spot diagram for solar altitude angle of 80°. Ray intersections are moderately uniformly distributed in this perspective view.

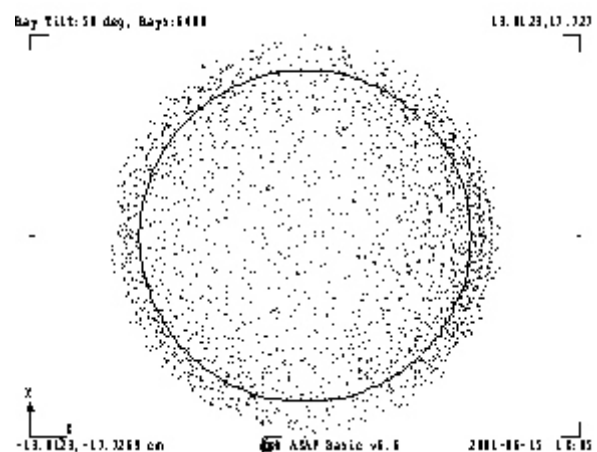


Figure 21. Spot diagram for ray intersections with cooking pot, projected onto the X-Z plane.

Improved Flux Collection Assessment

To assess the magnitude of any increases in flux on the cook pot resulting from the larger reflector aperture area, several ray traces were performed, for angles of 50, 60, 70 and 80 degrees. In each case, a total of 10,000 rays was launched. In order

to estimate the flux in watts received by the cooking pot, FSEC program SUNSPEC was run for the conservative case of a southeastern U.S. summer atmosphere and solar altitude angles of 50, 60, 70, and 80 degrees. This was then multiplied by the aperture area in m² and the flux collection efficiency to yield the estimated absorbed flux. The results are tabulated below. In an effort to improve the performance at 80 degrees sun angle, the front reflector was doubled in area, by extending it to the left. The last line in the table shows the results for the 80° case. The 50° case was unchanged because the rays incident at this angle are parallel to the front mirror and are unaffected by its size. One can see that the total solar flux absorbed by the black metal cooking pot ranges from a peak of 106 watts for the 60 degree angle of incidence to 44.5 watts at the 80° one.

Ray trace results for solar cooker design without and with larger front mirror at 80° sun angle						
Solar Altitude, °	Irradiance, W/m ²	Rayset height, cm	Rayset area, cm ²	Theoretical area concentration	Flux collection efficiency, %	Absorbed flux, W
50	587.9	100	8086	11.4	17.2	81.8
60	633.6	101.9	8160	11.5	16.7	86.4
70	663.3	99.8	7987	11.3	12.1	64
80	678.0	94.6	7571	10.7	6.6	33.7
80, front mirror 2X	678.0	125	9973	14.1	7.82	52.9

It is clear that the extended front mirror helps performance at high sun angle.

Considering the large sizes of all the mirrors except the small one at the bottom and back of the cooker—the one connecting the horizontal bottom reflector to the vertical back reflector—we wonder if this reflector is really needed. It adds to the complexity of the reflector set. A case was run with this mirror eliminated, with the horizontal bottom mirror connecting to the vertical back mirror directly, at ground level.

Solar cooker performance without inclined back reflector		
Sun angle, degrees	Flux collection efficiency	Absorbed flux on the pot
50	14.6%	69.6 W
60	10.9%	56.4 W
70	6.57%	34.8 W
80	1.75%	9.0 W

The results for the first four cases in the previous table above are shown in the table above. Clearly the tilted back reflector is needed, especially for high solar altitude angles.

An alternate reflector design was considered and discarded. It is described in the next section.

Cube Corner Reflector

A paper by Nahar¹, describes a double reflector hot box solar oven, having a reflector design that appears of interest here. In the Nahar design, two vertical mirrors at right angles to each other reflect solar radiation down onto a honeycomb insulated transparent glazing over an insulated oven box. All radiation to the box enters from the top through this glazing. Only the two mirrors provide extra solar flux into the insulated aperture.

This design suggests an alternative reflector arrangement for the FSEC solar cooker. In this case a third reflector would be added, at right angles to the previous two, producing a set of mirrors called in optics a “cube corner” reflector.

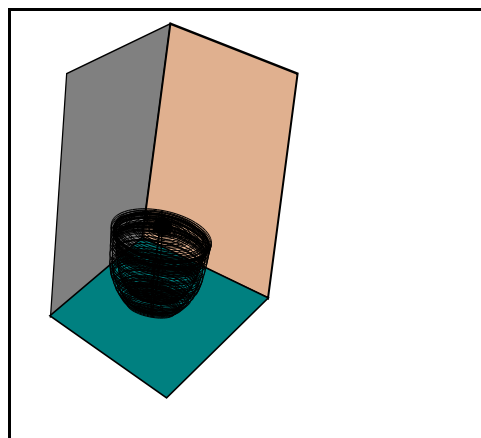


Figure 22. Cube corner reflector solar cooker design concept.

Such a reflector is shown schematically in Figure 22. Without the cooking pot in it, the reflector has the property that within a range of incident angles, every ray entering the reflector is translated laterally and then reflected back out in a direction parallel but opposite to the one followed by the incident ray. In miniature this design is part of many retro-reflecting materials, such as those used to mark lane edges in roadways.

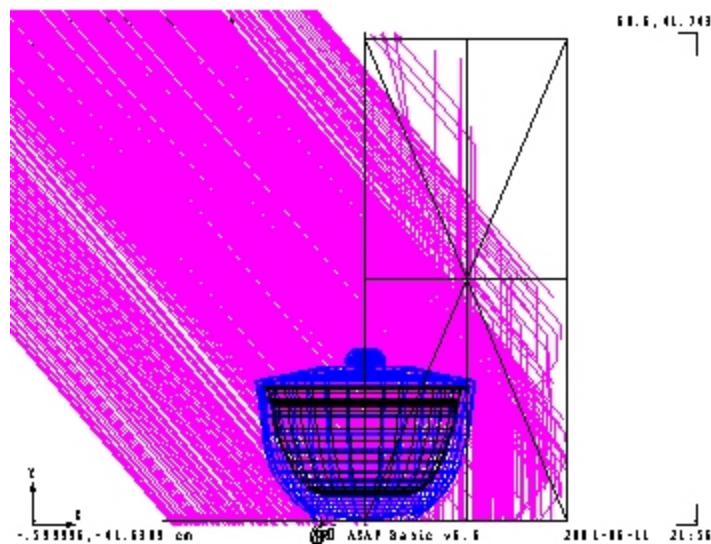


Figure 23. Ray trace for a 50° solar altitude angle with the cook pot and greenhouse placed in a cube corner reflector. Flux capture efficiency is low, around 3%.

If an absorbing object were to be placed near the vertex of the cube corner reflector, much as shown in Fig. 22, perhaps some concentration might be obtained. It is anticipated that with a proper geometry the pot can be positioned to intercept most of the incident rays before they can be reflected back out of the cube corner. Such a reflector design should be easy to fold for storage and transport. Figure 23 shows ray trace results for a cube corner reflector design. With this design it is very difficult to make the grid of incident rays illuminate only the

reflectors, so much of the incident flux misses them completely in this simulation, forcing the apparent efficiency to be lower than what it should be.

The design is especially inefficient at the 80° solar altitude angle, since the back reflectors hardly come into play and the bottom reflector sends most of the incident rays from around the cook pot back up to the sky. This could be avoided by tilting the cube corner reflector, but the design does not appear to have much promise for this application.

Because of the problems inherent in this design, it is not considered an acceptable alternative to the horizontally faceted reflector design described previously.

Conclusions

The 2-D faceted design described first appears promising. I like the idea of setting the back mirror vertically, 10 degrees higher than the rays incident at the 80 degree highest angle specified for the design, the highest noon sun altitude planned or expected. Setting the front mirror at an angle just at the lowest solar altitude angle of 50° also seems to produce good results, at and in between these two angular limits. The back mirror does most of the work at low sun angle and the front and back tilted ones at high sun angle.

To enhance the design, or to reduce the size of the front and back mirrors for the same total solar flux, side mirrors were added. They were tilted outward by 20 degrees, to capture additional solar flux on the side and redirect it onto the sides of the cook pot. They would not have to be attached to the other reflectors on any side but the bottom, or they could be separate mirrors, attached to the others when the cooker is folded out for use. Leaving small gaps between these side mirrors and the front and back mirrors probably reduce performance somewhat. Not having to connect them anywhere but at the bottom facilitates easy assembly and disassembly. Better performance could be achieved by integrating the side mirrors better into the front, back, and tilted ones. Some thought will have to be applied to the means of stabilizing these mirrors, of folding them for storage, and holding them at the proper angle in use.

The cooker design may be good for some uses without the side mirrors. If so, this would reduce the price of the cooker and make it more compact. If the side mirrors prove necessary to produce higher temperatures, they could be sold as additional cost add-ons.

The loss of flux absorbed by the cook pot at high solar altitudes may not be that much of a problem. Presuming that cooking starts a couple of hours before solar noon, the cooker will have been brought up to temperature by the time the sun is high and the flux received around noon should be sufficient to maintain cooking temperatures.

The remainder of the design needs to be done in the experimental phase. For testing the optical and thermal performance, one can purchase relatively thin mirrored acrylic sheets and cut them to the desired dimensions. Brevard Glass Company can order this mirror material in 1/4" and 1/8" thicknesses. The former would provide most rigidity but the latter would provide less weight.

The reflectivity might not be optimum and their costs might be too high for the final market, but their stiffness and optical quality should make them good for seeing where the solar beam goes for a variety of sun angles, and for preliminary tests of the temperatures achievable with this basic design. If a specific design appears good with these mirrors, then less expensive, more reflective substitute materials could be sought.

Wooden or metal blocks can be slotted to accept the acrylic mirrors, holding them to each other at the required angles without the need for hinges and allowing for easy disassembly. Several different such blocks could be fabricated for testing purposes, providing different angles between the mirrors. Several different mirrors could also be fabricated, to enable quick testing with a variety of configurations.

When the design matures, a set of mirrors can be attached by hinges, with stops to set their angles to each other when folded out, and this arrangement could be tested for practicality, portability, and expected durability.

Reference

1.Nahar, N.M., "Design, development and testing of a double reflector hot box solar cooker with a transparent insulation material," Renewable Energy 23 (2001) 167-179, Pergamon/Elsevier Press.