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THE CONE-AND-COLUMN: A NEW CONCEPT IN SOLAR ENERGY CONCENTRATION

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1. INTRODUCTION

The effective use of solar energy to generate electric power in space becomes more difficult as electric power requirements increase. Increasing power in systems using solar concentrators gives rise to the following problems.

1. The weight of the structure required for concentrator support and positioning increases rapidly.
2. Stowage volumes grow.
3. Erection mechanisms become complex.
4. Control of thermal distortion becomes more difficult.
5. Radiator weights increase disproportionately.
6. High moments of inertia introduce attitude control problems.
7. Dimensional control of tooling for large paraboloidal shapes becomes difficult and costly.
8. Process control in the fabrication of large shapes becomes difficult.
9. Large collection areas interfere with telemetry and reconnaissance.

Because of these problems, solar power conversion systems have not been considered much for use beyond the region of 15 electrical kilowatts (kwe). However, many of these problems can be diminished or overcome by using a double reflector system and extending the practical range of solar energy conversion to 100 kwe or more. Also, the many advantages of the cone-and-column concentrator should make it highly competitive in the 1- to 10-kwe range.

CONE-AND-COLUMN CONCENTRATOR CONCEPT

The fabrication, folding, and unfolding of large paraboloidal reflectors within strict weight and dimensional limitations present many problems.

Although several methods of folding paraboloidal reflectors have been investigated in detail, little attention has been given to the possibility of optically folding them. Optical folding is a technique commonly used to place conveniently parts of an optical system such as objects, images, components, and the eye. It is accomplished by placing a plane mirror in the path of the light and relocating the shadowed parts so that their images in the mirror coincide with their original positions; that is, the parts are interchanged with their images in a plane mirror (see Figure 1).

The principle of optical folding can be extended to folding with curved mirrors if proper account is taken of the magnification of curved mirrors. When a suitable conical mirror is placed in front of a paraboloidal reflector (see Figure 2), the image of the reflector can be made to lie near the reflector axis. The paraboloidal reflector then can be interchanged with its image.

The new reflector (column reflector), combining with the conical mirror, will be the optical equivalent of the paraboloidal reflector. The focal points and apertures of the two systems will be identical. The column reflector will be a parabola of revolution with its axis of revolution lying on the convex side of the parabola.

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When a paraboloidal solar concentrator is optically folded, the area of the parabolic surface required is reduced greatly. For the primary interception of solar energy, the conical reflector is substituted for the paraboloidal reflector. Solar energy incident on the cone is reflected to the column reflector. Energy reflected from this column is focused to a point on the axis after having been reflected from the cone a second time.

The two modes of concentration of the paraboloidal reflector have been preserved. The first mode, in which rays are reflected to an axis, is due to the paraboloid being a surface of revolution. This mode is preserved by using only surfaces of revolution in the new system. The second mode, in which rays are reflected to a single point on the axis, is due to the parabolic cross section of the paraboloid. This mode is preserved by retaining the parabolic cross section in the column reflector.

With the optical principles of the cone-and-column reflector combination established, further steps can be taken to minimize the surface area of the column. From Figure 2, it is seen that the column flares at the top and at the bottom. This flaring should be minimized, not only to reduce weight and volume, but also to prevent the top of the column from intercepting rays approaching the focal point. The flaring can be alleviated by shallowing the basic paraboloid, but this operation undesirably increases the focal length. A better method is to step the surface of the basic paraboloid so that the steps lie in a straight line. The steps, then, will be segments of confocal paraboloids, and the resulting configuration will be as shown in Figure 3. To avoid the ray blockage, which is typical of Fresnel reflectors, the steps should rise as they move out from the axis on the basic paraboloids; that is, the focal lengths should decrease for succeedingly larger diameter segments. Proper stepping is accomplished by proper selection of the apex angle of the cone.

3. SELECTION OF GEOMETRY

With perfect geometry, the cone-and-column concentrator will focus perfectly collimated and aligned light rays to a point. Under these conditions the column diameter needs only to be infinitesimal. The angular spread of incident rays from the sun, orientation errors, and geometric errors in the cone all will require increases in the column diameter so that the column can intercept all the rays and reflect them at a reasonably accurate angle.

Many combinations of cones and basic paraboloids are possible. The chief objectives in selecting a particular combination are: (1) minimizing the size of the hot spot in the focal plane, (2) minimizing the weight of the column, (3) minimizing blockage by the steps, and (4) suitably locating the focal point. An analysis of the geometric parameters affecting these objectives suggests the geometry shown in Figure 3. In this arrangement the size of the hot spot has been minimized by making the maximum angle of incidence of rays on the focal plane 45 deg (called the effective rim angle since it is the rim angle of the basic paraboloid). This angle tends to locate the focal point a convenient distance above the top of the column. By making the reflecting surface at the top of the column parallel to the axis, several advantages are obtained. First, ray blockage by the steps on the column is eliminated. Second, no error is introduced at this location from rays striking the column off-center. This absence of error is advantageous since it is the rays at this point that determine the diameter of the hot spot. Third, the remainder of the column then can be sized so that the error due to off-center incidence will not spread the rays beyond this spot diameter. This procedure tends to minimize the diameter of the column.

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The above combination of effective rim angle and top column slope fixes the apex half-angle of the cone at 33.75 deg. Then, for the geometry shown:

Effective rim angle, β_o = 45 deg

Top column slope, α_o = 0 deg

Cone half-angle, θ = 33 deg 45 min

Concentrator radius (reference), R = 1

Focal distance from apex, S = 1.451

Cone depth, U = 1.498

Column height from apex, H = 1.095

Column radius at top, P = 0.035

4. CONCENTRATOR OPTICS

A complete optical analysis of the cone-and-column concentrator shows (1) that the column radius required to accommodate misaligned solar rays is proportional to the concentrator radius and the square root of the misalignment angle; and (2) that the required radius increases from zero at the apex to a maximum just below the top of the column (see Figure 4).

The effect of slope errors in the reflecting surfaces also is determined in the optical analysis. Solar deviations due to the size of the sum and orientation errors affect image size the same as they do a paraboloidal reflector. Also, as in the case of the paraboloidal reflector, slope errors in the parabolic surface have twice the effect on image size as do solar deviations. Slope errors in the cone have about three times the effect on image size as do solar deviations. The significance of these relationships (see Table I) is that to maintain a high-level concentration ratio, high surface accuracy must be maintained. However, the column diameter need never become very large to obtain the desired concentrator accuracy.

5. REFLECTION LOSSES

Folding the optical system incurs the additional losses of two additional reflections. Figure 5 shows the spectral reflectances of aluminum and silver for single and triple reflectance plotted against the solar energy spectrum. A wave length scale has been added to the abscissa to permit convenient correlation of wave length to position in the energy spectrum. The average ordinate of each curve gives the integrated solar reflectance. The single reflectance curves are from published test data on freshly deposited surfaces. The triple reflectances were obtained by cubing the single reflectance values. The integrated solar reflectances obtained from these curves are:

Number of reflections	Aluminum	Silver
1	92.5 percent	92.1 percent
3	80.5 percent	86.5 percent

The curves show that silver is inferior to aluminum for one reflection because of its (silver's) high ultraviolet absorptivity. However, on subsequent reflections silver is superior since most of the poorly reflected wave lengths have been removed. The net result is a triple solar reflectance for silver that is substantially higher than that of aluminum.

Spectral reflectance is not the only factor to be considered in determining reflective losses. Films, such as those that would be used in the construction of the cone, have reflectances with a significant diffuse component that is a total loss, a component presently about five percent of the total reflectance. Another factor to be considered is the effect of coatings on the reflective surfaces. These coatings can be applied to protect the reflective surfaces from oxidation, to provide thermal emissivity control, or to enhance the reflectance. Transparent dielectric coatings currently being investigated will provide the thermal emittance and environmental protection required.

All the above factors affecting reflective losses indicate that an over-all reflectivity of 70 to 80 percent can be expected with the cone-and-column concentrator.

6. THERMAL DESIGN PROBLEMS

Some thermal problems in the design of the cone-and-column concentrator result from low-order concentrations on the reflective surfaces. The lower region of the cone is used to reflect solar energy twice. The intensity of incident radiation therefore is increased in this region. The maximum intensity is nearly three times the solar constant near the top of the lower region. The top of the column will receive about 25 solar constants, depending on the column diameter used.

With the cone being a thin film, conduction of absorbed energy to the back side and subsequent emission present little problem. If necessary, pigments can be added or coatings applied to the film to increase its emissivity.

Energy absorbed by the column must be emitted from the reflective surface if the use of a coolant system is to be avoided. A high-emittance dielectric coating is required. If the column is silvered, 3 percent of the incident energy will be absorbed and an emittance of 0.3 will produce a temperature of about 435 F. If the column is aluminized, 6.5 percent of the incident energy will be absorbed and an emittance of 0.35 will produce a temperature of 585 F. Since these calculations use room temperature optical properties, they only indicate the magnitude of the problem. General conclusions are: (1) that the column reflector must be designed as a high-temperature reflector with high-emissivity coatings, and (2) that it is highly desirable to use the cone reflector as a reflective filter to diminish the energy in those wave lengths readily absorbed by the column.

Although rejecting absorbed energy from the reflecting surface of the column poses certain temperature problems, it does have the advantage of eliminating thermal gradients through the reflector into the support structure. This type of gradient presents a distortion problem in many conventional concentrators.

7. STOWAGE AND DEPLOYMENT

The primary method of folding the concentrator is to retract the ring supporting the cone. This method alone will reduce the stowed diameter to about one-tenth the concentrator diameter. To reduce the length of the stowed concentrator, a longitudinal folding is being considered. The longitudinal folding can be accomplished by telescoping the column reflector and its supports. An additional series of folds then will be required for the cone material.

8. MATERIALS AND WEIGHTS

Since the cone-and-column concentrator is still in the conceptual design stage, no accurate weight analysis can be presented. However, preliminary weight estimates are extremely encouraging. The weights of the principal components are given in the following table for a concentrator with a 100-ft-diameter aperture.

TABLE II - WEIGHTS OF CONE-AND-COLUMN CONCENTRATOR COMPONENTS

Component	Material	Dimensions	Weight (lb)	Specific weight (lb per sq ft)
Column	Metalized electroformed nickel	0.010 in. thick by 3.5 ft diam by 50 ft long	254	0.0323
Cone	Metalized Mylar	0.001 in. thick by 14,150 sq ft	102	0.0129
Cone support ring	Spring steel	0.006 in. thick by 3 in. diam tube	60	0.0077
Total			416	0.0529

The weight of any additional support structure required will depend on the amount of folding desired; more compact stowage will require more complex and heavier mechanisms. Concentrator specific weights of one-tenth pound per square foot seem well within reach for large concentrators using the compact stowage scheme.

9. RELATIVE MERITS OF CONE-AND-COLUMN CONCENTRATOR

The cone-and-column concentrator has many advantages over its optical equivalent, the paraboloidal dish. First, the cone, curving in only one direction, can be made of lightweight flexible material and can be stretched into position between two erectable rigid rings. Second, the column, having a double curvature surface, must be formed to shape, but since its surface area has been reduced, the associated weight penalty also is reduced. Third, the column can be made of sections that telescope readily for stowage. As an example of the size reduction possible, the column diameter required is only about 3.5 percent of the concentrator diameter. Thus, for a typical case, the column surface is only about 7 percent of the concentrator frontal area while the conical surface will be about 180 percent of the frontal area. Fourth, thermal distortion problems are expected to be fewer than in other types of concentrators. Thin-wall construction of both reflector elements will produce fast thermal response and practically will eliminate front-to-back thermal gradients.

The chief disadvantage of the double-reflector concentrator is the power loss due to the two additional reflections. This loss will amount to about 20 percent of the incident energy and must be compensated for by a diameter increase of about 10 percent.

Preliminary weight estimates indicate that specific weights of one-tenth to one-twentieth pound per square foot seem to be practical goals for the cone-and-column concentrator. This estimate represents a weight saving of 80 to 90 percent over foldable paraboloidal dishes, a saving that in most cases will more than compensate for the 20 percent performance loss.

An indirect advantage of very lightweight concentrators is less significant system efficiency. Higher radiator temperatures then become practical and a saving in radiator weight can be effected.

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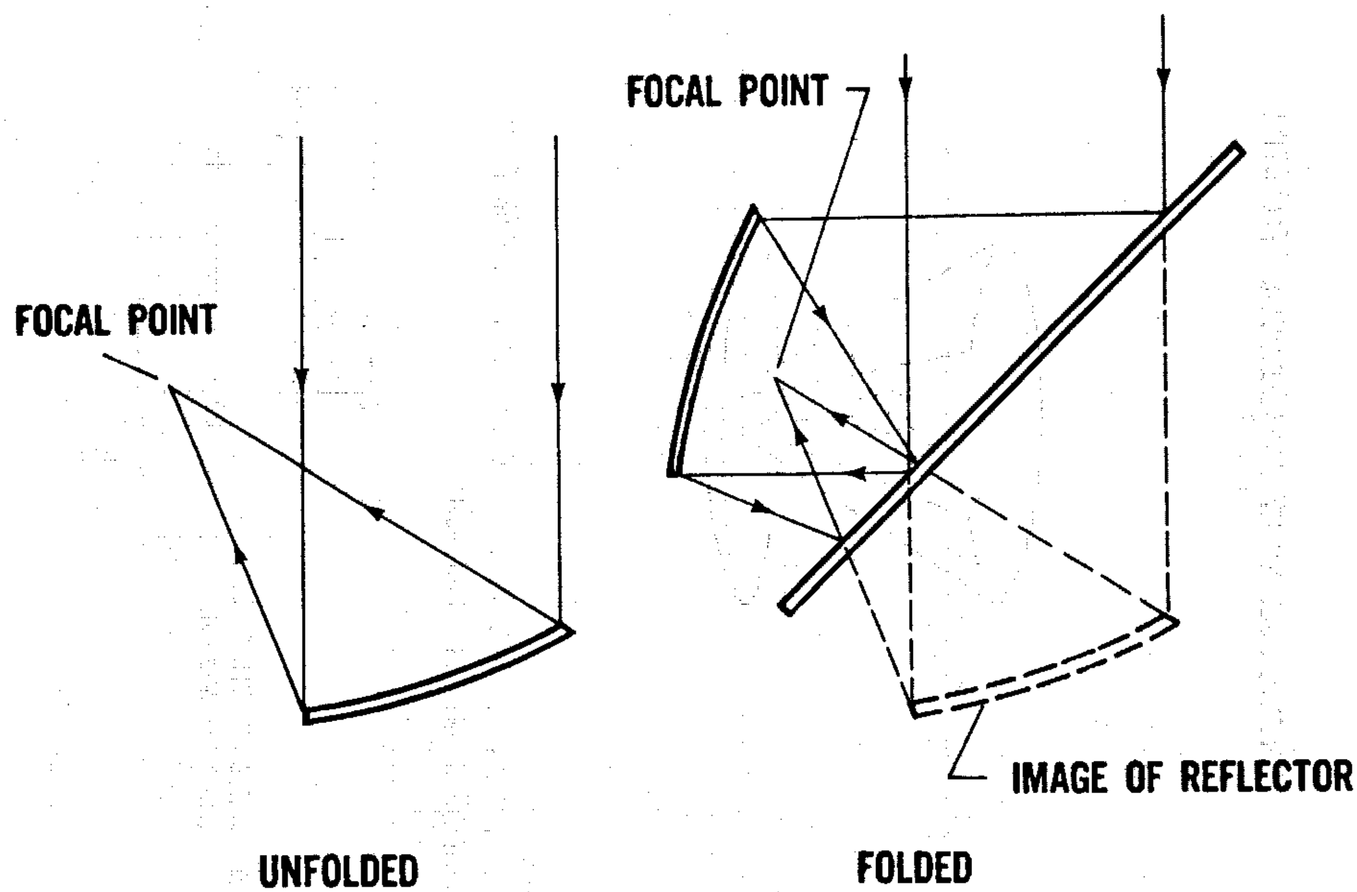
TABLE I - EFFECT OF VARIOUS ERRORS ON COLUMN SIZE AND CONCENTRATION RATIO

Case	1	2a	2b	2c	3a	3b	3c	4a	4b	4c
Solar radius (minutes)	16	16	16	16	16	16	16	16	16	16
Orientation error (minutes)	0	0	6	15	0	6	15	0	6	15
Cone slope error (minutes)	0	6	6	6	12	12	12	24	24	24
Column slope error (minutes)	0	3	3	3	6	6	6	12	12	12
Column radius/cone radius	0.018	0.024	0.026	0.030	0.029	0.031	0.034	0.036	0.038	0.040
Area concentration ratio	11,500	1850	1390	980	720	600	470	236	212	183

OPTICALLY EQUIVALENT SYSTEMS - FIG 1



OPTICAL FOLDING OF PARABOLOIDAL REFLECTOR
FIG. 2

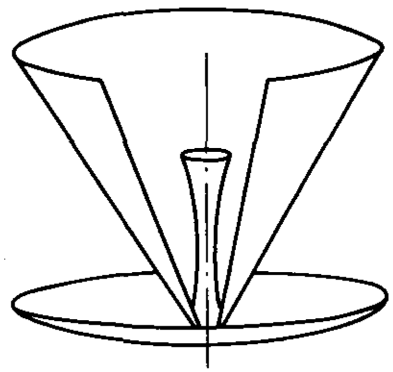


FIG. 3
CONE-AND-COLUMN CONCENTRATOR

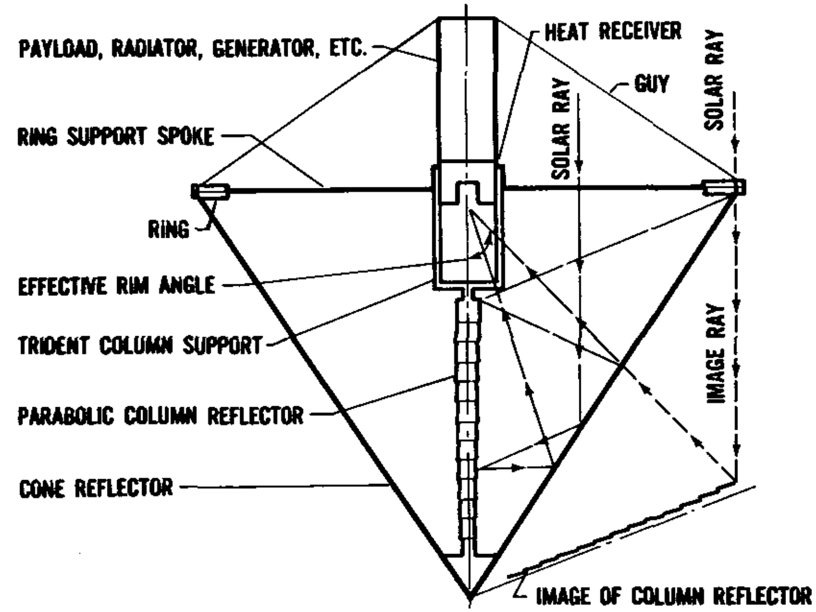


FIG. 4
COLUMN RADIUS REQUIRED TO ACCOMMODATE SOLAR RAYS γ DEGREES OUT OF ALIGNMENT

β = ANGLE BETWEEN FOCUSED SOLAR RAY AND AXIS

R = CONCENTRATOR RADIUS

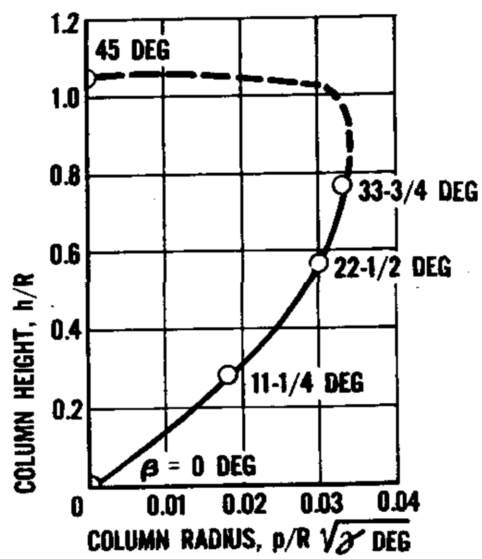
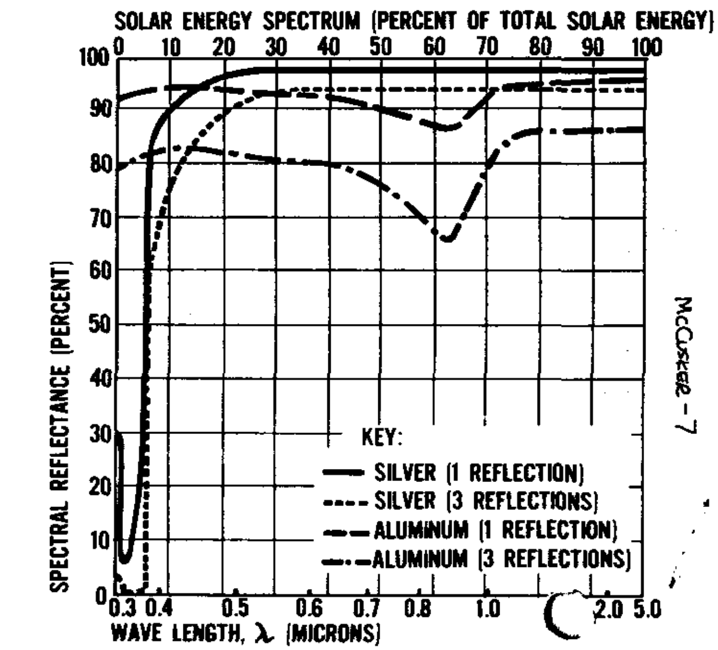


FIG. 5
SPECTRAL REFLECTANCES OF SILVER AND ALUMINUM



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