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CROSSBOW CONTROLLED HELIOSTAT DEVELOPMENT

by S.C. Plotkin & Associates

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October 12, 1978

for info -

Mr. Richard Wayne, Manager
Solar Energy Department
Sandia Laboratories
P. O. Box 969
Livermore, CA 94550

Subject: AIAA/ASERC Conf. on Solar Energy

Dear Mr. Wayne:

In accordance with AIAA instructions, I am sending you, my session chairman, the enclosed copy of Paper No. 78-1755.

I received degrees in E.E. from Penn State (B.S. in 1942) and Aero. E. from N.Y.U. (M.S. in 1946). I held positions as Asst. Prof. of E.E. at Loyola Univ., Sr. Research Engineer at Hughes Helicopters and supervisor of preliminary structural dynamics at Sikorsky Aircraft. At present, I am Solar Program Manager at S. C. Plotkin & Associates.

Regarding the choice of slides for my paper, I can either use exactly the figures being published or I could switch to more emphasis on hardware details on our experimental power plant which won first prize at the Sun Day exhibit at the Los Angeles Museum Of Science And Industry (Fig. 3). Have you a preference?

I would like most to know which organization or agency in U.S. should be considered most likely to become interested in R&D aimed at further evaluation of the Crossbow Central Receiver concept and the 25% cost reduction which it offers. Do you believe that it is more appropriate for you or for Dr. Henry Marvin, the Keynote Speaker to be asked this question?

Sincerely,

W. H. Raser

William H. Raser
Solar Program Mgr.

WHR/a
Encl. 1

CC: Dr. Henry Marvin, Deputy Program Director
DOE Office of Solar, Geothermal, Electric & Storage Systems
Washington, D.C.

FLEXED BEAMS IN CENTRAL RECEIVER HELIOSTAT DRIVES

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S. C. Plotkin & Associates
Los Angeles, California

Abstract

Horizontally-flexed "crossbow" beams in the form of large leaf springs are considered as a means for supporting and steering mirrors in central receiver systems. Their use reduces requirements for (1) heavy structural materials, (2) the number of tracking drives, (3) component machining precision and (4) land area. Although the exact amount depends upon the pointing accuracy and wind tolerance specifications, the economy in plant construction resulting from these changes could be over 25 percent.

I. Introduction

Fig. 1 shows an early application of a flexed beam to a solar furnace reflector built by physicist Dr. Robert H. Goddard. In Goddard's furnace, thin mirror strips were flexed by means of cables attached with turnbuckles for manual adjustment. A 400 kW solar plant at Georgia Tech also uses long horizontal beams as heliostat supporting structure but without provision for utilization of beam flexure.

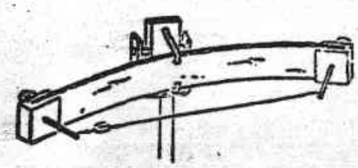

Fig. 1. (1) Goddard's flexed beam reflector

Fig. 2 shows a sketch of a power tower in which such beams are used not only as supporting structure for heliostats but also as significant parts of the heliostat tracking drives. Fig. 3 shows an experimental application of this type of solar power plant used to drive a small steam engine and electric generator. This model

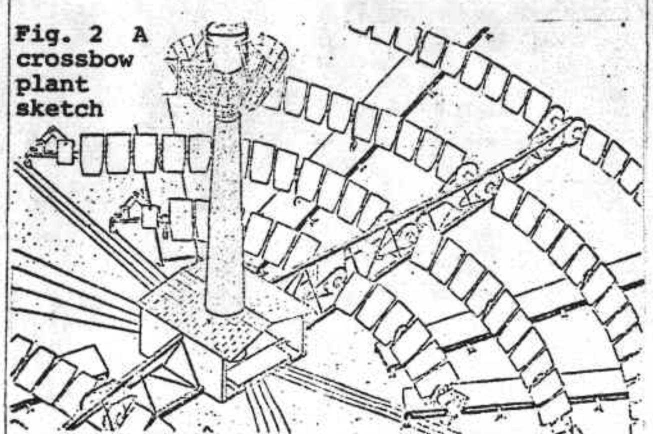

Fig. 2 A crossbow plant sketch

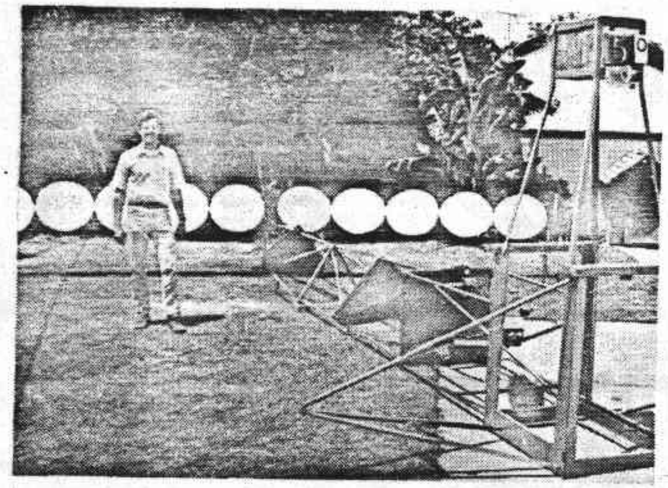

Fig. 3 A small experimental crossbow plant

with its 40 sq. ft. of mirror area won the Los Angeles Sun Day Exhibit first prize, May 3, 1978. This model has ten mirrors which track the sun and focus sunlight on a fixed point, the receiver, that is on top of a tower. Instead of having a pedestal supporting each mirror, this model has one long horizontally-flexible beam or leaf spring providing all ten mirrors with not only structural support but also azimuth aiming angles. A leaf spring which provides both of these is called a "crossbow".

First, a general description of the crossbow heliostat configuration is given. Following that, the theory of central receiver concentrators is extended to apply to the groups of mirrors which can be mounted on a crossbow beam. Implementing schemes are then discussed, particularly for the mechanization of the required azimuth angles. Finally, some general characteristics of crossbow heliostats are reviewed including wind tolerance, area utilization and estimated relative construction costs.

II. Crossbow Heliostat Description

Not counting the receiver and other parts of the tower, a very simple system with only one crossbow beam could consist of foundation structure to support a vertical-axis hinge or pivot, the beam with its midpoint supported by and hinged at this pivot or hingepoint, mirrors mounted along the beam so as to be rotated about the local beam axis in accordance with the required mirror elevation angle, tension cables connected to the beam tips and means for controlling beam curvature. The beam

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is a leaf spring consisting of two leaves, n pairs of bearings to support n mirrors, fewer than n pressure pads at various stations along the leaf spring to create and control a separation distance between the two leaves and a number of brackets including tip brackets. Each leaf can be a bar of spring steel arranged to resist vertical deflections while permitting horizontal deflections. Each bracket provides an offset point on one side of the leaf spring centerline; the offset distance is zero at the hinge, e at the tip, and a proportional fraction of e everywhere in between. The tip offset points are for pulley attachment while the others are for guiding cables.

Figs. 4 and 5 show a plan view of two main parts of the crossbow heliostat structure. One part is longitudinal trusswork with two hingepoints and four pulley points. The other part is a leaf spring beam with its brackets and with four separators capable of controlling the distance between the two leaves. These separators are hydraulically expanded pads or bellows. Fig. 4 also shows part of another leaf spring.

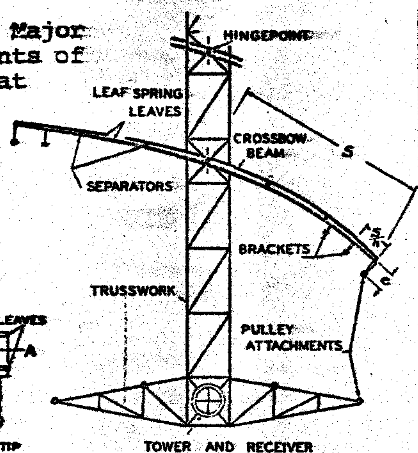


Fig. 4 Major components of heliostat array

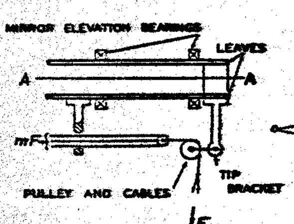


Fig. 5 Detailed view of crossbow beam tip

Not shown in these two figures are wheels and tracks for beam support, mechanical vibration dampers and angle control mechanisms. The wheels in the unit shown in Fig. 3 are bicycle wheels, one at each beam tip. For the longer beams depicted in Fig. 2, more than two wheels are used per beam. The tracks which engage these wheels can be curved pipes supported by heavy stakes driven into the ground. This process of driving stakes into the ground avoids the use of concrete, requires no digging or grading and is particularly appropriate for installing transportable structure which may be prefabricated. Unless extensive computer useage is planned, all of the tracks should be in one plane.

The main advantage of the crossbow configuration is the elimination of heavy and costly parts, particularly the use of fewer and simpler azimuth drives using cable systems rather than high torque, high precisian gear boxes. As will be demonstrated there is not only a distinct reduction in the number of needed servo drives for azimuth angle controls but also the possibility of this for elevation angle controls. Futhermore, reducing the number of servo motors required per heliostat can provide some secondary benefits.

These secondary benefits of an increase in the ratio of the number of mirrors to the number of servos are simply the benefits of not being restricted (by servo costs) to having such large heliostat mirrors. First, there is reduced cost per square foot of mirror as smaller sizes encourage less expensive fabrication techniques. Second, area utilization is improved as will be discussed. A third advantage is wind load reduction considering the mirror to be an airfoil. Aerodynamic moment is more sensitive to chord than to span, being roughly proportional to the second and first powers, respectively. Wind moment loads constitute the main specification affecting the cost of heliostat drive systems.

III. Optical Requirements For The Beam

The main requirement of the crossbow beam and its system of controls has to do with its horizontal displacement, i.e., its rotation and flexure within a horizontal plane. At each mirror location, the tangent to its centerline (e.g., line AA in Fig. 5) must coincide with the elevation axis of a typical heliostat at that location. The continuous curve in a horizontal plane which satisfies this condition is called the optical locus. Three theorems from physics and geometry are

(1) Any surface which reflects parallel rays onto a single point is a paraboloid of revolution. See Fig. 6.

(2) The intersection of a paraboloid and a plane (e.g., a horizontal plane) is a conic section.

(3) If a conic section formed in this way is an ellipse, the projection of the axis of the paraboloid on the given plane is the major axis of the ellipse.

Therefore, for the optical locus to have tangents which satisfy requirements at all points, it must be a conic section. If the sun is directly overhead, this conic should be a circle. If the elevation angles were zero, the conic would be a parabola. Neglecting these two extremes, the optical locus should be an ellipse.

The only point on the optical ellipse

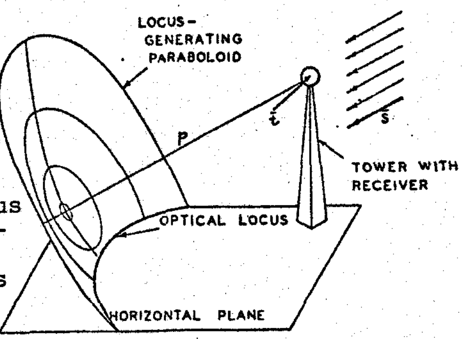
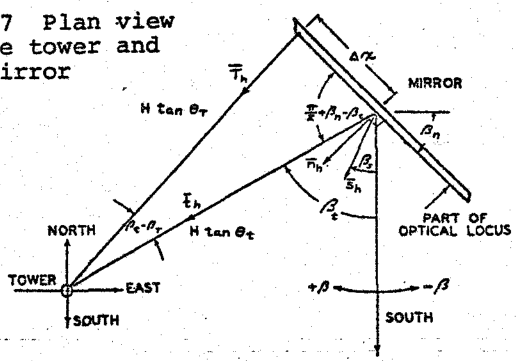


Fig. 6 The optical locus as an intersection of two surfaces

which is at a fixed location is the beam hingepoint. See Fig. 4. Being fixed, this point relates to the sun and receiver geometry like a conventional pedestal heliostat. For example, the normal to the optical locus at a hingepoint has azimuth equal to β_n. This azimuth, like the tilt (elevation) angle of the mirror is a function of the usual three sun-relating angles, λ, δ and τ. Fig. 7 represents the projection of some important angles onto the horizontal plane.

Fig. 7 Plan view of the tower and one mirror



IV. Nomenclature

a,b	semiaxes (radii) of an ellipse
A,B	curvefitting constants
c	displacement of the ellipse
C	damping constant (force/velocity)
e	normal offset at beam tip bracket
E	Young's modulus of elasticity
F	resultant transverse cable force
g	gain of servo amplifier
H	tower height
I	beam section moment of inertia
J	mass moment of inertia of structure
K	structural spring rate (force/displ.)
m	mechanical advantage of pulley system
M	beam bending moment
$\bar{n}$	unit mirror vector (outward normal)
2n	number of mirrors per crossbow
p	focal length of generating paraboloid
q,s	coordinates of generating parabola
Q	a generalized mirror position angle
R	radius of curvature of beam
$\bar{s}$	unit sun vector (toward sun)
s	complex variable in Laplace transforms
S	semilength of crossbow beam
$\bar{t}$	unit tower vector (toward receiver)
T	distance of mirror to receiver
x,y	rotated and translated normal axes
LGP	locus-generating paraboloid
β_n	azimuth orientation of mirror normal
β_s	azimuth orientation of sun
β_t	mirror-to-tower ray azimuth orientation
θ_n	mirror tilt angle (mirror from horizon.)
θ_s	sun zenith angle
θ_t	mirror-tower distance angle
δ	declination angle from celestial equat.
λ	latitude on earth
τ	time angle from local noon
ω	natural frequency of some structure

Subscripts

c	crossbow heliostat design
h	horizontal plane projection of vector
n,N	mirror normals
o	output
p	pedestal heliostat design
s	sun
t,T	tower
1,2	components

V. Generating The Optical Locus

From Riaz, [3] at any point where θ_t, β_t, etc. are applicable,

$$\tan \beta_n = \frac{\sin\theta_s \sin\beta_s + \sin\theta_t \sin\beta_t}{\sin\theta_s \cos\beta_s + \sin\theta_t \cos\beta_t} \quad (1)$$

where

$$\cos\theta_s = \sin\lambda \sin\delta + \cos\lambda \cos\delta \cos\tau \quad (2)$$

$$\sin\beta_s = \sin\tau \cos\delta / \sin\theta_s \quad (3)$$

$$\tan\theta_t = (\text{mirror-tower distance})/\text{tower height} \quad (4)$$

In Fig. 7, $\bar{t}_h$, $\bar{n}_h$ and $\bar{s}_h$ are projected unit vectors from the hingepoint in directions toward the target, normal to the mirror and toward the sun respectively. Consider a second mirror located a distance Δx from the first along the optical locus and denote its vectors by replacing t with T, etc. From Fig. 7, eq.(1) and the laws of cosines and sines, curvature can be determined.

$$H^2\tan^2\theta_T = H^2\tan^2\theta_t + (\Delta x)^2 + 2(\Delta x)H\tan\theta_t \sin(\beta_n-\beta_t) \quad (5)$$

$$\beta_T = \beta_t - \sin^{-1}\left[(\Delta x/H \tan\theta_T) \cos(\beta_n-\beta_t)\right] \quad (6)$$

$$\tan\beta_N = \frac{\sin\theta_s \sin\beta_s + \sin\theta_T \sin\beta_T}{\sin\theta_s \cos\beta_s + \sin\theta_T \cos\beta_T} \quad (7)$$

$$\beta_n' = \frac{d\beta_n}{dx} = \lim_{\Delta x\to 0}\left(\frac{\beta_N-\beta_n}{\Delta x}\right) = \frac{1}{R} \quad (8)$$

at the hingepoint.

Before determining other characteristics of the optical locus, it is convenient to find the focal length, p of the Locus-Generating Paraboloid (LGP). This length, together with the $\bar{s}$ unit vector determine the LGP surface as shown in Fig. 6. Now consider the plane containing unit vectors $\bar{s}$ and $\bar{t}$; since this plane contains the axis of LGP, its intersection with LGP must be the parabola which generated LGP, namely,

$$q^2 = 4ps \qquad (9)$$

where q,s are coordinates in this plane parallel and perpendicular to $\bar{s}$ respectively. Since the hingepoint lies on both the $\bar{t}$ vector and on the optical locus which the LGP generates, it lies on the parabola and must be equidistant from the focal point and the directrix of the parabola. Since the distance between the directrix and the q axis is p, this equality and equation (9) yield

$$p = (T/2)\ (1 + \bar{t}\cdot\bar{s}) \qquad (10)$$

which serves to determine p since both T and the dot product (the direction cosine between two known unit vectors) are known.

Now consider the vertical axial plane shown in Fig. 8. Since this plane also contains $\bar{s}$, eq. (9) also applies to its LGP intersection. Its intersection with the horizontal plane is given by the function of slope and intercept given in Fig. 8. Note that these intersections (lines) meet at two points; let 2a represent the distance between these two points. Solving simultaneously the two equations shown in Fig. 8,

$$q/p = 2\tan\theta_s \pm 2\left[\sec^2\theta_s - (H/p)\sec\theta_s\right]^{1/2} \qquad (11)$$

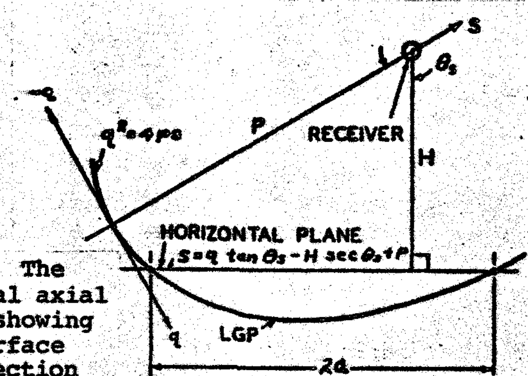


Fig. 8 The vertical axial plane showing two surface intersection lines

Let Δq represent the difference between the above plus and minus values and let Δs represent a corresponding s difference. Since these are perpendicular,

$$a = 2p\left[(1+4\tan^2\theta_s)(\sec^2\theta_s - H\,p^{-1}\sec\theta_s)\right]^{1/2} \qquad (12)$$

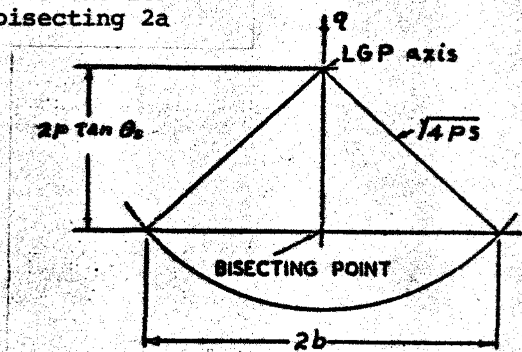
Likewise, consider the plane of Fig 9, a plane normal to the LGP axis bisecting the 2a length of the horizontal plane intersection. In terms of the coordinates of Fig. 8, the midpoint is located by dropping the second term of equation (11). Substituting the resulting q in the horizontal plane intersection equation,

$$s = 2p\tan^2\theta_s - H\sec\theta_s + p \qquad (13)$$

In other words, using the coordinates shown in Fig. 8, eq. (13) represents the transverse plane shown in Fig. 9. Note that the intersection of this plane and the LGP is a circle having a radius given by q in eq. (9). Note also that the vertical leg of a triangle in Fig. 9 is the value of q previously determined from eq. (11). Noting it to be a right triangle and substituting equation (13),

$$b = 2p\left[\sec^2\theta_s - (H/p)\sec\theta_s\right]^{1/2} \qquad (14)$$

Fig. 9 A plane normal to the LGP axis bisecting 2a



The optical tracking requirements of each beam can be summarized as follows:

(a) The beam, which is horizontal (and of length 2S) has a fixed vertical-axis hinge at its midpoint where its elastic centerline has the azimuth angle $\beta_n + \pi/2$.

(b) This elastic centerline coincides with the optical locus which is an arc of an ellipse having axial diameters 2a, 2b.

(c) The azimuth angle of the axis of the ellipse is β_s.

Eqs. (1) to (14) have defined the optical locus as an ellipse which is a function of λ, δ & τ. The left half of Fig. 10 illustrates a family of "crossbow" beams determined in this way for the case where θ_s is 45 degrees. The right half of Fig. 10 is a corresponding family of iso-tilt (constant elevation angle) lines from the Riaz study [3] of continuum of mirror fields for the same parameter values.

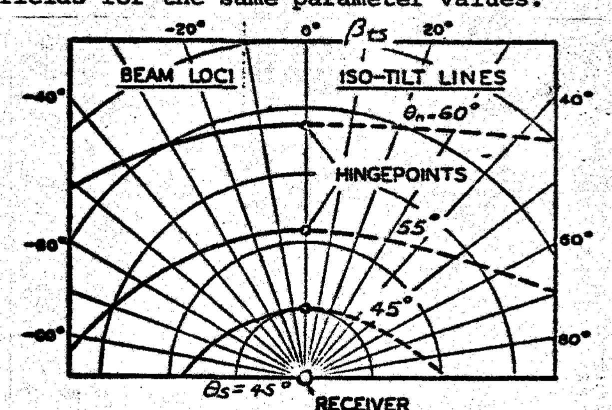


Fig. 10 Loci (solid) and iso-tilt lines

VI. Implementing Azimuth Control

One of the main purposes for seeking to develop the flexed beam (crossbow) type of heliostat is to achieve a reduction in azimuth channel costs by requiring fewer and simpler servo drives. To achieve this, a key step is replacing the elliptical optical locus with a curve which is more adaptable to a mechanically centralized implementation. An attractive candidate for this is the finite power series,

$$y = A\,(x+x_1)^2 + B\,(x+x_2)^3 + \ldots + k\,(x+x_z)^{z+1} \qquad (15)$$

which uses coordinates that involve a tangent to the ellipse shown in Fig. 11. The ellipse is defined by eqs. (12) and (14) and by the point of tangency from eq. (3). With this definition, no first power of x in eq. (15) can exist.

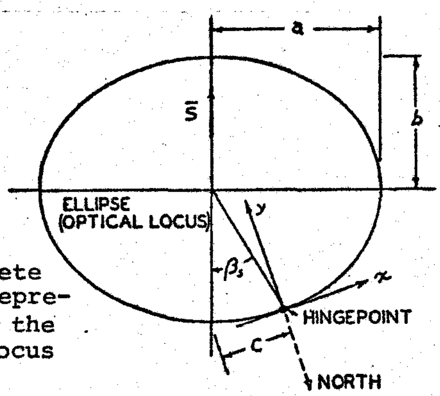


Fig. 11
The complete ellipse represented by the optical locus

Alternatively, the second power term can be a circular function. For large crossbow beams, more terms must be retained. For the small beam shown in Fig. 3, only the following was used:

$$y = A\left[1 - \left\{1-(x/A)^2\right\}^{1/2}\right] + B\left[x-c\right]^3 \qquad (16)$$

where c is a function of β_S in accordance with Fig. 11. In other words, the sum of a circular arc and part of a cubical parabola are used to curvefit the desired elliptical arc. Note that this sum is a curve which resembles a spiral.

The following simplifying assumptions are useful in estimating the curvefitting accuracy of this so-called spiral to part of the ellipse (the part with length 2S):

(1) For any sun position, mean slope error over any beam semilength S is the average of two values of $2\Delta y/S$ where Δy is the difference between eq. (16) and the ellipse of Fig. 11 at the midpoint of each semilength.

(2) The effect of the offset distance c can be considered simply by means of a linear interpolation between values of 0 and 1 for the ratio c/S. This is equivalent to interpolating between two special cases of the semicubic spiral, one where it is forced to become an arc of a circle and one where β_S subtends one semilength S (the condition where the corrective effectiveness of the cubical parabola component is maximized).

(3) The conditions which determine A and B of eq. (16) are that the tips of the beam lie on the optical locus and that the cosine of β_S is unity. Then

$$A = b/(2\,a^2) \qquad (17)$$

$$Ba^3/b = (a/c)^3\left[1-\left\{1-(c/a)^2\right\}^{1/2}-(c/a)^2/2\right] \qquad (18)$$

and the two special cases described in the preceding paragraph appear in Fig. 12.

Averaging between sunrise and sunset (for λ = 35 deg N. and δ = 0), these approximations yield an average slope error of about 4.9 milliradians. This much error is acceptable for very small systems, particularly those with outputs under 10 KWe. For plants where the output is in megawatts, average tracking error should be no more than one or two milliradians and it appears that one additional correcting term from eq. (15) will be needed.

The main reason for selecting the tracking stategy represented by eq. (15) is ease of implementation, i.e., the ease of mechanizing constants A, B and c. The semicubical spiral consists of a cubical parabola (having magnitude and offset given by B and c, respectively) superimposed on a circular arc of radius A. A uniform beam with a uniform bending moment as shown in Fig. 13 yields constant curvature. One hydraulic control with gain B simultaneously introduces deformations on one leaf of the crossbow leaf spring so as to have maximum effect at one end and minimum effect at the other. A second hydraulic control acts to shift this pattern according to the value of c.

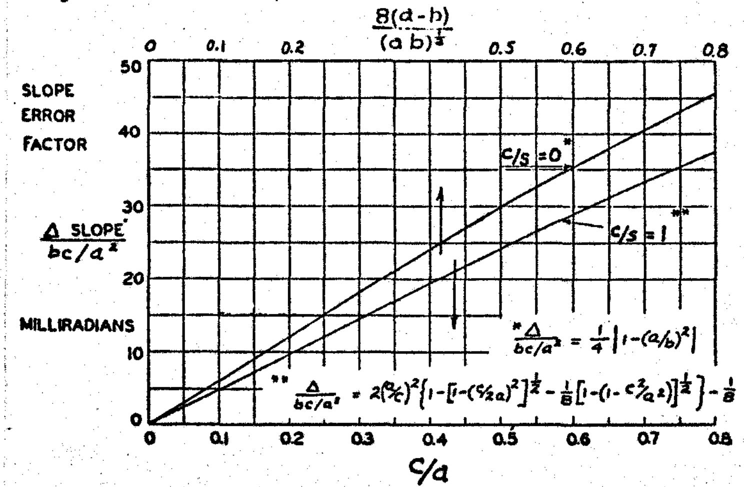
VII. Implementing Elevation Control

In the elevation angle channels, both the opportunities for economy and the difficulties which threaten to increase the crossbow system costs have to be considered. Among the latter, two are as follows:

(1) By itself, the crossbow beam has very little torsional stiffness. In larger systems, this requires all points on the beams to have high stiffness with respect to vertical deflections and all elevation control structural foundations to be built upon the telescoping dampers which interconnect at least two beams.

(2) Since the mirrors have no fixed position on the earth, output angle sensing can not be done using fixed optical heads located on the ground near the mirrors. They must be clustered around the receiver as shown in Fig. 2.

Fig. 12 FACTORS INVOLVING ELLIPTICAL RADII a & b AND OFFSET, C



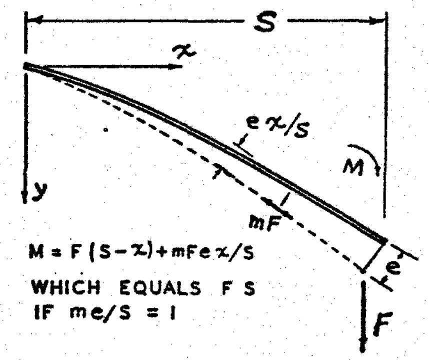


Fig. 13 Development of a uniform bending moment along a beam

The following appear equally important:

(3) As Fig. 10 shows, crossbow beams can be approximated by constant elevation requirements. All ten mirrors in Fig. 3 have the same tilt angles.

(4) Because of the above similarity, no shading losses occur by having adjacent mirrors almost touching each other. Thus, simple shaft-type couplings facilitate one servo drive controlling the elevation of a number of mirrors, e.g., ten in Fig. 3.

To the extent that items (3) and (4) offset items (1) and (2), the economic difference between crossbow heliostat tilt drives and pedestal heliostat tilt drives would be zero. However, this is a rather preliminary conclusion at this time as further research could change this.

VIII. Wind Response And Area Utilization

Like the area utilization factor, wind response is a separate factor to be considered in an economic evaluation of the merits of a heliostat design. In the crossbow heliostat, it is expected that structural stiffness and frequencies will be less than those of pedestal heliostats. To cope with vibrations, heavy dampers between adjacent crossbow beams have been designed for at least critical damping. But even with these dampers, the degradation of optical performance as a result of wind loads requires some attention. Extra storage, hybridization, etc. are examples.

For installations in windy areas, the combination of crossbow solar plants and small windmills are being considered. An attractive hybrid plant with 90% solar and 10% wind capacity can have almost constant output with respect to wind. However, it is not yet certain that the crossbow beam structure will always be associated with vibrations that will cause significant performance degradation due to wind.

In other words, while rigidity is always required for suitable wind resistance, this rigidity does not have to come from the crossbow beam. Instead, under certain conditions, it can come from the control system base. Fig. 14 illustrates the basic principles involved in this conclusion by comparing the block diagrams of the two heliostats using servo analysis techniques (Laplace transforms). The most important criterion for steady wind resistance is the amplitude of output angle per unit of steady change of aerodynamic moment load. This criterion, dQ/dM in Fig. 14 results from application of the final value theorem to each of the two heliostat transfer functions. In each case, two parameters are involved, a structural spring rate K and a servo gain g. If, for the crossbow, K_c is less than the corresponding K_p, the effective rigidity can still be as much as for the pedestal by increasing g_c above the g_p value. But it costs something to do this.

On the other hand, it costs something to not take advantage of the improved area effectiveness factor offered by the crossbow mirror configuration. This is true because of the characteristic which had been observed in Fig. 10; namely, the similarity between optical locus lines and lines of constant elevation angles.

Area effectiveness involves three types of losses, namely, sunlight striking the ground because of too much mirror-to-mirror separation, shadowing because of not enough mirror separation, and the incidence factor (cosine factor). In general, an ideal Fresnel mirror experiences only radial shadowing and radial and tangential incidence factors; however, if ⁄ is zero, it experiences no losses except radial incidence factor. Consider an array of quasi-concentric continuums of infinitesimal mirrors as Riaz postulated to have the same tangential area effectiveness characteristics as a Fresnel mirror. The area effectiveness characteristics of a mathematical model of this type are given in Fig. 8 of a study by Riaz [3]. Fig. 13 of that same study presents corresponding Houston data for arrays without the ribbonlike features.

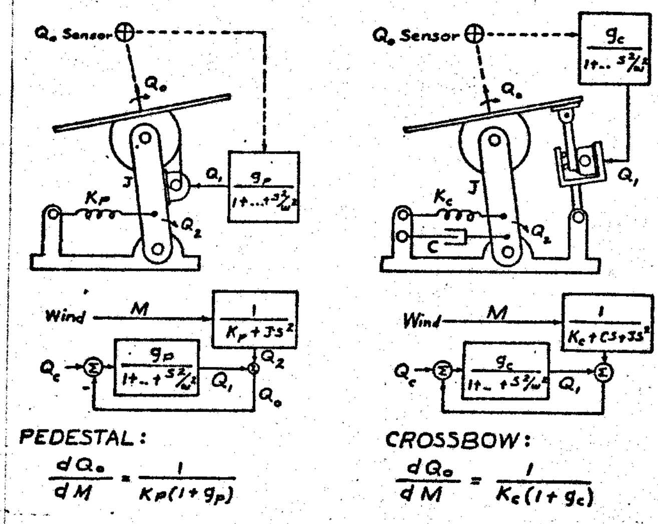


Fig. 14 Control and wind resistance models for pedestal (left) and crossbow heliostats

Averaging this data over a 10-hour day, a comparison of the two yields a 0.778 ratio.

It is interesting that the paper (3) referred to was followed by a discussion in which Dr. Vant-Hull raised the question of the practicability of recovering lost area effectiveness by means of an array in which "heliostat locations are continually changed". It is still not clear how much of this approximately 22.2% utilization difference can be recovered by going from a pedestal to a crossbow design or how its importance compares with that of the loss in wind resistance by making this change. At present, it appears reasonable to assume that they just cancel each other.

IX. Observations And Conclusions

To anyone accustomed to heliostats requiring heavy concrete pedestals and large expensive gear boxes, the proposition that central receiver mirrors should be placed on beams slender enough to be flexed by means of cables may appear radical. This feeling soon disappears, however, as the designer encounters pleasant surprises and interesting ways to economize. One of them is that when a crossbow beam is forced in to its desired shape within a horizontal plane, the desired tilt angles of a group of adjacent mirrors mounted along this beam are approximately equal. In fact, in a small plant, as many as ten such mirrors can be gang driven by a single large tilt-control servomotor.

Considering the optical performance of point-focusing heliostats, two factors become important when comparing pedestal and crossbow heliostats, namely, utilization of area and degradation due to wind. In a small plant, the effects of these two tend to cancel each other. Assuming that they do, the remaining difference is mainly an effect on plant construction costs.

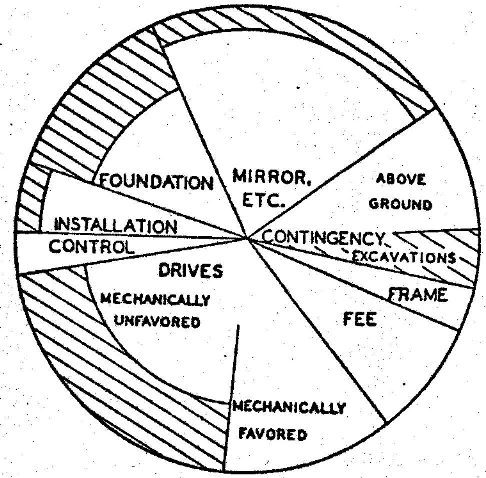


Fig. 15 Pedestal heliostat cost summary

Fig. 15 shows a 10-sector breakdown of typical pedestal heliostat costs based on an 8-sector breakdown from Sandia Labs.(4) Two of the original sectors are shown as being split into two subdivisions, namely, the cost of drives and the contingency fees. The assumptions behind these splits are an estimated 2:1 ratio of weight of materials required for the two drives and a 30% allocation of contingencies for the hazards of excavations and earthmoving operations in the desert, respectively.

The unshaded part of Fig. 15 can be used to represent the estimated cost of an equivalent crossbow heliostat. Five of the original ten sectors are essentially unaffected by this change. The excavation contingency is eliminated. By reducing the weight of materials used in the foundation and unfavored (azimuth) drive to less than one third, it is estimated that these costs are halved. A 20% reduction in the other two sectors is assumed due to numerous production conveniences made possible by the crossbow design including ease of prefabrication. Based on removing the shaded area from Fig. 15, a saving of 26.4% of the cost of heliostats results.

References

(1) Goddard, R. H.: U.S. Patent 1,951,404

(2) Raser, W.H.: U.S. Pat. ASN 747,561 and its CIP. See also U.S. Pat. 3,872,854

(3) Riaz, M.R.: A Theory of Concentrators of Solar Energy on a Central Receiver for Electric Power Generation, Engineering For Power, Vol. 98, No. 3, July 1976

(4) Sandia Laboratories: Recommendations for the Conceptual Design of the Barstow Solar Central Receiver Plant, SAND77-8035 (UC-62), Albuquerque, N.M., Oct. 1977

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AIAA/ASERC Conference and Technical Display on Solar Energy: Technology Status

Session 1

Central Power Systems

Paper No. 78-1750. 10 Megawatt Solar Central Receiver Pilot Plant. R.N. SCHWEINBERG, Department of Energy, El Monte, Ca., and J.L. RASBAND, Southern California Edison Co., Rosemead, Ca.

The U.S. Department of Energy has joined with the consortium of Southern California Edison, Los Angeles Department of Water and Power and the California Energy Commission in a cooperative effort to build and operate this nations first large scale integration of solar thermal central receiver hardware and software into a power generating plant whose performance will be assessed in a utility context. The 10 megawatt pilot plant will be located in the Mojave Desert near Barstow, California, and will begin operation in 1981. The total cost of the project is currently estimated at $123M.

Paper No. 78-1751 External Single Pass to Superheat Receiver. G. C. COLEMAN, McDonnell Douglas Astronautics Co., Huntington Beach, CA and J. M. FRIEFELD, Rocketdyne Division of Rockwell International, Canoga Park, CA.

The McDonnell Douglas/Rocketdyne solar receiver design selected by the Department of Energy for the Nation's first solar power plant is described.

The external, single pass to superheat, multiple panel concept provides a receiver with the light weight and fast thermal response consistent with the highly transient nature of insolation and the seismic sensitivity of a tower-mounted central receiver. Modular panel assemblies provide the freedom to size and arrange the external receiver into any geometric shape required by system analyses for optimum central receiver performance and lowest system cost.

Paper No. 78-1752. Dynamic Computer Simulation of the DOE 10 MW Solar Thermal Pilot Plant. K.F. STEFFAN, Software & Systems Analysis Subdivision, K.L. ZONDERVAN, System Test & Evaluation Department, and T.J. CONNOR, Energy & Resources Division, The Aerospace Corporation, El Segundo, California.

The Department of Energy has undertaken the construction of a 10 MW Pilot Plant based on the principle of solar energy conversion. The Plant utilizes tracking mirrors and a central receiver to generate steam for driving a turbogenerator. The performance of this plant is constrained by the variability of solar insolation, and this introduces important control aspects to the operational requirements. To explore these aspects, a dynamic simulation of the subsystems has been developed. Results will be presented showing the changes in state variables for normal daily startup, and mode changes caused by clouds. These are the first results published of the expected Barstow Plant performance.

Paper No. 78-1753. Alternative Central Rec Receiver Solar Power Plant Using Salt as a Heat Transfer and Storage Medium. THOMAS R. TRACEY and JOHN E. MYERS, Martin Marietta Aerospace, Denver, Colorado

A salt cooled central receiver solar thermal power plant has been conceptually designed. This plant has the capability of producing 300 MWe continuously on summer solstice in the southwest United States. Results of the major optimization trade studies are presented. These include North Heliostat field Vs. Surrounding Heliostat field, cost optimum number of Heliostat field modules, cost optimum plant thermal storage size. The yearly performance of this power plant has also been determined using the 1976 Barstow insolation and the resulting cost of electricity for a 30 year life has been determined.

78-1754

Paper No. 78-1755. Flexed Beams In Central Receiver Heliostat Drives. W.H. RASER, Solar Program Manager, S.C. Plotkin & Assoc., Los Angeles,CA

Horizontally-flexed beams in the form of large leaf springs are considered as a means for supporting and steering mirrors in central receiver systems. Their use offers not only a reduction in the quantity of material required including the number of azimuth tracking drives needed per heliostat but also a shift away from extensive precision machining requirements and an improvement in area effectiveness factor.

Cost, accuracy and tolerated wind velocity are closely interrelated in this "crossbow" collector as they are in pedestal heliostats.

Session 2

Solar Heating and Cooling

78-1756

ABSTRACT NOT AVAILABLE

Paper No. 78-1757. Dynamic Performance Testing of a 3 Ton Solar Absorption Chiller. JAMES M. FROEMMING and BYARD D. WOOD, Arizona State University, and FRANK P. MANCINI, Arizona Solar Energy Research Commission.

A test facility was designed and built to rate the performance of ARKLA Industries second generation refrigeration unit (#WF-36). This facility is capable of rating other comparable size heat driven water chillers. A steady state performance mapping of the WF-36 was completed and compared with ARKLA's published data. Cold start-up and one hour cycling tests have been performed to determine system transients and to verify the reliability of the test procedure.

78-1758

Paper No. 78-1759. The ClearView Solar Collector System and Associated One and Two Stage Evaporative Cooling-Interim Results. J.F. PECK, Solar Projects Engineer, and H.J. KESSLER, Architectural Designer, Environmental Research Laboratory, University of Arizona, Tucson, Arizona.

The ClearView Solar Collector system has been developed in response to the need for transparent, hot air-type solar collectors that can easily be constructed as part of the south wall of a residence. Both passive (natural-draft) and active (fan-driven) forms of ClearView Solar Collectors have been devised. Heat is stored either in the mass of the house or in a rockbed. Summer cooling is accomplished by either ordinary evaporative cooling, or the more powerful two-stage evaporative cooling. Various types of auxiliary heating are used, either to heat the daytime occupancy areas of the house, or the entire home. Also, some forms of the ClearView Solar Collector can be retrofitted to many existing homes.

Paper No. 78-1760

Jet Impingement Solar Air Heater

D.R. Rask, L.J. Mueller and J.H. Pejsa
Energy Resources Center
Honeywell, Inc.
Minneapolis, Minnesota

The results of the development of a flat plate solar air heater are presented. A unique jet impingement concept is used as the absorber plate-to-air stream heat transfer mechanism. The intention was to increase the efficiency of the air heater, over that of a "conventional" parallel-plate type, by increasing the absorber plate-to-air stream heat transfer coefficient. The program objective was to design, fabricate, test and evaluate the jet impingement concept collector. For comparison, a baseline parallel plate collector was analyzed, fabricated and tested.

Del Webb's TowneHouse
Phoenix, Arizona
November 27-29, 1978

AIAA/ASERC Conference and Technical Display on Solar Energy: Technology Status

Paper No. 78-1761. The Economic Performance of Passive Solar Heating: A Preliminary Analysis. S.A. NOLL, and FRED ROACH, Los Alamos Scientific Laboratory, and S. BEN-DAVID, University of New Mexico.

The economic performance of alternative passive solar designs for new homes are evaluated on a nationwide (state-by-state) basis. Emphasis is placed on two generic concepts: the thermal storage wall and direct gain. Discussion of the methodology briefly reviews the architectured design criteria, solar performance characteristics, incremental solar costs, conventional energy prices, and the optimal sizing/feasibility criterion employed in the economic performance analysis. The sensitivity of key parameters are evaluated, with differences in economic feasibility patterns highlighted. Potential impacts from two solar incentive proposals--income tax credits and low interest loans--are also examined. Finally, major findings and conclusions are summarized.

Paper No. 78-1762. Metal Hydride Solar Heat Pump and Power System (HYCSOS). R. GORMAN, Senior Member of the Technical Staff, and P. S. MORITZ, Member of the Technical Staff, TRW Energy Systems Planning Division, McLean, VA.

This report presents the design, performance and cost of a solar-powered metal hydride heat pump and power system for use on a residence. This system was first conceived of and its feasibility demonstrated by Dieter Gruen, et. al., at Argonne National Laboratory. The system design, which is limited by heat transfer, was optimized via an iterative computer program. The system, using high temperature solar collector input at 210°F to 280°F, provides heating with a COP of approximately 1.7, cooling with a COP of approximately .6, and electrical power during spring and fall, all for a cost comparable to a solar absorption cooler.

Session 3

Photovoltaics

Paper No. 73-1763 Photovoltaic Overview. M. B. Prince, Chief, Silicon Technology Programs Branch, Department of Energy, Washington, D. C.

The National Photovoltaic Program, under the Department of Energy sponsorship, is supporting work ranging from fundamental studies of materials for solar cells thru component development, systems analysis, tests and applications to market developments, and commercialization. Since the other speakers in this session will be covering systems applications and engineering and commercialization aspects of Photovoltaics, this paper will be devoted primarily to the status of the component development activities and briefly review the status of the thin-film research and development activities.

78-1764
78-1765

Paper No. 78-1766 A Venture Analysis of a Proposed Federal Photovoltaic 8-Year Procurement Initiative. DENNIS R. COSTELLO, Branch Chief, Solar Energy Research Institute, Golden, CO.

The results of the SERI Photovoltaic Venture Analysis are presented. The objective of the study, government programs under investigation, and a brief review of the approach are presented. Potential markets for photovoltaic systems relevant to the study are described. The response of the photovoltaic supply industry is then considered. A model also calculates over time was developed. This model which integrates the supply and demand characteristics of photovoltaics over time was developed. This model also calculates the economic benefits associated with various government subsidy programs. Results are derived under alternative possible supply, demand, and macroeconomic conditions. A probabilistic analysis of the costs and benefits of a $380 million federal photovoltaic procurement initiative, as well as certain alternative strategies, is summarized.

Paper No. 78-1767. Pennies a Day - Financing Early Deployment of Photovoltaic Utility Applications Through a User Subsidy. E. Siegel, Staff Engineer, The Aerospace Corporation, El Segundo, CA.

A preliminary analysis has been completed of the user subsidy required to permit photovoltaic systems to substitute for new coal plants or to replace existing oil plants in utility central station applications. It was found that relatively small increases in annual electric bills ($10-25 a year for typical residential customers) would allow a significant national or regional deployment of photovoltaic systems over the 1986-2000 time period even if the cost of coal or oil does not increase any more rapidly than the annual rate of inflation.

Paper No. 78-1768. NASA Lewis Research Center Photovoltaic Application Experiments. A. RATAJCZAK, Head, Application Engineering Section; W. BIFANO, Manager, Village Power; J. MARTZ, Aerospace Engineer; and P. O'DONNELL, Physicist

The NASA-Lewis Research Center has installed 16 geographically dispersed terrestrial photovoltaic systems as part of the DOE National Photovoltaic Program. Three additional experiments are in progress. Currently, operating systems are powering refrigerators, a highway warning sign, forest lookout towers, remote weather stations, a water chiller and insect survey traps. Experiments in progress include the world's first village power system, an air pollution monitor and seismic sensors. Under a separate activity, funded by the U.S. Agency for International Development, a PV-powered water pump and grain grinder is being prepared for an African village. System descriptions and status are included in this report.

78-1769

Session 4

Dispersed Systems

Paper No. 78-1770. Dispersed Power Systems and Total Energy. V. L. DUGAN, Manager, Solar Projects Department, Sandia Laboratories, Albuquerque, New Mexico.

The variations of solar systems being considered for dispersed applications are defined and their relative benefits and costs are examined. Also, the role and benefits of total energy systems in dispersed applications are discussed.

Although dispersed solar power systems offer large stored energy multiplication factors, they exhibit a large materials and land dependency. This underlines the importance of reducing the mass per ft^2 of aperture, using most plentiful and available materials, and planning on a recycling materials use strategy.

Paper No. 78-1771. Solar Thermal Power Systems Point-Focusing Distributed Receiver (PFDR) Technology: A Project Description. J. W. LUCAS, PFDR Technology Project Manager, and E. J. ROSCHKE, PFDR Technology Project Systems Manager, Jet Propulsion Laboratory, Pasadena, California.

The goal of the Project is to support the industrial development of PFDR technology that will provide favorable life-cycle costs per unit of electrical or thermal energy produced. The technology will be made available in the early 1980's for applications project experiments. PFDR systems utilize concentrator dishes to furnish energy to their own individual receivers and power conversion subsystems. Initial effort is with steam Rankine and gas Brayton cycles. Periodic assessments will be made to confirm or change the cycles initially selected. Subsystems will be designed, fabricated and tested together in modules as appropriate.

Paper No. 78-1772. Advanced Point Focusing Solar Concentrator Development. M.A. ADAMS and R.O. HUGHES, Members of the Technical Staff, Jet Propulsion Laboratory, Pasadena, CA.

Design activities in the DOE defined Advanced Point Focusing Solar Concentrator Development task have addressed the areas of optical design, structural and mechanisms design, tracking and control, low lost materials, manufacturing techniques and comparative costing and performance evaluation. A major objective of this task is to provide new concepts/technical knowledge which can be used to accelerate the commercialization of such systems. A cost target of $10-15 per square foot for the concentrator system has been chosen. Glass mirrors with a cellular glass backup appears to be the most promising candidate for the reflective surface/structure.

Paper No. 78-1773. Future Solar Total Energy Markets for the U.S. Industrial Sector. L. R. BUSH. Manager, Total Energy Systems, and P. K. MUNJAL, Staff Engineer, The Aerospace Corporation, El Segundo, Ca.

A computerized market penetration model has been developed to forecast commercialization of solar total energy systems in the U.S. industrial sector. The model makes use of performance relationships developed through extensive computer simulation which define solar system economics and energy displacement by fuel type as functions of industrial application characteristics (thermal-to-electric ratio, phasing, size), solar insolation and price of competing fuels. Results are presented for 140 industries, 50 states, and 7 time periods from 1985 thru 2015. Aggregated national totals indicate that considerable fuel displacement can be achieved by 1990, and even earlier if government incentives are employed.

Paper No. 78-1774. Optimum Selection of a Wind Turbine Generator System. J.K. SHULTIS, L.A. POCH, and N.D. ECKHOFF, Dept. Nucl. Engg. Kansas State University, Manhattan, KS 66506.

A method is described for the selection of the optimum size (i.e., rated power and speed) for a wind turbine generating system (WTGS) such that, for given wind speed conditions and for given demand power requirements, the annual economic savings are maximized by using the WTGS compared to purchasing all power from a utility. No storage of excess generated electricity is considered and any demand in excess of that generated by the WTGS is assumed to be supplied by the utility grid. The economic saving realized with the optimum sized WTGS is examined for various problem variables such as the degree of variability in the wind speed and in the demand load throughout the day and from season to season.

Paper No. 78-1775. Design of a Second-Generation Concentrating Tracking Solar Collector. Roy W. Miller, William D. Antrim, and Martin J. Pitasi, American Science and Engineering, Inc., Cambridge Ma.

A concentrating solar energy collector has been designed with emphasis on improving performance and reducing production unit cost. The collector is a second-generation system; in that, it makes maximum use of data and experience gained by AS&E through development of three previous solar collectors. The collector uses parabolic mirror concentrators in conjunction with cylindrical blackbody receivers. Concentration ratio is approximately ten-to-one and the design is for high temperature (120°C) output. The elevation tracking system employs photo-transistor sensors with position feedback used to drive the mirror concentrators. Predicted performance data is provided together with details of the improved design.

Paper No. 78-1776. Preliminary Design of Solar Total Energy - Large Scale Experiment at Shenandoah, Georgia. E. H. ERNST, Manager Energy Engineering, General Electric Company, Valley Forge, Pa.

The U.S. Department of Energy, with Sandia Laboratories providing technical support and technical project management, is developing a Solar Total Energy-Large Scale Experiment at Shenandoah, Georgia. The application is a 42,000 square foot knitware plant which receives knit material in dyed and finished form, cuts, sews, presses, packages, and ships high-quality knitware. The plant's total energy requirements will be supplied, in large part, by the Solar Total Energy System.

A preliminary design of the Solar Total Energy System (STES) for the U.S. Department of Energy's Large Scale Experiment at Shenandoah, Georgia, has been developed, defined, and evaluated. This STES supplies electric power; process steam; and hot water for space heating, cooling (via an absorption air conditioner), and plant hot water requirements.

Session 5

Advance Applications

78-1777
78-1778

ABSTRACT NOT AVAILABLE

Paper No. 78-1779. A Hybrid Thermochemical Hydrogen Production Cycle Using Solar Energy Process Heat. J.R. DAFLER, Manager, Alternative Fuels Production Research, S.E. FOH, Supervisor, Thermochemical Hydrogen Research, and J.D. SCHREIBER, Associate Chemical Engineer, Institute of Gas Technology, Chicago, IL.

Thermochemical hydrogen production is a laboratory proved concept and the subject of continuing research in the United States and Europe. For the process heat source generally assumed (HTR's) the limiting, Second Law Efficiency is about 69%, while for solar high temperature concentrators this limitation may go as high as 86%. The hybrid copper oxide-copper sulfate cycle, under development at IGT uses a very high temperature endothermic process and appears to be very attractive from the point of view of process separations and process materials requirements. A base-case flowsheet efficiency of 37.1% has been calculated.

78-1780

Paper No. 78-1781. Liquid Fuels from Biomass. JAMES L. KUESTER, Professor of Engineering, Arizona State University, Tempe, Arizona.

A project is described which is concerned with the conversion of cellulosic type material to storable, liquid fuels and chemical feedstocks. Possible sources of the cellulosic material include municipal refuse, agricultural, forest and sea sources. The research scale conversion system consists of a thermal gasification system (pyrolysis) and gasoline synthesis system. Possible products include fuels similar to diesel or jet fuel and a high octane gasoline suitable for internal combustion engines. The paper will characterize the feedstock candidates, describe the experimental system, present product analysis and discuss projected economics.

Paper No. 78-1782. Controlled Environment Systems For The Production Of Aquatic Vascular Plant Biomass For Conversion To Liquid and Gaseous Fuels. J.M. PHILLIPS, Research Associate, Environmental Research Laboratory, University of Arizona, Tucson, Arizona, 85706.

One innovative approach to the production of biomass for conversion to fuels currently under study in Arizona is the production of aquatic vascular plants, such as the water hyacinth (Eichhornia crassipes (Mart) Solm), in controlled environment systems. Production advantages of controlled systems are outlined. Information is presented on optimum mineral nutrient levels for maximum production of biomass. Results of carbon dioxide enrichment studies are reviewed, and an analysis of possible subsystems for economic enhancement of controlled environment biomass production are discussed..

ABSTRACT NOT AVAILABLE

UNSOLICITED PROPOSAL

FOR

CROSSBOW CONTROLLED HELIOSTAT

DEVELOPMENT

PART I. TECHNICAL SECTION

by

S.C. Plotkin & Associates
9911 W. Pico Boulevard
Suite 800
Los Angeles, California 90035

Table of Contents for Technical Section

I. Introduction

A. Overall Energy Problems

While it can be debated how long petroleum and coal are going to last us, there is no argument that such energy sources are going to be exhausted some time in the foreseeable future. When that happens, there will have to have been developed a series of alternate energy systems which will not only generate the energy required but also be reasonably economic. Experience thus far has indicated that development of such systems does not tend to produce energy anywhere near the cost we are presently accustomed to.

It is no accident that almost all alternate energy techniques simply cost too much. Energy sources like direct solar, wind, etc. are distributed in nature as compared with petroleum or coal. A gas-flame generates a large quantity of heat in a small volume. Therefore, it is relatively easy to enclose such an energy source, even being a little sloppy with regards to heat leaks, and obtain power in a useful form at a relatively low price, i.e. little work or effort on our part.

Distributed energy systems, because their energy is spread out, require large quantities of equipment which is also spread out in order to capture the energy available. It makes no difference whether we address ourselves to fuel crops for alcohol, direct solar for heat and/or electricity, wind, or ocean movement. They all present the same fundamental general problem, too much hardware spread out over too large an area. Faced with this basic overall dilemma, it is apparent that the cleverest of engineering concepts and ideas are required in order to reduce the cost of final output power from these alternate energy systems.

Another basic aspect of our future energy problems will be the fact that it will probably not be profitable or economic to rely on any one technique or one type of alternate energy system. Each area of the United States has one or more indigenous energy sources which would be beneficial to utilize. There is the Bay of Fundi in the Atlantic North East, large ocean currents off Florida, large ocean thermal gradients in the Gulf, geothermal sources in the Southwest, and wood in the Pacific Northwest -- just to mention a few examples.

B. Solar Energy Aspects

Of all the various alternate energy sources, direct solar energy is probably the most universally available. It has, therefore, been our conclusion that one very important area for worthwhile concerted engineering effort would be in the area of electric generation from direct solar incidence. Electric generation is emphasized because this is the most difficult energy form to obtain from alternate sources. Electricity is sometimes termed "high quality" energy as compared with "lower quality" energy like low temperature heat.

There are basically two ways for obtaining electricity from direct solar energy, photovoltaic cells and solar thermal conversion. In either approach a large area is required to collect the sun's energy. Photovoltaic cells tend to operate at relatively low efficiency. Additionally, they require a significant amount of energy in the growing of the silicon crystals. Both approaches require fabrication materials and energy for assembly. It is our contention that energy concentration techniques can provide increases in thermal efficiency which more than compensates for the decrease in area utilization. Thus, in the end, we believe that solar thermal conversion will probably prove to be the more useful of the two approaches.

II. Basic Aspects of Very Large Systems

One of the most important differences between exceptionally large electric generating systems as compared to smaller systems is the preclusion of cogeneration techniques. Waste heat from a very large system is generally large but relatively remote from urban centers that the usual cogeneration techniques of waste heat utilization in the form of hot water or hot air cannot be employed.

Therefore, the economic factors become all the more important because there is only the small thermal efficiency fraction of the total incident energy which is useful. Additionally, the cost must be in line, more or less, with the conventional energy cost from petroleum and coal sources. Thus the engineering pressures to develope more effective techniques are even greater with the very large systems because they have not the flexibility of the smaller ones.

The very large systems also have increased distribution, or long-line costs. This is, or course, forced on the system by the remote location dictated by the large land area requirements.

Advantages of the very large systems are well known, particularly of large steam turbines and need not be enumerated here at any great length. Economy of size coupled with higher operating temperatures with concommitant higher thermal efficiency can more than offset the long line costs. Electric generation system management, if performed for a large area, must rely on a relatively small number of large generating units to be practical. These aspects primarily make the development of large systems almost essential.

III. Power Tower Development

Eventually there will have to be an economic comparison of photovoltaics and solar thermal conversion. It would be premature to conclude which will prove best for specific applications. At present, as mentioned above, all systems are too costly. Concerted efforts at cost reduction requires innovative concepts for at least the most costly subsystems.

An economic breakdown of power tower subsystems reveals that approximately 60% of the total cost is required by the heliostat subsystem. This large a percentage of the total for one particular subsystem means that in the final analysis, any significant overall cost reduction must include a substantial cost reduction of the heliostat subsystem. Breakthroughs in receiver or generation technology, while important and not to be minimized, cannot have much effect on overall power tower economics without concommitant heliostat breakthroughs.

It is this heliostat subsystem that is addressed in this proposal. One very fundamental reason for the normal heliostats' costing so much is that they entail very large and heavy pedestals for each mirror. As long as such massive foundations are required, it makes little difference what the techniques are, because the cost will be high. Mass produced equipment from nonstrategic materials costs a certain number of dollars per pound, in general if no high technology operations are involved. In the old days, automobiles were about $1/lb. A 2000 pound vehicle used to cost (retail) about $2000. Today such costs have risen to about $4/lb. These numbers apply to mass produced items involving no exceptionally high cost manufacturing equipment or techniques.

It is not intended that we relate automobile manufacturing directly with solar thermal conversion power towers. However, the relative mass production aspects are applicable. One of the best, if not the only, basic approach toward heliostat cost reduction is weight reduction. While this is easy to say, it is not so easy to accomplish when one considers the potential accuracy requirements for wind environments. There is also an additional consideration,-- namely, "what is the most economical system obtainable from trading pointing accuracy loss for lighter, cheaper structures?"

Substantial economic savings can be accomplished by reducing the overall heliostat weight a very large amount. Additional secondary savings can be accomplished by minimizing the control mechanism required. Ganging mirrors together allows them to be controlled together. However, the major innovation to be developed here is the mirror mechanics. Any cost reduction facilitated by less expensive mirror fabrication techniques would be the same for any power tower design, not just the crossbow.

Large power towers have been termed "gold plated turkeys" by one prominent government official. Presumably, the implication is that the cost of output power from a commercial version would be prohibitive. If we consider that one commercially available small (7.5 Kw) solar thermal conversion unit sells retail in single units for $4/watt, it is apparent that the government official has a very incorrect view of the future of such electric generation units. With development of the crossbow heliostat control system, a final power output cost should be no more than $3/watt, at todays prices. This value does not seem to be very much larger, if at all, than the present cost of nuclear power which is $1.60/watt capital cost plus fuel costs, maintenance (which includes down time that has averaged 40% in the past), decommisioning costs, and waste disposal costs. Comparison with clean burning coal would be relatively favorable also considering the $1.25/watt capital cost for a clean burning plant plus slag disposal costs, future fuel cost increases caused by more stringent air pollution requirements as well as the fuel costs themselves, and finally the increased cost of coal because of increases in mine safety requirements.

IV. Crossbow Control Concept

The crossbow heliostat control system, conceived by William H. Raser and contained in U.S. Patent ASN 747.561, is described in detail in Appendix A. As explained above, only a reduction of weight and components can reduce the overall cost of the heliostat subsystem. The Raser approach is to gang a row of heliostats together on a large flexed beam and control them as a unit without heavy pedestals for each assembly. Thus the name "crossbow", because the beam and elongated support trusswork have the appearance of an ancient crossbow. The beam is flexed to approximate an arc of an ellipse during the day to facilitate the mirror tracking of the sun.

This concept requires that the ground surface be flat and must be geologically stable. By connecting all the mirrors in each row together, considerable rigidity is obtained. One large motor varies the elevation of the mirrors together, while small inexpensive vernier motors make small incremental changes. The entire subsystem will be substantially lighter than the competing pedestal subsystem and will employ fewer components. This is an oversimplified explanation, but the general concept is to minimize structure weight and repetitive control elements, thus facilitating significant cost reductions.

There will also be a certain increase in number of possible applications because of the reduced weight. It would appear that solar thermal systems have been automatically denied consideration in a number of potential applications just because they tend to be too heavy for the supporting structures involved. Thus it is contemplated that the crossbow heliostat technique will facilitate an increase use of the solar thermal power tower systems.

V. Crossbow Development Program

The purpose of this development program is to fabricate a 6 KW solar power plant having characteristics which lend themselves to an experimental study of the economic benefits of advanced concepts such as extended implementation of wind loads management. Such a plant employs horizontal reflector support structure, i.e., Crossbow Heliostats. This development can be conveniently split into three phases, as follows:

A. Experimental Studies Using the 60 W Table Model

The purpose of this phase is to determine the optimum number of control channels (heliostat tracking motors) to be used in the 6 KW plant considering both optical performance and cost. If optical performance were the only consideration, the optimum number of channel motors per reflector would be two, as in the case of pedestal heliostats. If reflectors are installed on a horizontal crossbow beam, fewer than two motors per reflector are needed. Figures 1 to 4 show the 60 W model with three crossbows containing

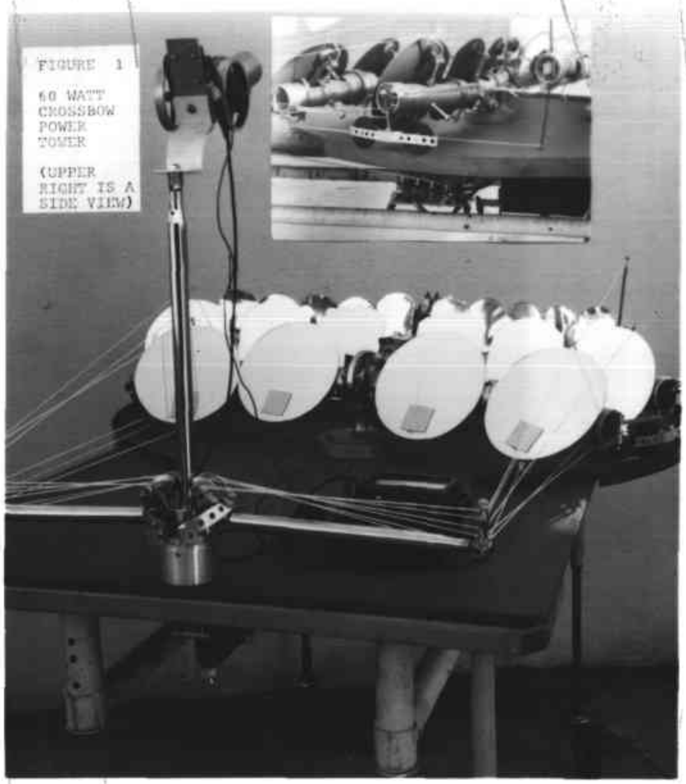


Figure 1. 60 Watt Crossbow Power Tower

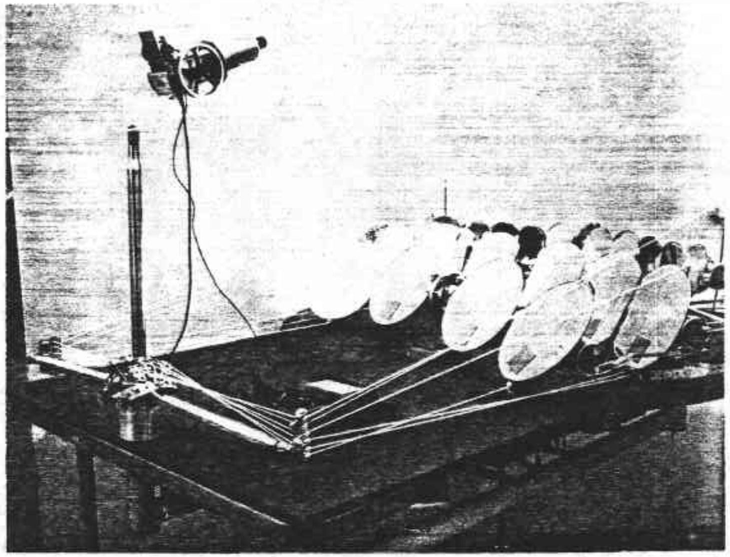


Fig. 2 Oblique View of 60w System

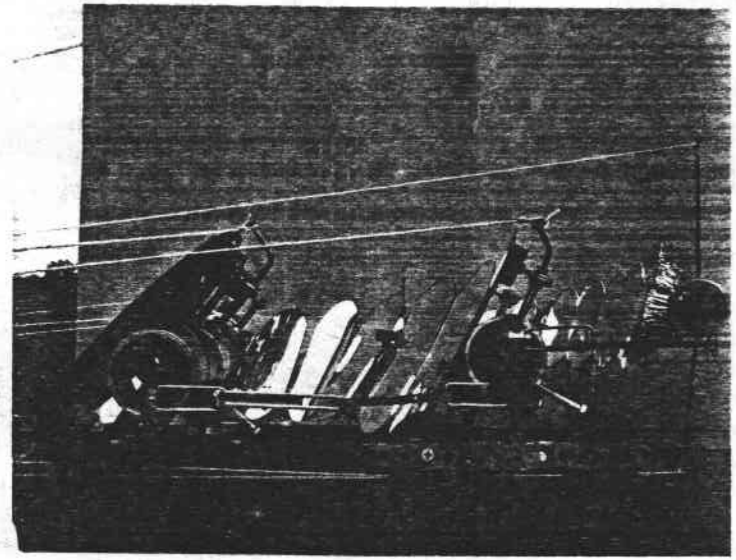


Fig. 3 Side View (note mirror curvature)

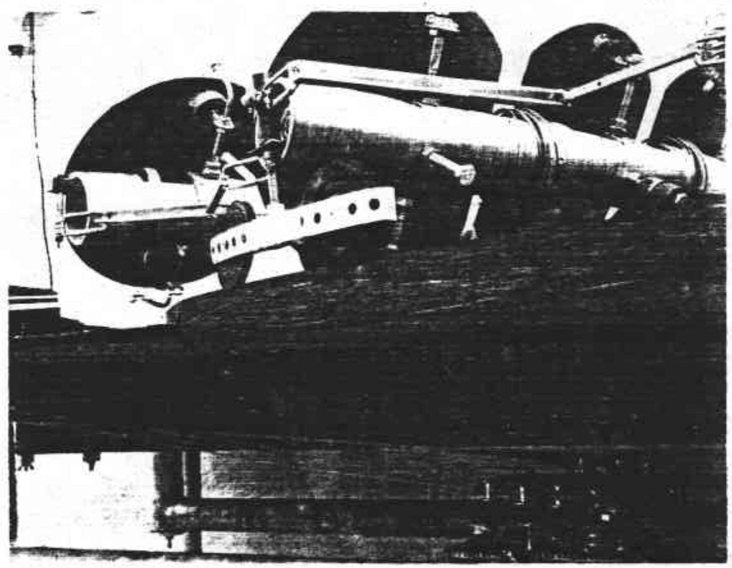


Fig. 4 Rear View (note motor partially visible)

a total of 20 reflectors and 12 control motors. In this model, as well as for the 6 KW plant, the optimum number is believed to be one of the three combinations listed in Table 1, namely 12, 15 or 18 (corresponding to 4, 5 or 6 motors per crossbow).

The tasks involved in Phase A are as follows:

1. Calibrate the output from the 60 W Model for a precise input. The model consists of controlled (but not yet automatically controlled) tracking reflectors, a Stirling heat engine receiver, and a DC motor-generator driven by the engine. For a precise power input to the engine, a 500-watt electrical heating element is used at the end of the engine in place of the radiation energy. The calibration establishes the steady-state constant of proportionality between input power to the heating element and the wattmeter-measured power going from the generator to the electrical load. It also should establish some measure of the deviation which is unavoidable due to temperature, friction, etc.

2. Extend the calibration to obtain the engine transfer function; i.e., determine the time constant or constants associated with thermal inertia. This can be measured for input power waveforms in the form of a pulse by use of a two-channel recording device such as a strip chart recorder. These time constants will be used to verify that later sections of this phase can be accomplished satisfactorily using constant velocity tracking drives.

3. Extend the calibration to determine the effect of wind on both of the above relationships. From this data, a measurement procedure can be developed which yields a generalized efficiency or Figure of Merit (FM).

4. Develop procedure whereby FM can be measured for the case where some radiation is concentrated (in place of the electric heating) using a single crossbow. In some cases, it may be desirable to use outside power to overcome engine friction by running some electrical power into the motor-or-generator machine to drive the engine and by observing changes in wattmeter readings. This procedure applies to only one crossbow at a time; therefore, in accordance with Table 1, the number of control motors involved is just 3, 4, 5 or 6. These motors are pulsed stepping motors of which two function as photo-optically-controlled digitally-operated position servo motors and up to four are driven by manually-controlled variable-frequency pulse generators to run at constant but adjustable speed. These two types are designated as closed-loop (CL) and open-loop (OL) types respectively in Table 1. Using a sequence from left to right in Table 2, the four columns of symbols represent the four steps of this procedure which results in up to 6 motors operating simultaneously for each crossbow.

5. Using the above procedure, of manually optimizing one motor at a time in four steps, determine the maximum efficiency or figure-of-merit during each of the last three steps.

6. By a combination of weighing some of the equipment used and of appropriate scaling, obtain estimates of the total weight of the crossbows with 4, 5, and 6 motors each. Using maximum thermal input power of 95 watts per sq. ft. times 5.3 sq. ft. of reflecting surface for this model and using 88 cents per pound of material as used in page 1-3 of Reference 3, compute the following ratio

$$\frac{\text{Output power}}{\text{Dollar cost}} = 572.2 \text{ (efficiency ratio)/weight, lbs.}$$

for each of the three above control configurations.

7. Investigate possible additional factors to be considered in choosing between 4, 5 and 6 control motors per heliostat (12, 15 or 18 control channels for the 20-reflector system).

8. Using items 6 and 7, select the number of motors to optimize the ratio of power to cost.

9. Report the results of this experimental study.

Table 1. Sequential plan for experimental control optimization

Channel of control	number of motors used per crossbow beam			
	3	4	5	6
Azimuth at the center	CL	CL	CL	CL
Mean elevation	CL	CL	CL	CL
Differential elevation	MA	OL	OL	OL
Mean beam curvature	F	MA	OL	OL
Elevation at the center	-	-	MA	OL
Differential curvature	-	-	-	MA

Symbols: CL = closed loop, F = fixed, MA = manual adjust, OL = open loop

B. Tracking Control System

Introduction

The crossbow concentrator system is a "thin" reflector field designed to make most effective use of a few movable mirrors. The system is most effective in a design which employs simple control concepts with correspondingly few active components.

An outline of an effective control procedure follows:

1. The crossbow assembly will be positioned so that the center mirror of the assembly is opposite the sun from the receiver tower, and so that it is always the same distance from the tower.

2. The mirror assembly for each beam will have a common elevation setting so that only one elevation servo will be required. The mirror mounts will be counterbalanced so that no static twisting of the crossbow beam will occur.

3. The crossbow beam will have a section shaped to produce a bent shape consistent with the constraints of having a common elevation angle for all the mirrors and having azimuth angles for each such that the normal to the mirror surface bisects the angle formed by lines to the sun and to the receiver tower center.

Constraints (1) and (2) allow use of a simple sensor arrangement for driving the center truck positioning servo and the beam elevation servo. The truck servo position error signal can be obtained by differencing the outputs from matched photodiodes attached to opposite sides of a flat vertical plate aligned between center mirror and receiver tower; that is, hard mounted to the center mirror truck. The elevation servo error signal may similarly be developed by differencing the outputs of diodes mounted to opposite sides of a flat plate containing a horizontal line and a line from the sensor mount to the receiver tower center. This plate will be mounted on a stub attached to the center mirror truck. It will, furthermore, be shielded from direct sunlight and mounted so as to receive reflected sunlight from the mirror.

A center mirror elevation angle transducer will be required to produce input signal to a function generator which will control crossbow cable winch tension. With the control scheme described, the required tension will be a function only of the common mirror elevation angle.

All three of the required control servos will function continuously. As the sun moves across the sky, the mirror assembly will move around the tower to its most advantageous location and the mirror beam will rotate and bend to direct the reflected sunlight onto the receiver.

Aiming

The design and development of an effective crossbow heliostat pointing control system involves a number of tradeoff studies and decisions.

Azimuth

First, the bow cable control interacts with the bow shape to yield a simpler control system as the structure is made more complicated and expensive. The ideal solar reflector structure is a paraboloid of revolution whose axis is the sun-tower line of sight. The intersection of this ideal reflector with the plane of the crossbow is an ellipse. Thus, deforming the bow to the shape of an ellipse will produce a set of mounting axes having the right azimuth direction for small mirrors which are "elements" of the paraboloid.

Elevation

Unfortunately, the elevation angle for these elements changes continuously along the ellipse. The curve of constant mirror elevation angles is a function of tower elevation and solar elevation angles. These curves lie near the "proper azimuth" ellipses only for limited crossbow lengths and only for certain combinations of crossbow center to receiver tower range and solar elevation angle. The elevation control is obviously greatly simplified along an "iso-tilt" line, but, as shown in Figure 5, a compromise is necessary between elevation control simplicity and aiming accuracy.

Single Bow vs. Field

If a "field" of crossbows is employed as mirror mounts, the bow center to receiver range is lost as a degree-of-freedom and differential elevation control of the mirrors along the bow will be required. Minimizing both shadowing and beam twist then become competing structural and control goals.

Bow Shape

The elliptical ideal azimuth mounting curve is not assumed by a uniform "collapsed" beam bent by a cable attached to its ends. For small deflections, the actual curve is nearly a sinusoid with chord (cable length) equal to the "critical" column length

$$l_{cr} = \pi\sqrt{\frac{EI}{T}}$$

where

E = Young's modulus for beam material

I = area moment of beam about a transverse axis through its center

T = cable tension

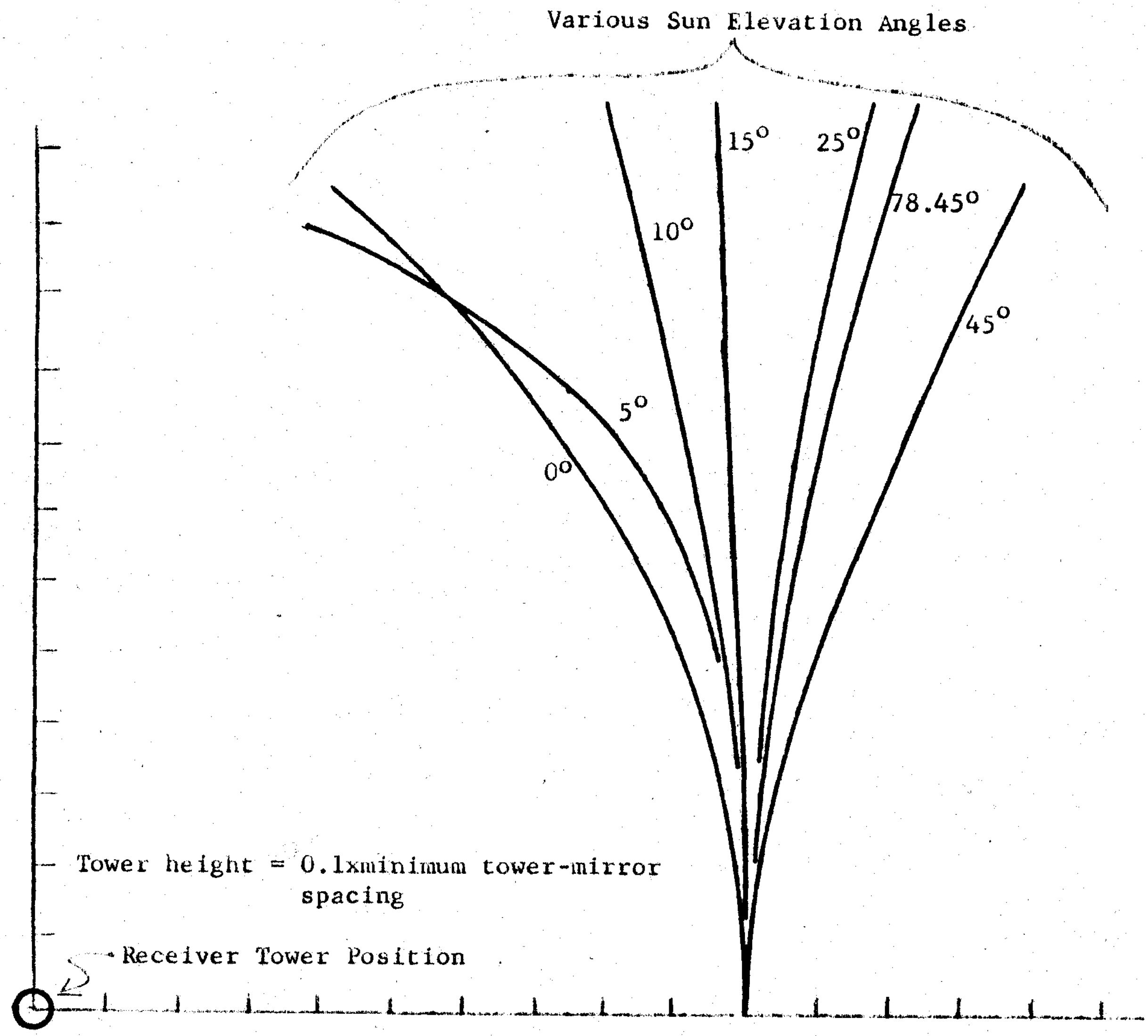


FIGURE 5 Constant Mirror Elevation Angles

By making the beam section variable we can produce an elliptical curve for one tension value, but not for others. A tradeoff is required to define most cost effective beam shape as shaping operations or built-up structure allow better mirror average aim.

Closed-Loop vs Open Loop Direction

The purpose of the aiming control system is to place the center of the sun's image from every mirror on the center of the solar tower receiver area. Two techniques for developing signals for the position motors are attractive for different reasons and for various circumstances.

Open-Loop

In the open-loop control technique, the aiming coordinates (angles) are continuously computed for each mirror (or group of ganged mirrors) and the actual aim, as indicated by position or angle transducers, compared with this to develop error signals to drive the aim correcting servo motors.

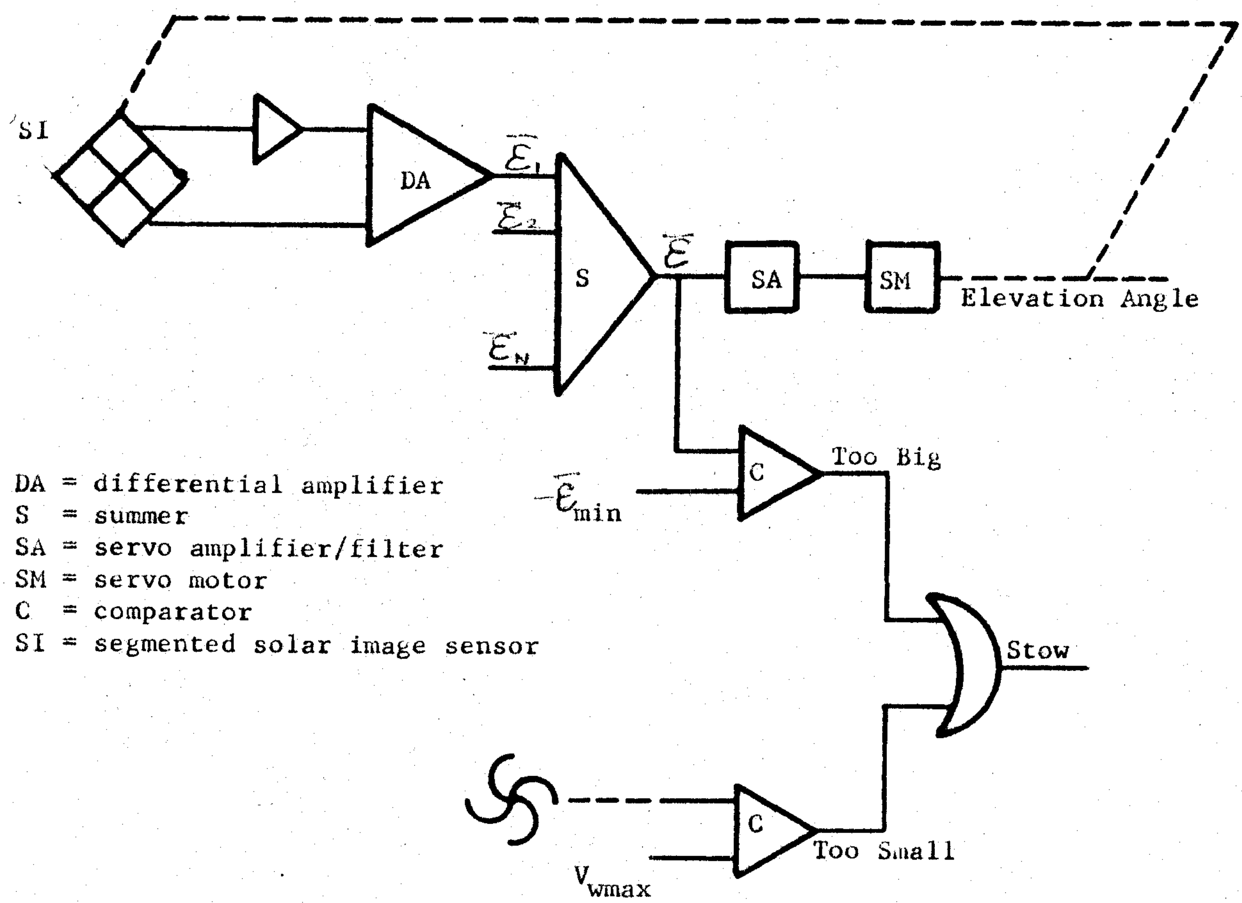
Closed-Loop

The alternative system employs an aiming error sensor whose output may be amplified and filtered directly to drive the aim point correction servo motors. (see Figure 6). The difficulties of this technique lie mostly in orienting a sensor enclosure (shade tube) along the line of sight from mirror to the target. For a fixed mirror location in the field this is a simple, one-time-only installation. For a crossbow with four degrees of freedom (2 position coordinates, a mean angle to LØS and a mean bowing or cable tension) the orientation problem is more difficult. Similarly, the generation of open loop attitude commands for each mirror is a function of the same four coordinates plus time-of-day and date. In the latter case, the implementation is largely computational rather than mechanical but the accuracies possible for similar cost systems may be comparable.

C. 6 KW Crossbow Plant (300 ft^2) Fabrication

The purpose of this phase is the upscaling of the 60 W Crossbow Heliostat design, the fabrication and the operational demonstration of a 6 KW solar power plant. Table 2 lists the design parameters proposed and, together with Figures 1 to 4, gives a fairly clear description of the heliostats.

Present plans call for the engine, the receiver and the stowing system to be the Winnebago Stirling 6 KW Power Package, an experimental cavity receiver borrowed from Biphase Engineering Division of Research Cuttrell Corp., and an inflatable bag structure to be borrowed from the Los Angeles International Airport. The inflation time for this protective bag to rise to meet the downturning reflectors is not included in the 5 seconds time required for the reflectors to reach the downward (stowed) position. Energy for this rapid turn down comes from strain energy stored in crossbow beams.



DA = differential amplifier
S = summer
SA = servo amplifier/filter
SM = servo motor
C = comparator
SI = segmented solar image sensor

FIGURE 6 C-L Elevation Control System

Table 2. Heliostat Parameter List

The following is a summary list of input parameters used in this development project.

Heliostat	First two rows	Last row
Dish diameter	5.19 ft.	3.36 ft.
Interference circle, adjacent unit	32 ft. diam.	
Turndown time	$<$5 seconds	
Skin support flexure with wind	$<$2.0 mrad	
Dish flexure	$<$3.0 mrad	
Structural normal modes	all natural frequencies $>$ 3 HZ	
Rms flexure	all mode dumping rates $>$ .01 critical	
Angle transducer error	$<$ 3.0 mrad	
Angle control resolution	$<$ 1.5 mrad	
Total errors	$<$ 15.0 mrad	
Solar width	9.38 mrad (radius = 4.69)	
Total (rms-sum)	15.88 mrad	
Reflectivity of solar spectrum at end of life	$>$ 85% at 5 years	

should be "less than"

Wind	
Image on target	$>$ 20 mph
Wind damage	$>$ 50 mph

Field Design	
Shadowing:	
Worst heliostat	$<$ 17% annual
Field average, yearly	$<$ 8% annual
Off-axis optics:	
Field average, yearly	$>$ 88% annual
Combined shadowing/off-axis and optics efficiency:	
Worst heliostat	$>$ 66%
Field average, yearly	$>$ 76%
Current heliostat field design:	
Heliostats	20
Area/heliostat	15 ft^2 (ave.)
Total reflecting area	300 ft^2
Field area	804.2 ft^2
Packing factor:	37.3%

D. Statement of Work

Phase A. No-new-Hardware Technical Evaluation

1. Detail test planning for 8.6 ft^2 Crossbow Laboratory Model (CLM).
2. Qualification of CLM for measuring $\int f(\text{optical efficiency,})\, dt$.
3. Qualification of CLM for measuring optical Figure of Merit (FM), W. & w_o wind.
4. Development of 12-, 15-, and 18-channel Initialization Procedure (IP).
5. Measure FM for above 3 IP's in a Fixed Position Mode (FPM) .
6. Measure FM for above 3 IP's in a Fixed Velocity Mode (FVM).
7. Non dimensialize the costs of 12-, 15-, and 18-channel drives.
8. Determine optimum no. of channels based on items 5, 6, and 7.
9. Present technical evaluation of concept including economics.

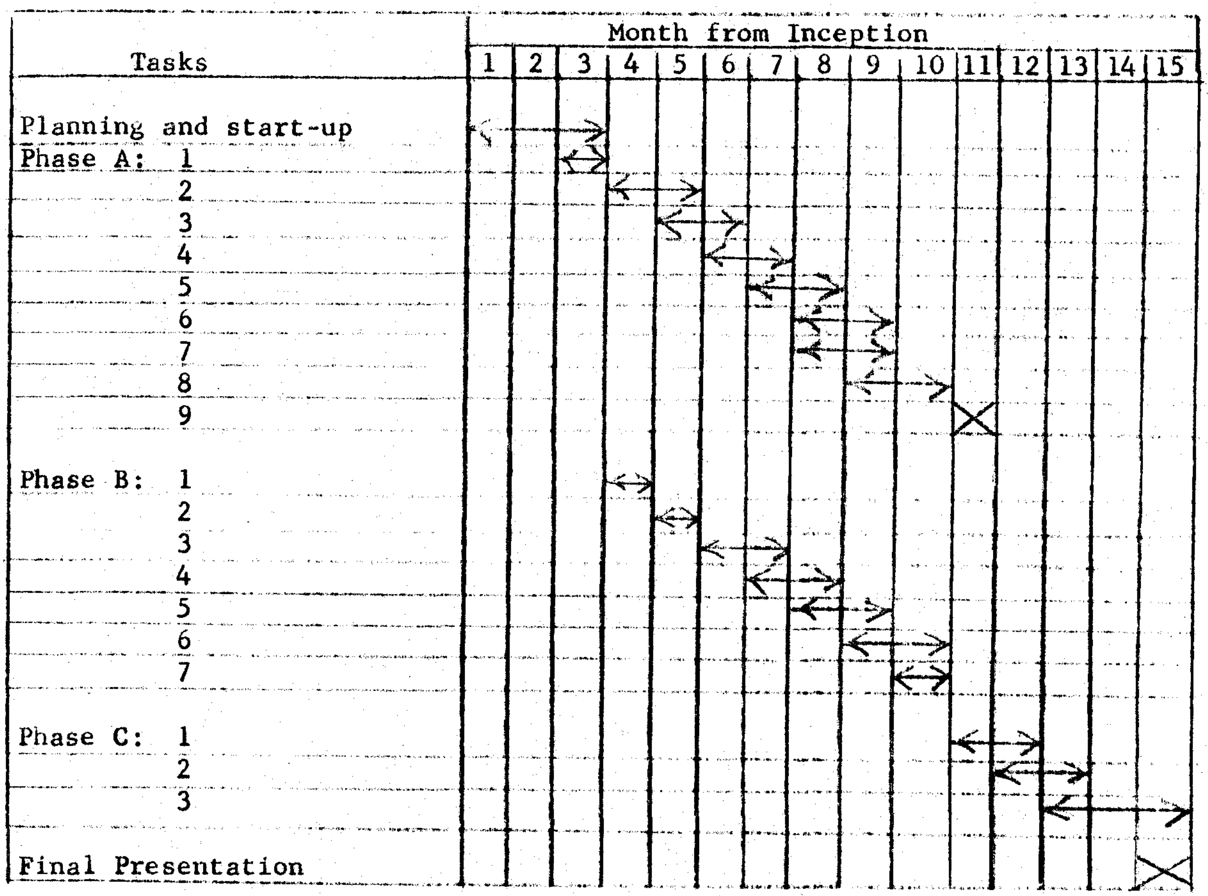
Phase B. Microprocessor System Development

1. Redefine control equations.
2. Write flow diagrams and programs.
3. Obtain and checkout equipment.
4. Program EPROMS and PROMS.
5. Debug and check.
6. Implement and test using 8.6 ft^2 CLM.
7. Measure FM.

Phase C. 6 KW Plant (300 ft^2) Implementation

1. Design, using water cooled Winnebago generator.
2. Analyze FM based on Gaussian wind mom. dist.
3. Fabricate and debug.

1). Time Schedule



VI. Crossbow Versus Pedastals

A. Economic Aspects

This section presents a preliminary comparison of the cost effectiveness of two general heliostat design concepts and the basis for evolving a more detailed comparative design study in the work proposed. It differs from an earlier preliminary comparison of the crossbow and pedestal designs given in Reference 4 by being tied to very simple models and being independent of non-analytical cost data obtained from various sources. Omitting the cost data obtained from previous designs does not make the results more accurate than those of Reference 4; however, basing the results on independent analytical approaches tends to clarify the nature of the advantages and disadvantages of each design. Since this is preliminary, gross simplifications have been made.

The two main assumptions are that cost is proportional to weight and that weight is required to resist structural loads which are due to wind. In other words, this comparison uses models which are basically structural models. The assumptions fall into two catagories, aerodynamic and structural. To keep the modeling simple, only static loads are considered.

Aerodynamic Assumptions

1. Each heliostat surface is a square flat plate which generates a wind force having a magnitude corresponding to an airfoil force, F having a force (drag or lift) coefficient equal to unity.

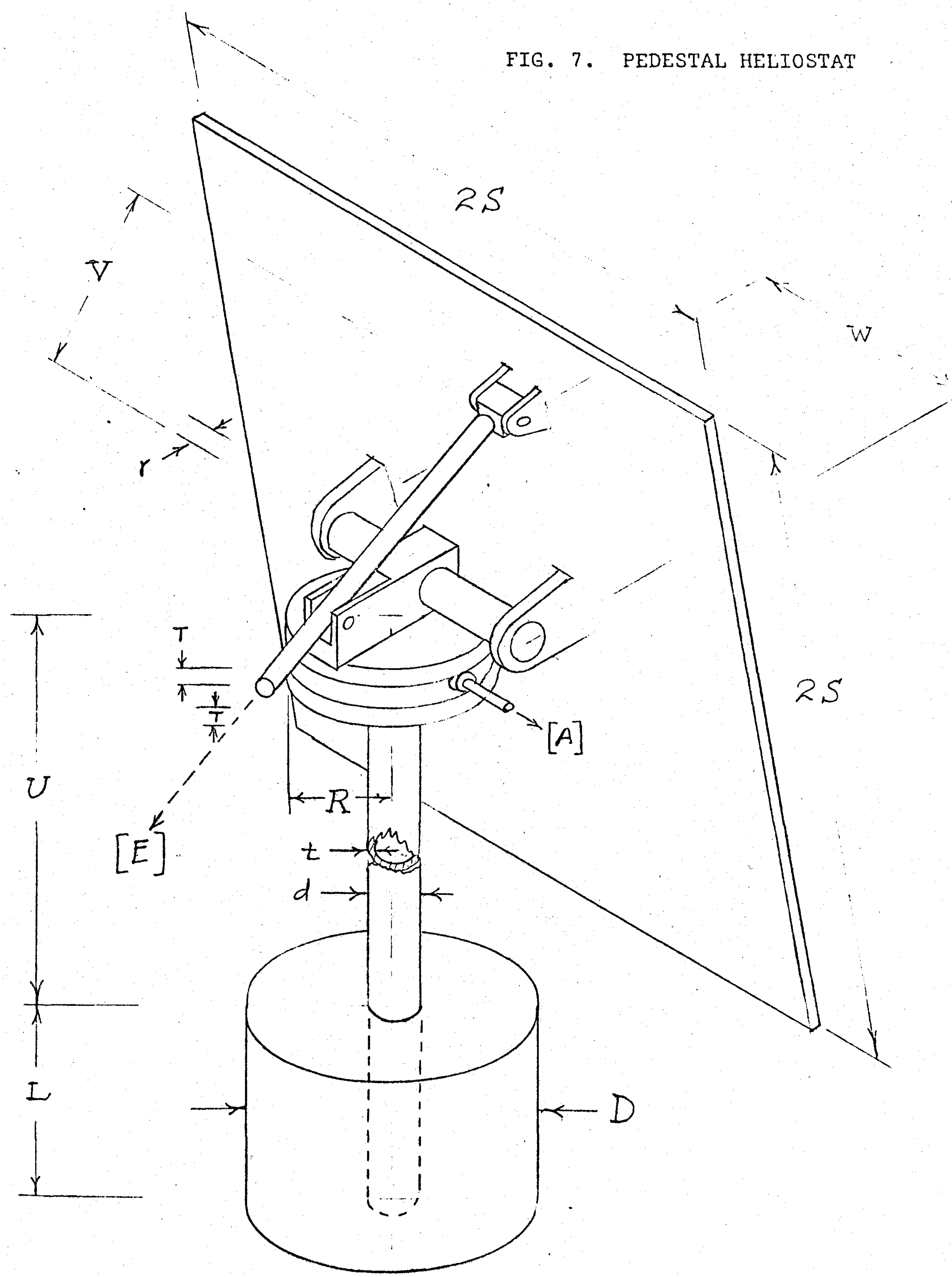
2. The center of pressure of this force lies midway between the area centroid and the quarter chord point of a corresponding airfoil.

Pedestal Heliostat Structural Assumptions per Figure 7

1. Not considering the reflector assembly, the structural componenents can be considered to be the following with their volumes given in parentheses: a foundation ($\pi L D^2/4$), the column (πUtd), the azimuth drive gears ($2\pi R^2 T$), an elevation trunnion ($\pi r^2 W$) which is part of the elevation drive and the rest of the elevation and azimuth drives which total 6.0 times the volume of the trunnion.

2. Not considering the reflector assembly, the foundation is concrete and the rest of the material is steel. The physical characteristics of these two materials are as follows:

FIG. 7. PEDESTAL HELIOSTAT



Material	Density, $\frac{lb.}{in.^3}$	Allowable Stress, S		E, Modulus of elasticity	
		tensile, psi	shear, psi	tensile, psi	shear, psi
steel	0.3	20,000	16,000	29×10^6	12×10^6
concrete	0.1	100	500	3×10^6	1.7×10^6

3. Allowable shear stress in the soil can be approximated by a relationship established by coulomb, namely, the product of the head pressure and the tangent of the angle of repose. For a soil specific gravity of 1.35 and a depth, Z below the surface in inches, shear stress developed is

$$S \approx 0.048723\ Z \tan 37^\circ = 0.0367\ Z \tag{1}$$

4. Optimum L and D in Figure 7 are values which cause the azimuth moment to be resisted by cylindrical shear forces using minimum foundation volume, provided $L \leq 2D$.

5. Letting azimuth loads be the critical ones, other relationships follow inspection of Figure 7. For example, since $d < 2R < D$, use of the geometric mean can not be very far from optimum value for 2R. This and similar observations follow:

$$(2R)^2 = dD \tag{2}$$

$$W = 3R \tag{3}$$

$$t/d = .00287 \tag{4}$$

$$T^2 = 8\pi td \tag{5}$$

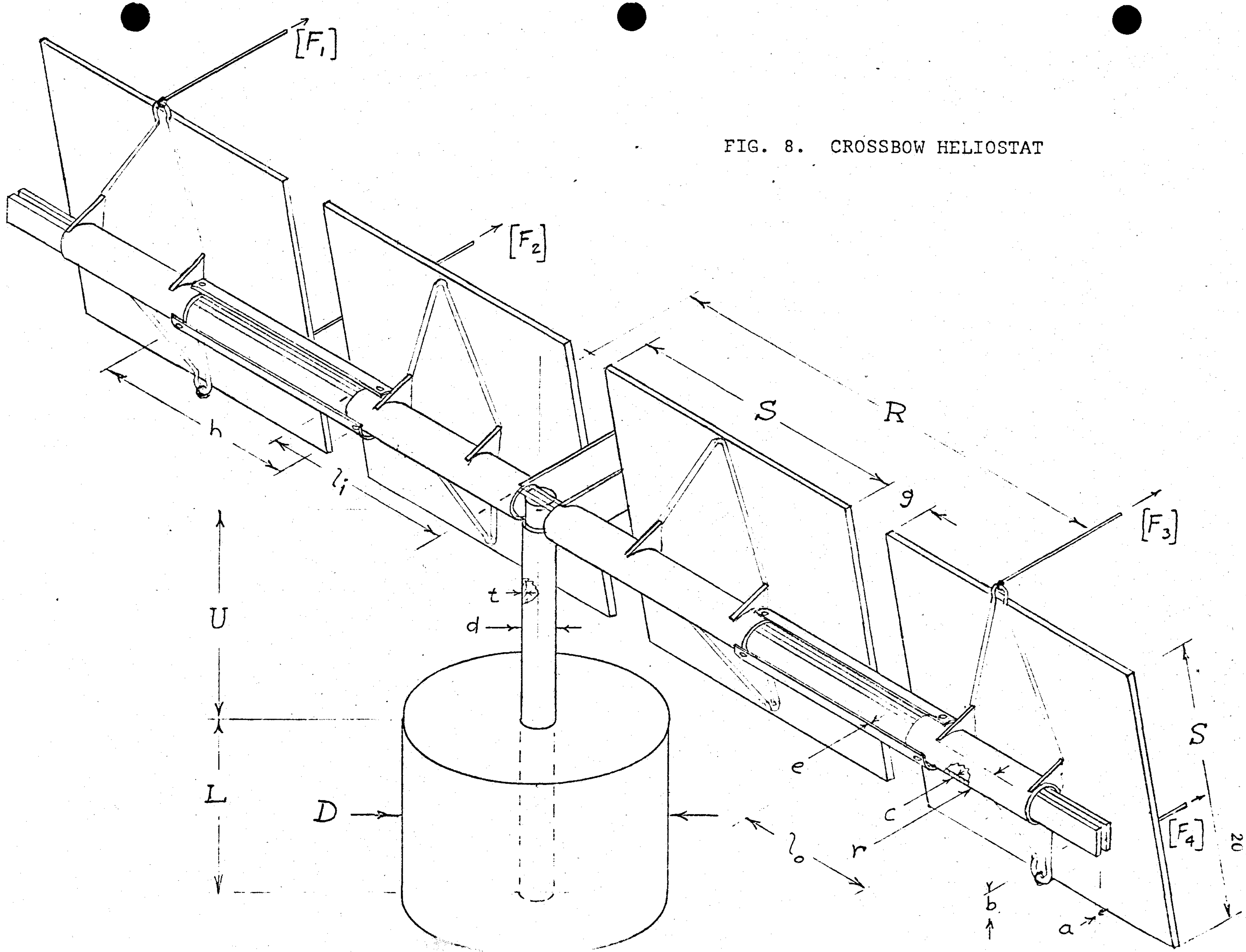
$$U = 1.2\ S \tag{6}$$

The last equation affords ground space needed.

Crossbow Heliostat Structural Assumptions per Figure 8

1. Considering a simple design with four heliostat reflectors but not considering the reflector assemblies themselves, the structural components can be considered to be the following with their volumes given in parentheses: a column ($\pi U\ td$), the equivalent of a two-leaf leafspring ($2\ a\ b\ [2R + S]$), four trunnions ($4\pi r\ c\ [l, + l_o]$), the equivalent of three split sleeves ($6\pi r\ e\ h$), four cables (12 RA where A is section area), and an assembly of parts including 9 bearings, 8 brackets, 12 pin joints, dampers, etc. having a combined volume equal to that of six of the above trunnions. For most soil conditions and for no extremely high wind velocity, no foundation of the type ($\pi L\ D^2/4$) shown in Figure 8 is required because, if bearing friction is neglected, the column now needs to have no torsional stiffness. For most soils, a long slender driven post subject only to flexure encounters soil compression strengths more

FIG. 8. CROSSBOW HELIOSTAT



closely resembling that of concrete than resembling shear stresses given by Equation (1).

2. For favorable installations, i.e., for either typical soil conditions or when extremely high winds can be avoided, the situation with respect to a foundation can be approximated as follows:

let $$U = 2\ (0.7\ S) \tag{7}$$

to represent U + L); the foundation represented by D in Figure 8 does not exist; two small foundations not shown, each approximately 10% of the $L\ D^4/4$ previously considered in Figure 7 are needed for the cable drives, one for F_1 and F_2 and their dampers and one for F_3 and F_4 and their dampers.

3. The conditions dominating the leaf spring design are, first, that no combination of small curvature (sun near horizon) and high wind (maximum F) relieves tension fully on any cable, and, second, that no combination of maximum curvature and direction of maximum F creates a natural frequency lower than what is aeroelastically acceptable. The second condition translates approximately into simply requiring about a 25% margin in meeting the first condition plus a requirement that

$$a \geq 0.2\ b \tag{8}$$

Let the gap between the two leaves be equal to a. Then, if the maximum radius of curvature is assumed to be 3R,

$$1/3R = 1.25\ \left(\frac{\text{Moment}}{EI}\right) = \frac{1.25\ FR}{4\ EI}$$

$$\frac{15\ F\ R^2}{16\ E} = I = \frac{(3a)^3 - a^3}{12/b} \tag{9}$$

Combining (7) and (8) and using the steel tensite modulus,

$$a = 0.008534\ \sqrt[4]{F\ R^2} \tag{10}$$

4. Let g/S, 1_i/S, 1_o/S and H/S be 0.1, 0.65, 0.65 and .65, respectively. Using the above 3R curvature, the inside radius of the trunnion section must be at least

$$(r\text{-}c)\ /\ R = \sqrt{(.006463 + 1.5a/R)^2 + (b/2)^2} \tag{11}$$

where $$R = 1.65\ S \tag{12}$$

5. Neglecting radius differences between the trunnion and the sleeve, let S be 16,000 psi in cases 6 and 12 of Table 4. Then

$$C = \frac{F\ S}{128\ \pi\ r^2\ 10^3} \tag{13}$$

$$e = \sqrt{\frac{3\ F\ S}{128\ \pi\ r\ 10^3}} \tag{14}$$

6. Although both t and d can both be less than for the pedestal heliostat because of no torsion and less bending moment, d is kept the same and t is decreased using the ratio of moments, namely, 0.7/1.2 from Equations (6) and (7).

7. The cable cross section area A is approximately 1/4 (F/20,000) in ^{2}.

Conclusions

Figure 9 compares the approximate weight of the pedestal and crossbow heliostats (without the reflector assemblies) for the same total reflector area (277.78 ft. ^{2}) corresponding to S = 100 inches. Total maximum wind load, F on this area is the independent variable. The curve for the pedestal heliostat is obtained by substituting Equations (1) - (6) in the volumes shown in pedestal Estimate 1, multiplying by the appropriate density in Estimate 2 and summing. ?

Likewise, substituting Equations (7) through (14) and the values in crossbow Estimates 2, 6 and 7 (along with the previous density values) in Estimate 1 yields the crossbow without reflectors. Also, both weight curves are without drive motor weights and with no weight allowed for structural safety margins. ?

Results are plotted in Figure 9. Of course it should be noted that the curves generally agree with the conclusion of Reference 4, namely, that the crossbow is 26% lighter than the pedestal heliostat.

B. Wind Susceptability

The McDonnell Douglas (MDAC) Concept of Wind Loads Management

During the course of the MDAC Prototype Heliostat Phase I study 1, five areas were identified in which research and development may lead to substantial . . . cost reductions. The discussion of one of these areas is repeated in this section as follows:

"Wind loads on the heliostat are typically those for an isolated heliostat in an undisturbed free stream. Preliminary results of wind tunnel tests indicate that the wind loads in a collector field with wind control fences surrounding the field will be reduced by at least 40 percent. The cost reductions which might result from designing to the reduced wind loads are estimated at about \$5/m^2.

The cost reductions might be achieved by further increases in reflective unit area per heliostat or by reduced material gages and drive unit component sizes. A comprehensive analysis would be required to select the better approach.

Before any design modifications can be recommended, it will be necessary to define new design wind load requirements. MDAC recommends the following steps:

1) Completion of the analysis of existing wind tunnel data.

2) Potential additional wind tunnel tests to complete the data base.

3) Analysis of data taken by MDAC during the heliostat array tests at Naval Weapons Center (Phase I Pilot Plant Collector SRE).

4) Instrumentation (for) . . . tests to verify scalability relationships.

5) Translation of wind load data to heliostat design requirements."

<u>Other concepts of Wind Loads Management</u>

As indicated above, MDAC (McDonnell Douglas) has proposed reducing wind loads by as much as 40% using field-surrounding wind fences. This is not the only primising load reducing concept which has been proposed for heliostats.

Brookhaven National Laboratory has made a study[2] of the degree of coincidence between when the sun is shining in the United States and when high wind velocities occur. In general, they found that solar energy is received during hours of low wind velocity; i.e., over 90% of all solar radiation occurs when the wind velocity is less than 20 mph. For areas of particular interest like Fresno, CA and Phoenix, AZ, essentially 100% occurs under 20 mph. Therefore, although contemporary Central Receiver STP System specifications usually call for 26 mph wind speed, 36 mph stowage initiation speed and 90 mph maximum tolerated stowed condition, Brookhaven proposes the use of the stowed position to limit the image-on-target maximum wind to 20 mph at the present time. In other words, Brookhaven suggests a second method of achieving an approximate 40% reduction in wind loads. A variation of this second method has been looked at at S.C. Plotkin & Assoc. to achieve the same results using ground cable connected viscous dampers attached to the reflectors instead of stowed position utilization.

A third concept of wind load reduction has to do with the aerodynamic shape of the heliostat mirrors and the resulting moments produced. A design has been studied at S.C. Plotkin & Assoc. which theoretically achieves about a 40% reduction of elevation angle moments

TABLE 3 —SHEAR, MOMENT, AND DEFLECTION FORMULAS FOR BEAMS

Notation: W = load (lb.); w = unit load (lb. per linear in.). M is positive when clockwise; V is positive when upward; y is positive when upward. Constraining moments, applied couples, loads, and reactions are positive when acting as shown. All forces are in pounds, all moments in inch-pounds; all deflections and dimensions in inches. θ is in radians and $\tan\theta = \theta$

Statically Determinate Cases

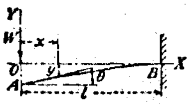
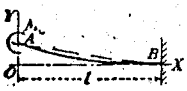
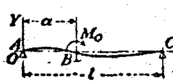
Loading, support, and reference number	Reactions R_1 and R_2, vertical shear V	Bending moment M and maximum bending moment	Deflection y, maximum deflection, and end slope θ
1. Cantilever, end load 	$R_2 = +W$ $V = -W$	$M = -Wx$ Max $M = -Wl$ at B	$y = -\frac{1}{6}\frac{W}{EI}(x^3 - 3l^2x + 2l^3)$ Max $y = -\frac{1}{3}\frac{Wl^3}{EI}$ at A $\theta = +\frac{1}{2}\frac{Wl^2}{EI}$ at A
9. Cantilever, end couple 	$R_2 = 0$ $V = 0$	$M = M_0$ Max $M = M_0(A$ to $B)$	$y = \frac{1}{2}\frac{M_0}{EI}(l^2 - 2lx + x^2)$ Max $y = +\frac{1}{2}\frac{M_0l^2}{EI}$ at A $\theta = -\frac{M_0l}{EI}$ at A $\alpha = \theta - \tan\frac{y}{l}$ $\approx \frac{M_0 l}{EI} - \frac{M_0 l}{2EI}$
20. End supports, intermediate couple 	$R_1 = -\frac{M_0}{l}$ $R_2 = +\frac{M_0}{l}$ (A to C) $V = R_1$	(A to B) $M = R_1x$ (B to C) $M = R_1x + M_0$ Max $-M = R_1a$ just left of B Max $+M = R_1a + M_0$ just right of B	(A to B) $y = \frac{1}{6}\frac{M_0}{EI}\left[\left(6a - 3\frac{a^2}{l} - 2l\right)x - \frac{x^3}{l}\right]$ (B to C) $y = \frac{1}{6}\frac{M_0}{EI}\left[3a^2 + 3x^2 - \frac{x^3}{l} - \left(2l + 3\frac{a^2}{l}\right)x\right]$ $\theta = -\frac{1}{6}\frac{M_0}{EI}\left(2l - 6a + 3\frac{a^2}{l}\right)$ at A; $\theta = +\frac{1}{6}\frac{M_0}{EI}\left(l - 3\frac{a^2}{l}\right)$ at C $\theta = \frac{M_0}{EI}\left(a - \frac{a^2}{l} - \frac{1}{3}l\right)$ at B

TABLE 4—FORMULAS FOR TORSIONAL DEFORMATION AND STRESS

General formulas: $\theta = \frac{TL}{KG}$, $s = \frac{T}{Q}$, where θ = angle of twist (rad); T = twisting moment (in.-lb); L = length (in.); s = unit shear stress (lb. per sq. in.); G = modulus of rigidity (lb. per sq. in.); K (in.^{4}) and Q (in.^{3}) are functions of the cross section.

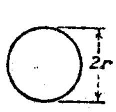
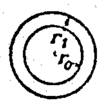
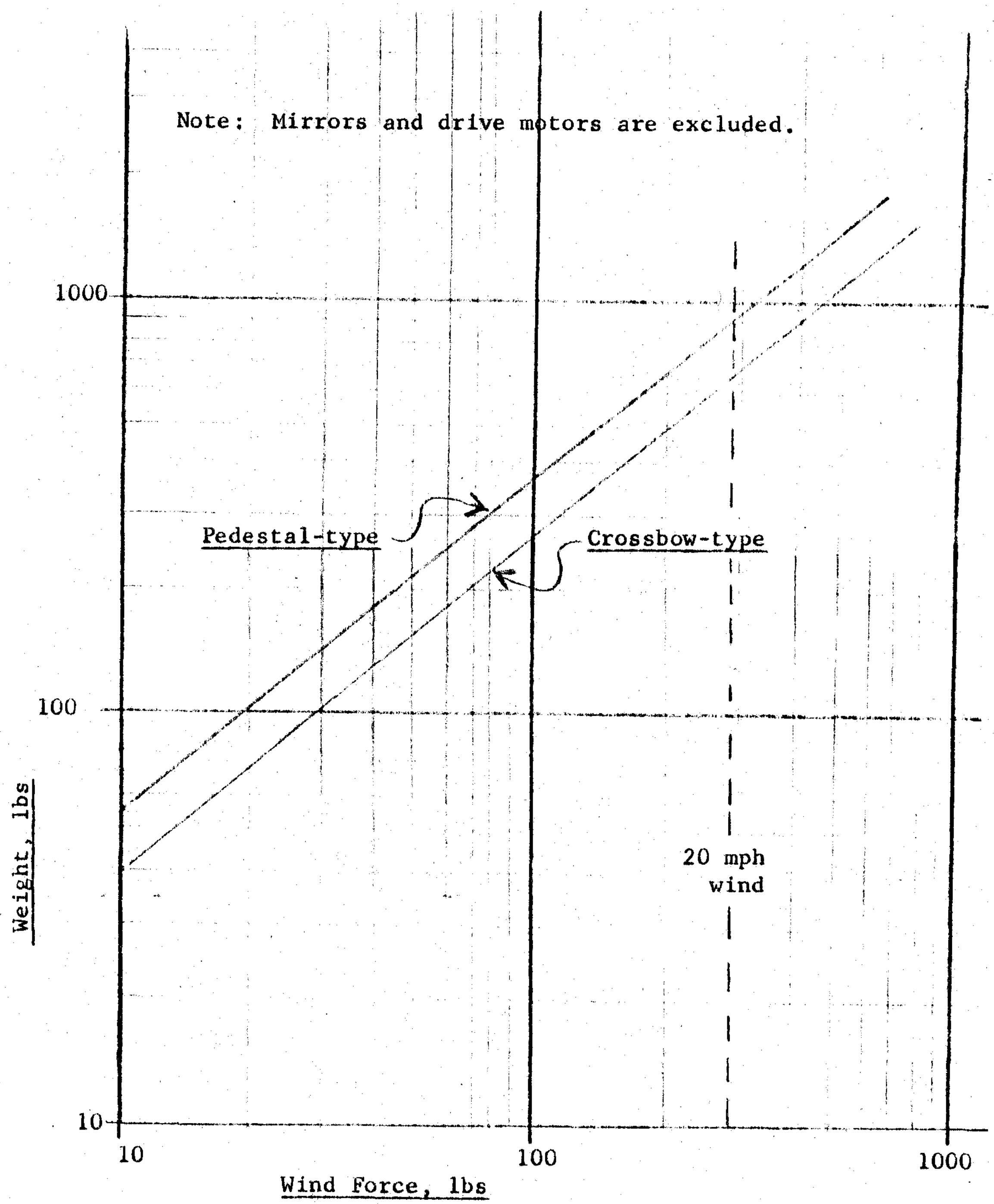
Form and dimensions of cross sections, other quantities involved, and case number	Formula for K in $\theta = \frac{TL}{KG}$	Formula for shear stress
1. Solid circular section 	$K = \frac{1}{2}\pi r^4$	Max $s = \frac{2T}{\pi r^3}$ at boundary
6. Hollow concentric circular section 	$K = \frac{1}{2}\pi(r_1^4 - r_0^4)$ $\approx 2\pi r^3(r_1 - r_0)$	Max $s = \frac{2Tr_1}{\pi(r_1^4 - r_0^4)}$ at outer boundary $\approx \frac{T}{2\pi r^2(r_1 - r_0)}$
12. Thin circular open tube of uniform thickness. r = mean radius 	$K = \frac{2}{3}\pi r t^3$	Max $s = \frac{T(6\pi r + 1.8t)}{4\pi^2r^2t^2}$, along both edges remote from ends (this assumes t small compared with mean radius; otherwise use formulas given for Cases 14 to 20) $s \approx \frac{3T}{2\pi r t^2}$

FIGURE 9. WEIGHT COMPARISON OF PEDESTAL AND CROSSBOW HELIOSTATS



for the same wind velocity. A small scale model using this design has been built. Testing this low-moment-coefficient mirror is not part of the proposed study.

In the discussion which follows, the implementation of any one of the above three methods for reducing wind loads on heliostat structure is called wind load management. The simultaneous use of more than one technique in the designing of any heliostat will be referred to as extended implementation of wind load management.

Purposes

This part of the proposed project, has two purposes. The first is to assist in the performing of research tasks already identified by MDAC[1]. This has to do with gathering and generating data that is useful for evaluating winds load management implemented by wind fences. A second part has to do with obtaining the economic benefits of extended implementation of wind loads management.

Verifying the economy of Wind Load Management

According to item 4 on page 3, MDAC recommends tests to verify the scalability of wind tunnel data which will provide a data base for evaluating the effectiveness of wind fences. Although the emphasis in such testing can be expected to be placed on large scale tests which check the applicability of data obtained using Reynolds numbers that are smaller than desired, it is also important to avoid neglecting the significant economy that might be available by concentrating on an initial experimental effort at a scale even smaller than the wind tunnel offers and using both the wind tunnel data and the large scale test data to verify the scalability of the small scale data. The economy of this approach is significant because a large fraction of the test equipment to do it adds only small cost, including the main part of the instrumentation.

Meeting the needs of Extended Implementation

At this time, the following assumptions appear reasonable:

1. Three concepts exist which individually promise 40% load reductions on heliostat structure, namely, wind fences, peak wind avoidance and aerodynamic reshaping.

2. The structure resisting these loads can be priced by the pound; i.e., its cost would be expected to drop by 40% in each case.

3. This structure represents how about 25% of total heliostat costs.

Therefore, extended implementation would involve diminishing returns. If one of these concepts were used successfully, the overall economy would be 10%. If a second such concept is implemented successfully, the amount and the marginal economy is now only 6%. If all three concepts are implemented successfully, the total is 19.6% which means that the last effect is only 3.6%.

This study aims to meet the needs of effective extended implementation by exploring configurational changes in heliostat structure which avoid the diminishing returns characteristic described above in general and by exploring one particularly applicable configurational change.[4]

The Horizontal Reflector Support Structure

It is widely recognized that the combination of large loads and small tracking angle error tolerance favors the use of vertical reflector support structure, i.e., the pedestal structure. It is less widely recognized that the absence of these two conditions favors some horizontal reflector support structure in combination with fewer than one pedestal per heliostat reflector. Figure 1 shows a heliostat reflector supported by both types simultaneously with the pedestal shown with solid lines and the horizontal structure with dotted lines. Use of the horizontal reflector support structure dates back to a solar furnace built by the famous physicist, Dr. Robert Goddard.

When the horizontal reflector support structure is constructed as a leaf spring and positioned by a single pivotal pedestal plus cables, the heliostat configuration is called a Crossbow. Figures 1, 2, 3, and 4 show a 20-reflector small-scale model of a solar electric power plant employing three crossbows.

Instrumentation for laboratory experiments

The apparatus shown in Figures 1 to 4 is a convenient form for experimental studies of the effect of wind on heliostat optical performance and lacks only an automatic control system for this purpose. Two features provide this convenience as follows: first, elevation and azimuth stiffnesses are adjustable; second, a Stirling engine serving as a receiver drives a D.C. generator, the output of which is a function of the total radiated power focused on the target area. This function can be expressed as a double-lag convolution integral having constants which are easily evaluated by means of a simulated heat impulse. The simulated heat impulse can be provided with electrical heating using a high intensity short duration current pulse.

Of particular interest is the use of this system to compare the drop in power output as a function of anemometer-measured wind velocity with theoretical relationships for different mirror stiffness adjustments. Mostly, the testing will be as close as possible to where all azimuth and elevation angular stiffnesses are the same value.

Configuration evaluation for extended implementation

Those parts of a heliostat characterized by a simple proportionality between wind loading and weight (and, therefore, cost) include a major part of almost every component except the controls and the reflector surface. They represent more than 50% of the weight of the heliostat. The fact that their estimated cost contribution is only about 25% of the total reflects the relatively low cost of the heavier components (like concrete). The diminishing returns effect described above is related to the smallness of this 25% figure.

A larger fraction of the heliostat cost can be saved by cost reducing elements. This is done by switching to the use of horizontal reflector support structure so that:

- the Crossbow Heliostat can be operated using fewer than the usual two servomechanisms per reflector
- because of better than 10:1 ratios of mechanical advantage improvements compared to the use of gear boxes, tip-connected cable drive forces are correspondingly lower
- the cost characteristics of cables and drums are more favorable than of gears and gearboxes
- horizontal reflector support structure resists azimuth deflections more efficiently than vertical support structure.

The first three of these reasons are explained in Reference 4, which also explains the unique feature of Crossbow reflector location, namely, that shading and blocking between adjacent reflectors on any one crossbow is negligible even if the spacing between them is zero. This zero spacing feature is a factor in the fourth reason listed above. Other factors are given in Table 5 and Figure 10. Figure 10 shows that if the crossbow beam had the same cross section as the pedestal it could span somewhere between 10 and 50 reflectors and still have the same azimuth angle rigidity as the pedestal (depending on wind load management implementation). As soon as the designer utilizes this, he finds economies in a variety of components such as less ground preparation, fewer pedestals, etc.

As new studies continue to reveal increased opportunities for heliostat cost reductions as a result of wind load management finding optimum heliostat structural configuration becomes more important. If the pedestal heliostat is to become a barrier to full realization of these opportunities, the Department of Energy will want to be apprised of this and to be in a position to plan accordingly.

TABLE 5
COMPARISON BETWEEN HORIZONTAL AND VERTICAL DEPLOYMENT OF PRIMARY HELIOSTAT SUPPORT STRUCTURE

Defining Examples

Vertical support = pedestal of Pedestal Heliostat

Horizontal support = curved beam of Crossbow Heliostat

Representative beam structure = steel tube $\begin{cases} OD = 24 \text{ in.} \\ t_{wall} = 0.0689 \text{ in} \\ \text{Ref.: Easton/MDAC} \end{cases}$

Structural Craracteristics of above Steel Tube

k_t = unit (per in. length) torsional stiffness $= \dfrac{dT}{d\theta}$

$$= KG/L = \tfrac{1}{2}\pi\left[12^4 - 11.9311^4\right]/(12 \times 10^6)$$

$$= 8.887 \times 10^9 \text{ lb./rad.}$$

k_f = given-span (l) flexural stiffness @ station a, Table 5, #20

$$= dM/d\theta = -EI/(a - a^2/l - l/3)$$

$$= \frac{3.2216 \times 10^{10}}{l - 3a(1 - a/l)}$$

k_{fm} ≡ mean value of k_f for $0 < a/l < 1$

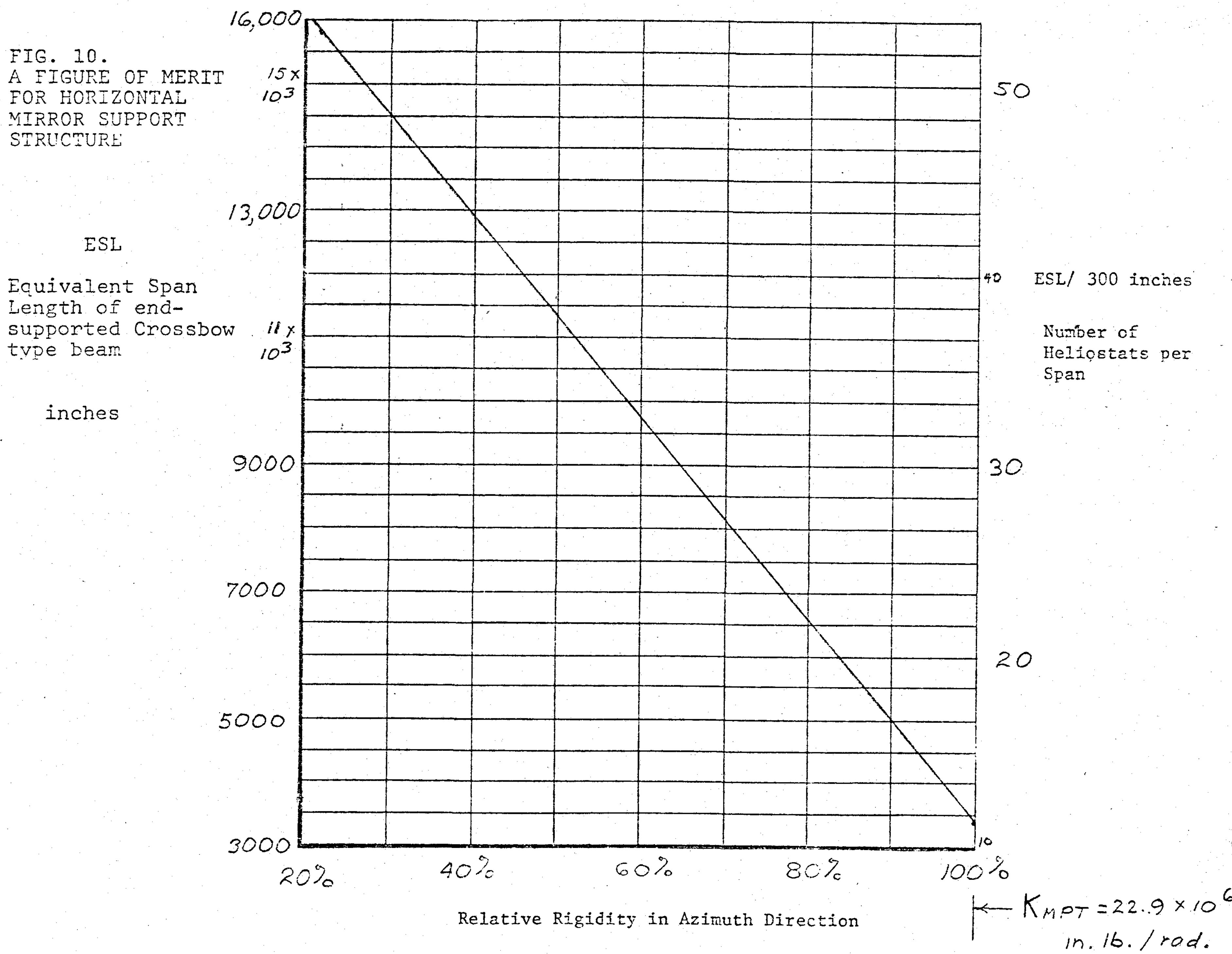
$$= \int_0^1 k_{fm}\, d(a/l) \Big/ \int_0^1 d(a/l)$$

$$= \frac{2(3.222 \times 10^6)}{\sqrt{3}\; l}\left[\tan^{-1}\frac{3}{\sqrt{3}} - \tan^{-1}\frac{-3}{\sqrt{3}}\right]$$

$$= 7.791 \times 10^{10} / l$$

$$l_{crit} = \frac{k_{fm}\, l}{k_t} = \frac{7.791 \times 10^{10}}{8.887 \times 10^9} = 8.7667 \text{ in.}$$

FIG. 10.
A FIGURE OF MERIT
FOR HORIZONTAL
MIRROR SUPPORT
STRUCTURE



VII. Future Development Programs

There are actually two separate types of future development programs. One is the obvious application to very large power towers and the other is small cogeneration applications.

A). Post-Barstow-type applications can utilize the crossbow control systems developed here. Some modification of the computer program will be required, but those additions should be relatively straightforward. This proposal and ensuing development program has had the large applications in mind.

B). The final 6 Kw unit, besides validating the results of the 60 watt table model, will provide definite numbers and conclusions regarding future economics. Testing and evaluation of the 6 Kw unit must be part of an on-going program. Of significance is the fact that, unlike the 60 watt table model, the 6 Kw unit will be an actual working system.

It is possible to include the follow-on efforts under a DOE cogeneration program rather than a strictly heliostat development. Because the electric generation will be by means of a commercially available Stirling motor-generator, the water cooling requirements will provide hot water output. Such output water can then be used for both water and space heating.

Of significance here is also a proper testing facility for the 6 Kw program. Initial contacts have already been made and the grounds investigated. It appears as though an ideal situation would be to consider incorporating the prototype 6 Kw unit into the already existing facilities at the City of Hope Medical Research Center, Duarte, California. Indications are that they will welcome such a program under the proviso that no City of Hope R&D funds will be required for the solar energy work. They are already hard pressed for medical research funding, so all the energy work would have to be supported by a separate contract. However, the use of such facilities for the 6 Kw unit test program appear to be quite cost effective.

It would be anticipated that S.C. Plotkin & Associates would provide full technical personnel, material, and operating supervision for the entire test program. All funding would be through the contract to S.C. Plotkin & Associates with City of Hope simply providing the test facilities and using the output to support its tax-free program.

In conclusion, it might be pointed out that the 6 Kw test program as discussed in (b) above must be carried out before application to larger systems as discussed in (a) is warranted. Evaluation of this contract will resolve the question, once and for all, whether or not there is really a decided advantage to changing from a pedestal mirror to a crossbow configuration.

VIII. References

1. Easton, C.R.: Solar Central Receiver Prototype Heliostat CDRL Item B.d, SAN-1605-7 (Vol. 2), August 1978.

2. Cottingham, J.G.: Solar-Powered Steam Generator Heliostat, BNL 50974, December 1978.

3. Easton, C.R.: Solar Central Receiver Prototype Heliostat CDRL Item B.d SAN-1605-7 (Vol. 1), August 1978.

4. Raser, W.H.: Flexed Beams in Central Receiver Heliostat Drives, A.I.A.A. Paper No. 78-1755, November 1978.

5. Roark, R.J.: Formulas For Stress And Strain, McGraw-Hill Book Co., 1943.

Appendix A.

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78-1755

Flexed Beams in Central Receiver Heliostat Drives

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FLEXED BEAMS IN CENTRAL RECEIVER HELIOSTAT DRIVES

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Abstract

Horizontally-flexed "crossbow" beams in the form of large leaf springs are considered as a means for supporting and steering mirrors in central receiver systems. Their use reduces requirements for (1) heavy structural materials, (2) the number of tracking drives, (3) component machining precision and (4) land area. Although the exact amount depends upon the pointing accuracy and wind tolerance specifications, the economy in plant construction resulting from these changes could be over 25 percent.

I. Introduction

Fig. 1 shows an early application of a flexed beam to a solar furnace reflector built by physicist Dr. Robert H. Goddard. In Goddard's furnace, thin mirror strips were flexed by means of cables attached with turnbuckles for manual adjustment. A 400 KW solar plant at Georgia Tech also uses long horizontal beams as heliostat supporting structure but without provision for utilization of beam flexure.

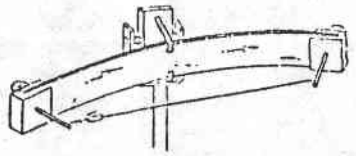
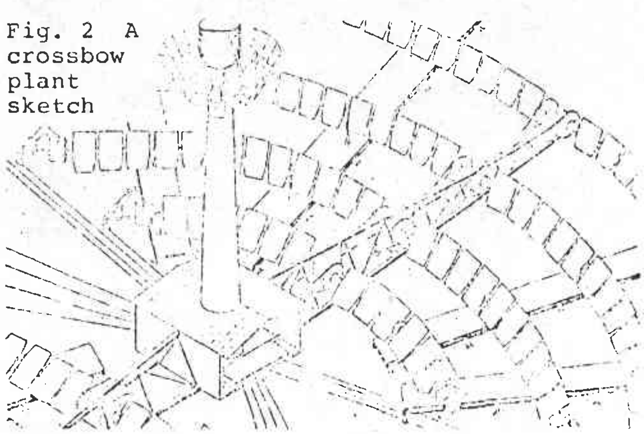


Fig. 1. Goddard's flexed beam reflector (1)

Fig. 2 shows a sketch of a power tower in which such beams are used not only as supporting structure for heliostats but also as significant parts of the heliostat tracking drives. Fig. 3 shows an experimental application of this type of solar power plant used to drive a small steam engine and electric generator. This model

Fig. 2 A crossbow plant sketch



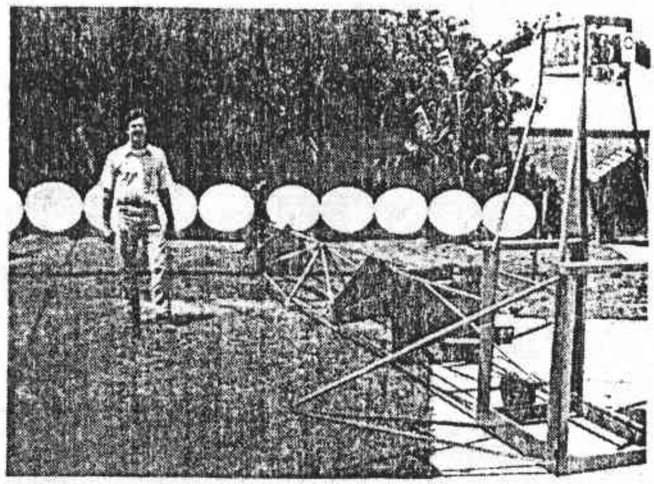


Fig. 3 A small experimental crossbow plant

with its 40 sq. ft. of mirror area won the Los Angeles Sun Day Exhibit first prize, May 3, 1978. This model has ten mirrors which track the sun and focus sunlight on a fixed point, the receiver, that is on top of a tower. Instead of having a pedestal supporting each mirror, this model has one long horizontally-flexible beam or leaf spring providing all ten mirrors with not only structural support but also azimuth aiming angles. A leaf spring which provides both of these is called a "crossbow".

First, a general description of the crossbow heliostat configuration is given. Following that, the theory of central receiver concentrators is extended to apply to the groups of mirrors which can be mounted on a crossbow beam. Implementing schemes are then discussed, particularly for the mechanization of the required azimuth angles. Finally, some general characteristics of crossbow heliostats are reviewed including wind tolerance, area utilization and estimated relative construction costs.

II. Crossbow Heliostat Description

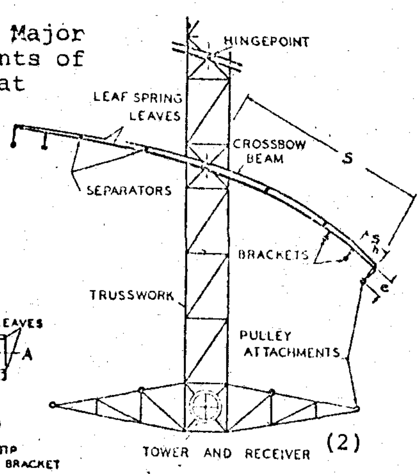
Not counting the receiver and other parts of the tower, a very simple system with only one crossbow beam could consist of foundation structure to support a vertical-axis hinge or pivot, the beam with its midpoint supported by and hinged at this pivot or hingepoint, mirrors mounted along the beam so as to be rotated about the local beam axis in accordance with the required mirror elevation angle, tension cables connected to the beam tips and means for controlling beam curvature. The beam

*Member AIAA

is a leaf spring consisting of two leaves, n pairs of bearings to support n mirrors, fewer than n pressure pads at various stations along the leaf spring to create and control a separation distance between the two leaves and a number of brackets including tip brackets. Each leaf can be a bar of spring steel arranged to resist vertical deflections while permitting horizontal deflections. Each bracket provides an offset point on one side of the leaf spring centerline; the offset distance is zero at the hinge, e at the tip, and a proportional fraction of e everywhere in between. The tip offset points are for pulley attachment while the others are for guiding cables.

Figs. 4 and 5 show a plan view of two main parts of the crossbow heliostat structure. One part is longitudinal trusswork with two hingepoints and four pulley points. The other part is a leaf spring beam with its brackets and with four separators capable of controlling the distance between the two leaves. These separators are hydraulically expanded pads or bellows. Fig. 4 also shows part of another leaf spring.

Fig. 4 Major components of heliostat array



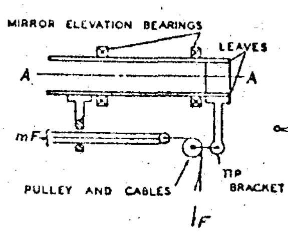


Fig. 5 Detailed view of crossbow beam tip

Not shown in these two figures are wheels and tracks for beam support, mechanical vibration dampers and angle control mechanisms. The wheels in the unit shown in Fig. 3 are bicycle wheels, one at each beam tip. For the longer beams depicted in Fig. 2, more than two wheels are used per beam. The tracks which engage these wheels can be curved pipes supported by heavy stakes driven into the ground. This process of driving stakes into the ground avoids the use of concrete, requires no digging or grading and is particularly appropriate for installing transportable structure which may be prefabricated. Unless extensive computer usage is planned, all of the tracks should be in one plane.

The main advantage of the crossbow configuration is the elimination of heavy and costly parts, particularly the use of fewer and simpler azimuth drives using cable systems rather than high torque, high precision gear boxes. As will be demonstrated there is not only a distinct reduction in the number of needed servo drives for azimuth angle controls but also the possibility of this for elevation angle controls. Futhermore, reducing the number of servo motors required per heliostat can provide some secondary benefits.

These secondary benefits of an increase in the ratio of the number of mirrors to the number of servos are simply the benefits of not being restricted (by servo costs) to having such large heliostat mirrors. First, there is reduced cost per square foot of mirror as smaller sizes encourage less expensive fabrication techniques. Second, area utilization is improved as will be discussed. A third advantage is wind load reduction considering the mirror to be an airfoil. Aerodynamic moment is more sensitive to chord than to span, being roughly proportional to the second and first powers, respectively. Wind moment loads constitute the main specification affecting the cost of heliostat drive systems.

III. Optical Requirements For The Beam

The main requirement of the crossbow beam and its system of controls has to do with its horizontal displacement, i.e., its rotation and flexure within a horizontal plane. At each mirror location, the tangent to its centerline (e.g., line AA in Fig. 5) must coincide with the elevation axis of a typical heliostat at that location. The continuous curve in a horizontal plane which satisfies this condition is called the optical locus. Three theorems from physics and geometry are

(1) Any surface which reflects parallel rays onto a single point is a paraboloid of revolution. See Fig. 6.

(2) The intersection of a paraboloid and a plane (e.g., a horizontal plane) is a conic section.

(3) If a conic section formed in this way is an ellipse, the projection of the axis of the paraboloid on the given plane is the major axis of the ellipse.

Therefore, for the optical locus to have tangents which satisfy requirements at all points, it must be a conic section. If the sun is directly overhead, this conic should be a circle. If the elevation angles were zero, the conic would be a parabola. Neglecting these two extremes, the optical locus should be an ellipse.

The only point on the optical ellipse

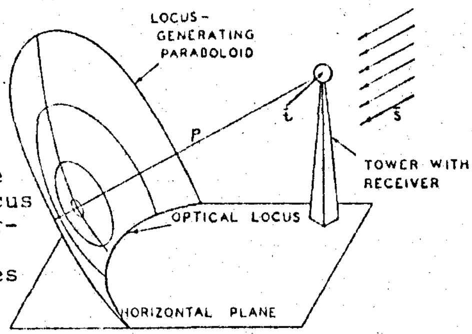
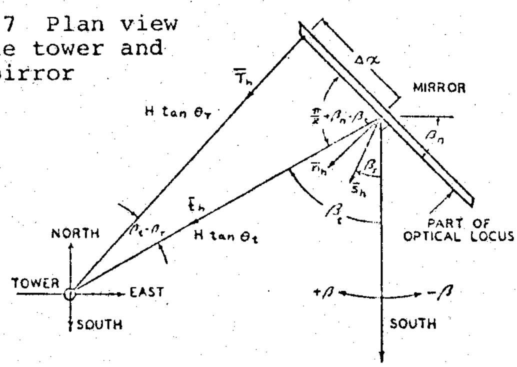


Fig. 6 The optical locus as an intersection of two surfaces

which is at a fixed location is the beam hingepoint. See Fig. 4. Being fixed, this point relates to the sun and receiver geometry like a conventional pedestal heliostat. For example, the normal to the optical locus at a hingepoint has azimuth equal to β_n. This azimuth, like the tilt (elevation) angle of the mirror is a function of the usual three sun-relating angles, λ, δ and τ. Fig. 7 represents the projection of some important angles onto the horizontal plane.

Fig. 7 Plan view of the tower and one mirror



IV. Nomenclature

a,b semiaxes (radii) of an ellipse
A,B curvefitting constants
c displacement of the ellipse
C damping constant (force/velocity)
e normal offset at beam tip bracket
E Young's modulus of elasticity
F resultant transverse cable force
g gain of servo amplifier
H tower height
I beam section moment of inertia
J mass moment of inertia of structure
K structural spring rate (force/displ.)
m mechanical advantage of pulley system
M beam bending moment
$\bar{n}$ unit mirror vector (outward normal)
2n number of mirrors per crossbow
p focal length of generating paraboloid
q,s coordinates of generating parabola
Q a generalized mirror position angle
R radius of curvature of beam
$\bar{s}$ unit sun vector (toward sun)
s complex variable in Laplace transforms
S semilength of crossbow beam
$\bar{t}$ unit tower vector (toward receiver)
T distance of mirror to receiver
x,y rotated and translated normal axes
LGP locus-generating paraboloid
β_n azimuth orientation of mirror normal
β_s azimuth orientation of sun
β_t mirror-to-tower ray azimuth orientation
θ_n mirror tilt angle (mirror from horizon.
θ_s sun zenith angle
θ_t mirror-tower distance angle
δ declination angle from celestial equat.
λ latitude on earth
τ time angle from local noon
ω natural frequency of some structure

Subscripts
c crossbow heliostat design
h horizontal plane projection of vector
n,N mirror normals
o output
p pedestal heliostat design
s sun
t,T tower
1,2 components

V. Generating The Optical Locus

From Riaz, (3) at any point where θ_t, β_t, etc. are applicable,

$$\tan\beta_n = \frac{\sin\theta_s \sin\beta_s + \sin\theta_t \sin\beta_t}{\sin\theta_s \cos\beta_s + \sin\theta_t \cos\beta_t} \quad (1)$$

where

$$\cos\theta_s = \sin\lambda \sin\delta + \cos\lambda \cos\delta \cos\tau \quad (2)$$

$$\sin\beta_s = \sin\tau \cos\delta / \sin\theta_s \quad (3)$$

$$\tan\theta_t = (\text{mirror-tower distance})/\text{tower height} \quad (4)$$

In Fig. 7, $\bar{t}_h$, $\bar{n}_h$ and $\bar{s}_h$ are projected unit vectors from the hingepoint in directions toward the target, normal to the mirror and toward the sun respectively. Consider a second mirror located a distance Δx from the first along the optical locus and denote its vectors by replacing t with T, etc. From Fig. 7, eq.(1) and the laws of cosines and sines, curvature can be determined.

$$H^2\tan^2\theta_T = H^2\tan^2\theta_t + (\Delta x)^2 + 2(\Delta x)H\tan\theta_t \sin(\beta_n - \beta_t) \quad (5)$$

$$\beta_T = \beta_t - \sin^{-1}\left[(\Delta x/H \tan\theta_T) \cos(\beta_n - \beta_t)\right] \quad (6)$$

$$\tan\beta_N = \frac{\sin\theta_s \sin\beta_s + \sin\theta_T \sin\beta_T}{\sin\theta_s \cos\beta_s + \sin\theta_T \cos\beta_T} \quad (7)$$

$$\beta_n' = \frac{d\beta_n}{dx} = \lim_{\Delta x \to 0}\left(\frac{\beta_N - \beta_n}{\Delta x}\right) = \frac{1}{R} \quad (8)$$

at the hingepoint.

Before determining other characteristics of the optical locus, it is convenient to find the focal length, p of the Locus-Generating Paraboloid (LGP). This length, together with the $\bar{s}$ unit vector determine the LGP surface as shown in Fig. 6. Now consider the plane containing unit vectors $\bar{s}$ and $\bar{t}$; since this plane contains the axis of LGP, its intersection with LGP must be the parabola which generated LGP, namely,

$$q^2 = 4ps \quad (9)$$

where q,s are coordinates in this plane parallel and perpendicular to $\bar{s}$ respectively. Since the hingepoint lies on both the $\bar{t}$ vector and on the optical locus which the LGP generates, it lies on the parabola and must be equidistant from the focal point and the directrix of the parabola. Since the distance between the directrix and the q axis is p, this equality and equation (9) yield

$$p = (T/2)\ (1 + \bar{t}\cdot\bar{s}) \quad (10)$$

which serves to determine p since both T and the dot product (the direction cosine between two known unit vectors) are known.

Now consider the vertical axial plane shown in Fig. 8. Since this plane also contains $\bar{s}$, eq. (9) also applies to its LGP intersection. Its intersection with the horizontal plane is given by the function of slope and intercept given in Fig. 8. Note that these intersections (lines) meet at two points; let 2a represent the distance between these two points. Solving simultaneously the two equations shown in Fig. 8,

$$q/p = 2\tan\theta_S \pm 2\left[\sec^2\theta_S - (H/p)\sec\theta_S\right]^{1/2} \quad (11)$$

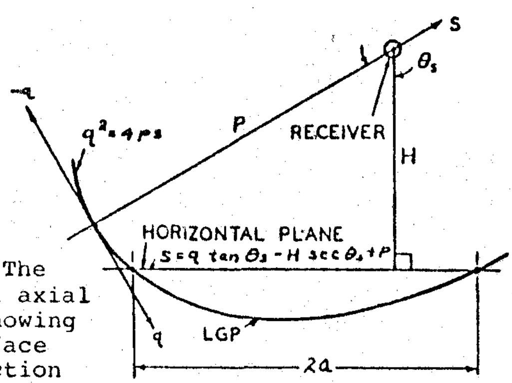


Fig. 8 The vertical axial plane showing two surface intersection lines

Let Δq represent the difference between the above plus and minus values and let Δs represent a corresponding s difference. Since these are perpendicular,

$$a = 2p\left[(1+4\tan^2\theta_S)(\sec^2\theta_S - H\,p^{-1}\sec\theta_S)\right]^{1/2} \quad (12)$$

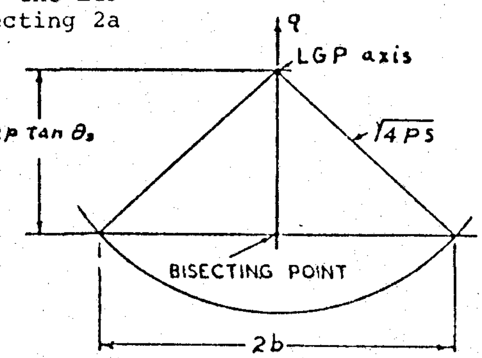
Likewise, consider the plane of Fig 9, a plane normal to the LGP axis bisecting the 2a length of the horizontal plane intersection. In terms of the coordinates of Fig. 8, the midpoint is located by dropping the second term of equation (11). Substituting the resulting q in the horizontal plane intersection equation,

$$s = 2p\tan^2\theta_S - H\sec\theta_S + p \quad (13)$$

In other words, using the coordinates shown in Fig. 8, eq. (13) represents the transverse plane shown in Fig. 9. Note that the intersection of this plane and the LGP is a circle having a radius given by q in eq. (9). Note also that the vertical leg of a triangle in Fig. 9 is the value of q previously determined from eq. (11). Noting it to be a right triangle and substituting equation (13),

$$b = 2p\left[\sec^2\theta_S - (H/p)\sec\theta_S\right]^{1/2} \quad (14)$$

Fig. 9 A plane normal to the LGP axis bisecting 2a



The optical tracking requirements of each beam can be summarized as follows:

(a) The beam, which is horizontal (and of length 2S) has a fixed vertical-axis hinge at its midpoint where its elastic centerline has the azimuth angle $\beta_n + \pi/2$

(b) This elastic centerline coincides with the optical locus which is an arc of an ellipse having axial diameters 2a, 2b.

(c) The azimuth angle of the axis of the ellipse is β_S.

Eqs. (1) to (14) have defined the optical locus as an ellipse which is a function of λ, δ & τ. The left half of Fig. 10 illustrates a family of "crossbow" beams determined in this way for the case where θ_S is 45 degrees. The right half of Fig. 10 is a corresponding family of iso-tilt (constant elevation angle) lines from the Riaz study [3] of continuum of mirror fields for the same parameter values.

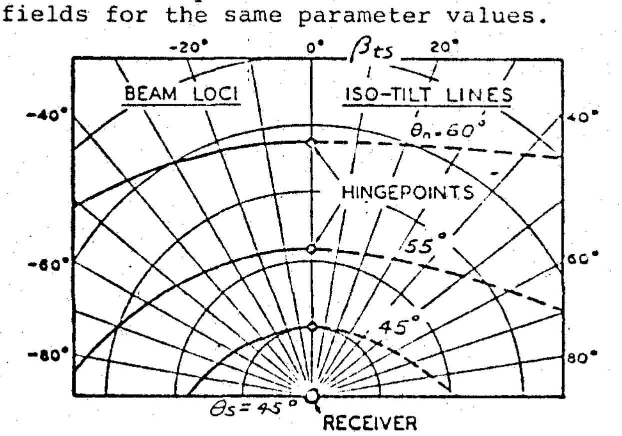


Fig. 10 Loci (solid) and iso-tilt lines

VI. Implementing Azimuth Control

One of the main purposes for seeking to develop the flexed beam (crossbow) type of heliostat is to achieve a reduction in azimuth channel costs by requiring fewer and simpler servo drives. To achieve this, a key step is replacing the elliptical optical locus with a curve which is more adaptable to a mechanically centralized implementation. An attractive candidate for this is the finite power series,

$$y = A\,(x+x_1)^2 + B\,(x+x_2)^3 + \ldots + k\,(x+x_z)^{z+1} \qquad (15)$$

which uses coordinates that involve a tangent to the ellipse shown in Fig. 11. The ellipse is defined by eqs. (12) and (14) and by the point of tangency from eq. (3). With this definition, no first power of x in eq. (15) can exist.

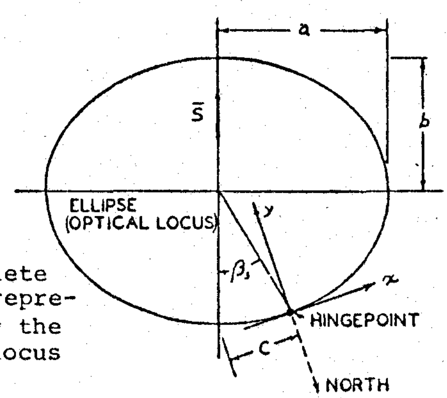


Fig. 11
The complete ellipse represented by the optical locus

Alternatively, the second power term can be a circular function. For large crossbow beams, more terms must be retained. For the small beam shown in Fig. 3, only the following was used:

$$y = A\left[1 - \left\{1-(x/A)^2\right\}^{1/2}\right] + B\left[x-c\right]^3 \qquad (16)$$

where c is a function of β_S in accordance with Fig. 11. In other words, the sum of a circular arc and part of a cubical parabola are used to curvefit the desired elliptical arc. Note that this sum is a curve which resembles a spiral.

The following simplifying assumptions are useful in estimating the curvefitting accuracy of this so-called spiral to part of the ellipse (the part with length 2S):

(1) For any sun position, mean slope error over any beam semilength S is the average of two values of $2\Delta y/S$ where Δy is the difference between eq. (16) and the ellipse of Fig. 11 at the midpoint of each semilength.

(2) The effect of the offset distance c can be considered simply by means of a linear interpolation between values of 0 and 1 for the ratio c/S. This is equivalent to interpolating between two special cases of the semicubic spiral, one where it is forced to become an arc of a circle and one where β_S subtends one semilength S (the condition where the corrective effectiveness of the cubical parabola component is maximized).

(3) The conditions which determine A and B of eq. (16) are that the tips of the beam lie on the optical locus and that the cosine of β_S is unity. Then

$$A = b/(2\,a^2) \qquad (17)$$

$$Ba^3/b = (a/c)^3\left[1-\left\{1-(c/a)^2\right\}^{1/2}-(c/a)^2/2\right] \qquad (18)$$

and the two special cases described in the preceding paragraph appear in Fig. 12.

Averaging between sunrise and sunset (for $\lambda = 35$ deg N. and $\delta = 0$), these approximations yield an average slope error of about 4.9 milliradians. This much error is acceptable for very small systems, particularly those with outputs under 10 KWe. For plants where the output is in megawatts, average tracking error should be no more than one or two milliradians and it appears that one additional correcting term from eq. (15) will be needed.

The main reason for selecting the tracking stategy represented by eq. (15) is ease of implementation, i.e., the ease of mechanizing constants A, B and c. The semicubical spiral consists of a cubical parabola (having magnitude and offset given by B and c, respectively) superimposed on a circular arc of radius A. A uniform beam with a uniform bending moment as shown in Fig. 13 yields constant curvature. One hydraulic control with gain B simultaneously introduces deformations on one leaf of the crossbow leaf spring so as to have maximum effect at one end and minimum effect at the other. A second hydraulic control acts to shift this pattern according to the value of c.

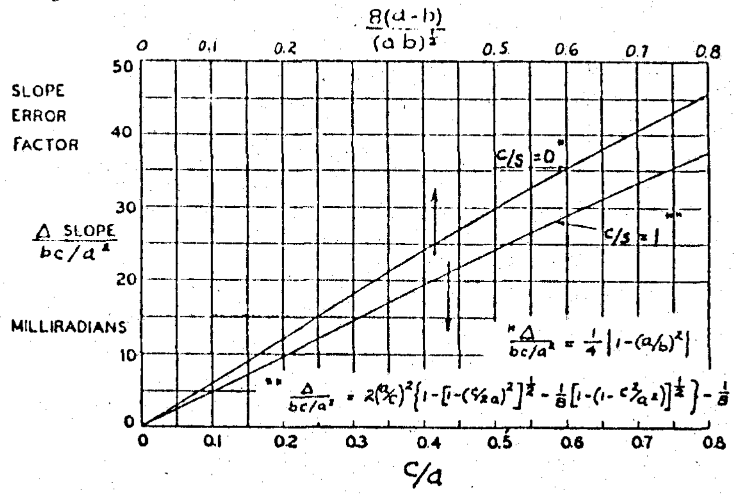
VII. Implementing Elevation Control

In the elevation angle channels, both the opportunities for economy and the difficulties which threaten to increase the crossbow system costs have to be considered. Among the latter, two are as follows:

(1) By itself, the crossbow beam has very little torsional stiffness. In larger systems, this requires all points on the beams to have high stiffness with respect to vertical deflections and all elevation control structural foundations to be built upon the telescoping dampers which interconnect at least two beams.

(2) Since the mirrors have no fixed position on the earth, output angle sensing can not be done using fixed optical heads located on the ground near the mirrors. They must be clustered around the receiver as shown in Fig. 2.

Fig. 12 FACTORS INVOLVING ELLIPTICAL RADII a & b AND OFFSET, C



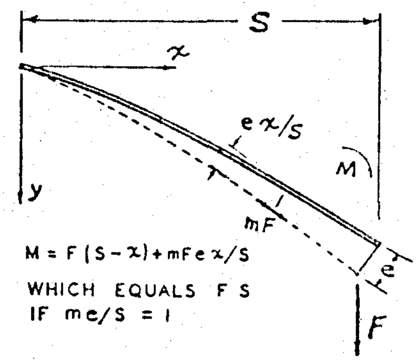


Fig. 13 Development of a uniform bending moment along a beam

The following appear equally important:

(3) As Fig. 10 shows, crossbow beams can be approximated by constant elevation requirements. All ten mirrors in Fig. 3 have the same tilt angles.

(4) Because of the above similarity, no shading losses occur by having adjacent mirrors almost touching each other. Thus, simple shaft-type couplings facilitate one servo drive controlling the elevation of a number of mirrors, e.g., ten in Fig. 3.

To the extent that items (3) and (4) offset items (1) and (2), the economic difference between crossbow heliostat tilt drives and pedestal heliostat tilt drives would be zero. However, this is a rather preliminary conclusion at this time as further research could change this.

VIII. Wind Response And Area Utilization

Like the area utilization factor, wind response is a separate factor to be considered in an economic evaluation of the merits of a heliostat design. In the crossbow heliostat, it is expected that structural stiffness and frequencies will be less than those of pedestal heliostats. To cope with vibrations, heavy dampers between adjacent crossbow beams have been designed for at least critical damping. But even with these dampers, the degradation of optical performance as a result of wind loads requires some attention. Extra storage, hybridization, etc. are examples.

For installations in windy areas, the combination of crossbow solar plants and small windmills are being considered. An attractive hybrid plant with 90% solar and 10% wind capacity can have almost constant output with respect to wind. However, it is not yet certain that the crossbow beam structure will always be associated with vibrations that will cause significant performance degradation due to wind.

In other words, while rigidity is always required for suitable wind resistance, this rigidity does not have to come from the crossbow beam. Instead, under certain conditions, it can come from the control system base. Fig. 14 illustrates the basic principles involved in this conclusion by comparing the block diagrams of the two heliostats using servo analysis techniques (Laplace transforms). The most important criterion for steady wind resistance is the amplitude of output angle per unit of steady change of aerodynamic moment load. This criterion, dQ/dM in Fig. 14 results from application of the final value theorem to each of the two heliostat transfer functions. In each case, two parameters are involved, a structural spring rate K and a servo gain g. If, for the crossbow, K_c is less than the corresponding K_p, the effective rigidity can still be as much as for the pedestal by increasing g_c above the g_p value. But it costs something to do this.

On the other hand, it costs something to not take advantage of the improved area effectiveness factor offered by the crossbow mirror configuration. This is true because of the characteristic which had been observed in Fig. 10; namely, the similarity between optical locus lines and lines of constant elevation angles.

Area effectiveness involves three types of losses, namely, sunlight striking the ground because of too much mirror-to-mirror separation, shadowing because of not enough mirror separation, and the incidence factor (cosine factor). In general, an ideal Fresnel mirror experiences only radial shadowing and radial and tangential incidence factors; however, if β_s is zero, it experiences no losses except radial incidence factor. Consider an array of quasi-concentric continuums of infinitesimal mirrors as Riaz postulated to have the same tangential area effectiveness characteristics as a Fresnel mirror. The area effectiveness characteristics of a mathematical model of this type are given in Fig. 8 of a study by Riaz [3]. Fig. 13 of that same study presents corresponding Houston data for arrays without the ribbonlike features.

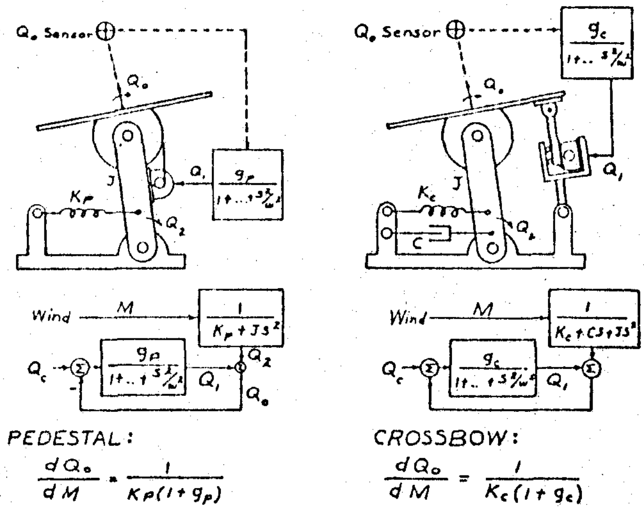


Fig. 14 Control and wind resistance models for pedestal (left) and crossbow heliostats

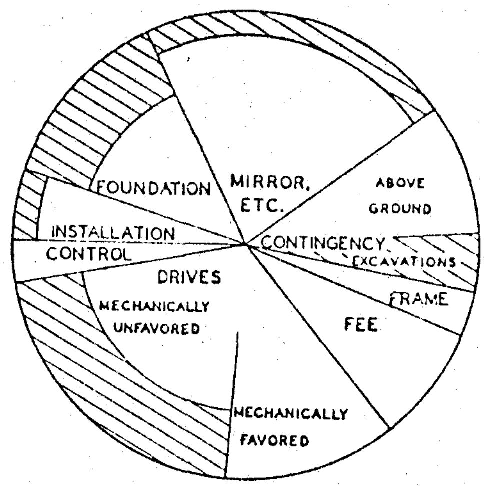


Fig. 15 Pedestal heliostat cost summary

Averaging this data over a 10-hour day, a comparison of the two yields a 0.778 ratio.

It is interesting that the paper (3) referred to was followed by a discussion in which Dr. Vant-Hull raised the question of the practicability of recovering lost area effectiveness by means of an array in which "heliostat locations are continually changed". It is still not clear how much of this approximately 22.2% utilization difference can be recovered by going from a pedestal to a crossbow design or how its importance compares with that of the loss in wind resistance by making this change. At present, it appears reasonable to assume that they just cancel each other.

IX. Observations And Conclusions

To anyone accustomed to heliostats requiring heavy concrete pedestals and large expensive gear boxes, the proposition that central receiver mirrors should be placed on beams slender enough to be flexed by means of cables may appear radical. This feeling soon disappears, however, as the designer encounters pleasant surprises and interesting ways to economize. One of them is that when a crossbow beam is forced in to its desired shape within a horizontal plane, the desired tilt angles of a group of adjacent mirrors mounted along this beam are approximately equal. In fact, in a small plant, as many as ten such mirrors can be gang driven by a single large tilt-control servomotor.

Considering the optical performance of point-focusing heliostats, two factors become important when comparing pedestal and crossbow heliostats, namely, utilization of area and degradation due to wind. In a small plant, the effects of these two tend to cancel each other. Assuming that they do, the remaining difference is mainly an effect on plant construction costs.

Fig. 15 shows a 10-sector breakdown of typical pedestal heliostat costs based on an 8-sector breakdown from Sandia Labs.(4) Two of the original sectors are shown as being split into two subdivisions, namely, the cost of drives and the contingency fees. The assumptions behind these splits are an estimated 2:1 ratio of weight of materials required for the two drives and a 30% allocation of contingencies for the hazards of excavations and earthmoving operations in the desert, respectively.

The unshaded part of Fig. 15 can be used to represent the estimated cost of an equivalent crossbow heliostat. Five of the original ten sectors are essentially unaffected by this change. The excavation contingency is eliminated. By reducing the weight of materials used in the foundation and unfavored (azimuth) drive to less than one third, it is estimated that these costs are halved. A 20% reduction in the other two sectors is assumed due to numerous production conveniences made possible by the crossbow design including ease of prefabrication. Based on removing the shaded area from Fig. 15, a saving of 26.4% of the cost of heliostats results.

References

(1) Goddard, R. H.: U.S. Patent 1,951,404

(2) Raser, W.H.: U.S. Pat. ASN 747,561 and its CIP. See also U.S. Pat. 3,872,854

(3) Riaz, M.R.: A Theory of Concentrators of Solar Energy on a Central Receiver for Electric Power Generation, Engineering For Power, Vol. 98, No. 3, July 1976

(4) Sandia Laboratories: Recommendations for the Conceptual Design of the Barstow Solar Central Receiver Plant, SAND77-8035 (UC-62), Albuquerque, N.M., Oct. 1977

Commendation

Whereas, RICHARD RASER, 1st place winner Inventors Workshop International,

having devoted generously of services to the California Museum of Science and Industry to the end of supporting and embellishing its unique image as a highly motivating educational institution and

Whereas, this deep personal interest in the Museum has benefited thousands of California citizens of all ages;

Be it therefore resolved that commendation is bestowed by the California Museum of Science and Industry.

President, Board of Trustees
California Museum Foundation

President
California Museum of Science and Industry

Appendix C.

SHELDON C. PLOTKIN, Ph.D., & ASSOCIATES
Systems Engineering Consultants
9911 West Pico Boulevard, Suite 800
Los Angeles, California 90035
(213)277-2793

RESUME OF SHELDON C. PLOTKIN

Education

BSEE from the University of Colorado in 1946; BSAeroE from the University of Colorado in 1949; and PhDEE from the University of California, Berkeley, in 1956.

Professional Experience (partial description only)

Private Consulting Practice -- 1971 to present.
Alternate energy systems and smog-free engine development. Accident and safety analyses including reconstruction, design, human factors, and mathematical formulation for vehicle accidents, highway design, slip and fall accidents, human impact, electrical explosions, escalator and elevator safety, product design, tire failures, and criminal evidence.

RAND Corporation, Santa Monica, California -- 1969 to 1971.
Senior Engineer in the Engineering Sciences Department working on development of a variety of systems, including communication and transportation.

TRW Systems, Redondo Beach, California -- 1967 to 1969.
Senior Staff Engineer, ESD System Engineering Laboratory, working on automatic highway and high speed ground transportation development, large scale failure modes, automobile safety studies, and train air suspension. Also worked on numerous civil system developments.

Hughes Aircraft Company, Culver City, California -- 1961 to 1967.
Staff Engineer for G&C Advanced Systems Laboratory, Research Laboratories (Malibu), and Mathematics Consultation Department. Performed dynamic analyses, advanced control systems design, communication system analyses, mathematical modeling, and automobile system development. (Originated IR radar concept for vehicle control.)

University of Southern California, Los Angeles, California -- 1958 to 1961.
Assistant Professor in charge of both graduate and undergraduate electronics courses plus redesign of electrical engineering laboratories.

Hoffman Electronics Corporation, Los Angeles, California -- 1959 to 1961.
Consultant in the Communications Systems Department.

Energy Systems (formerly Levinthal Electronic Products), Palo Alto, California -- 1956 to 1958. Senior Project Engineer for design and safety of high voltage, high power pulse modulators.

University of California, Berkeley, California -- 1950 to 1956.
Teaching Assistant (1950 to 1954) in the EE Department. Project Engineer (1954 to 1956) for the Cosmic Ray Laboratory in charge of equipment and operation.

U.S. Naval Air Missile Test Center, Point Mugu, California -- 1949 to 1950.
Conducted and evaluated missile flight tests as an Aero and Electrical Engineer.

Los Alamos Scientific Laboratory, Los Alamos, New Mexico -- 1946 to 1947.
Design and construction of electronic equipment.

Professional Affiliations

Professional Safety Engineer, S.S.S., I.E.E.E., Pi Mu Epsilon, Eta Kappa Nu, and Sigma Xi.

Publications and Seminars

Many papers and reports in the public literature on various systems engineering topics plus several hundred company-private documents. ACCIDENT AND PRODUCT FAILURE ANALYSES (book). "Introduction to Accident, Safety, and Forensic Engineering" (seminar).

RESUME OF JACK R. JENNINGS

Education

BSEE in 1952; MSEE in 1953; and PhD Information and Control Engineering in 1962, all from the University of Michigan at Ann Arbor.

Professional Experience (partial description only)

TRW Systems, Redondo Beach, California -- 1979 - present. Senior Project Engineer for the MX missile project.

Hughes Aircraft Company, Culver City, California -- 1976 - 1979. Senior Staff Engineer engaged in mathematical modeling, deriving of Roland CW engagement system predictions, and development of CCM techniques for the TOW missile system.

McDonnell Douglas Aircraft Company, Long Beach, California -- 1975 - 1976. Development of algorithms for mechanically positioned tracking radars.

Litton Industries, Beverly Hills, California -- 1974 - 1975. Guidance and Controls Laboratory work on surface effect ships, mathematical modeling and control system design.

McDonnell Douglas Corporation, Long Beach, California -- 1972 - 1974. Infrared digital guidance and control technology development plus radar algorithms for missile aquisition and tracking.

Litton Industries, Beverly Hills, California -- 1971 - 1972. Supervisor of Advanced Analysis Controls for AMTD doing analytical propulsion design.

RAND Corporation, Santa Monica, California -- 1970 - 1971. Senior Engineer performing advanced communications satellite system analyses of adaptive antenna array stability and attitude control and station-keeping systems. Contributed a new analysis of stable orbits as well as linear induction motor and air cushion analyses for a high speed train application.

TRW Systems, Redondo Beach, California -- 1967 - 1970. Senior Staff Engineer working on dispatching criteria for high speed ground transportation development plus longitudinal control of "functional trains". Contributed the automatic control system design for the Washington Subway proposal as well as mathematical modeling for tracking errors in ASW. Performed as Project Manager for design and testing of spacecraft attitude control systems using control moment gyro actuators and strapdown attitude reference systems with digital computer data processing and control.

Hughes Aircraft Company, Culver City, California -- 1964 - 1967. Senior Staff Engineer designing on-line computer programs, simulation of staging dynamics and attitude control system design for various space vehicles. Also developed a linear dynamics analysis software program.

Aerospace Corporation, El Segundo, California -- 1963 - 1964.

Space Technology Laboratory, Redondo Beach, California -- 1961 - 1963. Spacecraft and MIR/V control system development.

University of Michigan, Ann Arbor, Michigan -- 1954 - 1960. Instructor for "Electronic Differential Analyzer", "Instrumentation", "Nonlinear Systems", and "Advanced Automatic Control Systems".

Douglas, Dow-Corning, and Textron -- 1948 - 1954. Programming, dielectric testing and vibration test equipment development.

Professional Affiliations

Sigma Xi, Phi Kappa Phi, Tau Beta Pi, Eta Kappa Nu, Phi Theta Kappa, National Honorary Society, and John F. Dodge Fellow.

Publications and Seminars

Multitude of company papers and reports on control systems, computer programs, and mathematical techniques. UCLA courses "Introduction to Linear Control and Systems" and "Nonlinear Differential Equations".

RESUME OF WILLIAM H. RASER

Education

BSEE in 1942 from Pennsylvania State University; MSAeroE in 1946 from New York University; graduate courses at Yale, USC, and UCLA.

Professional Experience (partial description only)

Hughes Helicopters, Culver City, California -- 1975 - present. Senior Staff Engineer performing fire control and dynamic systems control analyses besides computer simulation and software for hydraulic analyses and flight data reduction. Mathematical analyses of ground resonance characteristics and error budgets using covariance propagation techniques as well as multi-channel analyses of random data and stability criteria for servos on elastic foundations.

Loyola Marymount University, Los Angeles, California -- 1971,2 - 1973,4. Assistant Professor of Electrical Engineering teaching control systems, digital circuits, electric motors and telephone circuits.

Northrup Corporation, Hawthorne, California -- 1972 - 1973. Teaching and consultation to the Page Communications Company in Teheran, Iran.

Datatrace Incorporated, Carson City Nevada -- 1966 - 1970. Consultant responsible for design and production of first low cost graphic data digitizing computer peripheral.

McDonnell Douglas Corporation, Long Beach, California -- 1968 - 1970. Senior Staff Engineer performing stability analyses for the DC-10.

Teledyne Incorporated, Hawthorne, California -- 1966 - 1967. Analyses of stationkeeping flight modes for the Sikorsky-IHADDS system.

Systems Technology Corporation, Hawthorne, California -- 1964 - 1965. Senior Engineer performing advanced concepts development studies.

Hughes Helicopters, Culver City, California -- 1961 - 1964. Senior Research Engineer performing advanced dynamics control systems analyses.

Sikorsky Aircraft, Stratford, Connecticut -- 1954 - 1961. Supervisor for Preliminary Structural Dynamics. Responsible for all analytical and test request operations within the General Design Department relating to structural and control dynamics including all aspects. Projects involved ground resonance, blade flutter, turbine fuel governing instability, servo design and autopilot specification. Also performed work on nuclear warhead delivery programs.

Sperry Gyroscope Company, Long Island, New York -- 1952 - 1954.
North American Aviation, Downey, California -- 1950 - 1951.
Link Aviation, Binghampton, New York -- 1949 - 1950.
Boeing Aircraft, Seattle, Washington -- 1947 - 1949.
Performed numerous tasks having to do with autopilot control, trainer development, general control systems, and helicopter aerodynamics analyses.

Professional Affiliations

IEEE, Sierra Club, California Solar Energy Association, AIAA, Tau Beta Pi, Eta Kappa Nu.

Publications

Numerous company documents on control systems and mathematical analyses. Several papers in published literature on control theory. one paper on solar energy (see Appendix A). FATIGUE OF METALS (book), coauthored, published by J. Wiley and Sons.

UNSOLICITED PROPOSAL

FOR

CROSSBOW CONTROLLED HELIOSTAT

DEVELOPMENT

PART II. COST SECTION

by

S.C. Plotkin & Associates
9911 W. Pico Boulevard
Suite 800
Los Angeles, California 90035

Contract Pricing Proposal

From

S.C. Plotkin & Associates
9911 W. Pico Boulevard, Suite 800
Los Angeles, California 90035

Final Output

(1). Completed 60 W table model crossbow system, heliostats only.

(2). Microprocessor software program for heliostats control.

(3). Completely integrated 6 Kw system including "off the shelf" Stirling engine receiver.

Detailed Description of Cost Elements

1. Direct Material

Mirrors	$ 5,000.00	
Computer, peripherals, test accessories	$25,000.00	
Motors	$ 3,500.00	
Meters and sensors	$ 1,500.00	
Iron and cables	$ 5,000.00	
Miscellaneous	$ 5,000.00	
		$45,000.00

2. Material Overhead

10% of Direct Material	$ 4,500.00

3. Direct Labor

	Estimated Hours	Estimated Costs
S.C. Plotkin	1,000 hrs @ $25.00/hr.	$20,000.00
W.H. Raser	2,000 hrs @ $15.00/hr.	$30,000.00
J.R. Jennings	2,000 hrs @ $17.50/hr.	$35,000.00
Machinist	2,000 hrs @ $10.00/hr.	$20,000.00
Production technician	2,000 hrs @ $7.50/hr.	$15,000.00
		$120,000.00

4.	Labor Overhead		
	Engineering Department @ 157% x Direct Labor		$188,400.00
5.	Special Testing		
	none		
6.	Special Equipment		
	Stirling receiver, 6 Kw output		$ 3,500.00
7.	Travel		
	a. Transportation		
	(1) Los Angeles - Oakland, 4 @ $118.00	= $ 472	
	(2) Los Angeles - Washington, 4 @ $612	= $2448	
	b. Per diem		
	(1) Oakland, 4 @ $70.00	= $ 280	
	(2) Washington, 3 x 4 @ $70.00	= $ 840	
			$ 4,040.00
8.	Consultants		
	none		
9.	Other Direct Costs		
	none		
10.	Total Direct Cost and Overhead		$365,440.00
11.	General and Administrative Expense		
	@ 10% of Direct Labor and Overhead		$ 36,544.00
12.	Royalties		
	none		
13.	Total Estimated Cost		$401,984.00
14.	Profit @ 8%		$ 32,159.00
15.	Total Estimates Cost and Profit		$434,143.00

Business Information

S.C. Plotkin & Associates has employed only S.C. Plotkin on a full-time basis for nine (9) years. All Associates, numbering approximately twenty (20), have been part-time thus far, contributing specific talents to specific short-term projects. Funding of this proposal will allow for the following expansion of personnel, facilities, and activities:

1). Employment of at least seven (7) full-time people as well utilizing S.C. Plotkin's services half-time.

2). Leasing of approximately 2400 sq. ft. of development area for an estimated $2400/month.

3). Aquisition of tools, machinery, and test apparatus for the development work proposed. Dr. Jennings and Mr. Raser will both loan their lathes, tools, drill press, and personal test apparatus to the project. Additional items will be purchased with either contract funds or separate financing if necessary. (All fabrication over the past two years has been by Mr. Raser using his own personal equipment and facilities which will all be made available to the project on a loan basis.)

4). The office manager to be hired for this project will be Ms. Angel Gabriella, whose talents besides the entire array of office skills required includes intricate welding capability and mechanical systems experience. A bookkeeping system compatible with Federal Government criteria and requirements will be established.

Previous technical activity of S.C. Plotkin & Associates is reflected in the resume' of Dr. Plotkin. Specific civil system activity over the past nine (9) years besides solar thermal energy system development and safety system analyses includes a cryogenic internal combustion engine modification to meet long-term air pollution standards by creating a synthetic atmosphere (with Dr. Jennings). Another project is the substantial reduction of freeway traffic by increasing vehicle occupancy through use of advanced (and as yet untried) human factor techniques. Finally, it should be noted that Mr. Raser has developed an advanced Stirling engine ~~which~~ concept is based upon the use of relatively inexpensive bellows rather than pistons.

Thid proposal is submitted for use in connection with and in response to an unsolicited proposal entitled "Crossbow Controlled Heliostat Development".

Sheldon C. Plotkin, Ph.D., P.E.
S.C. Plotkin & Associates

Sheldon C. Plotkin
Principle Investigator

March 17, 1980
Date

United States Patent [19]

Rasèr

[11] **4,147,414**

[45] **Apr. 3, 1979**

[54] **SUNLIGHT CONCENTRATOR FOR ENERGY CONVERSION**

[76] Inventor: William H. Raser, 6451 W. 83rd St., Los Angeles, Calif. 90045

[21] Appl. No.: **899,244**

[22] Filed: **Apr. 24, 1978**

Related U.S. Application Data

[63] Continuation-in-part of Ser. No. 747,561, Dec. 16, 1976, abandoned.

[51] **Int. Cl.**[2] **G02B 5/12; F24J 3/02**

[52] **U.S. Cl.** **350/289; 126/270; 353/3; 350/304**

[58] **Field of Search** 126/270, 271; 353/3; 350/289, 304

[56] **References Cited**

U.S. PATENT DOCUMENTS

1,951,404	3/1934	Goddard	126/270
3,009,391	11/1961	Zagieboylo et al.	353/3
3,872,854	3/1975	Raser	126/270
3,905,352	9/1975	Jahn	126/270

Primary Examiner—Henry C. Yuen

[57] **ABSTRACT**

A system of mirrors which focuses solar radiation onto a receiver by means of controlled flexural deformations of supporting beams using controls which tilt the mirrors with respect to the beams. This combination of flexure and tilt causes the mirrors to track the sun using an inexpensive system of controls. The use of cables, of parts which can have shorter ranges of operation and of fewer controls than conventional heliostats all contribute to cost reductions.

13 Claims, 5 Drawing Figures

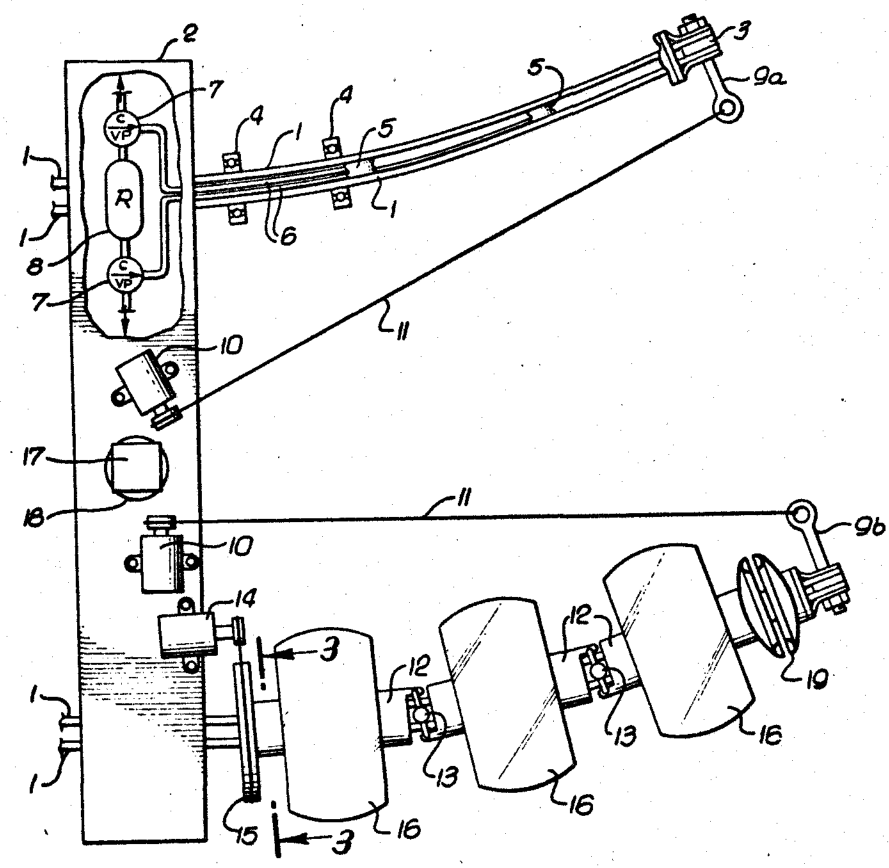


FIG. 1.

FIG. 4.

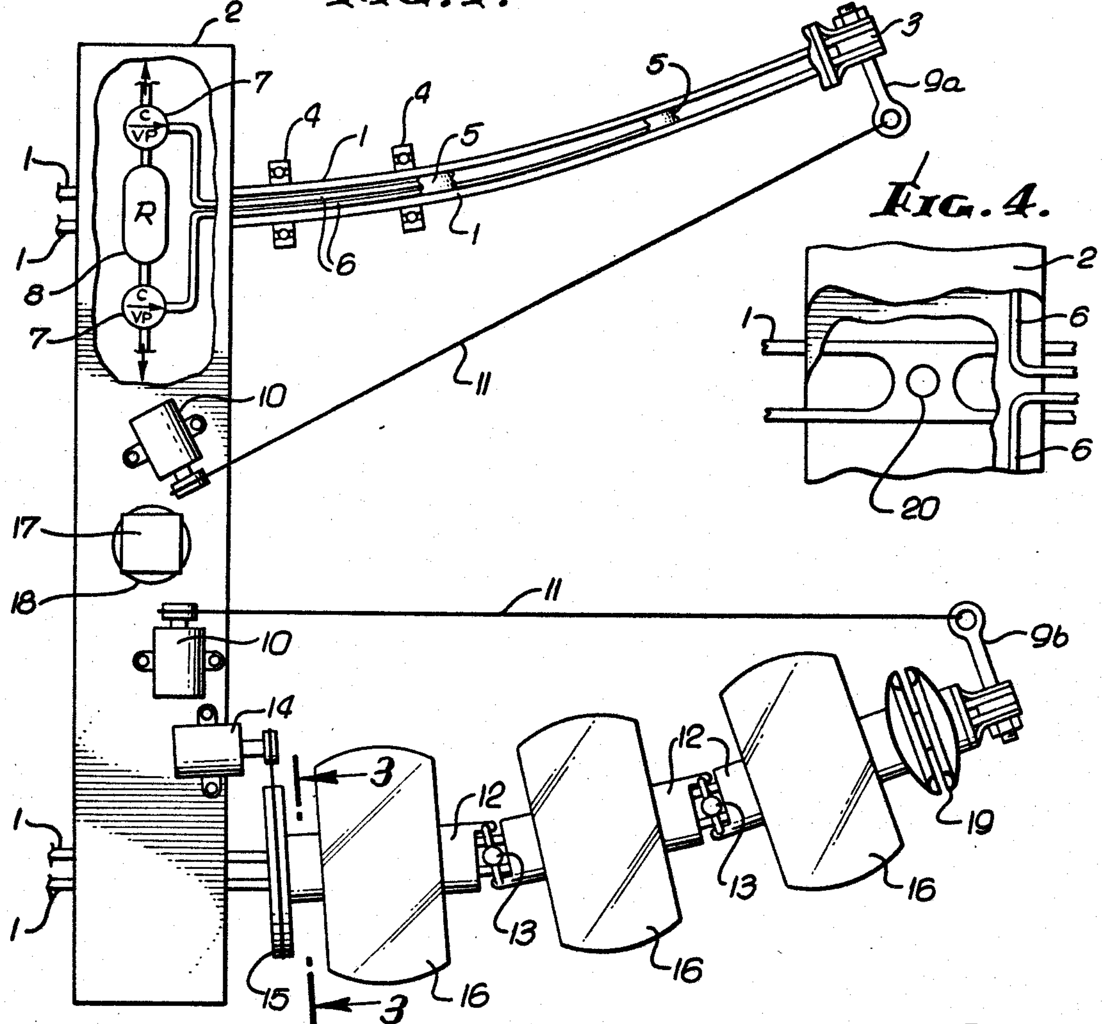


FIG. 3.

FIG. 2.

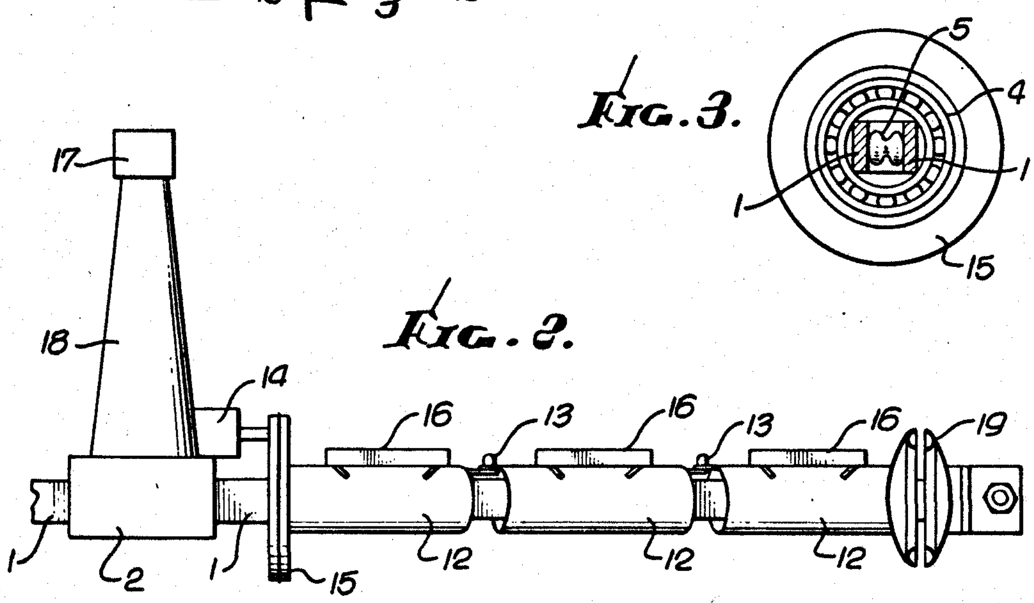


FIG. 5.

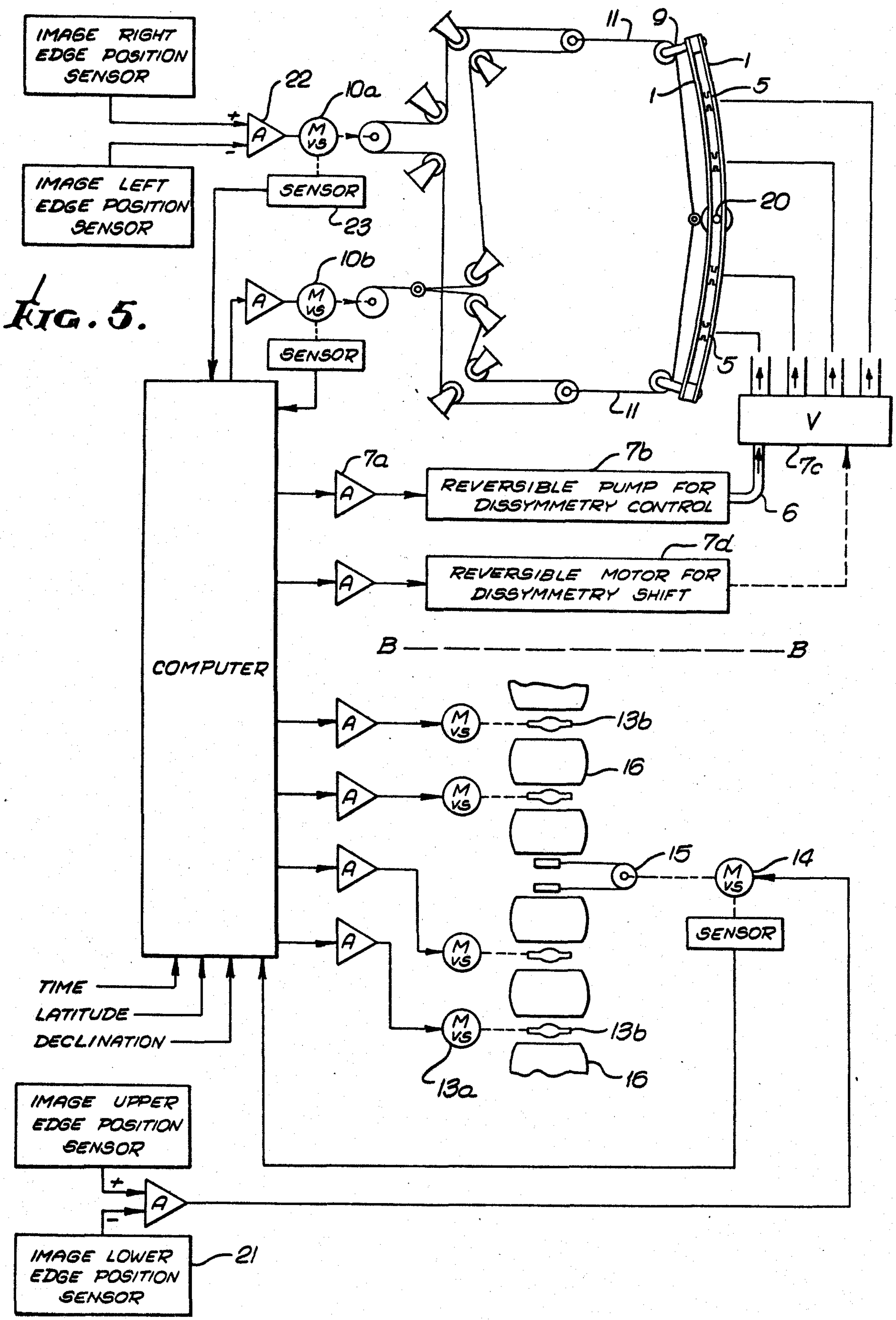


IMAGE RIGHT EDGE POSITION SENSOR
IMAGE LEFT EDGE POSITION SENSOR
SENSOR
SENSOR
COMPUTER
REVERSIBLE PUMP FOR DISSYMMETRY CONTROL
REVERSIBLE MOTOR FOR DISSYMMETRY SHIFT
V
B
B
SENSOR
TIME
LATITUDE
DECLINATION
IMAGE UPPER EDGE POSITION SENSOR
IMAGE LOWER EDGE POSITION SENSOR
22
10a
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7d
6
13b
16
15
14
13a
21

SUNLIGHT CONCENTRATOR FOR ENERGY CONVERSION

This application is a continuation-in-part of my co-pending application Ser. No. 747,561 filed Dec. 16, 1976, now abandoned, carrying the same title as this application.

Reference Cited: U.S. Pat. Nos.

1,951,404; March, 1934; Goddard; 126/270

3,872,854; March, 1975; Raser; 126/270

3,009,391; November, 1961; Zagieboylo et al.; 1353/3

3,905,352; September, 1975; Jahn; 126/270

Also co-pending Application Ser. No. 747,561.

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to equipment which produces heat from reflected sunlight. One use for this heat is the generation of electric power.

2. Description of the Prior Art

Solar power plants confront the designer with three major challenges, namely, the need to (1) minimize cost in order to be competitive, (2) achieve accuracy in order for high radiation concentration to permit high efficiency in the thermal conversion process, and (3) obtain stability in spite of possible strong winds. This invention is an improvement with respect to all three because it (1) reduces the requirements for precise and expensive parts such as gears, (2) obtains leverage by using tracking drives with greater mechanical advantage, and (3) utilizes the stabilizing effects of base structure breadth and viscous damping.

At present, large mirrors, which are called heliostats when positioned to track the sun, are mounted on pedestals with two directions of position control. These two directions of control correspond to position angles known as azimuth and elevation position angles (like a telescope). The controls and drives which impose these two tracking angles consist of two geared motor systems (servomechanisms). These servomechanisms can be large and expensive if wind imposes appreciable loading. A thousand or more heliostats may be used; the cost of their controls and drives (servomechanisms) has been over ⅓ of all concentrator costs.

FEATURES OF THE INVENTION

My invention reduces the number of azimuth servomechanisms required to a number which is less than the number of heliostats. The arrangement of the heliostats is as if shafts forming elevation angle axes were laid end to end. This array of shaft lengths is implemented by using a flexible or slightly elastic beam. This beam could be initially straight and then deformed in place by means of cables at the tips with reels to introduce tension into the cables. Hydraulic expanders inside the beam cause local stiffness increases in a way which manipulates the distribution of curvature of the beam.

SUMMARY OF THE INVENTION

The primary object of this invention is to provide the high concentration of sunlight required for efficient energy conversion using fewer and less expensive components. This objective is implemented in two ways. First, the array of heliostats is configured to permit the use of both fewer and smaller tracking servomechanisms, e.g., smaller total output range requirements. Second, less expensive components are used, e.g., cables

instead of gears, long beams instead of heavy individual pedestals, etc.

A very simple analogy for indicating the potential economy of the invention is the boom of a simple sailboat. Sailors today control the azimuth angle of the boom very well using a cable attached to the tip of this boom. However, if, instead, a strong gearbox were introduced between the mast and the boom so that the sailor introduced the desired angle of the boom by means of a crank without use of cables, the gears in the gearbox would be large and expensive and the sailboat would cost more. One reason why a cable drive is less expensive than a gear drive is its adaptability to attachment out of the point of maximum movement where the mechanical advantage is greatest and the forces involved become the smallest.

Additional objectives include prefabrication capability if not outright mobility, suitability in high winds and adaptability to unprepared ground. The latter refers to grading and other physical preparation only; preparation in the form of surveying and mapping will still be required. This is because the operation of the servomechanisms involves computer usage, i.e., some of the topographical data for the site will be stored and used by a computer.

The use of cables is essential to achieving the primary objectives. Goddard has employed structure with flexural deformation which satisfies optical requirements and which is provided by cables. In other words, Goddard used cables to achieve economical construction of a mirror strip having adjustable horizontal curvature. My U.S. Pat. No. 3,872,854 disclosed mirror structure with torsional deformation implemented using cables. It enabled economical adjustment in the other direction, e.g., in elevation rather than in azimuth control. A further objective of the present invention is to obtain construction which provides economical adjustment (tracking control) in both azimuth and elevation.

BRIEF DESCRIPTION OF THE DRAWINGS

One exemplary but not-specifically-limiting embodiment of the invention is illustrated five figures of the accompanying two sheets of drawing, in which:

FIG. 1 is a plan view of the solar power plant with some parts cut away.

FIG. 2 is an elevation view of this plant.

FIG. 3 is a partial section elevation view along the line 3—3 of FIG. 1. FIG. 3 shows mainly a generally concentric relationship between primary structure and some supported elements.

FIG. 4 is a part of the FIG. 1 view showing some additional details of a slightly different embodiment.

FIG. 5 is a combination of schematic and plan view of details of the more important control elements in both the azimuth drive means (shown above line B—B) and the elevation drive means (shown below line B—B).

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The primary structures forming the heliostat mirror mountings are leaf springs. Each such spring consists of two parallel steel bars 1 fixed to a structural base 2 at one end and separated by a thin spacer, 3 at the other. Although not shown, additional spacers may be required for support at stations where bearings 4 are placed around the bars. Elsewhere between the bars are located a plurality of hydraulic pads 5 along the length.

Each hydraulic pad **5** is actually a small high-pressure bellows connected to a pressure line **6**. Each of these lines is pressurized by a variable pressure control **7** which is supplied by a hydraulic reservoir **8**. Each pad controls the separation distance between the bars at the station where it is located and enough pads are used to match accurately any desired distribution of separation distance along the length. Since the flexural section moment of inertia is proportional to the square of the distance separating the centroids of the two bars and since the curvature per unit of moment applied is inversely proportional to this section property, the distribution of slope is controlled by these hydraulic components **5**, **6**, **7**, and **8**. This type of control requires sensing and computing means.

The leaf spring in the upper part of FIG. **1** has an eye **9***a* at its free end. This particular leaf spring is shown with curvature in the direction which corresponds to the case of no applied moment. A positioning motor **10** and a cable **11** are attached to eye **9***a* and apply tension and resulting bending moments.

The lower part of FIG. **1** shows another leaf spring which is complete and which carries eye **9***b* at its tip. Due to tension in a cable **11** to this eye, this particular leaf spring is forced to curve inward. With the proper separation distance between the pair of bars **1**, **1** as determined by controlled pad pressure, the shape of the curve is that of part of a conic section (usually an ellipse).

By means of bearings **4**, **4**, three sleeves **12**, **12** are mounted on each leaf spring between the base and the tip. At each place where there sleeves meet, a connecting link **13** having its length controlled by a small motor spans the distance between connecting points on each of the two confronting sleeves to introduce differential sleeve rotations. These variable-length links, together with protruding fingers or whatever serves as connecting points for these links, constitute differential gear mechanisms or the equivalent. The differential sleeve rotations are just like differential elevation angles for whatever is mounted on the sleeves. In airplanes, variable length links employing motor driven turnbuckles are used to rotate trim tabs and ailerons.

The rotation angle of each innermost sleeve is determined by a positioning motor **14** and its driven sprocket **15**. Therefore if the two interfacing link mechanisms **13**, **13** introduce differential (incremental) sleeve rotations, the tilting of the outermost sleeve about the longitudinal axis of the leaf spring will be an innermost sleeve angle plus two incremental sleeve rotations.

A mirror **16** is fixed to each sleeve. With this arrangement, the mirrors are able to concentrate sunlight on a central receiver **17** on top of a tower **18** which rests on the base **2**. To do this, each mirror must be tilted to the correct elevation (sleeve rotation) angle, the length of the leaf spring immediately supporting each sleeve **12** must have the correct azimuth angle, and there must be no significant vibrations due to the wind. A viscous damper **19** is inserted between the outermost sleeve and the tip of the leaf spring to suppress torsional vibrations. Such a device is the angular equivalent of a dashpot or shock absorber. Likewise, viscous circuitry of a similar nature can be introduced into the pad lines **6**, **6** to suppress horizontal plane vibrations. The spring bars **1**, **1** are very stiff in the vertical direction.

FIG. **1** shows two leaf springs cantilevered from the base **2** toward the right hand side. It also shows parts of four bars **1** which are intended to represent two additional similar leaf springs cantilevered toward the left hand side. Therefore, two points exist where a leaf spring extends outward in both directions. Such points are center points for pairs of cantilevered beams; such pairs resemble the beams of crossbow weapons and are called crossbow beams.

As shown in FIG. **4**, a second embodiment of the invention differs from the first primarily in that the two center points are hinge points instead of fixed crossbeam attachments. Each hinge consists of a vertical pin **20** serving as a vertical axis about which a pair of leaf springs can rotate. This pair of leaf springs consists of four bars **1**, **1**. However, since this second method of fabrication involves use of bars having this full (double) length of the crossbow beams, each of what would be called a pair of springs in the first embodiment is now a single leaf spring having two leaves. The length of each of these leaves corresponds to twice that of a bar **1** in the first embodiment. A pair of these leaves is now called a hinged beam. As a consequence of the hinges at the beam midpoints, these beams can now be flexed to perfect optical alignment of all mirrors **16**, **16**. Perfect optical alignment means that, for any position of the sun, a sunbeam coming to the center of every mirror **16** will be reflected toward the center of the receiver **17**. In other words, the azimuth and elevation angles of each mirror must be unique functions of sun position.

Consider the case where the sun is directly overhead. In this case, the beam tips are pulled inward strongly and the pads are programmed to cause uniform curvature. In other words, each leaf spring beam forms an arc of a circle of some radius R. The differential sleeve angles are set to zero and the most inboard sleeves are set at half the angle whose tangent is R/h where h is the tower height. Another simple example is where the sun and the receiver are both very low; in this case, the leaf spring beams must be shaped into parabolas. For intermediate positions of the sun, perfect optical alignment will require each hinged beam to conform to the shape of part of an ellipse.

The reason for this can be demonstrated using the laws of physics. At each point where optical reflection occurs, the angle of incidence equals the angel of reflection. Because of this equality, any surface capable of reflecting all parallel radiation (such as direct sunlight, approximately) onto a target point T must be a paraboloid of revolution having its axis both intersecting T and being parallel to the sunlight. Therefore, every mirror must have the azimuth and elevation angles at its center point, P equal to the azimuth and elevation angles of a plane tangent at P to a paraboloid satisfying the following three conditions: (1) it intersects P, (2) it has an axis TS where S is the center of the sun, and (3) it has a focal length extending from its vertex to T. It is possible to calculate all the azimuth and elevation angles along the beam from these conditions and from the fact that the beam centerline is a continuous curve.

This beam centerline lies in a horizontal plane. For perfect optical alignment, the shape of this beam centerline must be such that every mirror azimuth angle must coincide with that of the tangent to the beam centerline at the mirror centerpoint. Therefore, the conditions for perfect optical alignment are satisfied provided the beam centerline fits the desired curve, provided each bearing **4** is mounted concentric to the beam centerline and provided there is very small separation distance between each two bearings **4**, **4** on which is mounted each sleeve **12**.

As long as each beam remains in one plane, the shape of its desired centerline curve is always known. From analytic geometry, it is known that the intersection of a paraboloid and a plane is a conic. In general, this conic takes the form of an ellipse. Enough hydraulic pads 5, 5 are employed to caause the shape of each beam to be a close approximation to a part of whatever desired ellipse corresponds to a give sun position. As the direction of the sun changes, the parameters defining each ellipse change. At the same time, the servomechanisms 13, 14 which control elevation angles (sleeve rotations) are equally busy. In this way, perfect optical alignment is theoretically possible and is actually closely approximated.

Other embodiments are obvious. Higher concentrations can be achieved by having more than three mirrors on each side of a beam, by having more than two beams, and, sometimes, by having the receiver at other than the center location of the base. For simplicity, the unloaded centerlines of all beams can be straight lines and the sensing devices for angle position control can be a combination of optical (photovoltaic) and mechanical (wire reeling) means.

A minimum of four such photovoltaic optical sensing means are required. One of the four is a combined reflected image lower edge position sensor 21. The other three sense the upper, left and right edges of the combination of images. Each of these four sensors supplies half of a differential signal to an amplifier 22 which drives a servomechanism-type motor 10, 14. These servomechanism-type motors perform not only as drives for the heavily loaded part of the control system but also as reference sources for the rest of the control system. That is, all other (non-servomechanism type) motors 5, 13 are controlled by signals which are generated as computer output; to help obtain and to check this output, the position of each servomechanism-type motor is monitored by a sensor 23 which feeds position data to the computer.

In certain types of control systems, the sequence of feedbacks is important. Azimuth control can be characterized by assigning primary status to control of the beam tip positions 9, 9 (by means of cables 11, 11) and secondary status to the beam curvature (by means of pads 5, 5). Elevation control proceeds in the opposite direction, i.e., from base 2 to tip 9; this is because the motor 14 has absolute control of the innermost sleeve 12 whereas increased proximity to the tip introduced progressively more dependence upon other sleeve positions. Therefore, for these and other reasons, if the true continuous nature of the controls is ignored, the control operations can be approximated by an analogous sequence of four steps as follows: first, the tips of the beams are like platforms which are rotated to the desired azimuth angles; second, the inboard sections are similarly positioned; third, the inboard sleeves are tilted so their mirrors have the correct elevation angles; finally, the outermost mirror elevations are set. Therefore, an outer and inner section of a beam can be called a first and second platform, respectively, and an inner and outer sleeve can be called a first and second mirror, respectively.

While particular embodiments of my invention have been shown and described, it will be obvious to those skilled in the art that changes and modifications may be made without departing from my invention in its broader aspects, and, therefore, it is the aim of the claims to cover all such changes and modifications.

I claim:

1. A heliostat orienting system, including:
base means;
azimuth orienting means including a first horizontal arm supported by said base at a first point on said arm, for movement of points on said arm, remote from said first point, only in a horizontal plane;
elevation orienting means including a first sleeve encircling said first horizontal arm and rotatably supported therefrom for rotation thereabout;
a source of control signals;
azimutal drive means supported by said base means, coupled to said first horizontal arm and responsive to signals from said source for positioning each point along said first horizontal arm at a desired azimuthal position; and
elevational drive means supported from said base means coupled to said first sleeve and responsive to signals from said sources for positioning any point on said first sleeve at a desired elevational angle.

2. A system according to claim 1 including, in addition, a light reflector affixed to said first sleeve and rotatable therewith.

3. A system according to claim 1 in which said first horizontal arm is flexible in the horizontal plane only and said azimuthal drive means causes flexure thereof.

4. A system according to claim 3 in which said first arm comprises a leaf spring.

5. A system according to claim 1 which includes, in addition, a plurality of sleeves encircling said first horizontal arm and means for intercoupling, in angularly adjustable fashion, said plurality and said first sleeve.

6. A system according to claim 5 in which each of said plurality of sleeves and said first sleeve has a solar energy reflector affixed thereto for rotation therewith.

7. A system according to claim 1 in which said first horizontal arm is a leaf spring, said leaf spring comprises juxtaposed first and second beams, and incremental arm-flexing means are interposed between said first and second beams along their lengths.

8. A system according to claim 7 which includes, in addition, hydraulic actuating means coupled to said incremental arm-flexing means.

9. A system according to claim 1 in which cable means are connected to the outer extremity of said first horizontal arm for flexing of said arm.

10. A system according to claim 9 which includes, in addition, means for tensioning said cable.

11. A field of helisotats comprising:
a first platform which establishes a first horizontal axis,
a second platform which establishes a second horizontal axis,
a means for moving the said first platform so that its first horizontal axis has a desired azimuth angle,
a means for moving the said second platform relative to said first platform so that the difference between their two horizontal axes is a desired azimuth increment, this azimuth increment resulting from the curvature of a flexed beam,
a first mirror mounted on said second platform for rotation about its horizontal axis,
a second mirror mounted on said first platform for rotation about its horizontal axis,
a means for rotating the said first mirror about its horizontal axis so that its elevation angle has a desired value,

a means for rotating the said second mirror about its horizontal axis so that the difference between the elevation angle of the second mirror and the elevation angle of the first mirror has a desired value, this difference being observable as a twisting increment about a flexed beam, and

control means for four said means so that said mirrors will continuously focus sunlight onto a fixed receiver.

12. The sunlight concentrator of claim **11** in which said first platform is the tip of a leaf spring and said second platform is an intermediate station along the length of this leaf spring.

13. The sunlight concentrator of claim **11** in which the means for moving the said first platform is a cable connected to a motor, said first platform being stabilized by a viscous damping means.

* * * * *

United States Patent [19]

Raser

[11] **3,872,854**

[45] **Mar. 25, 1975**

[54] **SUNLIGHT CONCENTRATOR FOR ENERGY CONVERSION**

[76] Inventor: **William H. Raser**, 6451 W. 83rd St., Los Angeles, Calif. 90045

[22] Filed: **Feb. 7, 1974**

[21] Appl. No.: **440,522**

[52] **U.S. Cl.** **126/270**

[51] **Int. Cl.** **F24j 3/02**

[58] **Field of Search** 60/26; 126/270, 271

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Primary Examiner—William F. O'Dea

Assistant Examiner—Peter D. Ferguson

[57] **ABSTRACT**

An array of mirrors for focusing the sun's rays onto a steam-generating boiler. Mirrors are mounted on a large ring to serve as a variable-focal-length parabolic reflector. A second reflector with versatile position control is used in focusing sunlight onto a boiler which occupies a fixed position relative to the ground.

11 Claims, 3 Drawing Figures

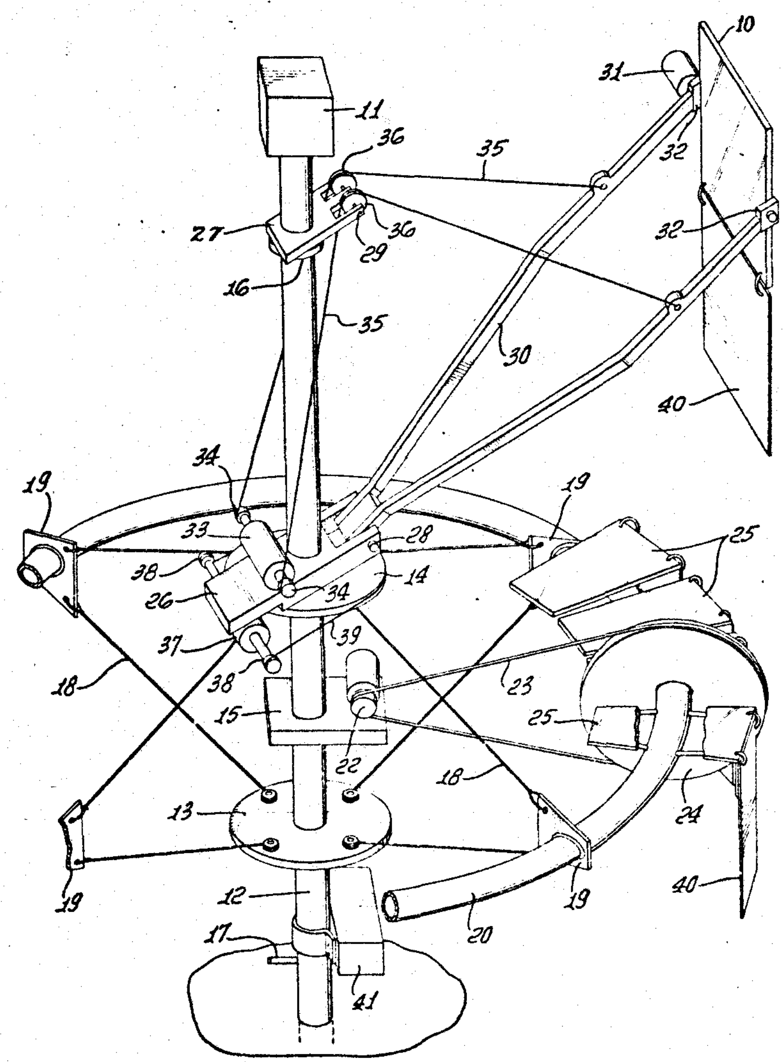

FIG. 1.

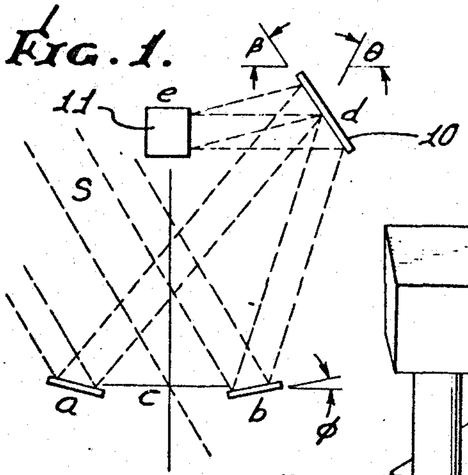
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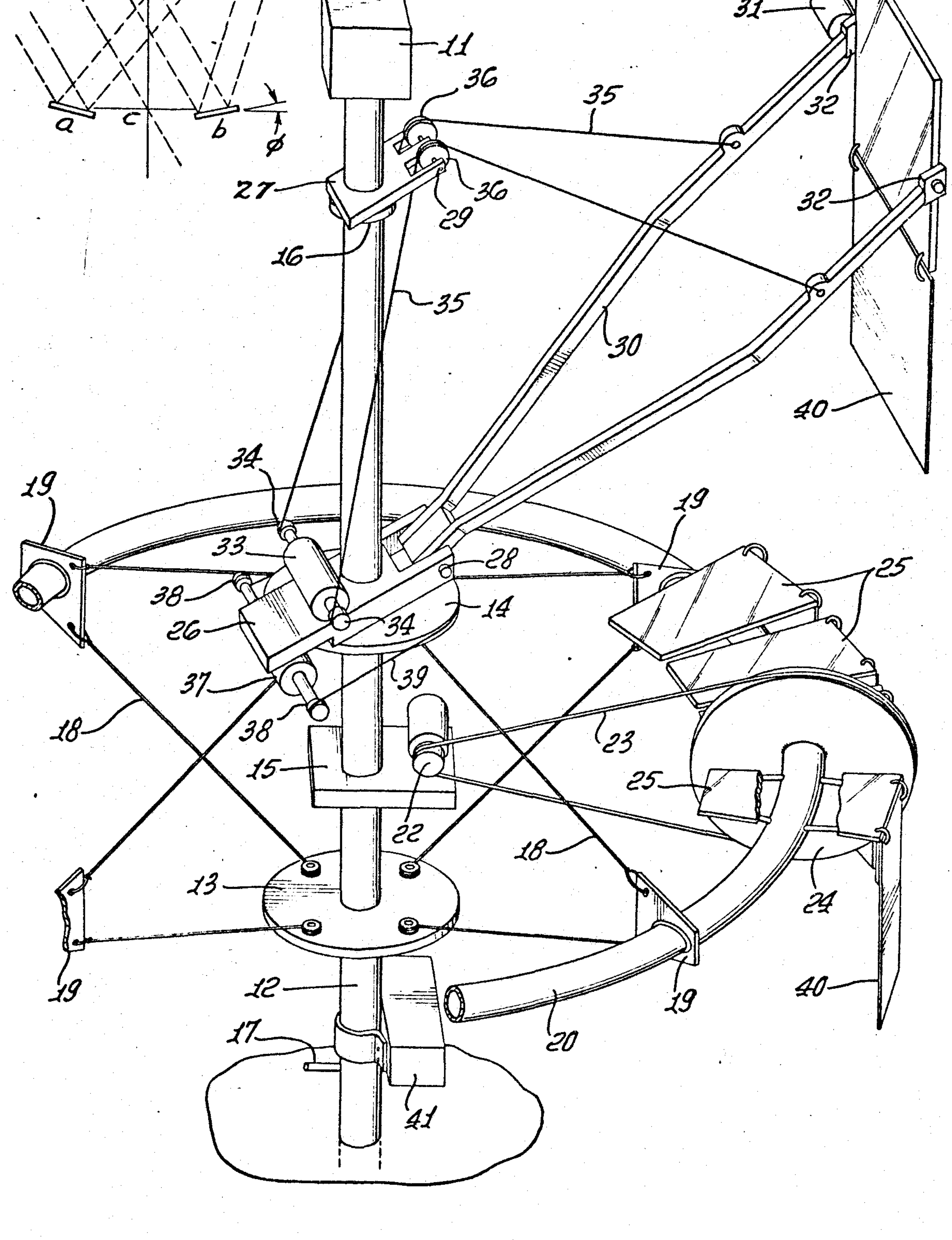
FIG. 2.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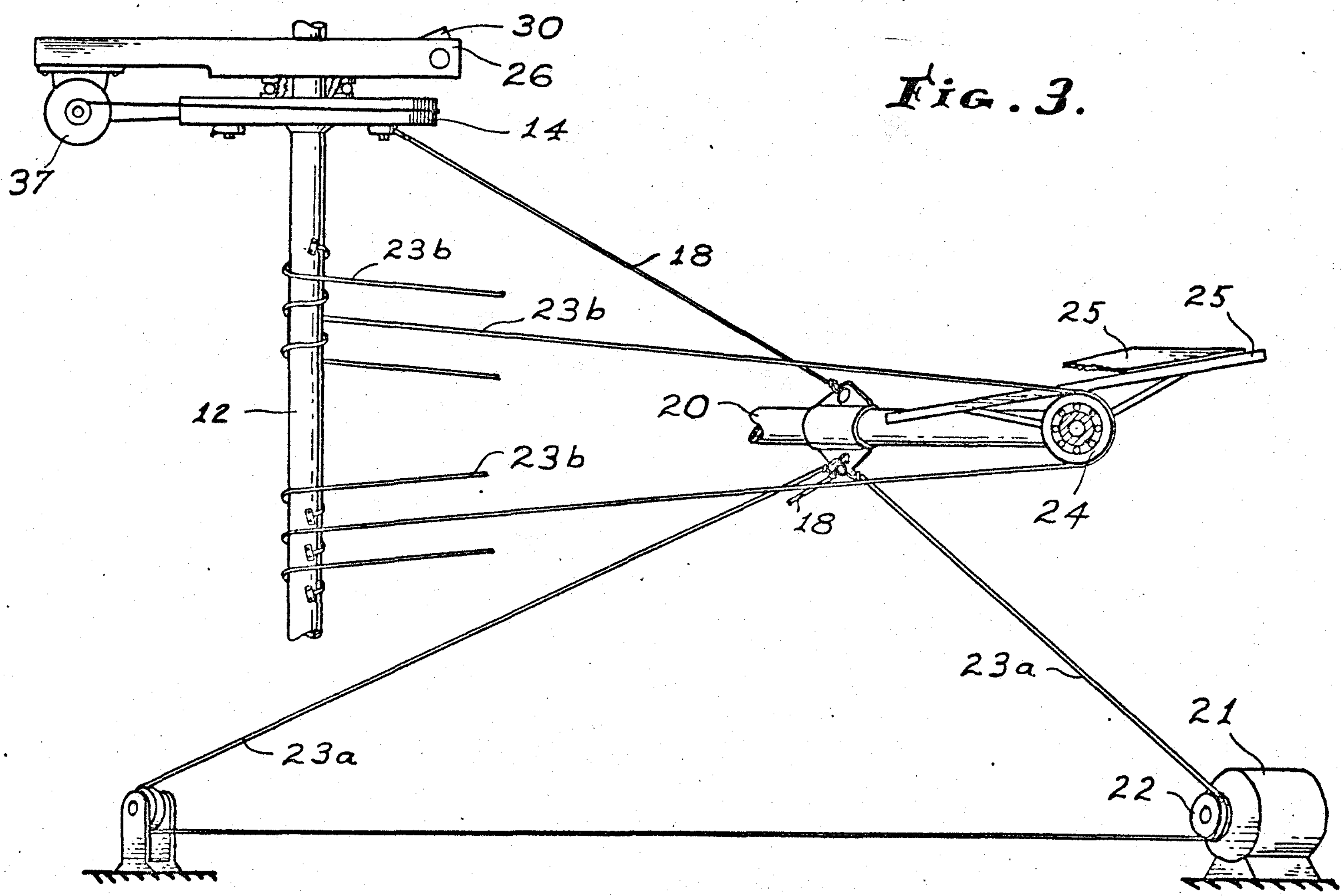

Fig. 3.

SUNLIGHT CONCENTRATOR FOR ENERGY CONVERSION

This invention relates to equipment which draws energy from reflected sunlight. One purpose is the generation of electric power from steam. A second purpose has to do with other methods of energy conversion.

As oil becomes less plentiful, greater need for solar power is being recognized. One of the results of this recognition has been increased efforts to reduce the cost of producing photovoltaic cells. At present, these efforts have not been fruitful as solar cell power still costs over one hundred times the cost of power generation by other methods. Therefore, a non-thermal use for this sunlight concentrator could be to reduce the required size and, hence, cost of photovoltaic cells whenever they are used.

Another result of this recognition has been the development of wavelength discriminating materials known as selective surfaces. Selective surfaces can be used to increase the ratio of absorbed energy to the lost or emitted energy when a body is placed in sunlight. They do this by being selective with respect to radiation frequency or wavelength. Approximately 90% of the solar spectrum is at wavelengths shorter than 1.3 microns, whereas the escaping radiation is infrared and occurs almost entirely at wavelengths above 1.3 microns. Thus, selective surfaces applied to a boiler in sunlight can increase the temperature because they can receive energy easily like a black body but avoid excessive emission losses by having outgoing radiation characteristics like that of a white body. The combination of a selective surface and a sunlight concentration is especially effective in producing high temperatures at a boiler.

The primary object of this invention is to provide sustained optical concentration of sunlight required for efficient energy conversion using a heat-absorbing surface in a fixed position. Since the sun position changes, this requires suitably controlled movements of reflecting surfaces.

The secondary object of this invention is to permit economical installation in remote and rugged areas. In some remote areas, many telephone poles have been installed easily into hand-dug holes by helicopter; a similar structure could have its installation problem solved the same way. A shank-base type of structure is therefore desirable. Also, the number of mechanical moving parts should either be a minimum or be inexpensive to produce and to assemble.

Some arrid regions experience sandstorms which adversely affect the optical properties of glass. Therefore, another object is to provide a means for covering all reflecting surfaces whenever a sandstorm alert signal is received.

A first exemplary, non-specifically-limiting embodiment of the invention is illustrated in two figures of the accompanying page of drawing.

FIG. 1 is an elevation showing rays of sunlight coming past a point s, being reflected by mirrors a,b, being reflected a second time by a mirror 10, and being focused on an absorbing surface 11.

FIG. 2 is a perspective view from a slightly different direction from that of FIG. 1 and with some parts cut away, including some of the mirrors represented by a,b in FIG. 1.

A second exemplary, non-specifically-limiting embodiment is illustrated in FIG. 3 on an accompanying second page of drawing.

FIG. 3 is an elevation view showing parts of the second embodiment which differ from those shown in FIG. 2.

The structural base of the apparatus is a vertical mast 12 with its lower end mounted in the ground or imbedded in concrete. Attached to this mast are two hub discs 13,14, a platform 15 between these discs, and a flange 16 above them. On top of the mast is mounted the heat-absorbing surface 11 which may be the surface of a boiler used to generate steam. Running lengthwise through the mast and thermally insulated from it is a steampipe 17 or other means of transmitting heat energy from the absorbing surface.

By means of long tension rods 18, 18 and bearing plates 19, 19, a large tubular ring 20 is held in a non-vertical plane concentric to the mast. The structural arrangement of this combination of discs, rods and ring is very similar to the arrangement of hub flanges, spokes and rim of a bicycle wheel except that the bearing plates 19, 19 allow one degree of freedom between the ring, 20 and rods 18, 18 that does not exist between the rim and the spokes of a bicycle wheel. This degree of freedom is a simultaneous rotation of every cross section of the ring by some angle, ϕ with no change in the location of the ring 20 or of the bearing plates 19, 19. This angle change, ϕ is called the inversion angle and is permitted by one bearing in each bearing plate 19.

The design of the ring reflects two important features of this embodiment. First, in order to have large power generating capacity, the ring must be large. Second, in order to change a certain optical characteristic which is analogous to a focal length, the elastic properties of the ring must be such that inversion angle change is facilitated; that is, it must be possible for the torsional resistance to change of ϕ to be overcome by a control motor 21 with sheave 22, a belt 23, and a large sheave 24 mounted on some section of the ring. This motor is mounted on platform 15. Accurately mounted on the ring are a number of mirrors 25, 25.

Rotatably mounted around the mast in horizontal planes is a plate 26, and a swivel 27; these are supported by the upper disc 14 and the flange 16, respectively. To each of these is attached a pin, pin 28 and pin 29, respectively. A boom 30 is rotatably mounted on pin 28 and carries a control motor 31 and a large reflector 10. This could be a slightly concave reflector but usually is just a plane mirror with the reflecting side toward the mast. It is mounted to rotate about a horizontal axis by means of two bearings 32, 32 on the boom 30. Measuring from a position where the reflecting side is downward, the position angle of this reflector is β and is controlled by the motor 31.

The elevation angle of the boom is called θ. This angle is controlled by a control motor 33 which has its shaft available at both ends. On each end is a small drum 34, 34. This motor is mounted on plate 26. Each small drum winds up a cable 35, 35 which is attached to the boom 30. On the way to the boom, these cables run over idler pulleys 36, 36 mounted on pin 29.

The vertical plane containing the elevation angle, θ is at some azimuth angle, ψ about the mast. This angle is the position of the length of plate 26. It is also the angle of the swivel 27 because of tension on the cables

35, 35. To control ψ, a second double-ended control motor **37** is mounted on the plate. Each end also has a cable-wound drum **38, 38**; the cable to these drums engages the outer surface of the upper disc **14**. Since this disc is fixed to the mast and since the two drums **38, 38** are wound in opposite directions, the azimuth angle of the boom is controlled by the motor **37** and its cable **39**.

Some regions having an abundance of sunshine are desert regions noted for having troublesome sandstorms. Covers **40, 40** are sometimes needed on these occasions to protect the large mirror **10** and the many small mirrors **25, 25** from surface erosion. Each of these covers hangs from one edge of the mirror which it covers; when its mirror rotates to the proper angle, each cover will be resting on top of its mirror. Reversals of these rotations will uncover the mirrors. A mechanism for tying down these covers is not shown.

The controls for the four control motors are located in a control box **41**. Since each motor is a servomechanism, it nulls at some electrical representation (analog or digital) of desired angle which is computed inside the control box. The motor wires are not shown. Also inside the box are batteries, clocks and small computing circuits.

There are two general ways in which the above four desired angle functions can be controlled, namely, mostly open loop controls and mostly closed loop controls. Table I summarizes how the open loop functions are obtained. In this table, time represents time of year as well as time of day; i.e., it includes all information about the position of the sun with respect to the location of the mast at any time. A fifth angle function, which is called teetering angle is included in this table but is listed in parentheses because it is not a part of this first embodiment.

Channel or Motor	Angle Controlled	Independent Variables
Azimuth	ψ	time (also τ)
Boom pitch	θ	time (also τ)
Reflector angle	β	θ
Inversion angle	ϕ	θ
(Teetering angle	(τ)	(time)

Table I. Controlled Angle Functions

All of these angles except τ are changing constantly because the sun changes position. They can be understood by considering all mirrors except the upper mirror **10** to form a reflector which is approximately equivalent to one big parabolic mirror having a focal length L, where, from FIG. 1,

$$L = \overline{cd} + \overline{de} \tag{1}$$

In other words, the azimuth control aims to keep the sun *s*, the center of the equivalent parabolic mirror *c* and the center of the reflector *d* all in one plane. The pitch control conforms to the angle of incidence, angle *sce* which must be equal to the angle of reflection, angle *ecd*. A similar incidence-reflection condition determines β. And finally,

$$\overline{cb} = L \tan 2\phi \tag{2}$$

If closed loop controls are selected, one or more of the above angle functions are determined instead by feedbacks of differential photoelectric signals in a manner known to those familiar with the art. In either case, photoelectric thresholds may be used for turning on and off the servos and wind velocity sensors could be used to trigger suitable mirror-covering sequences.

In this first embodiment, the ring **20** must be large but slender to permit generating, say, 25 kilowatts of electrical energy; the ring might need to have a radius of 35 feet but have a cross section diameter of only one-half inch. The allowable limit of cross section has to do with elastic properties of the ring material which could be steel.

It has been pointed out that the elastic properties of the ring must not prevent control motor **21** from satisfying the required ϕ condition. This required condition is given by equations (1) and (2), where L is a function of θ and, hence, of sun position. To illustrate the problem, consider a ring design that is not acceptable. An unacceptable ring **20** is one having zero residual stresses at any value of ϕ.

To consider why a ring with the above dimensions and with zero initial stresses would be unacceptable, consider 180° of inversion angle at one station; that is, rotate one single cross section of the ring by one half revolution. Consider what would happen if all cross sections followed by rotating 180° in the same way a rubber band can sometimes be inverted by twisting just one section. The innermost fiber around the ring and the outermost fiber around the ring would exchange dimensions, the maximum strain would be 0.000903, the maximum stress would be 26,200 psi and the total work done on the ring would be 37.7 in. lbs. During this half rotation, a peak torque of 18.8 lb.in. is required. A torsion bar with this section and with a length equal to one quadrant of this ring has a torsional stiffness of 42.0 lb.in./radian. From these torques, it can be shown that almost half a radian of lost inversion angle could occur at some mirror on the ring that is remote from the section where the inverting torque is applied. In other words, the mirrors would not operate to provide a uniform focal length.

An entirely different situation occurs if the ring is fabricated from a tube of the correct circumferential length with its ends cut at exactly right angles from its length and held at perfect facing while they are welded together. Such a tube will have residual hoop stresses proportional to ring radius minus mean radius; i.e., the outer fiber will be in tension and the innermost fiber will be in compression. If this ring is made of perfectly elastic material, inverting either one or all cross sections will cause a net change of total strain energy of zero. In this case, the causes of inversion angle errors will be minor causes like bearing friction and metal hysteresis. A ring fabricated in this way would be acceptable.

A ring that is acceptable is so because it responds to control motor **21** in an acceptable way, i.e., it changes the inversion angle, ϕ of all mirrors **25,25** equally or almost equally. If all mirrors have the same inversion angle, reasonably accurate focusing is possible and L can be controlled to conform to equation (1). This means that the boiler can remain in a fixed position and receive a heavy concentration of sunlight for all sun positions relative to the earth as long as the ψ, θ, β, and ϕ

controls are maintaining their intended or computed positions.

The above discussion has involved the inversion angle, ϕ to a large extent whereas implementation of ψ, θ and β controls has been given little attention. This is only because the inversion angle is more difficult and expensive to implement; it is not because it is any more important than the other three angles from an accuracy standpoint. In fact, for a number of reasons including the impossibility of perfect focusing even if ϕ were uniform, accurate ϕ control is not essential; for this reason, a certain amount of torsional flexibility in the ring can be tolerated. But limits to smallness of ring cross section exist and are related to the amount of wind velocity that can be tolerated.

A first embodiment of this invention has been described. It achieves simplicity by having a number of mirrors 25,25, each rigidly attached to a section of a large slender ring, 20. It achieves this simplicity because, although there may be many such mirrors, there may be a fewer number of places around the ring where it is necessary to control the twist angle or inversion angle of the cross section of the ring and still provide a correct and reasonably accurate focal length. Indeed, FIG. 2 illustrates only one such place for control, namely, the cross section where sheave 24 is attached.

A second embodiment can be visualized easily because it is an obvious alternative to the above method of achieving control of ϕ without requiring a separate motor for every one of the many mirrors 25,25. It results from five changes to the first embodiment as follows:

1. Many sheaves like sheave 24 are provided, one for each mirror 25.

2. Instead of being driven by a drum like drum 22, cables like cable 23 are wrapped around mast 12, one end clockwise and the other end counterclockwise.

3. Control motor 21 is located on the ground in such a way as to be able to impose an in-plane displacement of the ring up to an amount limited by excessive tension in rods 18,18.

4. Instead of being mounted rigidly on a section of ring 20, each of the mirrors 25,25 is fixed to its driving sheave and the two, together, are mounted on bearings around ring 20.

5. Bearings 19,19 are eliminated.

The combination of these five changes produces no change in the overall result, namely, that motor 21 has control of focal length L by changing the tilt angle ϕ of each mirror 25. To best understand this, it is necessary to visualize the above-mentioned in-plane displacement of the ring.

To do this, consider the ring 20 and rods 18,18 to be like the hub and spokes of a bicycle wheel, respectively. In a bicycle wheel, the spokes are not perfectly radial but tend to form triangles. These triangles add in-plane rigidity to the wheel; without this rigidity in a bicycle wheel, the bicycle rider who applied his brakes at the hub would discover that the rim would advance slightly ahead of hub rotation and this might cause excessive spoke tension. The resulting winding up of the rim relative to the hub is called in-plane displacement. In this embodiment, it is important that the rods are radial and that a small amount of in-plane displacement is allowed to occur.

If, say, five degrees of in-plane displacement angle are imposed by a ground-mounted control motor, each combination of sheave 24 and mirror 25 will tilt by some amount; if the diameter of sheave 24 is the same as the outside diameter of mast 12, this amount of change of tilt would also be five degrees. This relationship results from the way the cables like cable 23 are wrapped around mast 12; i.e., one end is wrapped one way and the other end the other way.

An example of causing something to rotate by means of a cable having ends wrapped around drums in opposite directions has already been described; it was used to rotate plate 26 relative to disc (sheave) 14 by cable 39 wrapped oppositely around two drums 38,38. In the second embodiment, the mast 12 cooperates with sheave 24 in the same manner as drums 38,38 cooperated with disc 14.

The above paragraphs describe the second embodiment in terms of how it differs from the first embodiment. In the paragraphs which follow, the second embodiment is described in detail by means of an independent explanation using FIG. 3.

The structural base of the apparatus is a vertical mast 12 with its lower end mounted in the ground. Rigidly attached to this mast in horizontal planes are a lower hub disc, an upper hub disc 14, a bearing on the upper hub disc to support a rotatable plate 26, and a flange to support a swivel means. At the top of the mast is mounted a boiler.

By means of tension rods 18, 18 which are attached to the upper and lower hub discs and which lie in planes that are purely radial to the mast 12, a large ring 20 is held in a horizontal plane concentric to the mast. The arrangement of this combination of discs, rods and ring is very similar to the arrangement of hub flanges, spokes and rim of a bicycle wheel except that the purely radial rods 18 allow one mode of freedom that does not exist between the rim and the non-radial spokes of a bicycle wheel. This mode of freedom is an in-plane rotational advancement of the ring by some angle, α as the rod positions become non-radial. This is permitted by some stretching of the rods 18, 18.

A number of mirrors 25, 25 are mounted on the ring 20 for rotation about lines tangent to the central fiber of the ring. If the ring is tubular so as to have no central fiber, the axis of rotation of each mirror is the axis of the cylinder formed by neglecting the curvature of a small confronting segment of the ring. A sheave or pulley 24 is attached to the mounting structure at each mirror 25 and is concentric to the axis of the small confronting segment of ring. A radial cable or belt 23*b* engages or wraps around pulley 24. The array of mirrors 25, 25 form a large concave reflector. Therefore, the effect of increasing or decreasing the radial distance from the mast 12 of a point on the radial cable 23*b* is to change the effective focal length of this large sunlight reflector by means of a change of an angle, ϕ of the position of each mirror 25.

There is one radial cable 23*b* for each ring-mounted mirror 25. One end of each radial cable 23*b* is attached to the mast using a clockwise-wrapping means and the other end uses a counterclockwise attachment in plan view. The clockwise direction is reserved for ends coming in from one direction only. Therefore, if an in-plane rotational advancement of the ring occurs relative to the mast, one end of each radial cable 23*b* will tighten and the other end of it will loosen; therefore, the inversion angle ϕ of each mirror will change.

At one point on the ring 20, there is an attachment means for a tangential cable 23a. This tangential cable is driven by a focal length control motor 21 which drives pulley 22 and which may be mounted on the ground. To the extent that the control motor can overcome the tension on the radial rods 18, 18, the ring 20 is forced into some in-plane displacement, pulley 24 is turned to some angle, ϕ, and focal length can be adjusted.

An intermediate reflector is needed to redirect onto the boiler the sunlight coming from the mirrors 25, 25. This intermediate reflector is mounted on a boom 30 which is hinged at plate 26 and supported by the swivel means associated with the flange on the mast. A control motor 37 on the plate 26 uses the rim of the upper hub disc 14 to control the azimuth angle, ψ of the boom 30. Two other control motors are used to focus the sunlight on the boiler, one to control the elevation or pitch angle, θ of the boom 30 and the other to control the angle, β of the intermediate reflector carried by this boom. With this apparatus, if the proper inputs are fed into the four control motors described, much radiation from the sun will be directed onto the boiler for any direction of sunlight.

A third embodiment resembles either the first or second except that the large tubular ring 20 is not held in a horizontal plane. The mast may still be vertical but it supports an axis that is inclined to the horizontal by some angle λ. This axis would generally lie in a north-south plane. The plane of ring 20 not only contains this axis but also dips or teeters about it, usually assuming one of a limited number of positions. If it had just two possible positions, it would dip down on one side in the morning and on the other side in the afternoon. This inclined axis forms what is called a teetering hinge; the angle by which ring 20 dips toward one side of the teetering hinge is called the teetering angle τ.

Table I includes τ along with the other four controlled angle functions. Unlike the other four, however, τ may be controlled manually. An attendant might simply crank the ring to one detent position in the morning and to the other of two possible positions in the afternoon.

In this discussion, a control motor is understood to mean any of a wide variety of means for actuation. It can be a servo motor, a stepping motor, a hydraulic actuator or a gravity-fed dashpot.

I claim:

1. Apparatus for solar thermal conversion comprising;
   - a mast protruding from the ground;
   - a ring-like structure encircling said mast;
   - a plurality of mirrors mounted on said ring-like structure;
   - a body to be heated mounted on said mast;
   - a beam rotatably mounted on said mast;
   - a tiltably controlled reflector mounted at the extremity of said beam; and
   - control means enabling the sunlight reflected from said mirrors to be directed by said reflector onto said body to be heated.

2. Apparatus in accordance with claim 1 wherein said mast is vertical and has said body to be heated mounted at its upper end where most of the reflected light converges.

3. Apparatus in accordance with claim 2 wherein said beam is mounted on said mast for controlled azimuth alignment with the plane containing both the sun and said mast and wherein said beam also has a horizontal hinge for controlled inclination from said mast so that said reflector receives most of the sunlight reflected from said mirrors.

4. Apparatus in accordance with claim 1 wherein most reflected light converges at some point between said body to be heated and said reflector.

5. Apparatus in accordance with claim 1 wherein said body to be heated is a boiler which supplies steam to a means for generating electricity.

6. Apparatus in accordance with claim 1 wherein said body to be heated has a selective surface which freely absorbs the low wavelength energy of sunlight but tends to retard the emission of radiant heat.

7. Apparatus in accordance with claim 1 wherein said ring-like structure is a slender, prestressed ring capable of controlled inversion which causes the sunlight reflected from said mirrors to converge toward a point and which, when changed, causes the distance from the center of said mirrors to this point to change.

8. Apparatus in accordance with claim 1 wherein each of said mirrors has an attached sheave and, together with its sheave, is mounted on said ring-like structure for limited rotation about ring cross section centers so that cables with ends oppositely wound around the mast can respond to forced in-plane displacements of said ring-like structure by exerting tension differences on the sheave of each said mirror to cause changes in mirror tilt and overall focal point distance.

9. Apparatus in accordance with claim 1 wherein control motors control the azimuth angle of said beam, the inclination of said beam, the tilt of said mirror and, to a limited extent, the focal length distance of said plurality of mirrors.

10. Apparatus in accordance with claim 9 wherein said mirrors and said reflector can be protected with dust covers in response to movements of control motors which control beam mirrior mirror and focal length change.

11. A solar heating apparatus comprising;
   - a substantially vertical pole,
   - a moveable ring encircling and in connection with said pole,
   - a plurality of mirrors mounted on said ring and adapted to reflect sunlight,
   - a beam connected to said pole, said beam adapted to be moved vertically and horizontally about said pole,
   - a reflector connected to said beam, said reflector adapted to receive reflected sunlight from said mirrors, and
   - a body associated with said pole, said body adapted to receive reflected sunlight from said reflector and to convert this sunlight into useable energy.

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