TERRESTRIAL PHOTOVOLTAIC POWER SYSTEMS WITH SUNLIGHT CONCENTRATION

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by

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ABSTRACT

This semiannual progress report is for the first half of the second year of a program to investigate the characteristics of the components and the total system using sunlight concentration onto solar cells. The second year's program was primarily to experimentally investigate the encouraging conclusions of the first year's investigation, which was an analytical study.

Analytical modeling of silicon solar cells under high illumination has been completed and it appears that they can be designed to operate at over 100 suns with conventional processing and with characteristics comparable with conventional space cells. Cells are currently being fabricated which are optimized for various intensities for testing in a single cell concentrator simulator and for four system tests.

Evaluation of various concentrator systems under actual weather conditions have been completed for the 20 locations on the Aerospace data tapes. Even at the location of the lowest direct insolation (Omaha), several of the concentrator systems collected more energy than flat, fixed tilted arrays. Surface accuracy, off-axis tracking, and packing factor optimization analysis has been started. System cost studies have been extended to additional concentration systems and for comparisons of silicon and GaAs cells.

Experiments on heat rejection coefficients have been started and indicate that the thermal conductances assumed in the first year's analytical study can be achieved.

Four photovoltaic concentration systems have been designed and are under construction. The concentration levels for these systems will be about 3, 10, 30 and 100.

1.0 INTRODUCTION

In this joint program, Arizona State University and Spectrolab, Inc. are investigating the degree of cost reduction achievable in photovoltaic power systems as a result of applying solar concentration techniques. This effort complements both the ERDA photovoltaic program that is primarily directed toward making low cost solar cells, and the ERDA solar thermal program that is using concentration techniques to increase efficiencies in thermodynamic generation. The first year of this joint program was completed and reported in NSF Report No. NSF/RANN/SE/GI-41894/PR/74/4. The summary of conclusions given in that report are repeated in Appendix A of this report.

Since the solar cell device is able to produce well over one hundred times the amount of power as it could without concentration, the cost of the power associated with the device becomes about 100 times smaller when compared on a dollar per watt basis. This provides a significant cost reduction tool with which to work. There must be a trade-off made to determine the largest advantage obtainable as one replaces the relatively expensive solar cell with a less expensive solar concentration system. As the concentration ratio increases the complexity of the cell, the heat transfer unit, the concentrator design and the orientation system increases. The primary objective of this program is to analyze the parameters applicable to this trade-off and to optimize to the lowest cost-to-watt ratio. The economic goals of the program are to show that photovoltaic systems can reach the competitive cost range of 50 cents to \$1 per peak watt without requiring any "breakthroughs" in the making of solar cells.

Spectrolab is primarily concerned with determining the photovoltaic cell performance characteristics as a function of light level and solar cell temperature. The cell must be designed differently for different ranges of light intensities. The device parameters that effect high intensity performance are: grid design, cell resistivity, semiconductor material (e.g., Si or GaAs), junction depth cell size and thickness, contact method, antireflection coating and light spectrum. Analysis and experimental verification can provide sufficient data for determining the optimum cell design parameters for all sunlight levels that are likely to be obtained in concentration systems.

The effort at Arizona State University is directed toward characterizing concentrators and investigating various cooling techniques. Concentrators with various concentration ratios (1-1000) must be compared and considered for coupling with photovoltaic cells. As the light intensity on the cells increase the cooling requirements also increase. A complete range of possible heat transfer techniques, both active and cooling, must be analyzed and their appropriateness for accommodating different concentrators determined.

After the various components have been characterized then they must be integrated into a concentration system and the system performance determined. Optimization studies including system performance and cost estimates must be made to determine the most attractive systems. The first year of this grant is to characterize components by analysis and to start system studies. The second year is to experimentally verify components and sub-systems and perform the optimization studies.

2.0 HIGH INTENSITY CELL DEVELOPMENT

The cost effectiveness of solar concentration as applied to photovoltaic systems is strongly governed by cell efficiency. Unfortunately solar cell efficiency generally decreases with increasing intensity. This results from power losses in internal series resistance and to increasing cell temperature which reduces the cell's output voltage. As a consequence, considerable effort has been directed towards: The theoretical prediction of cell efficiency; and the establishment of design requirements to maintain high efficiencies with increasing optical concentration. In general, changes in cell efficiency due to temperature are not a function of the basic cell design parameters. Therefore, given the high thermal conductivity of silicon, control of the cell temperature is largely a matter of providing a low thermal impedance between the cell and the surroundings. Progress in this area is reviewed in Section 4.0.

Cells are currently being fabricated in several design configurations which will be used in conjunction with the concentrator photovoltaic system experiments. Individual cells will be evaluated using the single cell concentrator simulator at irradiance levels up to 100 air mass one solar constants (approximately 10 w/cm^2). The design considerations and analysis leading to the optimum cell design recommendations are reviewed below.

2.1 DESIGN CRITERIA

The design work performed in this reporting period is an extension of the work reported on in this program's first annual report. In general, a set of non-linear partial differential equations are required to represent the current-voltage relationships of a solar cell. This is primarily a

result of the distributive nature of the series resistance. If however, the total voltage drop in the series resistance is small compared to the cell characteristic voltage, then algebraic equations can be found which adequately describe the cell performance. It is expected that this condition will always be satisfied for an optimum designed cell for a given insolation level.

As in the earlier work a rectangular solar cell with a front contact consisting of a grid of parallel metal fingers connecting to a terminal bar at one edge is assumed. For continuity and clarity the geometry and symbols used in the earlier work are repeated here in Figure 2-1. This idealized cell is analyzed in terms of parallel connection of a number of "unit fields".

The active area of the unit field is (ws) where w is the length of the finger and s corresponds to $1/2$ the separation between grid fingers. We assume that w is much larger than s which is usually true in practical cell designs. The potential drop along the finger from end to end is (ws_i) ($mw/2t$) where i is the current density; m the sheet resistance of the contact metalization; and t is $1/2$ the width of the finger. The potential drop in the diffused layer, from the centerline to the grid finger is (ws_i) ($rs/2w$) where r is the sheet resistance of the diffused layer. The total potential drop from the furthest position on the face of the cell from the terminal is therefore:

$$-\Delta v_o = w^2(ims/2t) + s^2(ir/2) \quad (2.1)$$

Since the potential drop increases as the square of s and w , a good approximation for the average potential drop is given by equation 2.2.

$$-\Delta v = i(mw^2s/3t + rs^2/3) \quad (2.2)$$

The potential drop due to the base material resistance is equal to $(ws/R_b t_c) / ws$ where R_b is the base material resistivity and t_c is the cell thickness.

$$\Delta v = AKT/q = 3^{-1} \quad (2.4)$$

The total voltage drop resulting from series resistance is therefore:

$$-\Delta v = i(mw^2 s/3t + rs^2/3 + R_b t_c) \quad (2.5)$$

(2.3)

The quantity in parentheses represents the effective series resistance of the unit field.

A primary design criteria has been established as a requisite for high intensity solar cell designs that require the maintenance of the cell curve shape and hence curve factor. This requires a fixed maximum voltage drop associated with the cell series resistance. Since the light generated current increases proportionally with intensity a corresponding reduction in series resistance must be accomplished by the cell design if the voltage drop is to remain fixed.

The approximation given in equation 2.3 rapidly loses validity as $-\Delta v$ increases beyond the cell characteristic voltage which is equal to AKT/q where:

A = Constant characteristic of the cell

K = Boltzman's constant

T = Absolute temperature

q = Charge on electron

This implies that a near optimum design voltage drop will be equal to approximately AKT/q which ranges between 26 and 42 mv and is denoted as $1/B$. Also, for good cells the maximum power current density is 90 to 95

percent of the light generated current density which is denoted as i_L .
Therefore for our design criteria we let:

$$\Delta v = AKT/q = B^{-1} \quad (2.4)$$

and

$$i = 0.9 i_L \quad (2.5)$$

Substituting these values into equation 2.3 gives us our basic design equation:

$$B^{-1} = 0.9 i_L (mw^2s/3t + rs^2/3 + R_b t_c) \quad (2.6)$$

2.2 PERFORMANCE PARAMETERS

In summary, when we specify a maximum voltage drop due to series resistance we substantially fix the curve shape. To design a high intensity cell to satisfy this voltage drop requirement we make some of the following adjustments relative to a typical cell design for non-concentration applications:

- a) Decrease sheet resistance of the diffused layer
- b) Decrease metalization sheet resistance by increasing the thickness of deposite.
- c) Increase grid finger width
- d) Reduce grid finger length
- e) Increase number of fingers
- f) Decrease cell thickness
- g) Decrease base material resistivity

As a result of a combination of these changes we will likely reduce the cell efficiency either by reducing the light generating current response or by reducing the useful cell area.

In establishing near optimum cell design parameters for a given concentration level it has been convenient to relate the anticipated performance to a pseudo "standard" space cell design. To accomplish this we have established efficiency performance factors normalized by the same respective performance characteristic of the standard cell. The product of the efficiency factors will thus provide the normalized efficiency of any prospective cell optimized for a given intensity level. A normalized efficiency of .8 would imply an efficiency of 80% of that obtained by the pseudo standard cell under 100 mw/cm^2 irradiation.

Performance factors used to calculate the normalized efficiency account for the following:

- a) Changes in light generated current response with diffused layer sheet resistance
- b) Active to total cell surface area
- c) Increase voltage with increased light intensity

The standard cell is assumed to have the following design parameters:

Base Material Resistivity: $R_b = 10 \text{ ohm-cm}$
Diffused Layer Sheet Resistance: $r = 80 \text{ ohms/square}$
Metalization Sheet Resistance: $m = .004 \text{ ohms/square}$
Cell Thickness: $t_c = .025 \text{ cm}$
Number of Fingers: $N = 3/\text{cm}$
Width of Fingers: $2t = .010 \text{ cm}$
Length of Fingers: $w = 2 \text{ cm}$

A reduction in the diffused layer sheet resistance reduces the blue response due to the deeper junction and may also reduce the red response due to reduced base lifetimes. An earlier experiment on this program showed that the variation of light generated current density with sheet resistance was well represented by the following expression:

$$i_L = i_{L0} \exp(-r_o/r) \quad (2.7)$$

for the particular process the coefficient i_{L0} equaled 35.8 ma/cm^2 and r_o equaled 2.5 ohms/square .

The performance factor for this characteristic is denoted as K_R where

$$K_R = \frac{i_{L0} \exp(-r_o/r)}{i_{L0} \exp(-r_o/80)} = 1.032 \exp(-2.5/r) \quad (2.8)$$

The ratio of active to total area of the cell can be expressed simply as $s/(t+s)$. This ratio divided by the corresponding ratio of the standard cell (which is .954) is the grid coverage performance factor and is denoted as K_c .

$$K_c = 1.048s/(t+s) \quad (2.9)$$

The increase in open circuit voltage of a cell can be expressed as

$$\Delta V_{oc} = \frac{AKT}{9} [\ln(CI_{sc}/I_o) - \ln(I_{sc}/I_o)] = \frac{AKT}{9} (\ln C)$$

Where in this case I_{sc} represents the short circuit current under a light intensity of 100 mw/cm^2 and C represents the concentration factor of the incident radiation.

It is assumed that the increase in open circuit voltage will equal the increase in maximum power voltage V_{mp} . The voltage at maximum power for a typical cell under AM1 irradiation is approximately .5 volts. Therefore the voltage performance factor K_v is defined as follows:

$$K_v \approx 1 + \Delta V_{oc}/V_{mp} = 1 + (B^{-1} \ln C)/0.5$$

The product of these various performance factors represents the predicted cell efficiency at a concentration level of C. This normalized efficiency value is denoted as K_t and is given by equation 2.12 which restricts

$$K_t = \frac{(K_R)(K_C)(K_V)}{K_t} = 1.082 [\exp(-2.5/r)] [s/(t+s)] [1+2B^{-1}Lnc] \quad (2.12)$$

2.3 PARAMETER SENSITIVITY

A short study was performed to examine the relationships between parameters and their sensitivities with respect to cell efficiency at various concentration levels. Equation 2.6 establishes the major relationships and hence restraint on cell design. Solving equation 2.6 for s (1/2 the distance between fingers) we get:

$s = [-b + (b^2 - 4ac)^{1/2}] / 2a$ where b is the standard metal mass approach for voltage drop and c is the concentration level. This number is somewhere between 1 and 2 for a finger length. For very

$$b = .9 i_L m w^2 / 3t$$

$$a = .9 i_L r / 3$$

Figure 2-3 illustrates the computation of c.

$$c = -B^{-1} + .9 i_L R_b t_c$$

A value for the light generated current density i_L of .035 amps/cm² times the concentration level has been used.

In establishing optimum cell designs for high concentration levels we must establish some practical limits associated with the ability to implement certain design parameters. Here we find ourselves attempting to distinguish

between the difficult, untried, and or perhaps the impossible.

We have therefore established a basic design approach which restricts parameter selection to those that can be implemented using conventional cell fabrication technology. This maximizes utilization of existing production processes and places a practical limit on the scope of developmental type investigations.

After establishing the various material parameters the grid geometry provides the primary means of reducing the series resistance.

With increasing concentration the number of fingers per cm can be increased reducing the separation between fingers. To maintain the coverage factor requires simultaneous reduction in finger width. Of course technical and economic limitations place finite limits on finger widths and finger density.

At some number N depending also on finger width, the standard metal mask approach for vacuum depositing grid configuration can no longer be implemented satisfactorily. This number is somewhere in the vicinity of 20 to 30 fingers per cm of cell length. For very thin finger widths and high finger density photolithography techniques following evaporation are required.

Figure 2-2 illustrates the computed normalized efficiency of solar cell designs as a function of concentration and finger length. The number of fingers per cm of cell length required to satisfy the performance criteria is also plotted.

These designs use finger widths of .009 cm (.0035 inch), metalization sheet resistance of .004 ohms/square and a diffused layer sheet resistance of 50 ohms/square. These parameters are not dissimilar to those used in current space cell production. A cell thickness of .025 cm (.010 inch) is assumed

and the base resistivity of the P material is 0.1 ohm-cm is used.

Examination of Figure 2-2 shows that finger length is certainly a sensitive parameter. For larger size cells the grid geometry will probably utilize a repeating grid pattern utilizing multiple terminals.

Having selected certain readily available values for material parameters cell designs were computed for various concentration levels. These designs, as previously described, were restrained by the fixed series resistance voltage drop performance criteria.

The sensitivity of base resistivity is illustrated in Figure 2-3. In this Figure the normalized efficiency of the cell design is plotted versus the base resistivity for a fixed concentration level of thirty. This illustrates that base resistance can be a limiting factor in establishing efficient high intensity cell designs.

- Notes: (1) $w, s,$ and t are dimensions (cm) which define front contact geometry (per unit length of cell in direction perpendicular to w).
- (2) m, r are sheet resistances (ohms/square) of metalization and diffused layer respectively.
- (3) i_L is the light-generated current density (amperes/cm²) per unit active area.
- (4) $i(v)$ is the useful output current density generated by an element of active area at potential v (volts); the current-voltage characteristic of the area element is $i(v) = i_0 [\exp (Bv) - 1] - i_L$
- (5) I and V are the current and voltage output of the cell as measured at the terminal bar.

FIGURE 2-1: DEFINITION OF TOP CONTACT GEOMETRY

FIGURE 2.2
 NORMALIZED EFFICIENCY & NO. OF FINGERS/CM
 vs.
 CONCENTRATION LEVEL

Finger Width = .009 cm
 Diffused Layer Sheet Resistance = 50 Ω /square
 Base Material Resistivity = 0.1 ohm-cm
 Cell Thickness = .025 cm
 Sheet Resistance of Metalization = .004 Ω /square

FIGURE 2.3

NORMALIZED EFFICIENCY & NO. OF FINGERS/CM

vs.

MATERIAL BASE RESISTIVITY

Finger Width = .009 cm

Diffused Layer Sheet Resistance = 50 Ω /square

Cell Thickness = .025 cm

Sheet Resistance of Metalization = .004 Ω /square

3.0 CONCENTRATOR PERFORMANCE/DESIGN

Work during the present reporting period has been divided into two distinct areas of analyzing collector performance. First, yearly energy collection capability studies have continued on various types of collectors. Whereas previous work (Ref. 3.1) was done on characterizing collector performance using clear weather data, present studies have incorporated more realistic insolation data. Second, studies of optical quality and its effect on intensity distributions at the absorber of an optical concentrator have been undertaken.

3.1 ENERGY COLLECTION

3.1.1 Collector Performance (No Shading)

The Aerospace insolation/weather data tapes have been used as a source of realistic solar data to compare energy received at the aperture of six (6) different collectors. These were "operated" in each of the twenty (20) different locations included in the four data base tapes. Table 3.1 summarizes the results of these studies. The six collectors referred to in Table 3.1 are:

Collector A - Fixed horizontal aperture that would accept both direct and diffuse radiation. (This is commonly called the total radiation on a horizontal surface).

Collector B - Fixed aperture facing south and tilted with respect to the horizontal at the local latitude angle. The collector is assumed to accept both diffuse and direct radiation. Diffuse radiation

on the tilted plate has been estimated from the total radiation on a horizontal surface and the direct normal contribution on the horizontal. This is then added to the direct radiation on the tilted surface. No ground reflected radiation has been assumed.

Collector C - Two-dimensionally tracked aperture whose normal always points toward the sun. It is assumed that the collector will accept only direct radiation. Thus, this model sums the normal incidence data available on the data base tape.

Collector D - One-dimensionally tracked aperture which rotates about a horizontal east-west axis. It is assumed that the collector will accept only direct radiation. Tracking is such that the angle between the normal to the aperture and a south pointing vector is the same as the solar East West Vertical altitude as defined by Tabor (Ref. 3.2).

Collector E - One-dimensionally tracked aperture which rotates about a horizontal north south axis. It is assumed that the collector will accept only direct radiation. Tracking is such that the sun is always in the plane formed by the axis of rotation and a normal to the aperture drawn through this axis.

Collector F - One-dimensionally tracked aperture which rotates about a line that is parallel to the earth's axis. This case differs from Collector E, only in the tilt of the axis.

The results presented are for no shading of the apertures by other adjacent collectors or objects. In practice this can be an important consideration. In the case of Collector D, a packing factor of 0.6 results in a decrease in the energy collected of 5% over the year with most of the decrease occurring near summer and winter solstice.

A general packing factor/shading subroutine is being completed for use in further studies of the above type and for the systems simulation studies described in Section 5.

Table 3.1 shows that 2-D tracking and 1-D tracking with N-S directed or polar oriented axes collect more energy than fixed, tilted flat arrays. This same conclusion was reached earlier (Ref. 3.1) using clear weather data.

Daily total energy incident at the aperture of the six collectors used here as a function of time of year are shown, for Albuquerque data, in Figs. 3.1 through 3.6. The two lines shown on each figure represent the two years, 1962 and 1963. Albuquerque data were used extensively in the systems studies reported earlier, but the present studies show that it is representative of high direct insolation areas such as Inyokern, Phoenix, Tucson and El Paso.

Figures 3.7 through 3.12 show similar incident energy data for Omaha, Nebraska. That location has the lowest insolation of any of the twenty stations included in the four data base tapes presently available. It is interesting to note that even in the Omaha, 2-D tracking and 1-D tracking with

N-S directed or polar oriented axes collect more energy than flat, fixed, tilted arrays.

Plans for the next period include extending these studies to other types of collectors such as the fixed mirror concept of movable absorber and fixed reflector, the fixed, or at most seasonally adjusted, concentrator and the vertical axis tracking concept.

3.1.2 Surface Accuracy and Image Quality

Work has begun during this period, on an analysis of the intensity distribution on the solar cell "absorbers" used with optical concentrators. This is important, since it is the local concentration ratios that determine series resistance within the cells and not just the average concentration.

In a related study (Ref. 3.3), an integral relationship was developed to calculate the intensity distribution in the focal plane of a perfect parabolic trough. Figure 3.13 shows the geometry and nomenclature. For a circular solar disk of constant intensity, the image intensity, I , at location y (measured upward from the focus of the parabola) can be calculated from:

$$I(y) = 2\rho I_s \int_{\theta_1}^{\theta_2} \sqrt{1 - \left[\left(Y - \frac{Y_0 + Y_1}{2} \right) \frac{f}{b} \right]^2} \times \sin \phi_s \sin \gamma \sec \left(\left| \theta \right| + \gamma \frac{\pi}{2} \right) \cos \theta d\theta. \quad (3.1)$$

Here, ρ is the reflectivity of the mirror surface, I_s is the normal incidence solar intensity at the aperture of the mirror, ϕ_s is the half angle subtended by the sun ($16'$), f is the focal length of the parabola, $Y = y/f$ and $b/f = (Y_0 - Y_1)/2$. Y_0 and Y_1 are the Y coordinates that define the intersection of the extreme rays of the sun with the focal plane (see Fig. 3.13).

Gamma (γ) is the angle between the mirror surface at point r, θ and the x axis, i.e.,

$$\gamma = \frac{\pi}{2} - |\theta|/2.$$

and θ_1 and θ_2 are the angles which define the edge of the rim. It can be shown that

$$\left. \begin{aligned} Y_1 &= \pm \frac{r \tan \phi_1 \sec \theta}{f(1 + \tan \phi_1 |\tan \theta|)} \\ Y_o &= \mp \frac{r \tan \phi_2 \sec \theta}{f(1 - \tan \phi_2 |\tan \theta|)} \end{aligned} \right\} \text{ for } |\theta| < 90^\circ$$

$$\left. \begin{aligned} Y_1 &= \mp \frac{r \tan \phi_1 \sec \theta}{f(1 - \tan \phi_1 |\tan \theta|)} \\ Y_o &= \pm \frac{r \tan \phi_2 \sec \theta}{f(1 + \tan \phi_2 |\tan \theta|)} \end{aligned} \right\} \text{ for } |\theta| > 90^\circ$$

where the top signs apply for $\theta > 0$ and the bottom signs for $\theta < 0$. Normally

$$\phi_s = \phi_1 = \phi_2$$

Work during this quarter has extended this analysis to incorporate a non-uniform solar disk and surface slope errors. An empirical equation (Ref. 3.4) for the sun's intensity distribution of the form

$$I(r) = \frac{R_o + 1.5641 \sqrt{R_o^2 - r^2}}{2.5641 R_o} I_o$$

has been used. Here R_o is the radius of the sun (or its image), r is the radial coordinate and I_o is the intensity at the center of the solar disk.

This equation has been used by Jose (Ref. 3.5) for solar furnace work for optics that possess cylindrical symmetry.

A paper on this subject is being prepared for publication and will be included in the annual report. Only the results will be presented here.

Figure 3.14 shows intensity distributions in the focal plane of a perfect cylindrical parabolic concentrator for the non-uniform solar disk. Results are in terms of local concentration ratio (perfect reflectivity assumed) vs. distance from the focus. The curves are symmetrical about $y/f=0$.

Figure 3.15 shows comparable results for a constant intensity circular solar disk (the solid curves). Again, perfect reflectivity has been assumed. Figure 3.16 shows results for a constant intensity square sun model using a perfect reflectivity mirror.

Results that appear in the literature (Refs. 3.6 and 3.7) are very similar to those shown in Figure 3.16, although the authors claim they are for a uniform solar disk.

Equation (3.1) lends itself to many applications. First, it can be used to study off-axis use such as would be encountered with tracking errors. Figure 3.17 shows the intensity distributions in the focal plane for off-axis operation of various amounts, for 30° and 75° rim angles.

Equation (3.1) can also be easily modified to yield intensity distributions for defocused use. Example results for a rim angle of 30° are shown in Figure 3.18 for four different distances (L) from the focal plane. (L is measured positive as shown on Figure 3.13.) The dotted segments of the curves show the effect of shading of the mirror by the absorber, were it just wide enough to collect all of the energy at a given distance L . Figure

3.19 shows similar calculations for a rim angle of 75°. Since absorber widths would be impractically wide in order to collect all energy at a given y, shading of the mirror has not been considered.

Through control of ϕ_1 and ϕ_2 , Eq. (3.1) can easily be used to investigate the effect of surface slope errors on image quality. A Monte Carlo technique has been used to predict intensity distribution in the focal plane under the assumption of random slope errors. Results for a rim angle of 15° are shown in Figure 3.20. Sigma (σ) is the standard deviation of the assumed normal distribution of surface slope errors.

Work is continuing on the random slope error calculations for other rim angles. Calculations are also being made for other non-random slope errors.

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6.8

FIG. 3.1 ALBUQUERQUE, COLLECTOR A

3.10

FIG. 3.2 ALBUQUERQUE, COLLECTOR B

FIG. 3.3 ALBUQUERQUE, COLLECTOR C

FIG. 3.4 ALBUQUERQUE, COLLECTOR D

3.13

FIG. 3.5 ALBUQUERQUE, COLLECTOR E

3.14

FIG. 3.6 ALBUQUERQUE, COLLECTOR F

FIG. 3.7 OMAHA, COLLECTOR A

FIG. 3.8 OMAHA, COLLECTOR B

FIG. 3.9 OMAHA, COLLECTOR C

3.18

FIG. 3.10 OMAHA, COLLECTOR D

3.20

FIG. 3.11 OMAHA, COLLECTOR E

FIG. 3.12 OMAHA, COLLECTOR F

FIG. 3.13 CROSS-SECTION OF CYLINDRICAL PARABOLIC CONCENTRATOR

FIG. 3.14 INTENSITY DISTRIBUTION IN FOCAL PLANE OF PERFECT CYLINDRICAL PARABOLIC CONCENTRATOR FOR NON-UNIFORM CIRCULAR SOLAR DISK.

FIG. 3.15 INTENSITY DISTRIBUTION IN FOCAL PLANE OF PERFECT CYLINDRICAL PARABOLIC CONCENTRATOR FOR UNIFORM CIRCULAR SOLAR DISK.

FIG. 3.16 INTENSITY DISTRIBUTION IN FOCAL PLANE OF PERFECT CYLINDRICAL PARABOLIC CONCENTRATOR FOR CONSTANT INTENSITY SQUARE OBJECT

FIG. 3.17. INTENSITY DISTRIBUTION IN THE FOCAL PLANE OF CYLINDRICAL PARABOLIC CONCENTRATORS FOR OFF-AXIS USE (PERFECT REFLECTIVITY ASSUMED)

FIG. 3.18. INTENSITY DISTRIBUTION FOR PERFECT CYLINDRICAL PARABOLIC CONCENTRATORS IN PLANES BEHIND THE FOCAL PLANE (DEFOCUSSED USE). (PERFECT REFLECTIVITY ASSUMED)

FIG. 3.19. INTENSITY DISTRIBUTIONS FOR PERFECT CYLINDRICAL PARABOLIC CONCENTRATORS IN PLANES BEHIND THE FOCAL PLANE (DEFOCUSSED USE). (PERFECT REFLECTIVITY ASSUMED)

FIG. 3.20. INTENSITY DISTRIBUTION IN FOCAL PLANE OF CYLINDRICAL PARABOLIC CONCENTRATOR FOR NORMAL SLOPE ERROR DISTRIBUTIONS OF STANDARD DEVIATION σ

TABLE 3.1

INSOLATION DATA BASE
STATION
ALBUQUERQUE, N.M.

WEATHER BUREAU NUMBER
STA. NO. LAT. N
23050 35.05

LONG. W
106.62

NORTH*	YEAR*	TOT ON A HOR*	TOT ON B TILT*	DIR C NORM*	EW D STRIP*	HOR NS E STRP*PLR NS	F STRP	
1	1962	111.	104.	209.	171.	144.	195.	(KWH/MO
2	1962	128.	105.	206.	160.	160.	201.	(KWH/MO
3	1962	182.	222.	258.	179.	229.	257.	(KWH/MO
4	1962	220.	228.	276.	190.	263.	266.	(KWH/MO
5	1962	273.	250.	336.	235.	329.	303.	(KWH/MO
6	1962	265.	228.	322.	235.	316.	285.	(KWH/MO
7	1962	230.	206.	271.	200.	266.	243.	(KWH/MO
8	1962	239.	235.	313.	214.	302.	292.	(KWH/MO
9	1962	169.	193.	206.	150.	168.	206.	(KWH/MO
10	1962	168.	229.	204.	191.	219.	260.	(KWH/MO
11	1962	112.	100.	207.	168.	149.	197.	(KWH/MO
12	1962	102.	180.	213.	175.	141.	196.	(KWH/MO
ALL OF	1962	2200.	2518.	3080.	2268.	2707.	2902.	(KWH/YR
1	1963	110.	103.	212.	173.	146.	198.	(KWH/MO
2	1963	125.	178.	192.	151.	149.	187.	(KWH/MO
3	1963	190.	253.	268.	189.	237.	267.	(KWH/MO
4	1963	219.	228.	270.	190.	257.	261.	(KWH/MO
5	1963	241.	223.	284.	204.	279.	260.	(KWH/MO
6	1963	253.	218.	302.	219.	297.	267.	(KWH/MO
7	1963	228.	206.	254.	189.	250.	229.	(KWH/MO
8	1963	208.	208.	239.	176.	231.	226.	(KWH/MO
9	1963	183.	211.	235.	170.	215.	235.	(KWH/MO
10	1963	157.	212.	244.	176.	203.	241.	(KWH/MO
11	1963	115.	103.	206.	166.	148.	195.	(KWH/MO
12	1963	114.	200.	235.	191.	157.	216.	(KWH/MO
ALL OF	1963	2142.	2402.	2942.	2194.	2569.	2783.	(KWH/YR
1	62-63	111.	103.	210.	172.	171.	197.	(KWH/MO
2	62-63	126.	182.	199.	156.	174.	194.	(KWH/MO
3	62-63	186.	227.	263.	184.	246.	262.	(KWH/MO
4	62-63	219.	228.	273.	190.	262.	264.	(KWH/MO
5	62-63	257.	250.	310.	220.	294.	281.	(KWH/MO
6	62-63	259.	223.	312.	227.	292.	276.	(KWH/MO
7	62-63	229.	206.	263.	194.	248.	236.	(KWH/MO
8	62-63	224.	221.	276.	195.	264.	259.	(KWH/MO
9	62-63	176.	202.	221.	160.	212.	220.	(KWH/MO
10	62-63	162.	220.	254.	184.	230.	251.	(KWH/MO
11	62-63	114.	101.	207.	167.	172.	196.	(KWH/MO
12	62-63	108.	190.	224.	183.	178.	206.	(KWH/MO
AVG	62-63	2171.	2500.	3011.	2231.	2745.	2842.	(KWH/YR

SPEEDREAD WITH EYE TRACK PATENT PENDING

3.36

TABLE 3.1 (cont)

INSOLATION DATA BASE WEATHER BUREAU NUMBER
 STATION STA. NO. LAT. N
 TUCSON, ARIZ. 23160 32.23

LONG. W
 110.95

MONTH*	YEAR*	TOT ON A HOR*	TOT ON B TILT*	DIR C NORM*	FW STRIP* HOR NS	E STRIP* PLP NS	F STRIP	
1	1962	120.	167.	213.	173.	152.	199.	(KWH/MO/M2)
2	1962	129.	177.	192.	148.	153.	187.	(KWH/MO/M2)
3	1962	196.	232.	265.	185.	240.	264.	(KWH/MO/M2)
4	1962	239.	246.	296.	205.	285.	287.	(KWH/MO/M2)
5	1962	260.	238.	321.	225.	316.	292.	(KWH/MO/M2)
6	1962	253.	218.	303.	219.	298.	267.	(KWH/MO/M2)
7	1962	218.	195.	247.	180.	243.	224.	(KWH/MO/M2)
8	1962	220.	217.	262.	186.	255.	249.	(KWH/MO/M2)
9	1962	171.	192.	209.	151.	194.	209.	(KWH/MO/M2)
10	1962	163.	213.	246.	170.	209.	243.	(KWH/MO/M2)
11	1962	118.	175.	194.	157.	143.	184.	(KWH/MO/M2)
12	1962	101.	161.	179.	151.	121.	165.	(KWH/MO/M2)
ALL OF	1962	2187.	2451.	2927.	2160.	2609.	2771.	(KWH/YR/M2)
1	1963	115.	177.	197.	161.	140.	184.	(KWH/MO/M2)
2	1963	135.	185.	207.	157.	167.	201.	(KWH/MO/M2)
3	1963	189.	225.	256.	170.	231.	255.	(KWH/MO/M2)
4	1963	210.	226.	269.	186.	259.	261.	(KWH/MO/M2)
5	1963	240.	228.	297.	211.	292.	271.	(KWH/MO/M2)
6	1963	264.	227.	320.	231.	315.	283.	(KWH/MO/M2)
7	1963	228.	205.	260.	191.	256.	234.	(KWH/MO/M2)
8	1963	189.	187.	217.	154.	212.	207.	(KWH/MO/M2)
9	1963	185.	208.	244.	165.	228.	244.	(KWH/MO/M2)
10	1963	152.	198.	222.	163.	188.	219.	(KWH/MO/M2)
11	1963	111.	166.	188.	149.	141.	179.	(KWH/MO/M2)
12	1963	110.	181.	216.	175.	149.	198.	(KWH/MO/M2)
ALL OF	1963	2145.	2413.	2892.	2122.	2577.	2737.	(KWH/YR/M2)
1	62-63	118.	182.	205.	167.	168.	192.	(KWH/MO/M2)
2	62-63	132.	181.	199.	153.	177.	194.	(KWH/MO/M2)
3	62-63	192.	229.	260.	182.	247.	260.	(KWH/MO/M2)
4	62-63	229.	236.	282.	196.	273.	274.	(KWH/MO/M2)
5	62-63	255.	233.	309.	218.	293.	281.	(KWH/MO/M2)
6	62-63	258.	223.	311.	225.	291.	275.	(KWH/MO/M2)
7	62-63	223.	200.	254.	186.	239.	229.	(KWH/MO/M2)
8	62-63	205.	202.	239.	170.	231.	228.	(KWH/MO/M2)
9	62-63	178.	200.	227.	158.	219.	226.	(KWH/MO/M2)
10	62-63	158.	206.	234.	171.	214.	231.	(KWH/MO/M2)
11	62-63	114.	171.	191.	153.	161.	181.	(KWH/MO/M2)
12	62-63	106.	171.	197.	163.	160.	182.	(KWH/MO/M2)
AVG	62-63	2166.	2432.	2910.	2141.	2673.	2754.	(KWH/YR/M2)

TABLE 3.1 (cont).

INSOLATION DATA BASE WEATHER BUREAU NUMBER
STATION STA. NO. LAT. N
SALT LAKE CITY, UTA. 24127 40.78

LONG. W
111.92

MONTH*	YEAR*	TOT ON	A HOR*	TOT ON	B TILT*	DIR	C NORM*	D EW STRIP*	HOR NS	E STRP*PLR NS	F STRP	
1	1962	67.		128.		146.		110.		94.	136.	(KWH/MO/M2)
2	1962	71.		107.		103.		84.		74.	101.	(KWH/MO/M2)
3	1962	168.		218.		250.		177.		213.	249.	(KWH/MO/M2)
4	1962	207.		225.		256.		171.		239.	241.	(KWH/MO/M2)
5	1962	234.		222.		264.		185.		255.	233.	(KWH/MO/M2)
6	1962	252.		217.		238.		216.		291.	257.	(KWH/MO/M2)
7	1962	248.		221.		301.		214.		293.	265.	(KWH/MO/M2)
8	1962	235.		237.		325.		214.		309.	300.	(KWH/MO/M2)
9	1962	183.		221.		270.		183.		242.	270.	(KWH/MO/M2)
10	1962	143.		216.		251.		187.		197.	248.	(KWH/MO/M2)
11	1962	79.		144.		165.		132.		111.	157.	(KWH/MO/M2)
12	1962	64.		132.		152.		127.		92.	140.	(KWH/MO/M2)
ALL OF 1962		1951.		2288.		2781.		2010.		2410.	2597.	(KWH/YR/M2)
1	1963	71.		140.		161.		131.		103.	150.	(KWH/MO/M2)
2	1963	95.		150.		161.		127.		117.	156.	(KWH/MO/M2)
3	1963	163.		213.		248.		173.		211.	247.	(KWH/MO/M2)
4	1963	155.		165.		192.		131.		180.	184.	(KWH/MO/M2)
5	1963	236.		220.		288.		190.		278.	262.	(KWH/MO/M2)
6	1963	232.		203.		263.		195.		257.	232.	(KWH/MO/M2)
7	1963	249.		222.		304.		217.		295.	273.	(KWH/MO/M2)
8	1963	211.		212.		284.		180.		270.	260.	(KWH/MO/M2)
9	1963	155.		190.		222.		154.		196.	222.	(KWH/MO/M2)
10	1963	132.		195.		223.		165.		176.	220.	(KWH/MO/M2)
11	1963	76.		138.		155.		126.		103.	147.	(KWH/MO/M2)
12	1963	50.		97.		104.		88.		61.	95.	(KWH/MO/M2)
ALL OF 1963		1824.		2146.		2605.		1895.		2249.	2449.	(KWH/YR/M2)
1	62-63	69.		134.		153.		125.		122.	143.	(KWH/MO/M2)
2	62-63	83.		129.		132.		106.		115.	129.	(KWH/MO/M2)
3	62-63	165.		216.		249.		175.		230.	248.	(KWH/MO/M2)
4	62-63	181.		195.		224.		151.		211.	213.	(KWH/MO/M2)
5	62-63	235.		221.		276.		192.		258.	248.	(KWH/MO/M2)
6	62-63	242.		210.		281.		205.		262.	245.	(KWH/MO/M2)
7	62-63	248.		221.		302.		216.		283.	269.	(KWH/MO/M2)
8	62-63	223.		224.		305.		201.		284.	280.	(KWH/MO/M2)
9	62-63	169.		206.		246.		169.		232.	246.	(KWH/MO/M2)
10	62-63	137.		206.		237.		176.		209.	234.	(KWH/MO/M2)
11	62-63	78.		141.		160.		129.		129.	152.	(KWH/MO/M2)
12	62-63	57.		114.		128.		108.		94.	118.	(KWH/MO/M2)
AVG 62-63		1887.		2217.		2693.		1953.		2430.	2523.	(KWH/YR/M2)

TABLE 3.1 (cont)

INSOLATION DATA BASE
STATION
PHOENIX ARIZ.

WEATHER BUREAU NUMBER
STA. NO. LAT. N
23183 33.43

LONG. W
112.02

MONTH*	YEAR*	TOT ON	HUR*TOT ON	TILT*	DIR	NORM*	EW	STRIP*HOR	NS	STRP*PLR	NS	STRP	
1	1962	111.		175.		194.		161.		135.		181.	(KWH/MO/M2)
2	1962	121.		168.		178.		141.		140.		174.	(KWH/MO/M2)
3	1962	180.		216.		240.		171.		214.		239.	(KWH/MO/M2)
4	1962	217.		225.		266.		186.		256.		259.	(KWH/MO/M2)
5	1962	251.		230.		302.		213.		296.		275.	(KWH/MO/M2)
6	1962	231.		200.		272.		196.		267.		241.	(KWH/MO/M2)
7	1962	244.		217.		291.		208.		286.		263.	(KWH/MO/M2)
8	1962	224.		221.		275.		192.		268.		260.	(KWH/MO/M2)
9	1962	170.		191.		215.		150.		199.		214.	(KWH/MO/M2)
10	1962	162.		215.		248.		181.		208.		245.	(KWH/MO/M2)
11	1962	112.		170.		169.		153.		138.		180.	(KWH/MO/M2)
12	1962	90.		160.		183.		152.		123.		168.	(KWH/MO/M2)
ALL OF	1962	2118.		2389.		2853.		2105.		2531.		2699.	(KWH/YR/M2)
1	1963	113.		180.		204.		167.		144.		191.	(KWH/MO/M2)
2	1963	131.		183.		206.		156.		164.		201.	(KWH/MO/M2)
3	1963	191.		231.		266.		185.		238.		265.	(KWH/MO/M2)
4	1963	217.		225.		272.		187.		261.		264.	(KWH/MO/M2)
5	1963	245.		225.		295.		208.		290.		269.	(KWH/MO/M2)
6	1963	255.		220.		308.		221.		303.		271.	(KWH/MO/M2)
7	1963	230.		210.		278.		200.		274.		250.	(KWH/MO/M2)
8	1963	202.		200.		237.		168.		230.		225.	(KWH/MO/M2)
9	1963	186.		212.		242.		170.		223.		241.	(KWH/MO/M2)
10	1963	150.		208.		235.		174.		198.		233.	(KWH/MO/M2)
11	1963	121.		185.		208.		168.		150.		196.	(KWH/MO/M2)
12	1963	115.		194.		228.		189.		154.		210.	(KWH/MO/M2)
ALL OF	1963	2168.		2472.		2980.		2193.		2630.		2818.	(KWH/YR/M2)
1	62-63	112.		177.		199.		164.		163.		186.	(KWH/MO/M2)
2	62-63	126.		176.		192.		149.		170.		187.	(KWH/MO/M2)
3	62-63	183.		223.		253.		178.		240.		252.	(KWH/MO/M2)
4	62-63	217.		225.		269.		186.		260.		261.	(KWH/MO/M2)
5	62-63	246.		227.		299.		211.		283.		272.	(KWH/MO/M2)
6	62-63	243.		210.		290.		209.		269.		256.	(KWH/MO/M2)
7	62-63	240.		213.		285.		204.		268.		256.	(KWH/MO/M2)
8	62-63	213.		211.		255.		180.		245.		242.	(KWH/MO/M2)
9	62-63	178.		202.		228.		160.		220.		227.	(KWH/MO/M2)
10	62-63	159.		211.		242.		178.		221.		239.	(KWH/MO/M2)
11	62-63	110.		176.		193.		160.		167.		188.	(KWH/MO/M2)
12	62-63	106.		177.		206.		170.		167.		189.	(KWH/MO/M2)
AVG	62-63	2143.		2450.		2910.		2149.		2674.		2758.	(KWH/YR/M2)

TABLE 3.1 (cont)

INSOLATION DATA BASE WEATHER BUREAU NUMBER
 STATION STA. NO. LAT. N LONG. W
 ELY, NEV. 23154 39.28 114.85

MONTH*	YEAR*	TOT ON	A HOR*	TOT ON	B TILT*	DIR	C NORM*	FW	D STRIP*	HOP	NS	E STRP*	PLP	NS	F STDP	
1	1962	96.		178.		205.		170.		133.		192.				(KWH/MO/M2)
2	1962	88.		134.		141.		111.		105.		137.				(KWH/MO/M2)
3	1962	171.		219.		246.		177.		212.		246.				(KWH/MO/M2)
4	1962	207.		221.		267.		184.		251.		257.				(KWH/MO/M2)
5	1962	200.		185.		237.		164.		230.		214.				(KWH/MO/M2)
6	1962	254.		218.		309.		221.		302.		270.				(KWH/MO/M2)
7	1962	248.		220.		269.		214.		282.		265.				(KWH/MO/M2)
8	1962	241.		242.		319.		216.		305.		295.				(KWH/MO/M2)
9	1962	195.		232.		274.		190.		246.		274.				(KWH/MO/M2)
10	1962	149.		219.		249.		188.		197.		246.				(KWH/MO/M2)
11	1962	100.		177.		201.		165.		136.		191.				(KWH/MO/M2)
12	1962	86.		175.		210.		174.		131.		194.				(KWH/MO/M2)
ALL OF	1962	2036.		2419.		2958.		2173.		2538.		2780.				(KWH/YR/M2)
1	1963	92.		171.		164.		162.		124.		181.				(KWH/MO/M2)
2	1963	103.		166.		179.		142.		133.		175.				(KWH/MO/M2)
3	1963	165.		212.		240.		171.		206.		239.				(KWH/MO/M2)
4	1963	172.		183.		210.		146.		197.		203.				(KWH/MO/M2)
5	1963	225.		208.		275.		191.		267.		249.				(KWH/MO/M2)
6	1963	213.		184.		249.		170.		244.		217.				(KWH/MO/M2)
7	1963	273.		240.		351.		243.		341.		310.				(KWH/MO/M2)
8	1963	217.		218.		282.		190.		269.		263.				(KWH/MO/M2)
9	1963	173.		207.		241.		167.		216.		240.				(KWH/MO/M2)
10	1963	139.		202.		226.		171.		179.		223.				(KWH/MO/M2)
11	1963	94.		166.		187.		153.		126.		177.				(KWH/MO/M2)
12	1963	85.		170.		200.		168.		123.		184.				(KWH/MO/M2)
ALL OF	1963	1958.		2326.		2834.		2083.		2426.		2661.				(KWH/YR/M2)
1	62-63	94.		175.		199.		166.		157.		186.				(KWH/MO/M2)
2	62-63	98.		150.		160.		127.		140.		156.				(KWH/MO/M2)
3	62-63	168.		215.		243.		174.		226.		242.				(KWH/MO/M2)
4	62-63	190.		202.		239.		165.		227.		230.				(KWH/MO/M2)
5	62-63	213.		196.		256.		177.		239.		231.				(KWH/MO/M2)
6	62-63	234.		201.		279.		200.		259.		243.				(KWH/MO/M2)
7	62-63	260.		230.		325.		228.		301.		288.				(KWH/MO/M2)
8	62-63	229.		230.		300.		203.		284.		279.				(KWH/MO/M2)
9	62-63	184.		219.		258.		179.		243.		257.				(KWH/MO/M2)
10	62-63	144.		210.		237.		180.		210.		234.				(KWH/MO/M2)
11	62-63	97.		171.		194.		159.		157.		184.				(KWH/MO/M2)
12	62-63	86.		173.		205.		171.		158.		189.				(KWH/MO/M2)
AVG	62-63	1997.		2373.		2806.		2128.		2600.		2720.				(KWH/YR/M2)

INSOLATION DATA BASE WEATHER BUREAU NUMBER
STATION STA. NO. LAT. N
GRAND JUNCTION, COL. 10790 39.12

LONG. W
108.53

MONTH*	YEAR*	TOT ON	A HOR*TOT ON	R TILT*	C DIR	NORM*	D FW STRP*	HOR NS	F STRP*PLR NS	F STRP	
1	1962	82.	148.	160.	137.	102.	150.	(KWH/MO/M2)			
2	1962	85.	131.	136.	109.	100.	132.	(KWH/MO/M2)			
3	1962	152.	193.	213.	154.	184.	213.	(KWH/MO/M2)			
4	1962	195.	208.	244.	170.	229.	240.	(KWH/MO/M2)			
5	1962	211.	195.	257.	178.	249.	233.	(KWH/MO/M2)			
6	1962	237.	202.	291.	205.	284.	254.	(KWH/MO/M2)			
7	1962	237.	209.	295.	205.	287.	262.	(KWH/MO/M2)			
8	1962	217.	217.	276.	189.	264.	264.	(KWH/MO/M2)			
9	1962	169.	200.	235.	162.	211.	234.	(KWH/MO/M2)			
10	1962	136.	197.	217.	167.	171.	214.	(KWH/MO/M2)			
11	1962	90.	156.	172.	142.	116.	163.	(KWH/MO/M2)			
12	1962	76.	145.	159.	139.	95.	147.	(KWH/MO/M2)			
ALL OF 1962		1886.	2200.	2657.	1956.	2293.	2507.	(KWH/YR/M2)			
1	1963	75.	133.	140.	121.	88.	131.	(KWH/MO/M2)			
2	1963	101.	155.	169.	133.	126.	165.	(KWH/MO/M2)			
3	1963	147.	196.	204.	147.	176.	203.	(KWH/MO/M2)			
4	1963	175.	186.	215.	150.	202.	212.	(KWH/MO/M2)			
5	1963	228.	209.	286.	196.	277.	259.	(KWH/MO/M2)			
6	1963	230.	196.	281.	198.	274.	245.	(KWH/MO/M2)			
7	1963	236.	209.	291.	204.	283.	259.	(KWH/MO/M2)			
8	1963	186.	188.	225.	157.	216.	217.	(KWH/MO/M2)			
9	1963	171.	204.	240.	166.	215.	239.	(KWH/MO/M2)			
10	1963	131.	188.	205.	158.	162.	202.	(KWH/MO/M2)			
11	1963	89.	154.	169.	141.	113.	160.	(KWH/MO/M2)			
12	1963	73.	138.	151.	132.	90.	139.	(KWH/MO/M2)			
ALL OF 1963		1842.	2148.	2576.	1901.	2222.	2432.	(KWH/YR/M2)			
1	62-63	79.	141.	150.	129.	116.	141.	(KWH/MO/M2)			
2	62-63	93.	143.	152.	121.	132.	149.	(KWH/MO/M2)			
3	62-63	149.	190.	208.	150.	193.	208.	(KWH/MO/M2)			
4	62-63	185.	197.	230.	160.	221.	226.	(KWH/MO/M2)			
5	62-63	220.	202.	271.	187.	254.	246.	(KWH/MO/M2)			
6	62-63	233.	199.	286.	201.	265.	249.	(KWH/MO/M2)			
7	62-63	236.	209.	293.	204.	273.	261.	(KWH/MO/M2)			
8	62-63	202.	202.	251.	173.	241.	241.	(KWH/MO/M2)			
9	62-63	170.	202.	237.	164.	225.	236.	(KWH/MO/M2)			
10	62-63	133.	192.	211.	162.	187.	208.	(KWH/MO/M2)			
11	62-63	90.	155.	171.	142.	138.	162.	(KWH/MO/M2)			
12	62-63	74.	142.	155.	135.	117.	143.	(KWH/MO/M2)			
AVG 62-63		1864.	2174.	2617.	1929.	2363.	2470.	(KWH/YR/M2)			

3.35

TABLE 3.1 (cont)

INSOLATION DATA BASE
STATION
OMAHA, NEB.

WEATHER BUREAU NUMBER
STA. NO. LAT. N
94918 41.37

LONG. W
96.02

MONTH*	YEAR*	TOT ON	A HOR*	TOT ON	B TILT*	DIR	C NORM*	EW	D STRIP*	HOR	NS	E STRP*	PLR	NS	F STRP	
1	1962	80.		159.		182.		151.		114.		170.				(KWH/MO/M2)
2	1962	74.		116.		118.		94.		86.		115.				(KWH/MO/M2)
3	1962	131.		172.		187.		133.		158.		186.				(KWH/MO/M2)
4	1962	171.		184.		219.		149.		203.		209.				(KWH/MO/M2)
5	1962	180.		175.		217.		153.		209.		197.				(KWH/MO/M2)
6	1962	190.		172.		226.		164.		220.		200.				(KWH/MO/M2)
7	1962	210.		192.		240.		178.		239.		223.				(KWH/MO/M2)
8	1962	192.		195.		240.		167.		227.		226.				(KWH/MO/M2)
9	1962	140.		177.		190.		140.		173.		196.				(KWH/MO/M2)
10	1962	100.		160.		173.		133.		132.		171.				(KWH/MO/M2)
11	1962	60.		113.		124.		100.		83.		118.				(KWH/MO/M2)
12	1962	60.		122.		133.		115.		77.		123.				(KWH/MO/M2)
ALL OF 1962		1621.		1940.		2262.		1676.		1921.		2132.				(KWH/YR/M2)
1	1963	70.		143.		164.		134.		105.		154.				(KWH/MO/M2)
2	1963	87.		138.		145.		115.		105.		141.				(KWH/MO/M2)
3	1963	126.		166.		180.		126.		152.		179.				(KWH/MO/M2)
4	1963	149.		162.		177.		125.		164.		171.				(KWH/MO/M2)
5	1963	174.		185.		189.		137.		162.		173.				(KWH/MO/M2)
6	1963	210.		190.		243.		160.		237.		217.				(KWH/MO/M2)
7	1963	210.		189.		243.		173.		235.		218.				(KWH/MO/M2)
8	1963	177.		179.		215.		149.		204.		203.				(KWH/MO/M2)
9	1963	134.		163.		160.		126.		159.		179.				(KWH/MO/M2)
10	1963	132.		196.		217.		164.		169.		215.				(KWH/MO/M2)
11	1963	81.		150.		172.		138.		115.		163.				(KWH/MO/M2)
12	1963	69.		145.		164.		141.		96.		151.				(KWH/MO/M2)
ALL OF 1963		1630.		1986.		2269.		1711.		1923.		2164.				(KWH/YR/M2)
1	62-63	70.		151.		173.		143.		134.		162.				(KWH/MO/M2)
2	62-63	81.		127.		131.		105.		113.		128.				(KWH/MO/M2)
3	62-63	130.		169.		183.		130.		169.		183.				(KWH/MO/M2)
4	62-63	160.		173.		198.		137.		187.		190.				(KWH/MO/M2)
5	62-63	181.		171.		203.		145.		191.		185.				(KWH/MO/M2)
6	62-63	207.		181.		235.		172.		218.		208.				(KWH/MO/M2)
7	62-63	212.		190.		245.		176.		229.		220.				(KWH/MO/M2)
8	62-63	184.		167.		227.		158.		215.		214.				(KWH/MO/M2)
9	62-63	140.		170.		188.		133.		176.		188.				(KWH/MO/M2)
10	62-63	119.		178.		195.		148.		173.		193.				(KWH/MO/M2)
11	62-63	72.		132.		146.		119.		123.		140.				(KWH/MO/M2)
12	62-63	65.		133.		149.		126.		114.		137.				(KWH/MO/M2)
AVG 62-63		1625.		1963.		2276.		1693.		2043.		2148.				(KWH/YR/M2)

TABLE 3.1 (cont.)

INSOLATION DATA BASE WEATHER BUREAU NUMBER
 STATION STA. NO. LAT. N LONG. W
 INYOKERN CHINA LAKE 93104 35.68 117.68

MONTH*	YEAR*	TOT ON	A HOR*	TOT ON	B TILT*	DIR	C NORM*	EW	D STRIP*	HOR NS	E STRP*PLR NS	F STRP	
1	1902	112.		192.		227.			183.		157.	212.	(KWH/MO/M2)
2	1902	118.		170.		185.			143.		144.	180.	(KWH/MO/M2)
3	1902	192.		237.		282.			193.		250.	281.	(KWH/MO/M2)
4	1902	230.		246.		308.			210.		294.	299.	(KWH/MO/M2)
5	1902	265.		242.		339.			233.		331.	307.	(KWH/MO/M2)
6	1902	278.		237.		349.			247.		342.	305.	(KWH/MO/M2)
7	1902	276.		244.		354.			247.		347.	312.	(KWH/MO/M2)
8	1902	259.		255.		350.			233.		338.	325.	(KWH/MO/M2)
9	1902	211.		244.		298.			202.		273.	297.	(KWH/MO/M2)
10	1902	164.		226.		265.			193.		219.	262.	(KWH/MO/M2)
11	1902	114.		183.		211.			171.		150.	200.	(KWH/MO/M2)
12	1902	101.		183.		221.			181.		146.	203.	(KWH/MO/M2)
ALL OF	1902	2327.		2660.		3389.			2437.		2991.	3184.	(KWH/YR/M2)
1	1903	110.		189.		223.			180.		154.	209.	(KWH/MO/M2)
2	1903	129.		188.		206.			162.		160.	201.	(KWH/MO/M2)
3	1903	186.		230.		275.			187.		244.	274.	(KWH/MO/M2)
4	1903	222.		232.		290.			196.		276.	279.	(KWH/MO/M2)
5	1903	252.		230.		322.			220.		314.	290.	(KWH/MO/M2)
6	1903	257.		220.		317.			226.		311.	277.	(KWH/MO/M2)
7	1903	275.		241.		353.			245.		346.	312.	(KWH/MO/M2)
8	1903	234.		231.		309.			207.		298.	289.	(KWH/MO/M2)
9	1903	180.		208.		244.			167.		224.	244.	(KWH/MO/M2)
10	1903	144.		197.		222.			165.		182.	219.	(KWH/MO/M2)
11	1903	111.		179.		200.			164.		141.	190.	(KWH/MO/M2)
12	1903	104.		169.		228.			187.		150.	209.	(KWH/MO/M2)
ALL OF	1903	2205.		2534.		3189.			2306.		2800.	2993.	(KWH/YR/M2)
1	62-03	111.		190.		225.			182.		183.	210.	(KWH/MO/M2)
2	62-03	124.		179.		195.			153.		173.	191.	(KWH/MO/M2)
3	62-03	189.		234.		279.			190.		262.	278.	(KWH/MO/M2)
4	62-03	229.		239.		299.			203.		286.	289.	(KWH/MO/M2)
5	62-03	250.		236.		330.			227.		311.	298.	(KWH/MO/M2)
6	62-03	268.		229.		333.			237.		309.	291.	(KWH/MO/M2)
7	62-03	276.		242.		354.			246.		330.	312.	(KWH/MO/M2)
8	62-03	246.		243.		330.			220.		314.	307.	(KWH/MO/M2)
9	62-03	190.		220.		271.			185.		258.	270.	(KWH/MO/M2)
10	62-03	154.		211.		244.			179.		219.	240.	(KWH/MO/M2)
11	62-03	113.		182.		200.			167.		170.	195.	(KWH/MO/M2)
12	62-03	102.		186.		224.			184.		178.	206.	(KWH/MO/M2)
AVG	62-03	2266.		2597.		3289.			2372.		2992.	3089.	(KWH/YR/M2)

TABLE 3.1 (cont)

INSOLATION DATA BASE
STATION
YUMA, ARIZ

WEATHER BUREAU NUMBER
STA. NO. LAT. N
23195 32.65

LONG. W
114.62

MONTH*	YEAR*	TOT ON A	HOR*TOT ON B	TILT* C	DIR NORM*	EW STRIP*HOR NS D	STRP*PLR NS E	STRP F	
1	1962	117.	184.	210.	171.	149.	196.	(KWH/MO/M2)	
2	1962	124.	172.	187.	145.	149.	182.	(KWH/MO/M2)	
3	1962	165.	223.	249.	176.	225.	249.	(KWH/MO/M2)	
4	1962	222.	223.	276.	169.	266.	271.	(KWH/MO/M2)	
5	1962	256.	233.	311.	218.	306.	287.	(KWH/MO/M2)	
6	1962	253.	216.	315.	222.	309.	276.	(KWH/MO/M2)	
7	1962	250.	220.	321.	225.	316.	288.	(KWH/MO/M2)	
8	1962	234.	229.	266.	198.	279.	277.	(KWH/MO/M2)	
9	1962	180.	211.	249.	170.	232.	248.	(KWH/MO/M2)	
10	1962	160.	213.	243.	184.	203.	239.	(KWH/MO/M2)	
11	1962	117.	173.	202.	162.	149.	191.	(KWH/MO/M2)	
12	1962	100.	165.	195.	159.	134.	179.	(KWH/MO/M2)	
ALL OF	1962	2220.	2481.	3042.	2220.	2716.	2884.	(KWH/YR/M2)	
1	1963	112.	175.	199.	162.	141.	186.	(KWH/MO/M2)	
2	1963	134.	180.	204.	159.	163.	199.	(KWH/MO/M2)	
3	1963	180.	223.	250.	178.	224.	249.	(KWH/MO/M2)	
4	1963	212.	218.	262.	179.	252.	258.	(KWH/MO/M2)	
5	1963	249.	227.	297.	210.	293.	276.	(KWH/MO/M2)	
6	1963	259.	222.	322.	228.	316.	283.	(KWH/MO/M2)	
7	1963	252.	222.	312.	219.	307.	280.	(KWH/MO/M2)	
8	1963	220.	221.	275.	191.	268.	267.	(KWH/MO/M2)	
9	1963	194.	218.	258.	177.	240.	258.	(KWH/MO/M2)	
10	1963	159.	207.	228.	173.	192.	225.	(KWH/MO/M2)	
11	1963	120.	181.	205.	165.	151.	195.	(KWH/MO/M2)	
12	1963	112.	164.	216.	178.	147.	199.	(KWH/MO/M2)	
ALL OF	1963	2214.	2485.	3028.	2221.	2694.	2873.	(KWH/YR/M2)	
1	62-63	114.	179.	204.	167.	167.	191.	(KWH/MO/M2)	
2	62-63	129.	179.	195.	152.	174.	190.	(KWH/MO/M2)	
3	62-63	186.	221.	249.	177.	237.	249.	(KWH/MO/M2)	
4	62-63	217.	223.	269.	184.	262.	264.	(KWH/MO/M2)	
5	62-63	252.	230.	304.	214.	291.	281.	(KWH/MO/M2)	
6	62-63	256.	219.	318.	225.	296.	279.	(KWH/MO/M2)	
7	62-63	253.	225.	317.	222.	298.	284.	(KWH/MO/M2)	
8	62-63	230.	225.	280.	195.	273.	272.	(KWH/MO/M2)	
9	62-63	191.	215.	254.	174.	245.	253.	(KWH/MO/M2)	
10	62-63	162.	213.	235.	179.	214.	232.	(KWH/MO/M2)	
11	62-63	119.	180.	203.	163.	172.	193.	(KWH/MO/M2)	
12	62-63	100.	174.	205.	169.	167.	189.	(KWH/MO/M2)	
AVG	62-63	2217.	2483.	3035.	2220.	2794.	2879.	(KWH/YR/M2)	

TABLE 3.1 (cont)

INSOLATION DATA BASE
STATION
EDWARDS AFB

WEATHER BUREAU NUMBER
STA. NO. LAT. N
23114 34.90

LONG. W
117.90

MONTH*	YEAR*	TOT ON	A HOR*	TOT ON	B TILT*	DIR	C NORM*	EW	D STRIP*	HOR NS	E STRP*	PLR NS	F STRP	
1	1962	102.		168.		190.		156.		130.		177.	(KWH/MO/M2)	
2	1962	107.		152.		162.		127.		126.		158.	(KWH/MO/M2)	
3	1962	172.		209.		232.		167.		205.		231.	(KWH/MO/M2)	
4	1962	204.		212.		255.		175.		244.		250.	(KWH/MO/M2)	
5	1962	243.		222.		298.		208.		292.		273.	(KWH/MO/M2)	
6	1962	259.		221.		322.		227.		316.		282.	(KWH/MO/M2)	
7	1962	261.		229.		328.		229.		321.		292.	(KWH/MO/M2)	
8	1962	239.		235.		299.		206.		290.		288.	(KWH/MO/M2)	
9	1962	196.		227.		271.		186.		250.		271.	(KWH/MO/M2)	
10	1962	153.		207.		229.		175.		188.		226.	(KWH/MO/M2)	
11	1962	107.		170.		191.		155.		137.		181.	(KWH/MO/M2)	
12	1962	94.		163.		184.		156.		120.		169.	(KWH/MO/M2)	
ALL OF	1962	2138.		2414.		2960.		2166.		2619.		2800.	(KWH/YR/M2)	
1	1963	103.		170.		192.		159.		132.		180.	(KWH/MO/M2)	
2	1963	113.		161.		174.		136.		136.		170.	(KWH/MO/M2)	
3	1963	171.		209.		232.		167.		205.		231.	(KWH/MO/M2)	
4	1963	203.		210.		252.		173.		241.		248.	(KWH/MO/M2)	
5	1963	238.		217.		290.		202.		285.		267.	(KWH/MO/M2)	
6	1963	252.		215.		311.		220.		305.		273.	(KWH/MO/M2)	
7	1963	259.		228.		327.		227.		320.		291.	(KWH/MO/M2)	
8	1963	229.		226.		285.		197.		276.		275.	(KWH/MO/M2)	
9	1963	182.		209.		247.		170.		227.		246.	(KWH/MO/M2)	
10	1963	143.		194.		212.		162.		174.		209.	(KWH/MO/M2)	
11	1963	102.		162.		183.		147.		131.		173.	(KWH/MO/M2)	
12	1963	96.		165.		188.		158.		123.		173.	(KWH/MO/M2)	
ALL OF	1963	2091.		2366.		2892.		2117.		2555.		2736.	(KWH/YR/M2)	
1	62-63	102.		169.		191.		157.		155.		179.	(KWH/MO/M2)	
2	62-63	110.		157.		168.		132.		148.		164.	(KWH/MO/M2)	
3	62-63	171.		209.		232.		167.		218.		231.	(KWH/MO/M2)	
4	62-63	203.		211.		253.		174.		246.		249.	(KWH/MO/M2)	
5	62-63	240.		219.		294.		205.		279.		270.	(KWH/MO/M2)	
6	62-63	255.		218.		317.		224.		294.		278.	(KWH/MO/M2)	
7	62-63	260.		228.		327.		228.		306.		292.	(KWH/MO/M2)	
8	62-63	234.		230.		292.		201.		283.		282.	(KWH/MO/M2)	
9	62-63	190.		218.		259.		178.		248.		258.	(KWH/MO/M2)	
10	62-63	148.		200.		221.		168.		199.		218.	(KWH/MO/M2)	
11	62-63	105.		166.		187.		151.		155.		177.	(KWH/MO/M2)	
12	62-63	95.		164.		186.		157.		146.		171.	(KWH/MO/M2)	
AVG	62-63	2115.		2390.		2926.		2142.		2678.		2768.	(KWH/YR/M2)	

TABLE 3.1 (cont)

INSOLATION DATA BASE
STATION
RIVERSIDE, CA.

WEATHER BUREAU NUMBER
STA. NO. LAT. N
23119 33.95

LONG. W
117.45

MONTH*	YEAR*	TOT ON	A HOR*	TOT ON	B TILT*	DIR	C NORM*	EW	D STRIP*	HOR	NS	E STRP*	PLR	NS	F STRP	
1	1962		99.		155.		160.		140.			107.			150.	(KWH/MO/M2)
2	1962		94.		128.		127.		101.			99.			124.	(KWH/MO/M2)
3	1962		161.		194.		209.		151.			186.			209.	(KWH/MO/M2)
4	1962		208.		216.		252.		178.			241.			245.	(KWH/MO/M2)
5	1962		233.		214.		280.		197.			274.			257.	(KWH/MO/M2)
6	1962		230.		200.		265.		194.			261.			240.	(KWH/MO/M2)
7	1962		261.		232.		317.		227.			311.			288.	(KWH/MO/M2)
8	1962		245.		241.		316.		216.			307.			299.	(KWH/MO/M2)
9	1962		196.		223.		257.		181.			237.			257.	(KWH/MO/M2)
10	1962		153.		205.		228.		171.			189.			225.	(KWH/MO/M2)
11	1962		109.		169.		187.		152.			134.			177.	(KWH/MO/M2)
12	1962		101.		171.		197.		164.			131.			181.	(KWH/MO/M2)
ALL OF 1962		2089.		2347.		2795.		2071.		2478.		2651.				(KWH/YR/M2)
1	1963		97.		154.		167.		139.			115.			156.	(KWH/MO/M2)
2	1963		118.		164.		172.		136.			135.			168.	(KWH/MO/M2)
3	1963		180.		218.		246.		175.			219.			245.	(KWH/MO/M2)
4	1963		205.		213.		247.		174.			236.			240.	(KWH/MO/M2)
5	1963		210.		196.		238.		172.			233.			223.	(KWH/MO/M2)
6	1963		224.		195.		256.		189.			252.			231.	(KWH/MO/M2)
7	1963		269.		238.		333.		237.			327.			303.	(KWH/MO/M2)
8	1963		233.		230.		296.		203.			287.			282.	(KWH/MO/M2)
9	1963		186.		212.		248.		171.			229.			247.	(KWH/MO/M2)
10	1963		146.		195.		215.		161.			178.			212.	(KWH/MO/M2)
11	1963		113.		175.		197.		159.			142.			186.	(KWH/MO/M2)
12	1963		117.		201.		242.		198.			164.			223.	(KWH/MO/M2)
ALL OF 1963		2097.		2391.		2858.		2114.		2518.		2717.				(KWH/YR/M2)
1	62-63		98.		155.		164.		139.			132.			153.	(KWH/MO/M2)
2	62-63		106.		146.		149.		119.			133.			146.	(KWH/MO/M2)
3	62-63		170.		206.		228.		163.			216.			227.	(KWH/MO/M2)
4	62-63		206.		215.		249.		176.			241.			243.	(KWH/MO/M2)
5	62-63		221.		205.		259.		184.			248.			240.	(KWH/MO/M2)
6	62-63		227.		197.		261.		191.			246.			235.	(KWH/MO/M2)
7	62-63		265.		235.		325.		232.			307.			296.	(KWH/MO/M2)
8	62-63		239.		235.		306.		209.			294.			291.	(KWH/MO/M2)
9	62-63		191.		217.		252.		176.			242.			252.	(KWH/MO/M2)
10	62-63		150.		200.		222.		166.			200.			219.	(KWH/MO/M2)
11	62-63		111.		172.		192.		155.			160.			182.	(KWH/MO/M2)
12	62-63		109.		186.		220.		181.			177.			202.	(KWH/MO/M2)
AVG 62-63		2093.		2369.		2827.		2092.		2598.		2684.				(KWH/YR/M2)

TABLE 3.1 (cont)

INSOLATION DATA BASE

WEATHER BUREAU NUMBER

STATION
FORT WORTH, TEX.STA. NO. LAT. N
03927 32.83LONG. W
97.05

MONTH*	YEAR*	TOT ON A HOR*TOT ON B TILT*	DIR C NORM*	EW STRIP*HOR NS D	STRP*PLR NS E	STRP F	
1	1962	97.	149.	160.	133.	112.	150. (KWH/MO/M2)
2	1962	115.	159.	167.	132.	131.	162. (KWH/MO/M2)
3	1962	153.	165.	197.	143.	176.	197. (KWH/MO/M2)
4	1962	152.	158.	165.	120.	158.	151. (KWH/MO/M2)
5	1962	225.	209.	254.	186.	249.	236. (KWH/MO/M2)
6	1962	204.	179.	224.	167.	220.	291. (KWH/MO/M2)
7	1962	220.	196.	254.	184.	259.	229. (KWH/MO/M2)
8	1962	220.	217.	267.	187.	259.	253. (KWH/MO/M2)
9	1962	150.	179.	195.	139.	180.	195. (KWH/MO/M2)
10	1962	131.	172.	165.	139.	154.	182. (KWH/MO/M2)
11	1962	84.	123.	129.	104.	90.	123. (KWH/MO/M2)
12	1962	82.	132.	143.	120.	96.	132. (KWH/MO/M2)
ALL OF	1962	1842.	2060.	2340.	1753.	2084.	2221. (KWH/YR/M2)
1	1963	94.	145.	156.	129.	109.	146. (KWH/MO/M2)
2	1963	101.	139.	147.	112.	118.	143. (KWH/MO/M2)
3	1963	166.	201.	218.	157.	195.	217. (KWH/MO/M2)
4	1963	161.	167.	174.	127.	167.	171. (KWH/MO/M2)
5	1963	198.	184.	215.	158.	211.	200. (KWH/MO/M2)
6	1963	217.	169.	246.	161.	242.	220. (KWH/MO/M2)
7	1963	240.	214.	282.	204.	277.	254. (KWH/MO/M2)
8	1963	220.	216.	275.	189.	267.	257. (KWH/MO/M2)
9	1963	158.	173.	192.	137.	177.	191. (KWH/MO/M2)
10	1963	140.	191.	213.	157.	180.	211. (KWH/MO/M2)
11	1963	99.	147.	153.	128.	114.	143. (KWH/MO/M2)
12	1963	80.	123.	138.	116.	93.	127. (KWH/MO/M2)
ALL OF	1963	1882.	2100.	2411.	1795.	2151.	2285. (KWH/YR/M2)
1	62-63	95.	147.	156.	131.	129.	143. (KWH/MO/M2)
2	62-63	106.	149.	157.	122.	137.	153. (KWH/MO/M2)
3	62-63	161.	193.	208.	150.	197.	207. (KWH/MO/M2)
4	62-63	156.	163.	170.	123.	164.	166. (KWH/MO/M2)
5	62-63	211.	197.	234.	172.	225.	218. (KWH/MO/M2)
6	62-63	211.	184.	235.	174.	220.	210. (KWH/MO/M2)
7	62-63	230.	205.	268.	194.	252.	241. (KWH/MO/M2)
8	62-63	220.	216.	271.	188.	258.	255. (KWH/MO/M2)
9	62-63	158.	179.	194.	138.	186.	193. (KWH/MO/M2)
10	62-63	158.	181.	199.	148.	182.	196. (KWH/MO/M2)
11	62-63	91.	135.	143.	116.	122.	136. (KWH/MO/M2)
12	62-63	61.	130.	141.	118.	112.	130. (KWH/MO/M2)
AVG	62-63	1862.	2060.	2376.	1774.	2184.	2253. (KWH/YR/M2)

TABLE 3.1 (cont)

INSOLATION DATA BASE

WEATHER BUREAU NUMBER

STATION
DODGE CITY, KAN.STA. NO. 13935
LAT. N 37.77

LONG. W 97.97

MONTH*	YEAR*	TOT ON A	TOT ON B	TILT*	DIR C	NORM*	EW D	STRIP*HOR NS	STRP*PLR NS E	STRP F	
1	1962	89.	159.		184.		149.		123.	172.	(KWH/MO/M2)
2	1962	101.	152.		164.		128.		124.	160.	(KWH/MO/M2)
3	1962	161.	204.		227.		162.		197.	226.	(KWH/MO/M2)
4	1962	176.	187.		218.		150.		206.	209.	(KWH/MO/M2)
5	1962	204.	158.		243.		171.		236.	220.	(KWH/MO/M2)
6	1962	216.	182.		237.		173.		232.	211.	(KWH/MO/M2)
7	1962	227.	203.		266.		193.		260.	239.	(KWH/MO/M2)
8	1962	220.	220.		280.		193.		268.	263.	(KWH/MO/M2)
9	1962	134.	157.		167.		118.		150.	166.	(KWH/MO/M2)
10	1962	120.	173.		199.		146.		160.	196.	(KWH/MO/M2)
11	1962	80.	138.		154.		123.		108.	146.	(KWH/MO/M2)
12	1962	81.	161.		202.		160.		134.	186.	(KWH/MO/M2)
ALL OF 1962		1812.	2123.		2540.		1868.		2198.	2394.	(KWH/YR/M2)
1	1963	90.	161.		186.		151.		125.	174.	(KWH/MO/M2)
2	1963	115.	173.		168.		147.		142.	183.	(KWH/MO/M2)
3	1963	161.	203.		239.		163.		209.	238.	(KWH/MO/M2)
4	1963	203.	215.		258.		178.		243.	247.	(KWH/MO/M2)
5	1963	183.	171.		211.		148.		205.	192.	(KWH/MO/M2)
6	1963	210.	182.		273.		187.		266.	233.	(KWH/MO/M2)
7	1963	234.	209.		276.		200.		269.	247.	(KWH/MO/M2)
8	1963	195.	194.		249.		168.		239.	231.	(KWH/MO/M2)
9	1963	161.	190.		214.		150.		193.	213.	(KWH/MO/M2)
10	1963	134.	188.		213.		157.		173.	211.	(KWH/MO/M2)
11	1963	97.	161.		186.		148.		130.	176.	(KWH/MO/M2)
12	1963	77.	147.		174.		142.		113.	160.	(KWH/MO/M2)
ALL OF 1963		1863.	2193.		2606.		1938.		2308.	2504.	(KWH/YR/M2)
1	62-63	89.	160.		185.		150.		149.	173.	(KWH/MO/M2)
2	62-63	108.	162.		176.		137.		154.	171.	(KWH/MO/M2)
3	62-63	161.	204.		233.		162.		217.	232.	(KWH/MO/M2)
4	62-63	190.	201.		258.		164.		226.	228.	(KWH/MO/M2)
5	62-63	194.	180.		227.		159.		214.	206.	(KWH/MO/M2)
6	62-63	213.	182.		255.		180.		233.	222.	(KWH/MO/M2)
7	62-63	231.	200.		271.		196.		253.	243.	(KWH/MO/M2)
8	62-63	208.	207.		265.		181.		250.	247.	(KWH/MO/M2)
9	62-63	148.	173.		190.		134.		181.	190.	(KWH/MO/M2)
10	62-63	138.	183.		206.		152.		185.	204.	(KWH/MO/M2)
11	62-63	89.	150.		170.		136.		142.	161.	(KWH/MO/M2)
12	62-63	79.	154.		188.		151.		147.	173.	(KWH/MO/M2)
AVG 62-63		1836.	2161.		2603.		1903.		2351.	2449.	(KWH/YR/M2)

INSOLATION DATA BASE

WEATHER BUREAU NUMBER

STATION
MIDLAND, TEX.STA. NO. 23023
LAT. 31.93 NLONG. W
102.20

MONTH*	YEAR*	TOT ON A	TOT ON B	TILT*	DIR	C	D	E	F
		HOR*	TOT ON			NORM*	EW STRIP*HOR NS	STRP*PLR NS	STRP
1	1902	100.	152.			167.	137.	120.	157. (KWH/MO/M2)
2	1902	123.	171.			184.	143.	148.	179. (KWH/MO/M2)
3	1902	162.	191.			206.	148.	187.	206. (KWH/MO/M2)
4	1902	193.	198.			231.	159.	223.	227. (KWH/MO/M2)
5	1902	229.	211.			229.	190.	262.	247. (KWH/MO/M2)
6	1902	228.	195.			269.	194.	265.	239. (KWH/MO/M2)
7	1902	216.	194.			255.	182.	251.	231. (KWH/MO/M2)
8	1902	229.	224.			275.	192.	269.	267. (KWH/MO/M2)
9	1902	171.	192.			219.	151.	204.	219. (KWH/MO/M2)
10	1902	144.	135.			199.	151.	169.	196. (KWH/MO/M2)
11	1902	103.	151.			165.	133.	123.	157. (KWH/MO/M2)
12	1902	92.	145.			161.	135.	110.	148. (KWH/MO/M2)
ALL OF 1902		1994.	2211.			2598.	1915.	2329.	2473. (KWH/YR/M2)
1	1903	110.	169.			189.	155.	135.	177. (KWH/MO/M2)
2	1903	119.	162.			173.	135.	139.	169. (KWH/MO/M2)
3	1903	173.	211.			233.	167.	210.	232. (KWH/MO/M2)
4	1903	190.	195.			223.	156.	215.	219. (KWH/MO/M2)
5	1903	211.	193.			236.	171.	233.	221. (KWH/MO/M2)
6	1903	221.	191.			261.	188.	257.	231. (KWH/MO/M2)
7	1903	232.	206.			273.	197.	274.	251. (KWH/MO/M2)
8	1903	209.	204.			247.	173.	242.	240. (KWH/MO/M2)
9	1903	176.	197.			225.	156.	210.	224. (KWH/MO/M2)
10	1903	154.	199.			213.	163.	182.	213. (KWH/MO/M2)
11	1903	114.	169.			190.	152.	142.	181. (KWH/MO/M2)
12	1903	82.	128.			136.	116.	94.	127. (KWH/MO/M2)
ALL OF 1903		1997.	2223.			2611.	1928.	2333.	2486. (KWH/YR/M2)
1	02-03	105.	160.			178.	146.	148.	167. (KWH/MO/M2)
2	02-03	122.	166.			179.	139.	158.	174. (KWH/MO/M2)
3	02-03	170.	201.			220.	157.	210.	219. (KWH/MO/M2)
4	02-03	192.	196.			227.	158.	221.	223. (KWH/MO/M2)
5	02-03	220.	203.			251.	181.	241.	234. (KWH/MO/M2)
6	02-03	224.	194.			265.	191.	248.	235. (KWH/MO/M2)
7	02-03	223.	200.			267.	190.	251.	241. (KWH/MO/M2)
8	02-03	219.	214.			261.	182.	254.	254. (KWH/MO/M2)
9	02-03	173.	195.			222.	154.	214.	221. (KWH/MO/M2)
10	02-03	149.	192.			207.	157.	191.	205. (KWH/MO/M2)
11	02-03	109.	160.			178.	142.	152.	169. (KWH/MO/M2)
12	02-03	87.	137.			149.	125.	118.	137. (KWH/MO/M2)
AVG 02-03		1996.	2220.			2604.	1922.	2407.	2479. (KWH/YR/M2)

TABLE 2.1 (cont)

INSOLATION DATA BASE
STATION
EL PASO, TEX.

WEATHER BUREAU NUMBER
STA. NO. LAT. N
23044 31.81

LONG. W
106.40

MONTH*	YEAR*	TOT ON A	TOT ON B	DIR C	NORM*	EW STRIP*	HOR NS	STRP*PLR NS	STRP	
1	1962	124.	191.	218.	177.	157.	204.	(KWH/MO/M2)		
2	1962	146.	200.	227.	172.	184.	221.	(KWH/MO/M2)		
3	1962	193.	228.	259.	181.	235.	259.	(KWH/MO/M2)		
4	1962	232.	238.	286.	199.	276.	278.	(KWH/MO/M2)		
5	1962	277.	233.	340.	239.	335.	308.	(KWH/MO/M2)		
6	1962	261.	227.	305.	224.	301.	271.	(KWH/MO/M2)		
7	1962	231.	209.	250.	190.	247.	228.	(KWH/MO/M2)		
8	1962	240.	233.	294.	206.	286.	278.	(KWH/MO/M2)		
9	1962	171.	193.	216.	130.	201.	216.	(KWH/MO/M2)		
10	1962	171.	222.	255.	137.	216.	252.	(KWH/MO/M2)		
11	1962	119.	174.	190.	155.	141.	180.	(KWH/MO/M2)		
12	1962	107.	170.	192.	161.	132.	177.	(KWH/MO/M2)		
ALL OF	1962	2270.	2540.	3032.	2240.	2710.	2872.	(KWH/YR/M2)		
1	1963	130.	199.	226.	185.	162.	212.	(KWH/MO/M2)		
2	1963	150.	205.	229.	176.	185.	224.	(KWH/MO/M2)		
3	1963	206.	246.	283.	199.	255.	282.	(KWH/MO/M2)		
4	1963	231.	238.	282.	197.	272.	274.	(KWH/MO/M2)		
5	1963	255.	234.	310.	218.	305.	281.	(KWH/MO/M2)		
6	1963	266.	230.	318.	231.	313.	281.	(KWH/MO/M2)		
7	1963	243.	217.	280.	205.	276.	251.	(KWH/MO/M2)		
8	1963	220.	217.	253.	185.	247.	239.	(KWH/MO/M2)		
9	1963	170.	191.	230.	150.	215.	229.	(KWH/MO/M2)		
10	1963	174.	227.	264.	191.	225.	260.	(KWH/MO/M2)		
11	1963	127.	183.	210.	170.	156.	199.	(KWH/MO/M2)		
12	1963	121.	194.	226.	188.	155.	208.	(KWH/MO/M2)		
ALL OF	1963	2293.	2586.	3111.	2294.	2766.	2940.	(KWH/YR/M2)		
1	62-63	127.	193.	222.	181.	184.	208.	(KWH/MO/M2)		
2	62-63	146.	203.	228.	174.	204.	222.	(KWH/MO/M2)		
3	62-63	200.	237.	271.	190.	259.	270.	(KWH/MO/M2)		
4	62-63	231.	238.	284.	198.	275.	276.	(KWH/MO/M2)		
5	62-63	260.	243.	325.	229.	308.	295.	(KWH/MO/M2)		
6	62-63	263.	228.	311.	228.	291.	276.	(KWH/MO/M2)		
7	62-63	237.	213.	283.	198.	249.	239.	(KWH/MO/M2)		
8	62-63	230.	226.	273.	195.	263.	258.	(KWH/MO/M2)		
9	62-63	171.	192.	223.	150.	215.	222.	(KWH/MO/M2)		
10	62-63	173.	225.	259.	169.	238.	256.	(KWH/MO/M2)		
11	62-63	123.	181.	200.	162.	170.	190.	(KWH/MO/M2)		
12	62-63	114.	182.	209.	174.	170.	193.	(KWH/MO/M2)		
AVG	62-63	2282.	2563.	3071.	2267.	2825.	2906.	(KWH/YR/M2)		

TABLE 3.1 (cont)

INSOLATION DATA BASE

STATION

LA CIVIC CENTER

WEATHER BUREAU NUMBER

STA. NO. 93134

LAT. N 34.05

LONG. W 118.23

MONTH*	YEAR*	TOT ON A	HOR* TOT ON B	TILT* C	DIR NORM*	EW STRIP*HCR NS D	STRP*PLR NS E	STRP F	
1	1962	98.	158.	179.	146.	124.	167.	(KWH/MO/M2)	
2	1962	62.	115.	119.	93.	93.	115.	(KWH/MO/M2)	
3	1962	155.	168.	213.	146.	169.	212.	(KWH/MO/M2)	
4	1962	190.	199.	228.	160.	218.	223.	(KWH/MO/M2)	
5	1962	215.	201.	244.	176.	239.	228.	(KWH/MO/M2)	
6	1962	192.	169.	211.	155.	208.	191.	(KWH/MO/M2)	
7	1962	244.	220.	277.	206.	272.	255.	(KWH/MO/M2)	
8	1962	231.	230.	274.	198.	266.	253.	(KWH/MO/M2)	
9	1962	177.	203.	222.	162.	203.	221.	(KWH/MO/M2)	
10	1962	127.	170.	180.	137.	148.	178.	(KWH/MO/M2)	
11	1962	94.	147.	161.	131.	116.	153.	(KWH/MO/M2)	
12	1962	89.	150.	174.	143.	117.	160.	(KWH/MO/M2)	
ALL OF	1962	1693.	2151.	2482.	1852.	2192.	2365.	(KWH/YR/M2)	
1	1963	85.	137.	152.	124.	105.	142.	(KWH/MO/M2)	
2	1963	103.	145.	153.	120.	119.	149.	(KWH/MO/M2)	
3	1963	171.	211.	242.	169.	214.	241.	(KWH/MO/M2)	
4	1963	203.	213.	251.	174.	240.	244.	(KWH/MO/M2)	
5	1963	175.	165.	192.	135.	168.	181.	(KWH/MO/M2)	
6	1963	183.	162.	194.	144.	191.	176.	(KWH/MO/M2)	
7	1963	260.	233.	301.	223.	296.	276.	(KWH/MO/M2)	
8	1963	228.	228.	275.	195.	266.	265.	(KWH/MO/M2)	
9	1963	174.	201.	228.	160.	209.	227.	(KWH/MO/M2)	
10	1963	134.	161.	206.	149.	170.	202.	(KWH/MO/M2)	
11	1963	101.	157.	176.	142.	127.	166.	(KWH/MO/M2)	
12	1963	100.	170.	199.	164.	134.	184.	(KWH/MO/M2)	
ALL OF	1963	1917.	2201.	2568.	1900.	2259.	2453.	(KWH/YR/M2)	
1	62-63	91.	148.	165.	135.	133.	154.	(KWH/MO/M2)	
2	62-63	93.	130.	136.	106.	121.	132.	(KWH/MO/M2)	
3	62-63	162.	199.	227.	157.	215.	227.	(KWH/MO/M2)	
4	62-63	197.	206.	240.	167.	231.	233.	(KWH/MO/M2)	
5	62-63	195.	163.	218.	155.	210.	204.	(KWH/MO/M2)	
6	62-63	188.	165.	202.	149.	192.	184.	(KWH/MO/M2)	
7	62-63	252.	226.	289.	214.	274.	265.	(KWH/MO/M2)	
8	62-63	230.	226.	274.	197.	260.	264.	(KWH/MO/M2)	
9	62-63	176.	202.	225.	161.	215.	224.	(KWH/MO/M2)	
10	62-63	130.	176.	193.	143.	175.	190.	(KWH/MO/M2)	
11	62-63	90.	152.	169.	136.	141.	159.	(KWH/MO/M2)	
12	62-63	94.	160.	187.	154.	150.	172.	(KWH/MO/M2)	
AVG	62-63	1905.	2170.	2525.	1876.	2322.	2409.	(KWH/YR/M2)	

SPEEDREAD WITH EYE TRACK PATENT PENDING

3.45

TABLE 3.1 (cont)

INSOLATION DATA BASE

WEATHER BUREAU NUMBER

STATION

STA. NO.

LAT. N

LONG. W

LOS ANGELES AIRPORT

23174

33.93

118.38

MONTH*	YEAR*	TOT ON A	TOT ON B	DIR C	EW D	STRIP*HCR I,S	STRIP*PLR NS	STRIP F	
									(KWH/MO/M2)
1	1962	100.	161.	183.	149.	128.	171.		
2	1962	94.	151.	141.	107.	112.	138.		
3	1962	174.	215.	233.	161.	207.	233.		
4	1962	196.	207.	228.	162.	218.	221.		
5	1962	233.	218.	266.	186.	260.	245.		
6	1962	187.	168.	188.	143.	185.	171.		
7	1962	229.	206.	246.	184.	242.	227.		
8	1962	227.	227.	265.	186.	256.	251.		
9	1962	184.	212.	205.	151.	187.	205.		
10	1962	127.	170.	185.	138.	152.	182.		
11	1962	95.	145.	148.	122.	105.	140.		
12	1962	84.	138.	152.	126.	100.	140.		
ALL OF	1962	1929.	2196.	2442.	1822.	2154.	2322.		(KWH/YR/M2)
1	1963	99.	154.	153.	126.	106.	143.		
2	1963	112.	155.	153.	119.	120.	149.		
3	1963	173.	215.	250.	171.	223.	250.		
4	1963	201.	210.	253.	173.	242.	244.		
5	1963	182.	170.	200.	142.	196.	186.		
6	1963	192.	171.	197.	146.	194.	178.		
7	1963	239.	214.	272.	202.	268.	249.		
8	1963	219.	219.	254.	179.	246.	242.		
9	1963	166.	192.	206.	147.	189.	206.		
10	1963	123.	173.	194.	141.	160.	191.		
11	1963	109.	155.	170.	137.	122.	160.		
12	1963	100.	170.	200.	164.	135.	184.		
ALL OF	1963	1911.	2197.	2503.	1845.	2201.	2382.		(KWH/YR/M2)
1	62-63	99.	158.	168.	136.	135.	157.		
2	62-63	103.	143.	147.	113.	130.	143.		
3	62-63	173.	214.	242.	166.	228.	241.		
4	62-63	196.	206.	241.	167.	231.	233.		
5	62-63	207.	194.	233.	165.	223.	216.		
6	62-63	190.	169.	192.	144.	182.	174.		
7	62-63	234.	210.	259.	193.	246.	233.		
8	62-63	223.	223.	260.	184.	250.	247.		
9	62-63	176.	202.	206.	149.	197.	205.		
10	62-63	127.	172.	189.	140.	171.	186.		
11	62-63	98.	150.	159.	129.	133.	150.		
12	62-63	92.	154.	176.	146.	142.	162.		
AVG	62-63	1920.	2197.	2472.	1833.	2268.	2352.		(KWH/YR/M2)

TABLE 3.1 (cont)

INSOLATION DATA BASE

STATION
SAN DIEGO, CA.

WEATHER BUREAU NUMBER

STA. NO. 23186 LAT. N 32.73

LONG. W 117.18

MONTH*	YEAR*	TOT ON	A HOR*TOT ON	B TILT*	DIR	C NORM*	D EW STRIP*HOR NS	E STRP*PLR NS	F STRP	
1	1962	107.	107.	168.		189.	155.	133.	177.	(KWH/MO/M2)
2	1962	101.	101.	140.		145.	114.	114.	141.	(KWH/MO/M2)
3	1962	154.	154.	187.		201.	145.	179.	200.	(KWH/MO/M2)
4	1962	176.	176.	164.		204.	144.	195.	201.	(KWH/MO/M2)
5	1962	200.	200.	167.		220.	160.	216.	207.	(KWH/MO/M2)
6	1962	184.	184.	163.		195.	147.	193.	179.	(KWH/MO/M2)
7	1962	223.	223.	200.		249.	185.	246.	232.	(KWH/MO/M2)
8	1962	215.	215.	213.		245.	179.	236.	238.	(KWH/MO/M2)
9	1962	172.	172.	195.		211.	154.	195.	211.	(KWH/MO/M2)
10	1962	140.	140.	165.		191.	152.	156.	188.	(KWH/MO/M2)
11	1962	96.	96.	146.		158.	130.	114.	149.	(KWH/MO/M2)
12	1962	91.	91.	145.		159.	134.	106.	146.	(KWH/MO/M2)
ALL OF	1962	1862.	1862.	2114.		2367.	1801.	2085.	2268.	(KWH/YR/M2)
1	1963	94.	94.	140.		159.	132.	111.	148.	(KWH/MO/M2)
2	1963	110.	110.	152.		161.	127.	127.	157.	(KWH/MO/M2)
3	1963	170.	170.	206.		223.	162.	198.	223.	(KWH/MO/M2)
4	1963	201.	201.	209.		242.	169.	233.	239.	(KWH/MO/M2)
5	1963	190.	190.	178.		208.	151.	204.	196.	(KWH/MO/M2)
6	1963	184.	184.	162.		198.	148.	196.	181.	(KWH/MO/M2)
7	1963	222.	222.	199.		250.	185.	247.	232.	(KWH/MO/M2)
8	1963	211.	211.	210.		239.	176.	232.	232.	(KWH/MO/M2)
9	1963	169.	169.	193.		216.	152.	199.	215.	(KWH/MO/M2)
10	1963	136.	136.	160.		191.	147.	157.	188.	(KWH/MO/M2)
11	1963	107.	107.	162.		180.	145.	132.	170.	(KWH/MO/M2)
12	1963	106.	106.	174.		202.	167.	137.	186.	(KWH/MO/M2)
ALL OF	1963	1901.	1901.	2170.		2469.	1860.	2174.	2367.	(KWH/YR/M2)
1	62-63	101.	101.	157.		174.	143.	141.	163.	(KWH/MO/M2)
2	62-63	106.	106.	146.		153.	121.	135.	149.	(KWH/MO/M2)
3	62-63	162.	162.	190.		212.	154.	201.	211.	(KWH/MO/M2)
4	62-63	189.	189.	190.		223.	156.	217.	220.	(KWH/MO/M2)
5	62-63	195.	195.	162.		214.	156.	206.	202.	(KWH/MO/M2)
6	62-63	184.	184.	162.		197.	147.	187.	180.	(KWH/MO/M2)
7	62-63	222.	222.	200.		250.	185.	239.	232.	(KWH/MO/M2)
8	62-63	213.	213.	211.		242.	177.	235.	235.	(KWH/MO/M2)
9	62-63	171.	171.	194.		214.	153.	205.	213.	(KWH/MO/M2)
10	62-63	138.	138.	183.		191.	149.	172.	189.	(KWH/MO/M2)
11	62-63	103.	103.	155.		169.	138.	142.	160.	(KWH/MO/M2)
12	62-63	96.	96.	160.		180.	150.	146.	166.	(KWH/MO/M2)
AVG	62-63	1881.	1881.	2142.		2418.	1830.	2226.	2317.	(KWH/YR/M2)

TABLE 3.1 (cont)

INSOLATION DATA BASE

WEATHER BUREAU NUMBER

STATION

STA. NO.

LAT. N

LONG. W

SANTA MARIA, CA

23273

34.90

120.45

MONTH*	YEAR*	TOT ON A	TOT ON B	TILT*	DIR	NORM*	EW	STRIP*HOR NS	STRP*PLR NS	F	
1	1962	107.	178.	203.		167.		140.		190.	(KWH/MO/M2)
2	1962	96.	158.	147.		114.		115.		143.	(KWH/MO/M2)
3	1962	163.	205.	231.		162.		203.		230.	(KWH/MO/M2)
4	1962	219.	250.	278.		192.		265.		269.	(KWH/MO/M2)
5	1962	254.	256.	305.		217.		296.		281.	(KWH/MO/M2)
6	1962	232.	204.	256.		193.		252.		232.	(KWH/MO/M2)
7	1962	246.	223.	268.		206.		263.		249.	(KWH/MO/M2)
8	1962	233.	232.	280.		201.		270.		269.	(KWH/MO/M2)
9	1962	175.	203.	216.		160.		196.		216.	(KWH/MO/M2)
10	1962	146.	200.	225.		166.		184.		221.	(KWH/MO/M2)
11	1962	103.	165.	185.		151.		131.		175.	(KWH/MO/M2)
12	1962	91.	158.	186.		152.		124.		171.	(KWH/MO/M2)
ALL OF	1962	2065.	2370.	2779.		2082.		2439.		2647.	(KWH/YR/M2)
1	1963	92.	151.	167.		138.		113.		155.	(KWH/MO/M2)
2	1963	105.	151.	163.		126.		127.		158.	(KWH/MO/M2)
3	1963	173.	215.	252.		173.		223.		251.	(KWH/MO/M2)
4	1963	199.	210.	251.		172.		239.		241.	(KWH/MO/M2)
5	1963	176.	167.	193.		137.		186.		178.	(KWH/MO/M2)
6	1963	215.	168.	238.		177.		234.		216.	(KWH/MO/M2)
7	1963	239.	214.	277.		203.		272.		255.	(KWH/MO/M2)
8	1963	220.	219.	258.		186.		249.		250.	(KWH/MO/M2)
9	1963	163.	195.	220.		155.		201.		219.	(KWH/MO/M2)
10	1963	129.	176.	190.		145.		155.		187.	(KWH/MO/M2)
11	1963	96.	153.	169.		136.		120.		160.	(KWH/MO/M2)
12	1963	100.	178.	216.		175.		145.		198.	(KWH/MO/M2)
ALL OF	1963	1912.	2215.	2593.		1924.		2266.		2470.	(KWH/YR/M2)
1	62-63	99.	164.	185.		152.		147.		173.	(KWH/MO/M2)
2	62-63	101.	144.	155.		120.		137.		151.	(KWH/MO/M2)
3	62-63	163.	209.	241.		167.		227.		241.	(KWH/MO/M2)
4	62-63	209.	220.	265.		182.		253.		255.	(KWH/MO/M2)
5	62-63	215.	201.	249.		177.		238.		230.	(KWH/MO/M2)
6	62-63	223.	196.	247.		185.		234.		224.	(KWH/MO/M2)
7	62-63	242.	218.	273.		204.		259.		252.	(KWH/MO/M2)
8	62-63	226.	226.	269.		194.		260.		259.	(KWH/MO/M2)
9	62-63	172.	199.	218.		157.		208.		218.	(KWH/MO/M2)
10	62-63	137.	168.	208.		157.		185.		204.	(KWH/MO/M2)
11	62-63	100.	159.	177.		144.		146.		167.	(KWH/MO/M2)
12	62-63	95.	166.	201.		164.		161.		185.	(KWH/MO/M2)
AVG	62-63	1989.	2293.	2686.		2003.		2454.		2556.	(KWH/YR/M2)

TABLE 3.1 (cont)

INSOLATION DATA BASE

STATION

FRESNO, CALIF.

WEATHER BUREAU NUMBER

STA. NO. 93193

LAT. N 36.77

LONG. W 119.72

MONTH*	YEAR*	TOT ON HOR*	TOT ON TILT*	DIR NORM*	EW STRIP*HOR NS	STRP*PLR NS	F	
1	1962	58.	95.	93.	77.	63.	87.	(KWH/MO/M2)
2	1962	63.	87.	81.	61.	64.	80.	(KWH/MO/M2)
3	1962	143.	177.	195.	136.	172.	195.	(KWH/MO/M2)
4	1962	181.	190.	232.	155.	221.	224.	(KWH/MO/M2)
5	1962	200.	190.	241.	170.	235.	223.	(KWH/MO/M2)
6	1962	252.	217.	304.	216.	297.	268.	(KWH/MO/M2)
7	1962	272.	241.	338.	239.	330.	302.	(KWH/MO/M2)
8	1962	247.	245.	327.	221.	315.	306.	(KWH/MO/M2)
9	1962	196.	229.	273.	188.	248.	272.	(KWH/MO/M2)
10	1962	142.	196.	217.	163.	176.	214.	(KWH/MO/M2)
11	1962	91.	147.	157.	131.	107.	149.	(KWH/MO/M2)
12	1962	60.	103.	107.	92.	67.	99.	(KWH/MO/M2)
ALL OF 1962		1910.	2115.	2566.	1852.	2296.	2419.	(KWH/YR/M2)
1	1963	79.	133.	141.	117.	93.	131.	(KWH/MO/M2)
2	1963	80.	112.	105.	85.	80.	103.	(KWH/MO/M2)
3	1963	156.	195.	207.	154.	179.	206.	(KWH/MO/M2)
4	1963	180.	169.	226.	153.	215.	220.	(KWH/MO/M2)
5	1963	230.	214.	268.	194.	261.	247.	(KWH/MO/M2)
6	1963	248.	215.	293.	213.	287.	260.	(KWH/MO/M2)
7	1963	260.	236.	323.	232.	316.	290.	(KWH/MO/M2)
8	1963	231.	231.	292.	203.	281.	275.	(KWH/MO/M2)
9	1963	165.	192.	214.	152.	194.	214.	(KWH/MO/M2)
10	1963	127.	174.	187.	143.	151.	185.	(KWH/MO/M2)
11	1963	60.	103.	104.	85.	73.	99.	(KWH/MO/M2)
12	1963	34.	52.	43.	35.	28.	39.	(KWH/MO/M2)
ALL OF 1963		1863.	2048.	2403.	1767.	2157.	2269.	(KWH/YR/M2)
1	62-63	69.	113.	117.	97.	97.	109.	(KWH/MO/M2)
2	62-63	71.	99.	93.	73.	84.	91.	(KWH/MO/M2)
3	62-63	150.	166.	201.	145.	189.	200.	(KWH/MO/M2)
4	62-63	181.	190.	229.	154.	220.	222.	(KWH/MO/M2)
5	62-63	213.	202.	255.	182.	241.	235.	(KWH/MO/M2)
6	62-63	250.	216.	298.	215.	279.	264.	(KWH/MO/M2)
7	62-63	269.	239.	330.	235.	310.	296.	(KWH/MO/M2)
8	62-63	239.	238.	310.	212.	295.	291.	(KWH/MO/M2)
9	62-63	181.	211.	244.	170.	231.	243.	(KWH/MO/M2)
10	62-63	134.	185.	202.	153.	160.	200.	(KWH/MO/M2)
11	62-63	78.	125.	131.	108.	103.	124.	(KWH/MO/M2)
12	62-63	47.	78.	75.	64.	55.	69.	(KWH/MO/M2)
AVG 62-63		1887.	2082.	2484.	1809.	2283.	2344.	(KWH/YR/M2)

4.0 THERMAL ANALYSIS AND TESTING

Because of its simplicity, a potentially attractive cell cooling scheme for plants where the rejected heat cannot be effectively utilized is passive cooling directly to ambient air through a finned heat sink structure. Systems simulations performed during the first year of the program indicated that the cooling system effectiveness over the range to be reasonably expected via direct passive cooling can significantly affect cell output fixed costs. This is due to the effect of cell operating temperatures over the year on the yearly average cell efficiencies. Therefore, for design purposes reasonably accurate knowledge of the cooling effectiveness is essential. Even when air flow speed and direction with respect to a finned array is constant and uniquely specified prediction of heat transfer rates from first principles with any real confidence is, in general, not possible. When the finned array is subject to the random nature of actual local wind patterns the difficulty is compounded. In most applications of finned heat transfer surfaces the flow direction with respect to a particular fin configuration can be controlled. Test results for finned configurations arbitrarily oriented with respect to flow direction are essentially nonexistent, as are results under actual wind conditions. Hence, most of the effort on the thermal analysis and testing task for the first half of the second year of the program has been directed toward wind tunnel testing of finned configurations with particular emphasis on the effect of orientation with respect to flow direction. Plans have also been formulated for field tests of such arrays under existing wind conditions. These tests

are now in preparation and will be performed during the second half of the year.

4.1 WIND TUNNEL TESTS OF FINNED ARRAYS

For a given wind speed and direction relative to a heated fin-array (heat-sink), the thermal conductance, K_c , for convective heat transfer from the finned array referred to the base area is defined by

$$Q = K_c A_b (T_b - T_o)$$

where A_b is the base area, T_b is the base temperature, T_o is the ambient air temperature, and Q is the convective heat rate from the finned side of the array. Determination of these quantities allows calculation of K_c from the defining equation. Q is determined by measuring the power input to a nichrome wire heating element mounted on the base surface and correcting for total heat loss from the non-finned side of the base and radiation loss from the finned side, in order to isolate the convective conductance for the finned side.

4.1.1 Experimental Test Facility

Figure 4.1 is a diagram of the experimental facility indicating basic dimensions of the wind tunnel and placement of the finned plate. An existing fan and drive motor assembly in the ASU Mechanical Engineering Laboratory was utilized, but the wind tunnel was constructed especially for these tests. Figure 4.2 is a photograph of the facility in the working configuration. The apparatus is designed to direct a controlled flow of air down the wind

tunnel in which an orientable test array is positioned. The bulk of the tunnel is 18 gauge sheet steel with the test section constructed using .00635m (1/4 inch) thick plexiglas sheet. Air-flow down the tunnel is achieved by using a General Electric axial-flow fan-dynamometer set connected to a 1.812 m^3 (64 ft.³) plenum chamber. The fan-dynamometer set is capable of pushing air down the tunnel at a speed of .5 m/s to 6 m/s (2 ft./sec to 20 ft./sec). The regulation of the air speed down the tunnel is accomplished using a General Electric speed variator.

The air-flow speed is measured by using two .00794 (5/16 inch) diameter pitot tubes. The pitot tube positioners are placed on the top and side of the test section with the tubes projecting into the airstream through the test section walls. The pressure differential from each pitot tube is measured using a Dwyer inclined manometer with a full scale reading of .00635 m (.25 inches) of water. Pitot tube readings are accomplished by switching channels through a two channel pressure valve. The airstream stagnation temperature is measured using a shielded copper-constantan thermocouple connected to a digital voltmeter through a thermocouple switch.

The orientable array is supported by a .0127 m (1/2 inch) diameter round steel rod .457 m (18 inches) long projecting into the interior of the test section with the finned plate mounted on an orientation mechanism at the top of the rod.

Temperatures of the array are measured using copper-constantan thermocouples cemented to the points at which the temperatures are desired. The thermocouples are connected to a Hewlett Packard 3440A digital voltmeter via a thermocouple switch.

Power input to the heater is measured through a calibrated alternating current ammeter and voltmeter.

4.1.2 Test Models

Initially five test configurations are being tested. The configurations consist of one flat plate and four finned plates (Fig. 4.3). A cross-sectional view illustrating the construction of the test models is shown in Fig. 4.4. On completion of tests with these configurations it is also planned to test several pin fin configurations.

The material used for the flat plate and finned plates is aluminum. Bonded heaters are made on each plate by first applying a .001 m (.04 inch) thick coat of porcelain sealing cement. Nichrome wire, .00023 m (0.009 inches) diameter, is placed on the porcelain and then a .005 m (.02 inch) thick layer of plaster of paris is applied. The heater assembly is then encased in a .0064 m (.25 inch) thick layer of insulation. Plate and fin temperatures are measured by using copper-constantan thermocouples cemented into holes at the appropriate locations. The heat loss from the insulation is measured by a heat-flow meter on the insulation. The heat-flow-meter consists of two pieces of metal foil placed opposite one another on the plate side and ambient side of the insulation. The temperature of each foil is measured with a copper-constantan thermocouple allowing calculation of the heat loss.

Table 4.1 presents a summary of the important dimensions of each of the arrays. The nominal length of 0.46 m (18 inches) is limited by the wind tunnel test section dimensions with allowance for the boundary layer thickness on the test section walls. Figure 4.5 presents the nomenclature used to describe the orientation of the array with respect to the air-flow down the tunnel.

4.1.3 Experimental Results

The experiments were conducted so as to furnish data which would describe the effect of variations of orientation and air-flow speed on the thermal convection conductance. At this time tests have been completed on three of the test models; the flat plate without fins (Fig. 4.3a), the finned plate with stubby trapezoidal fins parallel to the long dimension (L) of the array (Fig. 4.3b), and the finned plate with long trapezoidal fins also parallel to the major axis of the array. A range of airflow velocities was investigated by testing at three airflow rates. A range of orientations was investigated by testing at 5 orientations with the flat plate and 11 orientations with the finned plates.

The ranges of the parameters are as follows:

$$\text{Air-flow speed: } 1 \frac{\text{meter}}{\text{sec}} \leq U_{\infty} \leq 5.5 \frac{\text{meter}}{\text{sec}}$$

Test Model Orientation: α (inclination) $0^\circ, 45^\circ, 90^\circ, -45^\circ, -90^\circ$
(see Fig. 4.5)

β (yaw) $0^\circ, 45^\circ, 90^\circ$

γ (roll) $0^\circ, 45^\circ, 90^\circ, -45^\circ, -90^\circ$

Flat Plate. A flat plate test model was constructed and tested in the same manner as the finned plates to serve as a check on the test facility and to obtain some baseline data for the flat plate case. Figures 4.6 and 4.7 show the effect of air-flow velocity and orientation on the thermal convection conductance for a .076 m by .46 m (3 inch by 18 inch) flat plate for a range of air-flow speeds and 5 different orientations with respect to the air-flow direction. The uncertainty associated with results is indicated in these plots by the size of the symbols used to

represent the data points. The convection coefficients for the several orientations relative to a selected baseline orientation are shown in Fig. 4.8. The baseline case is chosen here as the record of the thermal convection conductance when the plate is oriented at 0° inclination, 0° yaw, and 0° roll. It is apparent that for the flat plate the thermal convection coefficient for all orientations tested is greater than for the baseline case.

Figure 4.9 shows a comparison between the data obtained for the flat plate in a parallel flow ($\alpha=0$, $\beta=0$, $\gamma=0$) situation and calculated values based on existing theory and correlations, both for the case of a laminar boundary layer and a turbulent boundary layer. This plot indicates that a laminar to turbulent transition occurs on the plate with the majority of the plate covered by a turbulent boundary layer as evidenced by the proximity of the data to the turbulent theory curves. Early transition is to be expected for bluff leading edge as is the case for the geometry tested here.

Finned Plates. Figures 4.10 through 4.13 show the effect of air-flow speed and plate orientation on the thermal convection conductance for a 3.38 inch by 18.125 inch finned plate. The fins are of trapezoidal shape, stubby and parallel to the major axis of the plate (Fig. 4.3b). Comparisons of the convection coefficients relative to a baseline case are shown in Figs. 4.14 through 4.16. The baseline case is again chosen as the record of the thermal convection conductance when the array is oriented at 0° inclination, 0° yaw, 0° roll.

From Figs. 4.10 and 4.11, where only the inclination angle changes, the dependence of the convection conductance upon orientation appears to be similar for the finned plate and the flat plate previously tested. In both

cases the indicated convection conductance from the plate is lower when the plate faces away from the airflow (inclination: -45° , -90°) than when the plate faces the airflow (inclination: 45° , 90°).

From Fig. 4.12 where only the yaw angle changes, the dependence of the convection conductance upon orientation does not differ by more than 30% for the three values of the yaw angle.

Figure 4.13 shows the convection conductance for a 90° yaw angle and different values of the roll angle. Once again the indicated convection conductance from the plate is lower when the plate faces away from the airflow (roll: -45° , -90°) than when the plate faces the airflow (roll: 45° , 90°).

Examining Figs. 4.14 through 4.16 it is apparent that only two orientations have convection conductances less than the baseline case. All orientations with velocities greater than 3 m/s have convection conductances greater than the baseline case.

Test results for the longitudinal fins of 0.305 m (1.20 inch) height (Fig. 4.3c, Table 4.1) are plotted in Figs. 4.17 through 4.20. Trends are similar to those for the stubby longitudinal fin cases. The magnitudes are somewhat higher because of the additional fin surface area. However the percentage increases over the stubby fin case are less than the percentage increase in heat transfer surface area. This is reasonable due to the reduction of local heat transfer coefficients caused by the more confined nature of the flow at the base of the cavities formed by adjacent fins.

It should be reemphasized that the thermal conductances being discussed here have been calculated for a unit base surface area, and are for convective transfer from the finned side of the base element only. Addition of radiation from all surfaces and convection from the nonfinned side of

the base element would increase the overall effective thermal conductances for these systems somewhat over the values plotted here. For example, for the fins of Figs. 4.17 through 4.20 values for most orientations at a wind speed of about 2 m/s would be around $100 \text{ W/m}^2 - ^\circ\text{C}$.

Tests just beginning on the models in which the fins are transverse to the major axis of the array are expected to yield higher thermal conductances than for the longitudinal fins, while tests on pin fin arrangements should give further improvement in these values.

4.2 OUTDOOR TESTS OF FINNED ARRAYS

Preparations are currently underway for outdoor testing of electrically heated finned arrays to determine the cooling effectiveness of such arrays under field conditions. These tests are to be conducted during the second half of the year.

Tests will be conducted using the same test models that were used for the wind tunnel tests in order to determine the degree of confidence which can be placed in results of future wind tunnel tests for design purposes. The length of these models is limited to about 0.46 m (18 inches) due to the wind tunnel test section size. Since this limitation does not exist for the outdoor tests, selected configurations will also be tested outdoors using longer sections of 1.22 m (4 ft.) to minimize end effects.

The larger arrays will be tested in pairs with each member of the pair oriented differently so as to determine the significance of orientation relative to wind direction under field conditions. Preliminary calculations indicate that the temperature response of the arrays to a change in convective heat transfer coefficient caused by a change in wind speed or direction

is of the order of a few minutes. Therefore, it is planned to provide in the data acquisition system for integration of the signals from the wind speed and direction transducers over the appropriate time intervals in order to provide more meaningful correlation of the data. During the tests the power input to the resistance heaters will be maintained constant.

FIG. 4.1. Wind Tunnel Facility for Tests of Heat Transfer Rates from Finned Arrays at Various Orientations

Fig. 4.2a. Photograph of Wind Tunnel Facility

Fig. 4.2b. Photograph of Test Section with Test Model in Place

(a) Flat Plate

(b) Finned Plate with Stubby Trapezoidal Fins (Longitudinal)

(c) Finned Plate with Long Trapezoidal Fins (Longitudinal)

(d) Finned Plate with Stubby Trapezoidal Fins (Transverse)

(e) Finned Plate with Long Trapezoidal Fins (Transverse)

Fig. 4.3. Photograph of Test Models (see Table 4.1 for Dimensions)

TABLE 1

Dimensions of Finned Plate Test Models

ARRAY DESCRIPTION		ARRAY DIMENSIONS								
		N_f	A_t/A_b	L	W	B_1	B_2	H_f	S_1	Z
FLAT PLATE(Fig. 4.3a)		0	1	.459m (18.0")	.076m (3.00")	-	-	-	-	.0030m (.12")
FINNED PLATE WITH STUBBY TRAPEZOIDAL FINS	LONGITUDINAL (Fig. 4.3b)	21	4.59	.459m (18.0")	.093m (3.66")	.00038m	.00076m	.0081m	.0046m	.0020m
	TRANSVERSE (Fig. 4.3d)	101	4.47	.462m (18.2")	.089m (3.50")	(.015")	(.030")	(.32")	(.18")	(.08")
FINNED PLATE WITH LONG TRAPEZOIDAL FINS	LONGITUDINAL (Fig. 4.3c)	12	7.86	.462m (18.2")	.103m (4.06")	.00051m	.0025m	.305m	.0091m	.0046m
	TRANSVERSE (Fig. 4.3e)	49	7.25	.459m (18.0")	.102m (4.00")	(.02")	(.10")	(1.20")	(.36")	(.18")

Fig. 4.4. Cross-sectional View of the Construction of the Finned Test Models.
(A) Side View; (B) End View.

Fig. 4.5. Nomenclature for Description of Orientation of Test Models with Respect to Flow Direction.

Fig. 4.6. Experimental Thermal Convection Conductances for a Flat Plate at Various Orientations and Airflow Speeds

Fig. 4.7. Experimental Thermal Convection Conductances for a Flat Plate at Various Orientations and Airflow Speeds

Fig. 4.8. Experimental Thermal Convection Conductances for a Flat Plate at Various Orientations Relative to a Baseline

Fig. 4.9. Comparison of Measured Thermal Convection Conductances from Present Study to Calculated Values Based on Existing Theory and Correlations for the Case of a Flat Plate in Parallel Flow

Fig. 4.10. Experimental Thermal Convection Conductances for a Finned Plate (Fig. 4.3b) at Various Orientations and Airflow Speeds

Fig. 4.11. Experimental Thermal Convection Conductances for a Finned Plate (Fig. 4.3b) at Various Orientations and Airflow Speeds

Fig. 4.12. Experimental Thermal Convection Conductances for a Finned Plate (Fig. 4.3b) at Various Orientations and Airflow Speeds.

Fig. 4.13. Experimental Thermal Convection Conductances for a Finned Plate (Fig. 4.3b) at Various Orientations and Airflow Speeds.

Fig. 4.14. Experimental Thermal Convection Conductances for a Finned Plate (Fig. 4.3b) at Various Orientations Relative to a Baseline Orientation.

Fig. 4.15. Experimental Thermal Convection Conductances for a Finned Plate (Fig. 4.3b) at Various Orientations Relative to a Baseline Orientation.

Fig. 4.16. Experimental Thermal Convection Conductances for a Finned Plate (Fig. 4.3b) at Various Orientations Relative to a Baseline Orientation

Fig. 4.17. Experimental Thermal Convection Conductances for a Finned Plate (Fig. 4.3c) at Various Orientations and Airflow Speeds.

Fig. 4.18. Experimental Thermal Convection Conductances for a Finned Plate (Fig. 4.3c) at Various Orientations and Airflow Speeds

Fig. 4.19. Experimental Thermal Convection Conductances for a Finned Plate (Fig. 4.3c) at Various Orientations and Airflow Speeds.

Fig. 4.20. Experimental Thermal Convection Conductances for a Finned Plate (Fig. 4.3c) at Various Orientations and Airflow Speeds.

5.0 SYSTEMS ANALYSIS

Systems simulation and cost studies during this reporting period have been devoted to (1) active cooling studies on concentrating devices, (2) studies on the General Atomic fixed mirror concentrator, and (3) comparison studies between silicon and gallium arsenide (GaAs) cells. These studies all make use of methodology developed previously (Ref. 3.1)

5.1 ACTIVE COOLING STUDIES

Further studies have been conducted on the E-W linear focus concentrators and the 2-D point focus devices to better define the role played by the method of final heat rejection to the environment. The methods investigated included the use of dry cooling in both natural draft and forced draft heat exchangers, and the use of wet cooling. The first of these was simulated by assuming the coolant temperature at the inlet to the cell cooling passages was 25°C above the ambient dry bulb.

Forced draft dry cooling was simulated by assigning temperatures to the coolant that were 5°C above ambient dry bulb. Inlet coolant temperatures of 5°C above ambient wet bulb temperatures were used in simulating wet cooling. More details can be found in the paper entitled "Cost Studies on Terrestrial Power Systems with Sunlight Concentration," included in Appendix B.

5.2 FIXED MIRROR STUDIES

The Fixed Mirror Solar Concentrator (FMSC) that will be used in the experimental phases of this work has been modelled during this reporting period. A collector/tracking subroutine for use with the Aerospace insolation/weather tapes has been written and checked out. It makes use of the subroutines developed in Ref. 5.1 for calculating the edge losses.

Table 5.1 gives the projected yearly energy output for a FMSC having a mirror included angle of 120° , a mirror centerline that is tilted 15° from the zenith toward the south and a tangent slat that is also rotated 15° (angle ρ , see Figure 5.1). Silicon solar cells having an efficiency, η , given by

$$\eta = \eta_r [1 - \beta (T_c - T_r)] \quad (5.1)$$

was used where η_r , the reference efficiency was 15% at a reference temperature, T_r , of 25°C and β was chosen such that $\eta = 0$ at $T_c = 270^\circ\text{C}$. Here T_c is the cell temperature.

The values of K_e , the cell thermal conductance, given in Table 5.1, represent what should be realizable with passive cooling (Ref. 5.2) of the cells. Complete cell coverage of the absorber has been assumed.

The values of energy output/year are below that for the 2-D tracked device, the fixed flat array and the E-W linear focus concentrator considered in Ref. 5.1. . . This is due mainly to edge losses inherent in the mirror slat arrangement. If, however, this concentrator can be built at a sufficiently low cost it could produce electrical energy at more reasonable cost than either the moveable mirror devices or fixed flat arrays.

Figure 5.2 presents the cell output fixed costs for a concentrator cost of $\$20/\text{m}^2$ of aperture and a range of cell costs ($\$2000$, 200 and $50/\text{m}^2$ of cell). $\$20/\text{m}^2$ is often quoted as being a "reasonable" cost for construction of this device. Figure 5.3 displays the effect of changing the collector or other cost on cell output fixed cost ($K_e = 0.2 \text{ kW}/\text{m}^2 \cdot ^\circ\text{C}$ assumed).

If indeed these concentrators can be constructed for $\$20/\text{m}^2$, then they would be a very attractive alternative to fixed flat arrays, even at cell costs

of $\$20/\text{m}^2$ (nominal 15% efficiency assumed). At reasonable projected cell costs, optimum aperture to cell area ratios are lower for photovoltaic applications than what would be desirable for thermal driven power systems. This should result in some savings in cost. Also, the FMSC would most likely operate at a higher effective cell thermal conductance, K_e , than movable mirror linear concentrators (e.g., the cylindrical parabolic trough) since the absorber is less likely to be located in a separated flow area created by the mirror.

5.3 SILICON/GALLIUM ARSENIDE CELL COMPARISON

For this analysis gallium arsenide (GaAs) cells differ from silicon cells only in the value of the constants that are required in Eq. (5.1). For GaAs, η_r , the reference efficiency, was taken as 20% at $T_r = 25^\circ\text{C}$ since such efficiencies have apparently been obtained experimentally (Ref. 5.3). Beta (β) was chosen such that cell efficiency was zero at a cell temperature of 400°C .

Figure 5.4 presents a comparison between nominal 15% efficient silicon solar cells and nominal 20% GaAs cells for various cell costs. It is important to note that the GaAs cell costs used in Figure 5.4 are not projections of what might be possible.

Figure 5.5 presents similar data to Figure 5.4 but compares the two cell types on an equal efficiency basis. The results of Figure 5.5 can then be converted to costs at any reasonable efficiency by dividing the ordinate by the efficiency. Cell output is nearly linear with efficiency especially at low aperture to cell area ratios.

5.4 DETERMINATION OF OPTIMUM GEOMETRY FOR ARRAYS OF SOLAR COLLECTORS

If a solar collector is isolated, then the particular shape of its aperture has no effect on the yearly energy per square meter incident on the collector surface. However, when the collector is located in an array with other collectors the energy collecting capacity may be reduced because of shadows produced by neighboring collectors. In general, the more closely collectors are packed in the array the lower will be the energy collected. If the cost of land is taken into consideration, it is recognized that there will be an optimum packing factor (and corresponding geometry) for which the amount of energy per unit cost will be maximized. The purpose of this analysis was to determine the optimum packing factor and associated geometrical factors for 8 different tracking (or orientation) modes.

Since we are interested in the maximum yearly energy output per total cost, the factor to be optimized is defined as follows:

$$PCR = \frac{\text{Yearly energy incident on 1 square meter of collector in an array}}{\text{Cost of 1 square meter of collector} + \text{Cost of land to support 1 square meter of collector}}$$

PCR = Performance cost ratio

$$\text{Define PF} = \text{Packing Factor} = \frac{\text{Collector area}}{\text{Land Area}}$$

$$\text{Since collector area} = 1, \text{ then land area} = \frac{1}{PF}.$$

Let C be the cost of land per square meter; then

$$\begin{aligned} \text{Total Cost} &= \text{Cost of 1 square meter of collector} + \frac{C}{PF} \\ &= (\text{Cost of 1 square meter of collector}) \left(1 + \frac{x}{PF}\right) \end{aligned}$$

$$\text{where } x = \frac{\text{Cost of land/m}^2}{\text{Cost of collector/m}^2}$$

In order to compare various tracking (or orientation methods) it will be convenient to define a reference energy as the yearly energy incident on 1 square meter of collector which is isolated and tracked about two axes. Also for convenience the cost of 1 square meter of collector can be taken as unity. Then a relative performance-cost ratio is:

$$RPCR = \delta = \frac{(\text{PCR of collector cost} = 1) (100)}{\text{Yearly incident energy on 1 square meter of collector isolated, tracked about two axes}}$$

Hence

$$\delta = \frac{100 [\text{yearly incident energy/m}^2 \text{ collector in array}]}{(1 + \frac{x}{PF}) [\text{Yearly energy/m}^2 \text{ incident on isolated collector tracked about two axes}]}$$

It is noted that the maximum value δ can achieve is 100 for an array of collectors each tracked about two axes with the array spacing great enough that no shadows are produced.

Each collector is assumed to have a rectangular aperture with width W and height H. The geometric factors describing the array are shown in Fig. 5.6. The center bottom edge of the aperture plane of a collector is assumed to be located at each of the row intersections in the diagram. Note that east west spacing is normalized to 1.0 to number of parameters needed in the geometric description.

Eight different tracking methods (or collector orientation as the case may be) were investigated. These are as follows:

1. Fixed horizontal plane.
2. Tilted plane at 33.4° to south.
3. Plane tracking sun in N-S direction about a horizontal E-W axis.

4. Plane tracking sun in E-W direction about a horizontal N-S axis.
5. Tilted plane at 50° tracking sun about a vertical axis.
6. Plane tracking sun about a polar axis (33.4°).
7. Plane tracking sun about two axes, one vertical and the other horizontal.
8. Plane tracking sun about two axes one polar and the other perpendicular to the polar axis.

Calculations were made to find the particular values of Q, R, W, and H resulting in the maximum δ values of the land cost parameter ranging from 1 to 8% in 1% increments for each of the tracking methods. To avoid the shadows which would always occur at sunrise and sunset energy was assumed to be collected whenever the solar altitude angle is greater than 5° . The subroutine SUN was used to compute solar insolation factors. The cloud factor and clearness numbers were taken to be 1. The array factor was computed using subroutine ARRAY (developed under this contract) with the array factor = 0.0 when a shadow occurs. Calculations were made on a one day per month basis and yearly results extrapolated from the monthly data. For each day the daylight hours were divided into 20 equal intervals and power and shadow conditions evaluated at each interval.

Table 5.2 gives optimum geometrical factors and yearly performance for the 8 different tracking (or orientation) modes and for a land cost/ m^2 equal to 1% of the energy collecting system/ m^2 of aperture area. It is noted that tracking methods 5, 6, 7A and 7B give practically the same performance factors. In all instances the shadows occurred either early in the morning or late in the afternoon, typically within a half an hour after the 5° solar angle was reached in the morning and before the 5° solar altitude angle was reached in the afternoon. It is noted that the two axis

tracking system where one of the axes is vertical gives significantly better performance. All systems portrayed a true maximum in the δ function.

Table 5.3 gives the same data for a land cost equal to 5% of the energy collecting system cost/m² of aperture area. In this case tracking methods 4, 5, 6, 7A and 7B give essentially the same performance. Method 8 shows a margin of superiority.

REFERENCES

- 5.1 R. Bansal, "Theoretical Analysis of Fixed Mirror Solar Concentrator," M.S. Thesis, School of Engineering, Arizona State University, May 1974
- 5.2 L. Florschuetz, "On Heat Rejection from Terrestrial Solar Cell Arrays with Sunlight Concentration," 11th IEEE Photovoltaic Specialists Conference, Scottsdale, AZ, May 1975
- 5.3 L. W. James and R.L. Moon, "GaAs Concentrator Solar Cells," 11th IEEE Photovoltaic Specialists Conference, Scottsdale, AZ, May 1975

Fig. 5.1 The Fixed Mirror Solar Concentrator (FMSC) Geometry Defining Some of the Parameters. T.S. is the tangent slat. The concentrator has an included angle of θ_{in} , a tilt of the T.S. of ρ° and the centerline is not inclined toward the south.

FIG. 5.2. Cost Calculations for FMSC with Passive Cooling:
Cells, 15% @25°C; Other Costs, $Y = \$20/\text{m}^2$; Land Costs,
 $Z = \$1/\text{m}^2$; Reflectivity=0.85, Packing Factor 0.35.

FIG. 5.3. Cost Calculations for FMSC with Passive Cooling:
Cells, 15% @25°C; Land Cost, \$1/m², Reflectivity=
0.85, K_e=0.2 kW/m²°C.

FIG. 5.4. Cost Calculations for 2-D Tracked Concentrator Comparing Silicon and GaAs Cells. Other Costs, Y=\$60/m²; Land Costs, Z=\$1/m²; Reflectivity=0.85. Silicon Cells: 15% @25°C; GaAs Cells: 20% @25°C.

Fig. 5.5. Cost Calculations Under the Same Conditions as in Fig. 5.4 Except the Ordinate is Expressed in an Equal Efficiency for Both the Silicon and GaAs Cells.

TABLE 5.1

OUTPUTS FROM FMSC CONCENTRATOR ($\text{kWh}_e/\text{m}^2\cdot\text{yr}$)*
Albuquerque 1962

Aperture to Cell Area Ratio	$K_c=0.1$ $\text{kW}/\text{m}^2\cdot^\circ\text{C}$	0.2 $\text{kW}/\text{m}^2\cdot^\circ\text{C}$	0.3 $\text{kW}/\text{m}^2\cdot^\circ\text{C}$
5	212 (14.4%)	220 (14.9%)	222 (15.1%)
10	196 (13.3%)	212 (14.4%)	217 (14.7%)
15	179 (12.1%)	204 (13.8%)	212 (14.4%)
20	162 (11.0%)	196 (13.3%)	207 (14.0%)
25	144 (9.8%)	188 (12.7%)	201 (13.6%)
30	125 (8.5%)	179 (12.1%)	196 (13.3%)
40	85 (5.8%)	162 (11.0%)	185 (12.5%)
50	56 (3.8%)	144 (9.8%)	174 (11.8%)
60	39 (2.6%)	125 (8.5%)	162 (11.0%)

*15% (@25°C) Silicon Cells with Complete Absorber Coverage, Packing
Factor-0.35, Passive Cooling, Reflectivity-0.85.

TABLE 5.2

COMPARISON OF COLLECTOR PERFORMANCE IN AN ARRAY FOR DIFFERENT TRACKING (OR ORIENTATION) MODES

Latitude = 33.4°, Solar Altitude Angle for Collection $\geq 5.0^\circ$, Cloudless Days

System	OPTIMUM PARAMETER VALUES FOR LAND COST/M ² /SYSTEM COST/M ² = 0.01							KWH/YR/M ²	YEARLY HOURS
	Q	R	W	H	PF	δ			
1. Horizontal Fixed	0.0	1.0	1.0	1.0	1.0	60.1		1947	4081
2. Tilted 33.4° Fixed	0.0	1.0	1.0	0.37	0.37	68.3		2249	4040
3. Horizontal EW Axis Tracked NS	0.0	1.0	1.0	0.32	0.32	73.7		2438	4013
4. Horizontal NS Axis Tracked EW	0.0	1.0	0.21	1.0	0.21	83.2		2797	3877
5. Vertical Axis 50° Plane Tilt	0.5	0.21	0.31	0.10	0.15	88.6		3033	3877
6. Polar Axis Tracked	0.0	0.23	0.23	0.13	0.13	88.5		3059	3877
7A. Two Axis Tracking (one axis polar)	0.0	0.44	0.22	0.22	0.11	89.0		3114	3778
7B. Two Axis Tracking (one axis polar)	0.5	0.54	0.33	0.18	0.11	89.0		3114	3791
8. Two Axis Tracking (one axis vertical)	0.5	0.23	0.36	0.09	0.14	92.3		3172	3850

For an isolated collector tracked about two axes: KWH/YR/M² = 3208 YEARLY HOURS = 4081

TABLE 5.3

COMPARISON OF COLLECTOR PERFORMANCE IN AN ARRAY FOR DIFFERENT TRACKING (OR ORIENTATION) MODES

Latitude = 33.4°, Solar Altitude Angle for Collection $\geq 5^\circ$, Cloudless Days

System	OPTIMUM PARAMETER VALUES FOR LAND COST/M ² /SYSTEM COST/M ² = 0.05						
	Q	R	W	H	PF	δ	KWH/YR/M ² YEARLY HOURS
1. Horizontal Fixed	0.0	1.0	1.0	1.0	1.0	57.8	1947 4081
2. Tilted 33.4° Fixed	0.0	1.0	1.0	0.48	0.48	62.5	2215 3930
3. Horizontal E-W axis Tracked NS	0.0	1.0	1.0	0.42	0.42	66.8	2398 3902
4. Horizontal N-S Axis Tracked EW	0.0	1.0	0.21	1.0	0.21	70.4	2797 3877
5. Vertical Axis 50° Tilted Plane	0.5	0.21	0.34	0.10	0.16	71.5	3010 3823
6. Polar Axis	0.0	0.22	0.37	0.13	0.22	70.6	2779 3425
7A. Two Axis Tracking (one axis polar)	0.0	0.67	0.35	0.33	0.17	71.2	2958 3494
7B. Two Axis Tracking (one axis polar)	0.5	0.67	0.35	0.27	0.14	69.7	3034 3628
8. Two Axis Tracking (one axis vertical)	0.5	0.25	0.37	0.10	0.15	73.4	3140 3816

6.0 CONCENTRATED SOLAR CELL SYSTEM TESTING

6.1 FLAT ARRAY

A flat array will be employed at both test sites. These arrays which are currently being manufactured will consist of standard production terrestrial modules. The use of these arrays will provide a common denominator for performance evaluation of the experimental systems at both test sites. Such intercomparison data will also be directly beneficial in evaluating the merits of optical concentration relative to flat arrays.

In general, the flat arrays will be positioned so that they face South and tilted from horizontal by an angle equal to the local latitude. For a fixed orientation this angle is optimum for maximum year round energy collection. An angular adjustment capability will be provided in the array mounting hardware to allow for seasonal adjustments.

The total incident solar radiation consists of both direct and diffuse components. In the performance evaluation of a concentrator system it is essential that the normal incidence radiation be known or be estimated with reasonable accuracy. For performance predictions various techniques are available for estimating the direct component of the total insolation. The algorithm used at Spectrolab is based on various correlations established by Liu and Jordan which are presented in this program's 1974 semi-annual report.

Algorithms of this type are required since normal incidence radiation data has been acquired for only limited sites. The preponderance of recorded insolation data is daily sums of the total radiation incident on a horizontal surface. This data is obtained by pyranometers using thermopile detectors with spectrally flat response characteristics.

For these experiments pyranometers for measuring total insolation and normal incident pyrliometer for measuring the direct component will be used. These data in conjunction with the flat array output will be utilized in the concentrator system experiment performance evaluation and also as a check on the accuracy of available algorithms used for predicting the useful radiation.

6.2 NON-TRACKING CONCENTRATOR SYSTEM

One of the several schemes suggested for low concentration, non-tracking solar concentrator systems is Winston's Ideal Light Collector.⁽¹⁾ In the East-West oriented trough configuration, concentration of this device is the maximum theoretical $1/\sin\delta$, where δ is the half acceptance angle. One disadvantage of such a design is that the height is approximately proportional to the square of the concentration. For large concentrations, this leads to very large reflector area. To overcome this difficulty truncated versions of the Winston Concentrator have been evaluated by others⁽²⁾ and certainly appear more attractive from an economic standpoint.

For this program a two element concentrator approach has been selected which uses a modified Winston concentrator in conjunction with a cylindrical parabolic mirror.

This concept approach was selected with the hope that the resulting design would mitigate the two main disadvantages of the Winston design, which are:

- 1) The very large area of reflective surface required, and
- 2) The fact that a collimated beam falling on the aperture results in a narrow line image at the absorber. This latter characteristic would result in reduced system efficiency since the losses due to cell series resistance are proportional to the local illumination intensity, rather than to the average.

This compound concentrator is denoted as the Parabolic Trough Compound Elliptic Concentrator (PTCEC) and is schematically depicted in Figures 6.1 and 6.2. Placed at the focus of the parabolic trough is the aperture of the secondary collector. This consists of two mirrors of different elliptic cross-section, which funnel the rays from the primary onto the absorber. The parabola provides high concentration, and the compound elliptic concentrator maintains a high acceptance angle. The cylindrical axes of the reflective surfaces are oriented in the E-W direction. The N-S tilt is adjusted periodically during the course of the year.

Because this system is not "ideal", the attainable concentration is somewhat less than that available from the "ideal" Winston device. However, it will be shown that this concentration loss is more than offset by a large decrease in mirror area.

6.2.1 Design Equations

Although the experimental design utilizes the off-axis version of the PTCEC (secondary axis offset from primary axis), the design equations will be developed first for the on-axis configuration. Results will then be generalized to the off-axis design. Refer to Figure 6.3.

The following symbols are used:

m = half-primary aperture

Z = secondary geometrical concentration ratio

δ = half-acceptance angle

θ = primary half-rim angle

$$q = \overline{F_1 C}$$

$$p = \overline{F_1 C'}$$

$$a = \overline{CF_2}$$

Note that the secondary half-aperture is taken as one. Ellipse S has foci F_1 and F_2 , while ellipse S' has foci F_1' and F_2' . Because S is an ellipse,

$$q+a = p+a+2Z^{-1}$$

$$Z^{-1} = \frac{1}{2}(q-p).$$

Since

$$q = \frac{m+1}{\sin(\theta+\delta)} \quad \text{and} \quad p = \frac{m-1}{\sin(\theta-\delta)}$$

$$Z = \frac{2}{\frac{m+1}{\sin(\theta-\delta)} - \frac{m-1}{\sin(\theta+\delta)}}. \quad (1)$$

Now,

$$\frac{m+1}{m-1} = \frac{\tan(\theta+\delta)}{\tan(\theta-\delta)},$$

$$m = \frac{-\tan(\theta-\delta)-\tan(\theta+\delta)}{\tan(\theta-\delta)-\tan(\theta+\delta)}$$

$$= \frac{-\sin(\theta-\delta)\cos(\theta+\delta)-\sin(\theta+\delta)\cos(\theta-\delta)}{\sin(\theta-\delta)\cos(\theta+\delta)-\sin(\theta+\delta)\cos(\theta-\delta)}$$

Then,

$$m+1 = \frac{-2\sin(\theta+\delta)\cos(\theta-\delta)}{\sin(\theta-\delta)\cos(\theta+\delta)-\sin(\theta+\delta)\cos(\theta-\delta)}$$

$$= \frac{\sin(\theta+\delta)\cos(\theta-\delta)}{\sin\delta\cos\delta} \quad (2)$$

Similarly,

$$m-1 = \frac{\sin(\theta-\delta)\cos(\theta+\delta)}{\sin\delta\cos\delta} \quad (3)$$

substituting (2) and (3) into (1),

$$Z = \frac{2\sin\delta\cos\delta}{\cos(\theta-\delta)-\cos(\theta+\delta)}$$

$$Z = \frac{\cos\delta}{\sin\theta} \quad (4)$$

The overall geometric concentration ratio is denoted as M.

$$M = Z(m-1), \quad (5)$$

The quantities m-1 and Z are determined from equations (3) and (4) respectively. The factor of (m-1) occurs instead of m because the secondary mirror shades the primary.

The Off-Axis PTCEC

The shading problems associated with the above on-axis PTCEC can be eliminated by displacing the secondary collector out of the way of the

incoming solar radiation as shown in Figure 6.2. The secondary is offset just enough to allow all rays within the angular acceptance to reach the primary. In this case,

$$M = Zm \cos \psi \quad (6)$$

where $\cos \psi$ is necessary to account for the true projected aperture of the primary. Here,

$$Z = \frac{\cos \delta}{\sin \theta} \quad (7)$$

and

$$m = \frac{1}{2}[(m+1) + (m-1)]$$

$$\begin{aligned} m &= \frac{\sin(\theta+\delta)\cos(\theta-\delta) + \sin(\theta-\delta)\cos(\theta+\delta)}{2\sin\delta\cos\delta} \\ &= \frac{2\sin\theta\cos\theta}{2\sin\delta\cos\delta} = \frac{\sin 2\theta}{\sin 2\delta} \end{aligned} \quad (8)$$

The equation for the parabola is

$$y = \frac{1}{4f} x^2$$

for the positioning of the x-y axes as shown.

At each point on the parabola, the tangent line must be normal to the line which bisects the incident and reflected rays. Therefore, at point Q,

$$\frac{dy}{dx} = \frac{x}{2f} = \tan \delta$$

$$x = 2f \tan \delta \quad y = f \tan^2 \delta$$

Similarly, at point R,

$$x = 2f \tan(\theta + \delta) \quad y = f \tan^2(\theta + \delta)$$

then,

$$\psi = \tan^{-1} \left[\frac{\frac{1}{2} \frac{\tan^2(\theta + \delta) - \tan^2 \delta}{\tan(\theta + \delta) - \tan \delta}} \right]$$

$$\psi = \tan^{-1} \left\{ \frac{1}{2} [\tan(\theta + \delta) + \tan \delta] \right\}$$

$$\cos \psi = \left\{ \frac{1}{4} [\tan(\theta + \delta) + \tan \delta]^2 + 1 \right\}^{-\frac{1}{2}} \quad (9)$$

Finally, we have from (6), (7), (8), and (9),

$$M = Z \frac{\sin 2\theta}{\sin 2\delta} \left\{ \frac{1}{4} [\tan(\theta + \delta) + \tan \delta]^2 + 1 \right\}^{-\frac{1}{2}} \quad (10)$$

or

$$M = \frac{\cos \theta}{\sin \delta} \left\{ \frac{1}{4} [\tan(\theta + \delta) + \tan \delta]^2 + 1 \right\}^{-\frac{1}{2}} \quad (11)$$

Figure 6.4 shows how M varies as a function of δ , for different values of Z. Table 6.1 compares typical concentration ratios and reflector areas for the PTCEC on-axis, PTCEC off-axis, Ideal Concentrator, and Truncated Winston Concentrator^{*(2)}. The values of δ shown are in the region of interest. It can be seen that the off-axis PTCEC compares very favorably.

The Ideal Winston concentrator has sharply defined acceptance limits. That is, the absorber receives 100% of the energy falling within $\pm \delta$ of the axis of symmetry (assuming perfect reflectors), and none of the radiation

*Since the upper portions of the ideal concentrator intercept relatively little light, truncating the collector affords a large savings of mirror area, with a proportionally small loss of concentration.

arriving outside these limits. This is illustrated in Figure 6.5.⁽⁹⁾ Because the PTCEC is not "ideal", it has no such sharp limits. The absorber receives 100% of the energy arriving within $\pm \delta$ but still can receive some energy outside $\pm \delta$, tailing off to 0 at $\pm \delta'$. A typical case is shown in Figure 6.5.⁽⁶⁾

System Optimization

For the off-axis PTCEC, once values for δ , the half-acceptance angle, and Z, the secondary geometrical concentration ratio, are specified, the entire concentrator design is determined. Obviously, there exists a wide range of possible values for δ and Z. For purposes of the experiment, it was desired to choose these parameters such that:

- (1) The resulting concentrator would have the potential to provide the lowest cost electrical energy output.
- (2) The system could be built, using available tooling and materials, to accommodate at least one row of 2" diameter solar cells.

Even with a fully specified concentrator design, the best program of periodic N-S tilt adjustments must still be determined. A non-tracking device will see the sun at different angles and for different lengths of time each day. The average solar insolation also varies with the time of the year. Increasing the number of tilt adjustments will increase the yearly energy output, but will incur additional operating costs. Since one possible use of non-tracking concentrators is to provide power in remote (even inaccessible) areas, frequent tilt adjustments could be very expensive.

Roughly speaking, the cost of the electrical energy output is proportional to the construction and operating costs of the unit, and inversely proportional to the amount of energy delivered.

In return, the cost is a function of solar cell costs, mirror costs, concentration ratio (cells being much more expensive than reflectors) and other factors. The energy output is a function of δ , M (concentration ratio), cell efficiency, and the tilt routine.

Operation Of The PTCEC During The Course Of A Day

The angular acceptance limits of a PTCEC define an angle in a vertical plane normal to the E-W direction. See Figure 6.6. The angle ϵ is defined as the elevation from the horizon of the bisector of the full acceptance angle (2δ). The lower limit has elevation $\epsilon - \delta$, and the upper limit has elevation $\epsilon + \delta$.

The East-West-Vertical angle, EWV, as defined by Tabor⁽³⁾, is the angle to the horizon that a ray to the sun makes when projected onto a vertical plane normal to the East-West direction. See Figure 6.7. It can be seen that

$$\tan(\text{EWV}) = \frac{\tan \alpha}{\cos \phi} \quad (12)$$

where α is the solar attitude from the horizon, and ϕ is the solar azimuth angle.

The PTCEC sees the sun wherever the EWV is within the acceptance limits, that is, whenever

$$\epsilon - \delta \leq \text{EWV} \leq \epsilon + \delta \quad (13)$$

For purposes of the calculations it is assumed that the concentrator possesses sharp acceptance limits at $\pm\delta$.

Figure 6.7 shows the heavens as they appear to an observer at point P. $\overline{PP_n}$ is the axis of rotation of the earth, inclined λ (the latitude) from the horizon. The sun position travels in a circle about $\overline{PP_n}$ such that at solar noon (sun due south), $\alpha = 90 - \lambda + \Delta$, where Δ is the declination angle. From spherical trigonometry,

$$\cos(90 - \Delta) = \cos(90 - \alpha)\cos(90 - \lambda) + \sin(90 - \alpha)\sin(90 - \lambda)\cos(180 - \phi)$$

or

$$\sin \Delta = \sin \alpha \sin \lambda - \cos \alpha \cos \lambda \cos \phi$$

$$\cos \phi = \frac{\sin \alpha \sin \lambda - \sin \Delta}{\cos \alpha \cos \lambda} \quad (14)$$

Substituting this into (12) yields:

$$\tan(EWV) = \frac{\tan \alpha}{\left(\frac{\sin \alpha \sin \lambda - \sin \Delta}{\cos \alpha \cos \lambda} \right)}$$

$$\tan(EWV) = \frac{\sin \alpha \cos \lambda}{\sin \alpha \sin \lambda - \sin \Delta} \quad (15)$$

It is apparent from (15) and Figure 6.7 that the EWV starts at 0 at sunrise and reaches it's maximum value at noon in the winter time, and starts at 180° and reaches it's minimum value at noon in the summer time. EWV is a constant at the equinoxes, when the sun appears to travel a great circle path in the sky.

Solving (15) for $\sin \alpha$ gives,

$$\sin \alpha = \frac{\tan(EWV) \sin \Delta}{\tan(EWV) \sin \lambda - \cos \lambda} \quad (16)$$

Since,

$$\sin \alpha = \sin \lambda \sin \Delta + \cos \lambda \cos \delta \cos H$$

where H is the hour angle from noon,

$$\cos H = \frac{\sin \alpha - \sin \lambda \sin \Delta}{\cos \lambda \cos \delta} \quad (17)$$

If $\epsilon + \delta$ or $\epsilon - \delta$ is substituted for EWV in (16), equations (16) and (17) give the hour angle at which the sun crosses the boundary of the acceptance angle.

The sun makes an angle β with the normal to the aperture of the concentrator. In this case the normal is just ϵ . We have

$$\cos \beta = \sin \epsilon \sin \alpha + \cos \epsilon \cos \alpha \cos \phi$$

from which substitution of (13) and manipulation eventually gives

$$\cos \beta = \cos \Delta \cos H \sin(\epsilon + \lambda) - \sin \Delta \cos(\epsilon + \lambda) \quad (18)$$

The total direct radiation falling on the aperture of the concentrator and within the acceptance angle during the day is given by

$$Q_t = 2 \int_{T_1}^{T_2} K_0 \cos \beta dt \quad (19)$$

Here K_0 is the solar radiation constant, and t is time. T_1 and T_2 are the times between which the collector "sees" the sun on one side of solar noon. The integral is carried out for the afternoon and multiplied by 2 to give the total daily energy. Since

$$dt = \frac{12}{\pi} dH$$

for t in hours and H in radians, we have from equations (18) and (19)

$$Q_t = \frac{24}{\pi} \int_{H_1}^{H_2} K_o [\cos \Delta \cos H \sin(\epsilon + \lambda) - \sin \Delta \cos(\epsilon + \lambda)] dH$$

or

$$Q_t = \frac{24 K_o}{\pi} [\cos \Delta \sin(\epsilon + \lambda) (\sin H_2 - \sin H_1) + \sin \Delta \cos(\epsilon + \lambda) (H_1 - H_2)] \quad (20)$$

Limits of integration H_1 and H_2 are determined using equations (13), (16), and (17).

Computer Program

A computer program was written to calculate the yearly energy output, and from that the cost, of a given design. The goal of this program was not to give an absolute prediction of energy cost. The goal was to compare on a relative basis different PTCEC systems, both with each other and with other concentrator designs currently being studied.

The program uses equations (13), (16), (17) and (20) to calculate the direct radiation energy which reaches the absorber for each day. δ is a constant of the design, and ϵ is specified for each day. The declination is approximated by

$$\Delta = \sin^{-1}(\sin 23.45^\circ \sin \frac{360n}{365})$$

where n is the number of days from spring equinox.

The solar radiation constant K_o is determined in the following way⁽⁴⁾:
The atmospheric correction factor $\overline{K_t}$ is given by

$$\overline{K_t} = \frac{\overline{H}}{H_o}$$

Here $\overline{H}$ is the monthly average daily total insolation falling on a horizontal surface. This is given data. H_o is the calculated extraterrestrial daily insolation on a horizontal surface. It is found from

$$H_o = \frac{24I_o}{\pi} [\omega_s \sin \lambda \sin \Delta + \cos \lambda \cos \Delta \sin \omega_s]$$

where ω_s = Hour angle at sunset or sunrise

$$\cos \omega_s = -\tan \lambda \tan \Delta$$

I_o = solar constant, 116.4 Langleys/hour .

$\overline{D}$, the daily average diffuse radiation, is determined from $\overline{K_t}$ by the relationships established by Liu & Jordan⁽⁴⁾.

Then, K_o is given by

$$K_o = I_o \overline{K_t} \left(1 - \frac{\overline{D}}{\overline{H}}\right)$$

In calculating the amount of useful energy which the concentrator collects, the following assumptions are made:

- (1) Direct radiation is concentrated by a factor equal to the geometrical concentration ratio of the entire unit.
- (2) Diffuse radiation is received at a concentration of one.
- (3) End effects are ignored. In practice, the sun will usually be outside the acceptance limits when H is high enough for end effects to become important.
- (4) The sun is a point. δ is usually much greater than the angular size of the sun.

The total daily useful energy collected at the concentrator system aperture is given by

$$T = \frac{MQ_t + \bar{D}}{M}$$

The program calculates T for each day, and sums the daily energy over the year to obtain the total collected yearly energy.

The energy cost is estimated from the following equation,

$$C = \left(\frac{x}{A} + y + \frac{z}{P_f} \right) (fcr) / E$$

Where:

C = Energy cost, \$/KWH_E

x = Cost of solar cells, \$/m²

A = Overall system concentration ratio

y = Cost of concentrator construction & installation exclusive of cells, \$/m² of aperture

z = Land costs, \$/m²

P_f = Land utilization factor (packing factor)

fcrr = Fixed charge rate

E = Electrical energy output per year, KWH

E is given by

$$E = (\Sigma)(N)(R)$$

Where:

Σ = total usable solar energy collected per year per aperture area, KWH/m²

y = solar cell efficiency

R = total mirror reflectivity factor

Land costs are assumed to be \$1/m², and P_f is assumed to be .35.

A value of .18 is used for the fixed charge rate. Σ is obtained from the program.

A projected value of y for N-S tracking linear parabolic troughs is \$45/m². Since the construction of a PTCEC is similar, but lacks tracking, a projected cost of \$40/m² is used. However, values for y of 0, 20, 40, and 60 \$/m² were considered.

Values of x of 2000, 500, and 50 \$/m² were used in the analysis. These cover the range of cell costs from the present day to the projected goal of \$.50 per peak watt.

Solar cell efficiency η is a function of cell temperature, decreasing as temperature increases. The cell temperature depends on the concentration ratio and on the effective thermal conductance, K_e . For this

analysis, K_e is taken to be $0.2 \text{ KW/m}^2/\text{°C}$ (a typical value for passive cooling). η is assumed to be 15% at 25°C . Curve-fit data is used to determine η for a given concentration.

Since, for the range of δ and Z under consideration, the average ray from the sun undergoes about 1.5 reflections,⁽²⁾ a value of $(.85)^{1.5} = .784$ was used for R .

Results Of Computer Runs

For the experiment, it was anticipated that the two elliptic secondary mirrors and the absorber mounting surface would be formed as a one-piece aluminum extrusion. The maximum diameter extrusion die readily available to us is 9 inches. Figure 6.8 shows approximately how the length of the secondary collector varies with Z and δ . Note that here, the secondary aperture is equal to $2'' \times Z$. Since the minimum absorber width is 2 inches, Z is constrained to a low value. In addition, it was desired to incorporate most of the concentration into the primary. These two factors dictated that Z be on the order of 1.75 to 2.00.

Table 2 compares the approximate solar energy collected by the PTCEC for various δ 's and tilt routines, with a flat array as a reference. Figures 6.9 and 6.10 show electrical energy cost as a function of δ , for different x and y . Figure 6.9 shows the tradeoff between the factors of large concentration and large acceptance. For a large δ , a large amount of energy is collected per aperture area, but the concentration is low, so cell costs dominate. For a small δ , cell costs are low, but now little energy is collected, so the cost is again high. Here, for $x = \$500/\text{m}^2$ (a figure of practical

importance in the near future) and a tilt routine consisting of 8 adjustments, a broad cost minimum occurs for δ between about 5° and 7.5° . Figure 6.10 shows that if the number of tilt adjustments increases with decreasing δ , the "minimum" occurs at a significantly lower δ . However, the number of adjustments necessary becomes prohibitive (note that this factor was not included in the cost analysis).

The minimum cost point δ was found to not be a strong function of Z or y, nor of the number of tilt adjustments if this number is a constant.

Accordingly, for the experiment, a δ of 6° was chosen. This is near the minimum-cost point in both Figures 6.9 and 6.10, for $x = \$500/\text{m}^2$, and $y = \$40/\text{m}^2$.

A Z of 1.90 was selected. For a δ of 6° , this allows full use of the 9-inch extrusion die, and provides a good concentration ratio of approximately 7.5.

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6.3 FRESNEL TRACKING CONCENTRATOR SYSTEM

Another concentrator system experiment to be performed at Spectrolab utilizes the on-axis fresnel lens concept. With this concept each lens irradiates a single solar cell. The lenses to be used in this experiment are 7 inches square and have a focal length of approximately 8 inches. Nominal 2 inch diameter solar cell components are used which are mounted on a finned aluminum extrusion which acts as a heat sink and provides a large surface area for convective heat transfer to the ambient surroundings. A photograph of a thermal model showing the orientation of components is given in Figure 6-11.

Using a two inch cell diameter establishes an area concentration factor of 15.6. The cell is positioned between the focal point and the lens where the lens image on the cell is approximately a 1 inch square. Almost all of the useful energy transmitted by the lens falls within this 1 inch square resulting in a significantly higher effective concentration factor. This condition was chosen in order to allow for mechanical inaccuracies in locating the cells relative to the lenses and for pointing inaccuracies in the required tracking system.

The short focal length is used to minimize the pointing error. Unfortunately the optical transmission of the fresnel lens decreases with decreasing f/number and hence focal length. Typical optical transmission factors are shown in Figure 6-12. The increasing losses are associated with scattering and internal reflection.

The tracking system to be used in this experiment is an existing two axis tracking platform shown in Figure 6.13. This tracking system uses two near independent tracking axes; one for the daily hour angle and one for seasonal variation of the declination angle.

6.4 THE FIXED MIRROR CONCENTRATOR SYSTEM

The fixed mirror solar concentrator (FMSC) has not been discussed in previous progress reports in this program because it was being studied at ASU under separate funding. The encouraging results of this concept has lead to the design of a photovoltaic system experiment using this type of concentrator.

Most focusing concentrators use steerable arrays of mirrors which need heavy mechanical support structures to meet the wind loading and accuracy requirements. It would obviously be simpler and cheaper to fix the mirror and steer only the smaller heat absorber to stay in the focal zone of the concentrator. In the past, fixed parabolic and circular cylinders have been used. The circular cylinder never focuses to a line for any sun direction. The parabolic cylinder has a fine line focus but only when the sunlight is parallel with its axis. As the sun moves in other directions, the focal zone moves in a complex fashion and enlarges (off-axis aberration). This enlargement of the focal zone reduces the concentration ratio and the obtainable temperatures as well as requiring a larger area absorber.

The fixed mirror solar concentrator (FMSC) has a unique surface that is nonparabolic and exhibits no off-axis aberration.* Its faceted surface focuses all the parallel incident light into a sharp line focus regardless of the incident light directions. The mirror consists of a large number of long, narrow reflecting slats placed at fixed angles on a reference circular cylinder. Figure 6.14 shows a schematic of a cross section

*A patent has been applied for the FMSC by John L. Russell and Eugene P. DeLamb of the General Atomic Corporation

of one of these troughs. For a given sun position, the angle of each slat is fixed such that each of them reflect the light through the same line located at a projection on the same circle on which the slats are positioned (see Fig. 6.14). It can be shown that the focus is sharp for any incoming light direction and further that the focus always falls on the reference circle. The latter property is important since it means that the absorber pipe can simply be pivoted about the centerline of the reference circle.

The faceted or stepped surface of this mirror that gives the fine focus also contains an optical loss mechanism because of this shape. If incoming light strikes the area between the slats (i.e., the "edge" of the step) directly, or is reflected into this area, it cannot reach the focal line and thus is lost. These edge losses have been analyzed to determine how they can be minimized. Figure 6.15 helps define some of the parameters which can be varied to minimize the edge losses.

The slat which is tangent to the reference cylinder is referred to as Tangential Slat, or T.S., and is taken as the reference slat in further discussions. The position of all other slats are specified with respect to the T.S. A symmetrical FMSC is one whose T.S. position coincides with the centerline of FMSC. In general, FMSC's may not be symmetrical, i.e., the centerline of FMSC may not coincide with its T.S. position. But as long as the relationship between angular position on the reference cylinder and angular orientation of the slat is maintained, the non-aberrative property of FMSC is retained. In addition to the above deviation from a symmetrical FMSC, the centerline of FMSC may also be inclined at some angle to the vertical. The angle which the position of T.S. makes with the centerline of FMSC is referred to as the Tilt Angle and is denoted by β in further

discussions. The angle which the centerline of FMSC makes with the vertical is referred to as centerline inclination angle and is denoted by ζ . The parameter θ_{in} is called the rim angle for the concentrator.

The derivation of the equations to calculate the edge losses under all conditions becomes quite complicated. This is due mostly to the complex limits of integration which depend on several variables. For this analysis the slats were considered perfect reflectors for the purpose of comparing the percentage of energy loss for different configurations. Figures 6.16 and 6.17 give typical computer results from the edge loss analysis. Figure 6.16 is for a 90° rim angle with no inclination toward the south. As would be expected, the curve of percent losses is symmetrical for a 0° tilt angle. The losses are zero when the sunlight is normal to the tangent slat and is less than 10% as long as the sunlight is within $\pm 25^\circ$ of normal to the T.S. When the tilt angle exceeds the Local North Latitude then the edge losses are zero up to a given sun position. This is because the edges are in a shadow up to that angle.

Figure 6.17 shows the edge losses for a 60° rim angle mirror that is inclined 15° toward south at the same north latitude as Fig. 6.16, i.e., 33° . Certain tilt angles can be chosen to keep the energy losses by the edges to an average of less than 10% over a year's time.

These curves were calculated for east-west oriented troughs. For north-south oriented troughs, the flexibility of parameter adjustment is mostly lost. The line of focus is just as sharp, but the edge losses are greatly increased when compared to the east-west troughs. The sun would essentially go from 0° to 180° each day with the 0° tilt curve of Fig. 6.16. being a typical loss curve. Therefore it is concluded that east-west

axis troughs for this concentrator are highly superior to the north-south troughs. By contrast, the one axis tracking parabolic trough gives about the same energy collected per year from the different axis orientation with the main difference being in the summer to winter energy ratio.

The generating capacity of any solar power plant is directly related to the amount of light being collected by its absorbers. This, in turn, is dependent on the geometry and orientation of the collector, the time of day, the time of the year, geographical location and, of course, the weather. Since the cost of a solar power plant is dominated by the cost of the concentrators, an important parameter is the amount of energy collected per unit concentrator area per year. A computer program was thus developed to take into account the characteristics and losses to determine this. Direct irradiation using cloudless conditions were used in the calculations for comparisons of different geometries. Calculations of how the energy collected varied with the time of day for different times during the year have the same relative shapes as curves for energy incident on a horizontal surface. Figure 6.18 shows how the energy collected by a certain FMSC varies with the time of the year. The primary effect of inclining the mirror toward the south is to significantly change the winter/summer ratio of daily energy collected.

More complete analysis was performed that took into account surface slope errors, subtended sun angles and slat width variation. The general conclusions were that large aperture FMSC's can provide practical concentration ratios in the range of 40 to 50 whereas smaller aperture FMSC's can provide concentration ratios between 20 to 30 only. Both large and small aperture FMSC's can accommodate surface slope errors of standard deviations up to $1/8^\circ$.

System cost studies have been performed on the FMSC and are discussed in section 5.2 of this report. Considering this and other linear focusing collector analysis reported in earlier reports, the optimum concentration ratio is between 20 and 50 for passively cooled systems. Since this is the range for the FMSC it appears especially attractive for photovoltaic systems. The tracking required is quite simple since it involves only rotation about a single axis and the sensor can be two solar cells mounted on either side of the focal line.

Through funding from a group of southwestern utility companies, the small fixed mirror shown in Fig. 6.19 was built. Its initial intent was to investigate solar thermal applications but it is presently being modified to conduct photovoltaic experiments also. A silicon solar cell array is being designed for a concentration ratio of about 30 suns to fit into the focal line of this system. The mirror's optical characteristics will first be determined before solar cell testing will start.

6.5 PARABOLOIDAL CONCENTRATOR SYSTEM

In order to conduct experiments with high concentration ratios of sunlight (100-1000), a surplus searchlight is used as a platform on which to mount a paraboloidal reflector, the solar collector, and tracking mechanism. The searchlight shell has been fitted to hold a 1.52 M reflector with the collector (solar cell array) on a movable mount so that it can be placed at the focal point or any desired point on the axis of the reflector, the searchlight has a vertical axis for azimuthal tracking and a horizontal one for altitude tracking. A picture of the concentrator is shown in Fig. 6.20.

The tracking system (Fig. 6.21) consists of a sensor which detects movement of the sun from alignment with the axis of the concentrator, electronic components, stepping motors, and gearing from the stepping motors to the searchlight. The sensor is a long tube with a four solar cell, nulling circuit for alignment. The sensor and electronic components are able to detect misalignment of $.002^\circ$. The stepping motor shafts turn 1.8° per step. The gearing reduces this to $.0084^\circ$ for altitude and $.09^\circ$ for azimuth of the reflector.

Currently the tracking system is being modified so that control in the azimuthal direction will be refined to $.009^\circ$. Also the mount for the sensor is being redesigned so that alignment between the sensor and reflector axes can be adjusted to $\pm .003^\circ$.

When the tracking system is completed, evaluation of the reflectors will be made using a calorimeter to determine overall efficiency and high flux sensors for optical mapping of the intensity field. High intensity silicon cells are being designed by Spectrolab for intensities of about 100 suns for experiments with the concentrator.

FIGURE 6.1

EXPERIMENTAL
PARABOLIC TROUGH COMPOUND ELLIPTIC CONCENTRATOR
(NON-TRACKING)

Shown in Summer Position

6.26

FIGURE 6-2
 OFF-AXIS PTCEC
 RAY TRACE DIAGRAM

FIGURE 6.3
ON-AXIS PTCEC
RAY TRACE DIAGRAM

(a) IDEAL CONCENTRATOR

(b) TYPICAL PTCEC

FIGURE 6.5

FRACTION OF RADIATION INCIDENT ON APERTURE
THAT REACHES ABSORBER, FOR THE IDEAL
CONCENTRATOR AND THE PTCEC

FIGURE 6.6
MOUNTING ORIENTATION OF PTCEC

(a) Celestial Sphere

(b) East-West Vertical Angle

FIGURE 6.7
SUN ORIENTATION AND
EAST-WEST VERTICAL (EWV) ANGLE

Time of Year: Winter
Time of Day: Morning

FIGURE 6.8

GRAPH USED FOR ESTIMATING RATIO
OF SECONDARY LENGTH TO SECONDARY APERTURE

FIGURE 6.9
COST CALCULATIONS FOR PTCEC
EIGHT TILT ADJUSTMENTS PER YEAR
SECONDARY CONCENTRATION RATIO (%) = 1.75

FIGURE 6.10

ENERGY GENERATION COSTS

vs.

ACCEPTANCE ANGLE

NOTES:

$\delta = 7.5^\circ, 10^\circ$ - 14 TILT ADJUSTMENTS PER YEAR

$\delta = 5^\circ$ - 18 TILT ADJUSTMENTS PER YEAR

SECONDARY CONCENTRATION RATIO (Z) = 1.75

FIG. 6.11. Fresnel on Axis Thermal Model

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FIGURE 6 - 12

FIGURE 6-13

SPECTROLAB 2 AXIS TRACKING PLATFORM

Fig. 6.14. The Cross Section of a Fixed Mirror Solar Concentrator Trough

Fig. 6.15. An End View of a Non-symmetrical FMSC With the Important Parameters Identified

Fig. 6.16. Edge Losses in a South Facing FMSC Located at 33° North Latitude. The Rim Angle, θ_{in} , is 90° and its Inclination Toward the South is 0°.

Fig. 6.17. Edge Losses in a South Facing FMSC, Located at 33° North Latitude. The rim angle, θ_{in} , is 60° and its Inclination Toward the South is 15°.

Fig. 6.18. Annual Variation of Energy Collected by FMSC, located at 33° North Latitude with a 90° Rim Angle, Inclined Toward the South at 15° With a Tilt Angle of 15°.

Fig. 6.19. An Experimental Model of the FMSC is Approximately 1/10 Scale.

FIG. 6.20. The 1.5M Diameter Parabolic Concentrator

FIG. 6.21 Tracking System Schematic for the Parabolic Concentrator Experiment

TABLE 6-1

COMPARISON OF REFLECTOR AREA AND CONCENTRATION RATIO FOR
TYPICAL NON-TRACKING DEVICES

<u>δ</u>	<u>DEVICE</u>	<u>CONC. RATIO</u>	<u>APPROXIMATE REFLECTOR AREA PER UNIT LENGTH, FOR 5cm WIDTH ABSORBER</u>
3°	Ideal Winston	19.1	1900cm ²
3°	Truncated Winston	10.0	240
3°	On-Axis PTCEC	14.6	120
3°	Off-Axis PTCEC	15.6	120
5°	Ideal Winston	11.5	710
5°	Truncated Winston	8.00	160
5°	On-Axis PTCEC	7.95	85
5°	Off-Axis PTCEC	9.26	85
7.5°	Ideal Winston	7.66	330
7.5°	Truncated Winston	6.00	110
7.5°	On-Axis PTCEC	4.65	75
7.5°	Off-Axis PTCEC	6.08	75
10°	Ideal Winston	5.76	190
10°	Truncated Winston	4.00	50
10°	On-Axis PTCEC	3.01	70
10°	Off-Axis PTCEC	4.32	70

7.0 UTILIZATION AND COORDINATION WITH OTHER PROGRAMS

The results from the contract are made available for use to other people, mostly through the frequent papers presented at technical meetings. Appendix B lists and gives abstracts of some of these papers. There have been numerous requests for the last annual report with approximately 120 copies sent out from our office at ASU besides those distributed by NSF/ERDA.

Frequent contact is maintained with other researchers in concentrated photovoltaic systems. VMJ cells have been obtained from NASA Lewis and GaAs cells have been obtained from Varian Associates. After our experimental concentrators have been made operational and characterized, these cells will be tested, if time permits, under the present contract. It would be very valuable if independent testing could be done on cells from various concentration efforts around the country to provide a collaboration of results.

Reports and conversations are maintained with the appropriate solar thermal programs investigating concentration for power generation. In particular, the work of Colorado State/Westinghouse and the Aerospace Corp. have been valuable for the estimating of concentrator costs and system considerations.

APPENDIX A
SUMMARY FROM FIRST ANNUAL REPORT
January 31, 1975

Arizona State University and the Spectrolab, Heliotex Division of Textron, Inc., are investigating the degree of cost reduction achievable in photovoltaic power systems as a result of applying solar concentration techniques. Concentration provides possible significant system cost reductions. However, there must be a trade-off made to determine the largest advantage obtainable as one replaces the relatively expensive solar cell with a less expensive solar concentration system. Hence, the primary objective of this program is to analyze the parameters applicable to this trade-off and to optimize the system cost per unit of energy generated for many kinds of concentration schemes. Spectrolab is primarily concerned with determining the photovoltaic device performance characteristics as a function of the light level and solar cell temperature. ASU is evaluating concentration techniques and the means by which solar cells can be cooled for maintaining reasonable cell efficiencies.

SOLAR CELL DESIGN

As the sunlight intensity increases the light generated current increases and the internal resistance within the cell becomes a controlling factor on cell performance. This resistance is a combination of the sheet resistance of the surface diffused layer and the metalized gridlines applied to the surface for current collection. An analytical model of cell series resistance has been developed to study optimization of cell design. It has been shown that the optimum front contact, regardless of light level, is a very large number of very narrow gridlines. It is possible to design cells with coverage factors (the ratio of active area to total area, including that covered by gridlines) greater than 90% for operation at over 100 suns, provided the

finger length is reduced substantially below the customary value of 2 cm. Spectrolab is developing contact configurations which pick up the current at a number of points on the cell surface and transfer it to low-resistance collector busses laminated to the cell surface. It is believed that conventional processed silicon cells can operate at light intensities well over 100 suns at efficiencies comparable to current production space cells.

As a result of this encouraging prediction for silicon cells, the need to go to VMJ or Ga-Al-As cells for concentrators of less than 100 suns is not near as great as was anticipated at the beginning of this investigation.

CELL ENCAPSULATION

The two concepts selected for attractive low cost encapsulation approaches have been the potting of the cells under a protective plastic sheet and the use of a conformal plastic coating. Several types of materials are being evaluated in sunlight exposure tests both at Spectrolab and the Phoenix Sunshine Test Facility. So far all the materials have proven out satisfactory in short term exposure tests and these type tests are being continued to get long term exposure characteristics.

CELL BONDING MATERIALS

In the evaluation of attractive bonding materials of the cells to the heat rejection substrate the thermal resistance of the bonding material becomes an important consideration. Experimental tests were conducted on about a dozen available materials and the temperature difference between the top of the cell and heat sink was measured for various thermal energy densities. Typical bonding materials have less than a 5°C temperature difference at concentration levels of 100 suns. It thus appears the thermal resistances in silicon cells and their bonding materials are not significant except for very high concentrations of over 100 suns.

SOLAR SIMULATOR FOR HIGH INTENSITIES

During the first year of this study a facility for testing cells under intense illumination was designed and calibrated. This facility is a solar simulator capable of testing cells and determining their current-voltage characteristics at illumination levels up to 60 suns terrestrial (6 watts/cm^2). The water cooled cell test fixture can maintain desired cell temperature $\pm 2^\circ\text{C}$ by adjusting water temperature as the illumination on the cell is varied.

CONCENTRATOR EVALUATION

In order to characterize and compare various concentrator designs a computer oriented evaluation has been put into operation for rating the proposed concentrating schemes in terms of energy collected per day and, more importantly, per year. A subroutine SUN (developed by ASHRAE) was used for insolation information so that the concentrators could be compared on an equal basis. (More realistic insolation data were used for energy cost analysis.)

Energy incident on surfaces with different orientations and tracking techniques was determined. Low concentration devices such as side mirror reflectors and the Winston collector were analyzed. The latter has better technical characteristics but conclusions about attractiveness cannot be reached until cost information is available. Non-tracking concentrators such as linear Fresnel lens and reflectors experience large losses in energy collected due to the focal line varying with sun angle.

One-axis tracking devices such as parabolic troughs, linear Fresnel lens and reflectors, and fixed mirror-moveable receivers have been analyzed.

An interesting concept using a vertical axis with a fixed aperture plane has been extensively investigated. Also two-axis tracking concentrators such as circular Fresnels and paraboloids have been characterized. The information obtained from the various concentration studies provides the necessary input of energy incident on cells for different configurations for incorporation into the system performance and cost analysis.

OPTICAL FILTER DESIGN

Optical filters can be used to increase the cell output per energy incident on the cell but would usually result in a higher cost per electrical output of the system. A filtering characteristic of the reflector would be attractive if it could be incorporated at a very small additional cost during processing. The encouraging results from the cell cooling studies have somewhat reduced the incentive for filtering systems.

HEAT REJECTION

The objective of the heat rejection task was to analyze the wide range of possible cell cooling techniques to determine their constraints and influence on the concentration system. A simulation model for combining possible cooling heat transfer characteristics with assumed cell temperature characteristics has been developed. Heat rejection systems can be easily designed with effective thermal conductances varying by two orders of magnitude. For silicon cells, one can design an adequate heat rejection system for any practical concentration level. The most cost optimum design for a given system depends on a great number of parameters which are not constants. For example, the output from a passively cooled system (one requiring no power drain to effect cooling) depends very much on wind conditions so that they need to be designed for "typical" conditions with provisions made for extreme conditions.

Thermal analysis thus far indicates that passive cooling techniques can be adequate for relatively high aperture-to-cell area ratios of up to about 50. Simple active cooling systems (forced circulations) using water could be used for concentrations of several hundred. Several side studies and experiments (e.g., non-uniform thermal loading on cells, immersion of cells in liquids, etc.) have not indicated any major obstacles for keeping the cells in the desired temperature ranges for any of the concentration system concepts.

SYSTEM ANALYSIS

During the last quarter of the first year of this investigation the component characteristics determined were incorporated into a computer program to simulate system performance and to start preliminary cost analysis. Insolation/weather data tapes available from Aerospace Corporation were used. Flat photovoltaic arrays were simulated as well as various concentration systems to provide a basis for comparison. Shading studies were performed to find optimum area packing factors for different systems.

The system cost model and studies are quite preliminary but have indicated some results which are encouraging for the economics of photovoltaic concentration systems. Concentrator cost estimates from other NSF programs have been used as much as possible. Estimates of overall costs of electrical energy (¢/KWH) are plotted as a function of concentration ratio (aperture-to-cell area ratio). Optimum ratios for cost reduction depends on the projected costs of the cells themselves. The higher the costs of cells, the greater is the cost reduction with concentration and the higher is the optimum aperture-to-cell area ratio. The especially encouraging result is that even when cell costs get down to 50¢/peak watt concentration systems may still be cheaper than flat arrays.

GENERAL CONCLUSIONS OF FIRST YEAR PROGRAM

- Concentration systems can be cheaper than flat arrays even at projected costs for cells (50¢/peak watt)
- Conventionally processed silicon cells can operate at light intensities over 100 suns at efficiencies comparable to current production space cells
- Passive cooling techniques can be adequate for relatively high aperture-to-cell area ratios (~50)

APPENDIX B

PUBLICATIONS RESULTING FROM THIS GRANT

PREVIOUS PROGRESS REPORTS

Terrestrial Photovoltaic Power Systems with Sunlight Concentration,
First Quarterly Report, Quarter Ending April 15, 1974, Report No:
NSF/RANN/SE/GI-41894/PR/74/1

Terrestrial Photovoltaic Power Systems with Sunlight Concentration,
First Semi-Annual Progress Report, Period January 15-June 30, 1974,
Report No: NSF/RANN/SE/GI-41894/PR/74/2

Terrestrial Photovoltaic Power Systems with Sunlight Concentration,
Third Quarterly Report, Quarter Ending September 30, 1974, Report
No: NSF/RANN/SE/GI-41894/PR/74/3

Terrestrial Photovoltaic Power Systems with Sunlight Concentration,
Annual Progress Report, Period January 15-December 31, 1974,
Report No: NSF/RANN/SE/GI-41894/PR/74/4

PAPERS PRESENTED AND/OR PUBLISHED (see abstracts immediately following)

1. Photovoltaic Systems with Concentration, C.E. Backus, D.L. Evans and E.L. Ralph, presented at AIAA/AAS Solar Energy for Earth Conference, Los Angeles, CA, Apr 1975
2. On Heat Rejection from Terrestrial Solar Cell Arrays with Sunlight Concentration, L.W. Florschuetz, presented at 11th IEEE Photovoltaic Specialist Conference, Scottsdale, AZ, May 1975
3. Solar Energy Conversion at High Solar Intensities, C. E. Backus, presented at American Vacuum Society Meeting, New York, May 1975 and published in J. Vac. Sci. Technol., Vol. 12, No. 5, Sep/Oct 1975
4. Linear Fresnel Lens Concentrators, D.T. Nelson, D.L. Evans and R.K. Bansal, presented at ISES Intl. Congress, Los Angeles, CA, Aug 1975 and published in Solar Energy Journal.
5. Solar-Optical Analysis of a Mass-Produced Plastic Circular Fresnel Lens, S. Harmon, presented at ISES Intl. Congress, Los Angeles, CA, Aug 1975
6. Central Power Generation Using Fixed Mirror Concentrators, C.E. Backus, R.K. Bansal and J.L. Russell, presented at ISES Intl. Congress, Los Angeles, CA, Aug 1975
7. Cost Studies on Terrestrial Photovoltaic Power Systems with Sunlight Concentration, D.L. Evans and L.W. Florschuetz, presented at ISES Intl. Congress, Los Angeles, CA, Aug 1975
8. Design Optimization of Silicon Solar Cells for High Illumination Intensity, F.T.C. Bartels, presented at ISES Intl. Congress, Los Angeles, CA, Aug 1975

PHOTOVOLTAIC SYSTEMS WITH CONCENTRATION*

by

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Presented
at

AIAA/AAS SOLAR ENERGY FOR EARTH CONFERENCE

Los Angeles, California

April 21-24, 1975

In a joint program, Arizona State University and Spectrolab, Inc. are investigating the degree of cost reduction achievable in photovoltaic power systems as a result of applying solar concentration techniques. This effort complements both the US Photovoltaic program that is primarily directed toward making low cost solar cells, and the US solar thermal program that is using concentration techniques to increase efficiencies in thermodynamic generation.

Since the solar cell device is able to produce well over one hundred times the amount of power as it could without concentration, the cost of the power associated with the device becomes about 100 times smaller when compared on a dollar per watt basis. This provides a significant cost reduction tool with which to work. There must be a trade-off made to determine the largest advantage obtainable as one replaces the relatively expensive solar cell with a less expensive solar concentration system. As the concentration ratio increases the complexity of the cell, the heat transfer unit, the concentrator design and the orientation system increases. The primary objective of this study was to analyze the parameters applicable to this trade-off and to optimize to the lowest cost-to-watt ratio. The economic goals of the study were to show that photovoltaic systems could reach the competitive cost range of 50 cents to \$1 per peak watt without requiring any "breakthroughs" in the making of solar cells.

Spectrolab was primarily concerned with determining the photovoltaic cell performance characteristics as a function of light level and solar cell temperature. The cell must be designed differently for different ranges of light intensities. The device parameters that affect high intensity performance are: grid design, cell resistivity, semiconductor material (e.g., Si or GaAs), junction depth, cell size and thickness, contact method, antireflection coating and light spectrum. Analysis and experimental verification can provide sufficient data for determining the optimum cell design parameters for all sunlight levels that are likely to be obtained in concentration systems.

The effort at Arizona State University was directed toward characterizing concentrators and investigating various cooling techniques. Concentrators with various concentration ratios (1-1000) were compared and considered for coupling with

photovoltaic cells. As the light intensity on the cells increase the cooling requirements also increase. A complete range of possible heat transfer techniques, both active and cooling, were considered and their appropriateness for accommodating different concentrators determined.

After the various components were characterized they were integrated into a concentration system and the system performance determined. Optimization studies including system performance and cost estimates must be made to determine the most attractive systems. The first year of this study has been completed with its objective being to characterize components by analysis and to start system studies. The second year, just starting, is to experimentally verify component and subsystem characteristics and perform the optimization studies.

Solar Cell Performance at High Light Intensity

It is well known that, as light intensity increases, the efficiency of photovoltaic cells generally decreases due to increasing power losses in internal series resistance and to increasing cell temperature, which reduces voltage output. Because of the high thermal conductivity of silicon, control of cell temperature is largely a matter of providing a low thermal impedance between the cell and a heat sink, and will be discussed later.

Although all parts of the cell contribute to the total internal series resistance, in a conventional silicon cell the series resistance is nearly entirely in the diffused (top) layer and the metallic contact to this layer, which is normally in the form of a number of parallel narrow fingers. In order to obtain the maximum current output per unit area from the cell, it is necessary to make the diffused layer shallow, hence of high sheet resistance, and to make the fractional area covered by the contact fingers as small as possible by reducing their width and increasing their spacing. These steps increase the cell series resistance, leading to an engineering design trade-off. In typical conventional silicon

*This work was under NSF Grant No. GI 41894 entitled "Terrestrial Photovoltaic Power Systems with Sunlight Concentration".

ON HEAT REJECTION FROM TERRESTRIAL SOLAR
CELL ARRAYS WITH SUNLIGHT CONCENTRATION*

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SUMMARY

A simple model for preliminary assessment of cooling system requirements for heat rejection from solar cells subjected to concentrated solar irradiation levels is presented, based on an effective thermal conductance concept. Several basic passive and active cooling schemes are analyzed, and representative effective thermal conductance values determined. Results show that passive cooling to ambient air with extended surfaces can accommodate irradiation levels achievable with practical linear or trough type concentrators, but performance will depend on adequate local wind characteristics. Once through forced cooling with ambient air is not a viable alternative. For irradiation levels typical of paraboloid concentrators, appropriate types of water cooling should be adequate.

INTRODUCTION

A promising cost reduction technique for terrestrial photovoltaic power systems is the use of sunlight concentration. As the concentration of sunlight striking the cell is increased, it is necessary to provide adequate cooling, particularly if reasonable cell efficiencies are to be maintained.

In this paper the cell electrical output as a function of cell irradiation is determined with both cell and cooling system characteristics treated as parameters. A simplified model, useful for preliminary assessment of cooling system requirements in terms of an effective thermal conductance, is first presented. Then, the effectiveness of several basic cooling techniques, including both passive and active schemes** is analyzed. The objective is to assess the potential of these techniques as a function of concentrated solar irradiation level.

Since it is not the purpose here to analyze a complete or specific concentrated terrestrial photovoltaic power system, attention is restricted to the direct heat rejection from the cells. The external portion of the heat transfer loop, required to complete most active cooling schemes, is not considered in detail because its characteristics would depend rather strongly on the particular overall system design concept.

**BASIC MODEL FOR ASSESSMENT
OF ALTERNATIVE COOLING SCHEMES**

A simple, yet very useful model, combining cooling system and cell performance characteristics can be developed if it is assumed that the solar irradiation and

heat rejection are uniform over the absorber surface and the heat rejection rate is directly proportional to the temperature difference between the cell and the ambient air for passive cooling, or between cell and coolant for active cooling.

An energy balance on the absorber may be written as

$$PA_a = \alpha q_s A_a - Q, \quad (1)$$

where P is the electrical output per unit absorber area, A_a is the absorber area, q_s is the solar radiation incident per unit area on the absorber and Q is the heat rejection rate. α is the average solar absorptance of the absorber surface; i.e.,

$$\alpha = \alpha_c \frac{A_c}{A_a} + \alpha_{nc} \left(1 - \frac{A_c}{A_a}\right),$$

where A_c is that portion of the absorber surface covered by cells, and α_c and α_{nc} are the solar absorptances of the cell-covered and non-cell-covered portions of the absorber surface.

The heat rejection rate is given by

$$Q = K_e A_a (T_c - T_o) \quad (2)$$

Here, K_e is an effective unit thermal conductance for heat transfer between the cells at temperature T_c , and the coolant at temperature T_o . Note that K_e is defined per unit absorber area. Its evaluation will be discussed later.

The cell characteristics are introduced as follows. From the definition of cell efficiency, η , one has

$$PA_a = \eta q_s A_c \quad (3)$$

The cell efficiency may be assumed to decrease linearly with cell temperature according to

$$\eta = \eta_r [1 - \beta_r (T_c - T_r)] \quad (4)$$

where η_r is the cell efficiency evaluated at the reference temperature T_r , and β_r is given by

$\beta_r = (T_c^* - T_r)^{-1}$ where T_c^* is the cell temperature at which the efficiency drops to zero.

The set of equations (1) thru (4) may be combined to obtain

$$P = \frac{1 - \frac{\alpha q_s \beta_r}{K_e} - \beta_r (T_o - T_r)}{\frac{1}{q_s \eta_r} \cdot \frac{A_a}{A_c} - \frac{\beta_r}{K_e}} \quad (5)$$

which gives the electrical power output per unit absorber area, P , as a function of q_s and coolant temperature T_o , with the cell characteristics η_r and β_r , the

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**A passive technique refers to one which does not require any power drain on the system in order to effect the cooling. Conversely, an active technique does require some power drain on the system, however small it may be.

Solar energy conversion at high solar intensities

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(Received 26 June 1975)

Galley
Proof

The concentration of sunlight offers distinct advantages for solar-electrical generation either by thermal conversion or by photovoltaics. A large variety of concentration techniques are available with concentration ratios of 1-1000. Concentration is required for thermal conversion systems to attain the high temperatures needed for efficiencies in the desired range of about 25%-35%. The projected costs for some of the solar thermal systems (especially the central receiver and the fixed mirror) indicate that they could be economically competitive in the southwestern states. The southwest may be required for these high-concentration systems to overcome the main disadvantage of concentration, which is the use of the direct component of sunlight only. Other concerns of high-intensity systems are in tracking requirements, reflective surface accuracy, and material lifetimes of both the reflecting and absorbing components. Selective surface absorbers will be required for systems with concentration ratios below a few hundred. The present high cost of solar-cell-generated electricity can be reduced considerably by using concentrators. Cells can be used with any of the concentrator designs, and the major concern is keeping them at acceptable operating temperatures. Planar silicon cells, vertical multijunction, and gallium-aluminum-arsenide cells all look attractive for concentrating systems.

PACS numbers: 84.60.J, 89.30.

The two most common methods being investigated for converting solar energy into electricity are called Photovoltaic and Solar Thermal conversion. In solar thermal conversion, the photons from the sun are absorbed and transformed into thermal energy of a working fluid which is used in a thermodynamic cycle to provide mechanical energy for an electrical generator. In photovoltaic conversion, the photons from the sun are absorbed by interactions with the electrons of a material, thus giving them extra potential in such a way that a voltage can be developed across a device made from this material. This photovoltaic effect can be used to provide electrical energy directly without the need of any intermediate steps or processes.

The thermodynamic cycles used in solar thermal converters are essentially the same as those used in conventional power plants today. Conventional plants use a fuel (i.e., coal, oil, nuclear, etc.) that burns, providing the thermal energy to the working fluid. In a new, modern plant, about 30%-40% of the thermal energy is converted into electricity, with the remaining 60%-70% released into the environment. This range of efficiency is a consequence of the second law of thermodynamics when it is applied to a heat engine. The efficiency of any engine having heat as an input must have an efficiency less than the Carnot efficiency, η_{Carnot} . Therefore,

$$\eta \leq \eta_{\text{Carnot}} = (T_H - T_C)/T_H,$$

where T_H is the hot temperature at which energy is added to the working fluid, and T_C is the cold temperature at which energy is rejected to the environment. Due to other inefficiencies and losses in a system, most engines operate at only 50%-60% of the ideal or Carnot efficiency. The Carnot efficiency of a typical power plant that has an input temperature of 527°C and rejecting heat to a river at 27°C would be

$$\eta_{\text{Carnot}} = (800^\circ\text{K} - 300^\circ\text{K})/800^\circ\text{K} = 0.625.$$

If the plant was operating at 55% of Carnot, then the overall plant efficiency would be 34.4%.

It is obvious from the above discussion that one would like to have a solar thermal plant operating at as high a temperature as possible for maximum efficiency. As a result of the desirability of high temperatures, almost all of the solar thermal conversion concepts utilize some method of concentration of the sun's rays in order to obtain the high temperatures. The concentration devices used in high-concentration solar thermal systems dominate both the technical characteristics and the economics of the entire plant.

Photovoltaic converters, or solar cells, have been utilized mostly for space applications and have not used concentration techniques. Now that they are being used to compete for low-cost terrestrial applications, there appears to be an incentive to use concentrators. The cells have the characteristic that the output increases roughly linearly with intensity. For present-day high-

LINEAR FRESNEL LENS CONCENTRATORS*

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The use of the linear Fresnel lens as a seasonally adjusted or one-axis tracked solar concentrator is investigated. The lens is considered to be a series of parallel strip prisms, each of triangular cross section, molded into a single element. For seasonally adjusted operation the axis of the concentrator system is oriented in an east-west direction with the lens normal considered to be aimed toward the sun at noon (see Fig. 1). For one-axis tracking, rotation about a longitudinal east-west axis is permitted.

Ray tracing techniques applied to each prism are used to show that this type of lens provides very good collection efficiencies within one hour of solar noon. However, tilt in the east-west direction of the solar rays from the lens normal by an angle θ results not only in image motion along the lens axis but also motion transverse to it. As the solar rays move farther from the noon position, the fraction of incident radiation that falls on the absorber becomes smaller and smaller. This effect is shown in Fig. 1 as a rectangular bundle of radiation traverses an outer strip prism at noon and again at noon +2 hours.

Fig. 1

just fill a width of 1.0 cm at the absorber. The index of refraction for the lens material was taken as 1.48, the value for clear borosilicate glass (Corning 7251).

Solar insolation data were calculated using the ASHRAE algorithm SUN. No cloud cover modifier was used; therefore, the computations give cloud-free insolation. The calculations were for direct radiation at a latitude of 33 degrees north with a clearness number of 1.0. Reflection losses at the prism faces were calculated to determine lens transmittance. Internal absorption losses were not considered. Daily and yearly energy received at the absorber were then determined.

The curves in Fig. 2 illustrate the power delivered to the concentrator and absorber for times from 1200 (noon) to 1800 on March 21. The curves may be reflected about the vertical axis to obtain data for times from 0600 to 1200. Power delivered to the absorber is presented for two different distances separating the lens and the absorber. It should be noted that the power delivered to the absorber breaks sharply for the power incident upon the concentrator at approximately one hour from solar noon due to the increased refraction by the prisms. For that date, daily collection efficiencies are 44 and 51% for the 30 and 27 cm positions,

respectively. Although the aperture area to absorber area ratio was 9.8 for the particular lens/absorber combination investigated, daily weighted concentration ratios (geometrical area ratio times collection efficiency) would be approximately half that.

The choice of absorber width is shown to be a compromise wherein high collection efficiency is gained at the expense of weighted concentration ratio. Studies of energy collection vs. lens alignment accuracy show that weekly adjustment of concentrator alignment would maintain energy collection within $\pm 10\%$ of the maximum attainable value.

Yearly distribution of energy collected is shown in Fig. 3 for seasonal adjustment. Slightly higher collection efficiencies are experienced in the winter months than in the summer due to the fact that the major share of energy then reaches the absorber at times close to noon. During this mid-day period, the collector works most efficiently. One-axis tracking provides only slightly improved collection efficiency (56% vs. 52%). Decreasing the relative aperture also improves collection efficiency.

Figure 4 shows experimental results which qualitatively verify the theoretical results. Curve A is the measured insolation on the aperture of a glass linear Fresnel lens. Curves B and C show energy incident on a silicon solar cell "absorber" as determined from the short circuit current output. Curve C differs from curve B in that the center section of the lens has been blocked off to better illustrate behavior of the outer prisms. All curves have been normalized to their noon values.

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**Work conducted at Arizona State University while on Sabbatical leave from Luther College

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SOLAR-OPTICAL ANALYSIS OF A MASS-PRODUCED PLASTIC CIRCULAR FRESNEL LENS

by

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Thin-sheet plastic circular fresnel lenses are being considered for low concentration solar conversion schemes using solar cells. One such lens is commercially manufactured by the 3M Company. It finds its most common use as a safety device in left-turn lane traffic signals. A review of the literature revealed that using circular fresnel lenses as solar concentrators is no new idea, but that very little study had been done on the characteristics of the solar intensity distribution within the focal cone, an important factor of the solar cell loading problem. In this study experimental work was done to characterize the intensity distribution of a 3M lens. The data from this work was used with computer methods to produce a simulation of the intensity field anywhere within the theoretical focal cone.

The experimental work consisted of two parts. In the first part, the intensity as a function of radial distance was plotted for several radii, varying the parameters of polar angle and focal distance. These plots were constructed using a silicon photovoltaic cell and solar irradiation. Figure 2 is a reproduction of one of these plots taken at a focal distance of 8.5 cm. It shows the variation of the short circuit current of the photovoltaic device with increasing radial distance. The different curves represent radii at different polar angles. This data indicated the intensity to be a complex function of radial and focal distance with a very minor dependence on the angular symmetry of the lens. The intensity profiles shown in Fig. 3 illustrate the dependence on radial and focal distance (the angular variation is averaged out). The second part of the experimental work involved using a laser device to determine the deviation in the convergence of normal incident radiation to a single focal point. The resulting data showed that there were small deviations along the lens' centerline which when averaged were approximately 0.7 cm. The results of this experimental work showed this lens to have intensity variations within the focal cone that were not ideal but were relatively uniform. The lens had no gross optical anomalies. The data from the intensity profiles was used to construct a computer simulation of the intensity field at any point within the focal cone. This was

Fig. 1. Side View of a Circular Fresnel Lens

Fig. 2. Intensity Profile at a Focal Distance of 8.5 cm

done by assuming angular symmetry of the field and by selecting a function to describe the dependence of the radial profile on focal distance. To test the simulation, a situation was constructed that could be simulated and experimentally duplicated. This consisted of moving a 2 in. circular silicon solar cell along the centerline of the lens. The results of this comparison are illustrated in Fig. 4. The simulation agrees closely with the experimental data until the focal distance of 5 cm. It is close to this point that the area of the focal spot becomes less than that of the cell. More work is being done on the simulation to improve its ability to predict the intensity distribution within the focal cone of the lens accurately.

Fig. 3. Intensity vs. Radial Distance for Various Focal Distances

Fig. 4. Comparison of the Simulation Output vs. Solar Cell Output

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CENTRAL POWER GENERATION
USING FIXED MIRROR CONCENTRATORS

by

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A novel geometry for the concentration of sunlight, invented by the General Atomic Company has been the key component of a solar power concept being pursued by General Atomic and Arizona State University. The characteristics of this concentrator is such that the reflector surfaces remain in a fixed position and only the absorber tube moves to stay in the focus of the mirror. This fixed mirror eliminates the need of the large support structure normally required for the tracking mirrors. Since most economic analysis indicate that the cost of the mirrors dominate the cost of a solar power plant, the prospect of low cost fixed mirror concentrators makes this solar power concept very attractive.

The fixed mirror solar concentrator (FMSC) is a cylindrical trough built on or into the ground. As seen in Fig. 1 the reflecting surfaces are long narrow slats arranged on a reference cylinder. The angles of the slats are fixed so that they all focus on a given line of that reference cylinder for a given sun angle. (Note that for a normal smooth reflecting cylindrical surface the focal line would be at one half of the radius of the cylinder.) It can be shown that the focus is sharp for parallel light of any incident direction and further that the line focus always falls on the reference cylinder. These unique properties not only eliminate the normal aberration obtained from other fixed reflectors but allows the heat collector pipe to follow this sharp focal line by a simple radial movement with the pivot at the center of the reference cylinder.

A theoretical analysis has been made of this FMSC to determine its characteristics. A major objective was to minimize the losses inherent in this geometry due to the light impinging directly onto the "edges" between the slats and the light reflected onto these edges. Figure 1 defines several parameters that can be varied to minimize these edge losses. The rim angle, θ_{in} , is the angle between the lines drawn from the center of the reference cylinder to the edges, or rim, of the cylinder. Typically these rim angles vary from 60° to 120° . In order to optimize the light collected at a given terrestrial location the cylinder may be inclined toward the equator and the inclination angle is the angle made between vertical and the centerline or the bisecting line of the rim angle. The slat which is tangent to the reference cylinder is referred to as the "tangential slat" or T.S. and the position of all other slats are specified with respect to this slat. In general, FMSC's may not be symmetrical with the "tilt" of the mirror, β , being the angle between the centerline and the line going to the T.S.

Parametric analysis have been performed using the above quantities and computerized sun movements to determine edge losses, adjacent mirror shadowing and hourly, daily, monthly and annual variation in collected energy. The considerations of edge losses indicated that the window for efficient

light collection with FMSC's is only 60° to 90° wide depending upon the FMSC parameters and orientation. This ruled out the practicality of FMSC's with long axis in the north-south direction. However, FMSC's can be practical as the total edge losses over the year may be less than 10%. The effect of increasing the centerline inclination angle is to increase the winter to summer ratio of daily energy collected. The effect of increasing the tilt-angle is to decrease edge losses. Two dimensional accuracy analysis showed that large aperture FMSC's ($\theta_{in} \sim 120^\circ$) can provide practical concentration ratios in the range of 40 to 50, whereas smaller aperture FMSC's ($\theta_{in} \sim 60^\circ$) can provide concentration ratios between 20 to 30. Surface slope errors with standard deviations up to $1/8^\circ$ can be accommodated.

The unique characteristics of this concentrator has many advantages when incorporated into a solar power plant. The installation of these fixed reflecting surfaces on or in the ground permits the use of very inexpensive substrate supports such as concrete, asphalt or soil cement. It also provides for easier cleaning and reduced wind damage. Since the mirrors do not have to be moved, it is possible to consider very large mirrors such as 30 ft. across and several hundred ft. long (see Fig. 2). These large sizes allow large diameter collector pipes that could use gaseous coolants without excessive pumping losses. A gaseous coolant would also allow high temperature rock storage to be practical, which is highly attractive for constant, high temperature exit conditions. The relatively high concentration ratios available, 30 to 40, relieves most of the requirement for highly selective absorbers on the collector pipe.

The FMSC concept is jointly being pursued by the General Atomic Co. and Arizona State University with the sponsorship of several southwestern utility companies and the ERDA solar-thermal program. Partial support for a 4'X10' FMSC model was provided by Arizona Public Service, Southern California Edison and Utah Power and Light companies and is presently undergoing tests at Arizona State University.

Fig. 1. End View of a Non-Symmetrical FMSC

Fig. 2. Large-scale Deployment of a Fixed-Mirror Solar Concentrator

Dr. Charles E. Backus, Associate Professor of Engineering at ASU has been active in unconventional energy conversion systems for about 12 years with emphasis during the last 5 on solar energy systems. Mr. Ravinder K. Bansal, did his masters thesis in mechanical engineering at ASU on the analysis of the fixed mirror solar concentrator.

Dr. John L. Russell, Jr., the inventor of the FMSC, is the manager of Solar Energy Systems for the General Atomic Co. and is also responsible for the hydrogen generation program using HTGR reactors.

COST STUDIES ON TERRESTRIAL PHOTOVOLTAIC
POWER SYSTEMS WITH SUNLIGHT CONCENTRATION*

by
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The purpose of the work being reported on here is to define the role of sunlight concentration in reducing the cost of electrical energy generated by terrestrial photovoltaic systems. The work parallels the national effort to reduce the cost of solar cells in that it explores an alternative to the deployment of large areas of cells in flat unconcentrated arrays. Concentrating devices would decrease the amount of cell area required in converting the sunlight intercepted by a given area, thereby offering a potential for cost reduction. To be discussed are the cost advantages/disadvantages of both 1-D tracked (trough or line focus) devices and 2-D tracked (point focus) systems compared to flat arrays facing south with a tilt angle from horizontal equal to the local latitude.

A system simulation algorithm has been developed to calculate the amount of electrical energy produced over a year's time by alternative photovoltaic systems since this has direct influence on the energy cost. The simulation routines use the hourly solar irradiation and position data available on the Aerospace Corporation data tapes along with information on the collector (aperture area to cell area ratio, reflectivity or transmittance, orientation, type of tracking), to compute the hourly solar cell irradiation. Ambient weather data, available from the same data tapes, effective thermal conductance values for cell cooling, and cell efficiency characteristics are then coupled with the cell irradiation to predict cell operating temperature, efficiency, and electrical output.

Effective thermal conductance, K_E , is considered as a parameter. The values span the range of what might be realized in practice for passive cooling using finned surfaces or active cooling with water. A cell efficiency which decreases linearly with cell temperature but which is independent of intensity is incorporated. Results are presented for silicon cells characterized by a reference efficiency of 15% at 25 C.

Energy costs are calculated by the levelized fixed charge method commonly used in the utility industry. For comparative purposes only energy costs due to capital costs of cells, collector system and land are considered. Storage costs and DC to AC conversion costs are common to all solar photovoltaic systems and are therefore not considered. Operational costs, which in reality will have some dependence on the actual system used, also have not been considered.

As might be expected, the results show that concentration offers a distinct cost advantage at high cell costs. However, they also show that concentration has the potential for being a viable alternative to the flat unconcentrated arrays for cell costs as low as \$50/sq.m. The results also show that for a given concentrator cost, cell cost and cell conductance, there exists an optimum effective aperture area to cell area (i.e., concentration) ratio. For reasonable projected cell costs this optimum ratio is below 30 for passively cooled devices and below 60 for actively cooled systems. Also, although 2-D tracking concentrators may be more

Fig. 1

expensive to build than 1-D tracking devices, they may produce cheaper energy since they collect more energy per year.

Figures 1, 2 and 3 present example cell output fixed cost calculations for a 2-D tracked system in Albuquerque in 1962 assuming land cost of \$1/sq.m. Figure 1 is for passive cooling (a range of K_E's in kw/sq.m.°C, is shown) and capital costs (Y), excluding cell costs, of \$60/sq.m. Figure 2 shows the effect of different Y's on energy costs for a K_E of 0.4 kw/sq.m.°C. Figure 3 is for actively cooled concentrators assumed to cost \$60/sq.m. (excluding cell costs).

For comparative purposes, energy costs using fixed flat unconcentrated arrays in Albuquerque in 1962 were calculated to be 108, 11 and 3.4¢/kwh for cell costs of \$2000, \$200 and \$50/sq.m., respectively.

Fig. 2

Fig. 3

* Work supported by the National Science Foundation, RANN, Grant GI-41894

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DESIGN OF OPTIMIZATION OF SILICON SOLAR
CELLS FOR HIGH ILLUMINATION INTENSITY

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Silicon solar cells intended for use under intense illumination (e.g., in solar power systems employing optical concentration) require careful design to minimize series resistance and maximize power output. This paper presents results of a study of the effects of diffused layer sheet resistance and front contact configuration on solar cell I-V characteristics and power output at high illumination intensities.

Computer calculations have been made based on the analysis of Moizhes (1) which is not limited to the case of small voltage drop in the cell series resistance. An empirical approximation to the exact numerical results has been found which permits optimization of cell parameters for any illumination level without requiring computer calculations. Experimental measurements of the required parameters have been made, and measurements on solar cells have been made up to illumination levels of 4 watts/cm², showing good agreement with calculations. The mathematical model has also been used to determine optimum cell designs for a range of illumination intensities.

Regardless of intensity, the contribution of the diffused layer to the cell series resistance can be made negligible by increasing the number of grid fingers while reducing their width and spacing, maintaining the coverage factor (ratio of active to total cell area) constant. In this limit, the optimum coverage factor depends only on illumination, finger length and contact metallization sheet resistance. Figure 1 gives optimum coverage factor in this limit for a metallization sheet resistance of 4×10^{-3} ohms/square. However, processing considerations determine the minimum grid finger width consistent with adequate yield; the effect of this limitation is shown in Figure 2.

The diffused layer sheet resistance can be optimized if the variation of short-circuit current density is known. Figure 3 shows the results of 15-minute diffusions from a spin-on phosphorus source, and Figure 4 shows the result of calculations of the optimum diffused layer sheet resistance, using the data of Figure 3.

Silicon solar cells of conventional construction appear to be capable of high conversion efficiency up to about 10 watts/cm² illumination, provided that grid finger width is minimized and finger length is kept short. One approach to reducing finger length while retaining the cost advantages of large cell area is to combine evaporated contact fingers with a number of copper ribbon conductors laminated to the front surface of the cell. The performance of 2" diameter cells with this type of front contact will be discussed.

- (1) B. Ya. Moizhes: "On the Theory of Photocells with a P-N Junction";
Sov. Phys. Solid State 2, 202 (1960).

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Figure 2

Figure 2

Figure 3

Figure 4

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