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ESTIMATING HOURLY SOLAR RADIATION FOR ONE-AXIS TRACKING FOCUSING COLLECTORS

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ABSTRACT

Performance simulations of focusing parabolic collectors are hampered by a limited amount of useful insolation data. Hourly values of total radiation on a horizontal surface are the most common data available from the National Oceanographic & Atmospheric Administration. This paper develops a method to convert this total horizontal radiation to direct radiation on the surface of the tracking collector.

1. INTRODUCTION

The most common hourly solar radiation data base is the total horizontal data recorded by the National Weather Service. When simulating hourly performance for single-axis tracking focusing collectors, particularly the parabolic trough, one must estimate the radiation incident on the surface of the constantly moving collector.

In a design application of solar grain drying, sponsored by U.S. ERDA Contract No. E-(40-1)-5121, a simplified technique for estimating direct hourly radiation for a north-south axis, horizontally mounted parabolic trough was developed. This procedure, discussed in Section 2, is easily adapted to an east-west axis tracking orientation. This method may easily be adapted to software packages such as TRYSYS(1), a transient simulation model for solar heating and cooling systems developed by the University of Wisconsin. As a result of these calculations, the model may be used when the only radiation data available are of a total horizontal nature.

The method involves three primary steps:

a. Determine horizontal beam component of radiation from hourly total horizontal data,
b. Calculate direct-normal radiation from horizontal beam radiation,
c. Derive beam radiation on surface of collector from direct normal estimate as a function of collector orientation.

In some cases, due to the use of the Liu and Jordan relationship(2) estimating the beam component of the total solar radiation, unrealistic values often occur at dawn and dusk. These errors are due to the fact that these relationships between direct and total insolation were developed for estimating daily, not hourly insolation values.

However, no better relationship now exists. A limit must be placed on the beam component. This limitation occurs when solar radiation levels are quite low, so the effect on the total performance of the system is small.

In order to more accurately simulate the thermal performance of parabolic troughs, end losses due to shading effects should be calculated. These losses modify the effective aperature area of the collector. The affected area can be calculated as a function of collector geometry and solar position and is discussed in Section 3.

Orientation affects the annual distribution of radiation. Comparisons are made between orientations in Section 4. Different orientations lend themselves to different processes having various seasonal load profiles.

2. RADIATION CONVERSION

The hourly radiation falling on the surface of a one-axis tracking parabolic trough can be estimated by a three step process. The direct normal insolation is determined from the estimated value of the beam component of the total horizontal radiation. From this, the beam radiation on the surface of the collector is computed. The process is described below.

2.1 ESTIMATION OF HORIZONTAL BEAM COMPONENT

The estimation of the horizontal beam component of the total horizontal radiation makes use of the relationship between direct, diffuse, and total solar radiation developed by Liu and Jordan. The Liu and Jordan relationship was, however, developed for daily values, and it is used here to estimate hourly values. Unfortunately, no better relationship exists between direct, diffuse, and total radiation at this time. This discrepancy leads to small errors, especially just after dawn and just before dusk, when the altitute of the sun is low (as are the corresponding insolation values). The diffuse component of the total horizontal radiation is estimated from the following relationship[3] derived from the graphical information given in Figure 7 of Liu and Jordan[4]:

$$HB = HT - \left[HT\,(1.0045 + ((2.6313\ HT/HEX - 3.5227)\ HT/HEX + 0.04349)HT/HEX) \right] \qquad (1)$$

where:

- HB = intensity of beam radiation on a horizontal surface
- HT = intensity of total radiation on a horizontal surface
- HEX = intensity of exterrestrial radiation on horizontal surface

The exterrestrial radiation may be calculated by the following relationship[5]:

$$HEX = \frac{24}{\pi} I_{sc} \left\{ \left[1 + 0.033 \cos \left(\frac{360n}{365} \right) \right] [\cos \phi, \cos \delta \sin \omega_s + \frac{2\pi\omega_s}{360} \sin \phi \sin \delta] \right\} \qquad (2)$$

where:

- I_{sc} = solar constant
- n = day of year
- ϕ = latitude
- δ = declination
- ω_s = sunrise angle

The declination may be calculated as follows [6]

$$\delta = 23.45 \sin \left[\frac{360}{365} \{284 + n\} \right] \qquad (3)$$

The sunrise hour angle is defined [7] as:

$$\cos \omega_s = -\tan \phi \tan \delta. \qquad (4)$$

2.2 CALUCLATING DIRECT NORMAL RADIATION

Hourly values of direct normal radiation may be derived from the hourly values of the beam radiation of a horizontal surface. Figure 1 shows a surface normal to the incident radiation in relation to a horizontal surface. The zenith angle, θ_z, defined by:

$$\cos \theta_z = \sin \phi \sin \delta + \cos \phi \cos \delta \cos \omega \qquad (5)$$

where:

- ϕ = latitude
- δ = declination
- ω = hour angle, solar noon being zero, and each hour equalling 15 ^{o} of longitude with mornings positive and the afternoons negative

is the angle between the normal to the horizontal surface and a vector pointing directly toward the sun. θ_z is also the angle between the two surfaces because the angle between the normals to two surfaces is the same as the angle between the surfaces themselves.

The intensity of beam radiation on a surface normal to the incident radiation is equal to the intesity of beam radiation incident on a horizontal surface, divided by the cosine of the

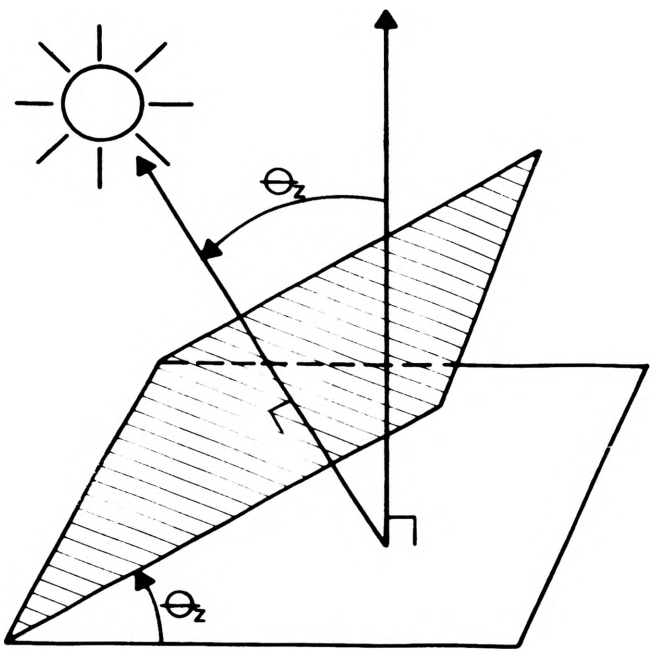

Figure 1. Angle Between Horizontal Surface and Direct Normal Surface.

zenith angle. Thus:

$$HDN = \frac{HB}{\cos \theta_z} \quad (6)$$

where:

HDN = the intensity of the direct normal radiation.

2.3 CALCULATING BEAM RADIATION ON COLLECTOR SURFACE

The beam radiaton on the focusing collector can be derived from the direct normal radiation. Figure 2 shows a cross section of the focusing collector. A vector normal to the plane tangent to the apex of the reflector and passing through the collector tube, and a vector from the apex of the reflector pointing toward the sun are drawn on the figure. North-south orientation insures that the vector pointing toward the sun always passes through the collector tube. In other words, the collector is always in focus. However, there can still exist an angle Delta between the incident radiation and the collector plane because there is only one-axis tracking. Delta is defined as a function of the latitude, declination and the hour angle by Eibling, et al [8]. For a north-south orientation Delta is defined as:

$$\cos \text{Delta} = \left[(\sin \phi \sin \delta + \cos \phi \cos \delta \cos \omega)^2 + \cos^2 \delta \sin^2 \omega\right]^{1/2} \quad (7)$$

The incidence angle Delta for an east-west orientation is defined[9] as:

$$\cos \text{Delta} = (1-\cos^2 \delta \sin^2 \omega)^{1/2} \quad (8)$$

The effect on seasonal radiation distribution of these orientations are discussed in Section 4.

As shown in Figure 3, the vector pointing toward the sun is normal to the surface on which the direct normal radiation is defined. The plane of the collector is therefore tilted at an angle Delta with respect to the direct normal surface because Delta is the angle between the normals of these two surfaces.

Referring to Figure 3 and using an argument similar to the one used in Step 2, the intensity of the beam radiation on the collector aperature is equal to the intensity of the direct normal radiation times the cosine of Delta or

$$HC = HDN (\text{Cos Delta}) \quad (9)$$

where: HC = the intensity of beam radiation on the plane of the collector.

Hourly values of HC can be expressd as a function of hourly values of the total radiation on a horizontal surface (HT), the exterrestrial solar radiation on a horizontal surface (HEX), the zenith angle (θ_z), the latitude (ϕ), the declination (δ), and the hour angle (ω).

This methodology is quite adaptable to TRNSYS in simulating the performance of a system including horizontally mounted parabolic troughs.

All of the above parameters are defined in the TRNSYS program and can be calculated in the program. Modifying the TRNSYS program to calculate HC enables the calculation of hourly values of the beam radiation on a horizontally mounted, north-south or east-west oriented focusing collector from data for the total radiation on a horizontal surface. HC is used as the incident radiation in all TRNSYS simulations of the focusing collector. HT, HB and HC from the modified

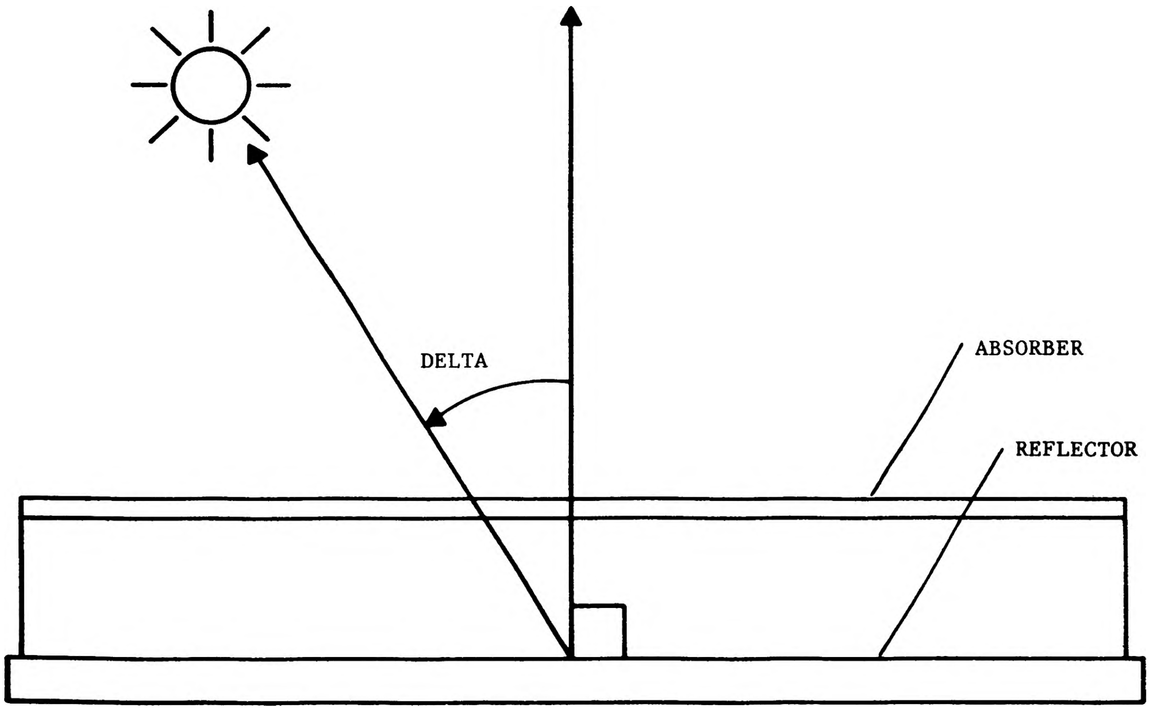

Figure 2. Cross Section of Focusing Collector

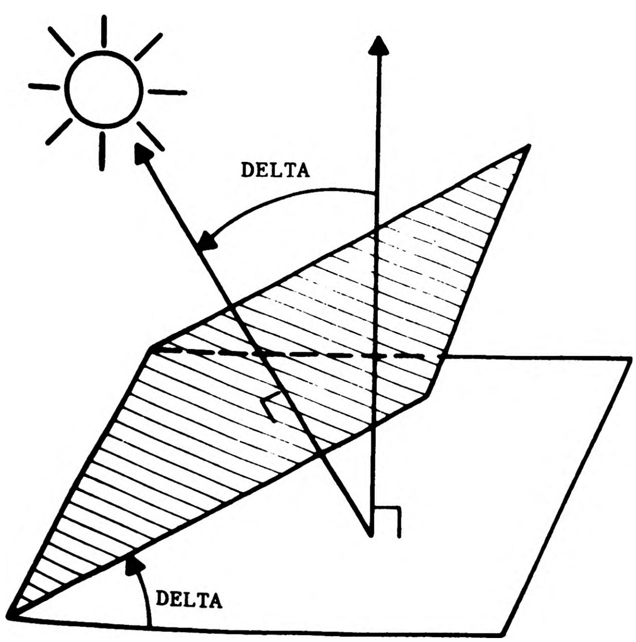

Figure 3. Angle Between Direct Normal Surface and Surface Tangent to the Apex of the Reflector

TRNSYS program are shown graphically in Figure 4 for June 21 at a latitude of 40° north.

2.4 LIMITATIONS TO LIU AND JORDAN APPLICATION

Due to the use of Liu and Jordan relationships, designed to estimate daily totals of beam radiation, for estimating hourly levels, some incongruities arise just after dawn and just before dusk in the level of direct insolation predicted. First of all, in equation (1), if HT is sufficiently small (say, less than three langleys), the diffuse term, HD, can become larger than the total horizontal term, HT. This is obviously impossible, leading to a negative value of the horizontal beam component, HB.

Also, if one looks at equation (5), the hourly variable is the hour angle, ω. When ω is large, say $\pm$ 105° at either 5 a.m. or 7 p.m. solar time, $\cos \theta_z$ becomes a very small number, and when, as in equation (6), used to calculate direct normal from direct horizontal radiation, one may obtain unrealistically high values of direct insolation, often above the solar constant.

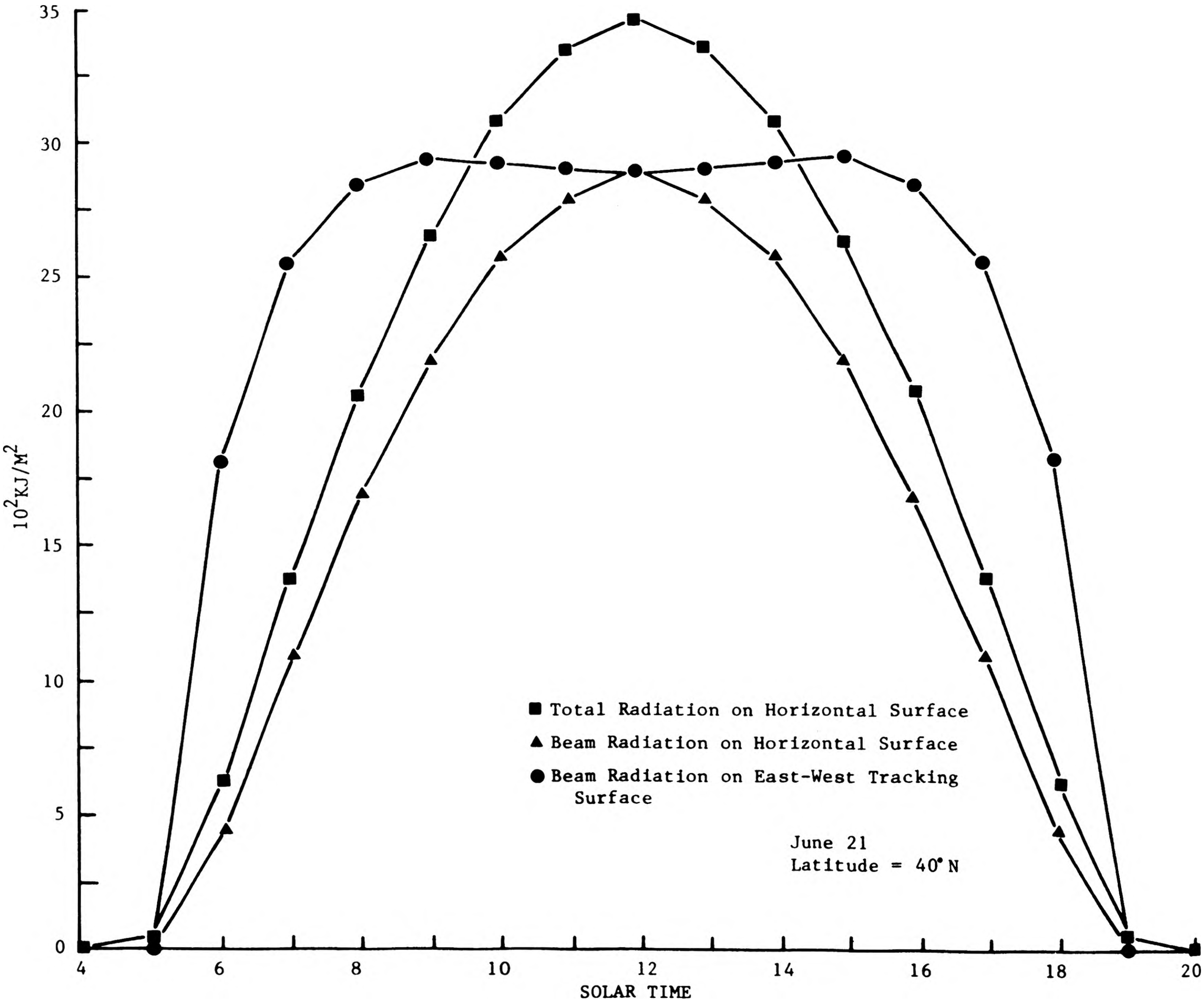

Figure 4. TRNSYS Output Showing Radiation Conversion for Focusing Collector

In order to correct these anomalies, it is necessary to put a limit on the estimated direct radiation on the surface of the collector. The maximum possible insolation level would correspond to the product of the clear day direct normal[10] radiation and the cosine of Delta, as defined above. Therefore, the value must be bounded by zero and this maximum theoretical level, i.e.,

$$0 < HC < \overline{HDN} \text{ Cos Delta} \qquad (10)$$

where $\overline{HDN}$ = clear day direct normal radiation.

Although the application of these limits on the estimated direct radiation could overestimate their true value, the problem only exists when the amount of total radiation is very small. This would have a small effect on the simulation of long range performance of the overall system.

3. END LOSSES

For some values of Delta in Figure 2, part of the reciver tube will not be illuminated. The incident radiation on the focusing collector is adjusted by the ratio of the illuminated length of the absorber to the total length of the reflector so that

$$HC' = HC \frac{X_H}{L_R} \qquad (11)$$

where: HC' = the intensity of beam radiation on the collector adjusted for end losses,

X_H = illuminated length of absorber,

L_R = length of reflector.

These variables are graphically portrayed in Figure 5.

The illuminated length of the absorber is calculated using the method outlined in the SOLSYS manual developed by Sandia Laboratories [11]. X_H is a function of Delta and the collector geometry. As shown in the SOLSYS manual, there are three cases for determining X_H:

1. $L_C \geq L_R + 2L_F \tan|\text{Delta}|$,
   $X_H = L_R$
2. $2L_F \tan|\text{Delta}| - L_R \leq L_C < L_R + 2L_F \tan|\text{Delta}|$ (12)
   $X_H = \dfrac{L_C + L_R}{2} - L_F \tan \text{Delta}$
3. $L_C < 2L_F \tan|\text{Delta}| - L_R$
   $X_H = 0$

where:

L_F = focal length of solar collector.

Values for Delta are calculated using equation (7) for a north-south orientation or equation (8) for an east-west orientation. Substituting the appropriate values for X_H, L_R, and H_C, into equation (11) yields hourly values for the intensity of the beam radiation on the collector, adjusted for end losses.

4. ORIENTATION EFFECTS

The collector orientation should be determined with respect to the annual load profile, i.e., applications requiring energy primarily in the winter or summer may be oriented differently than

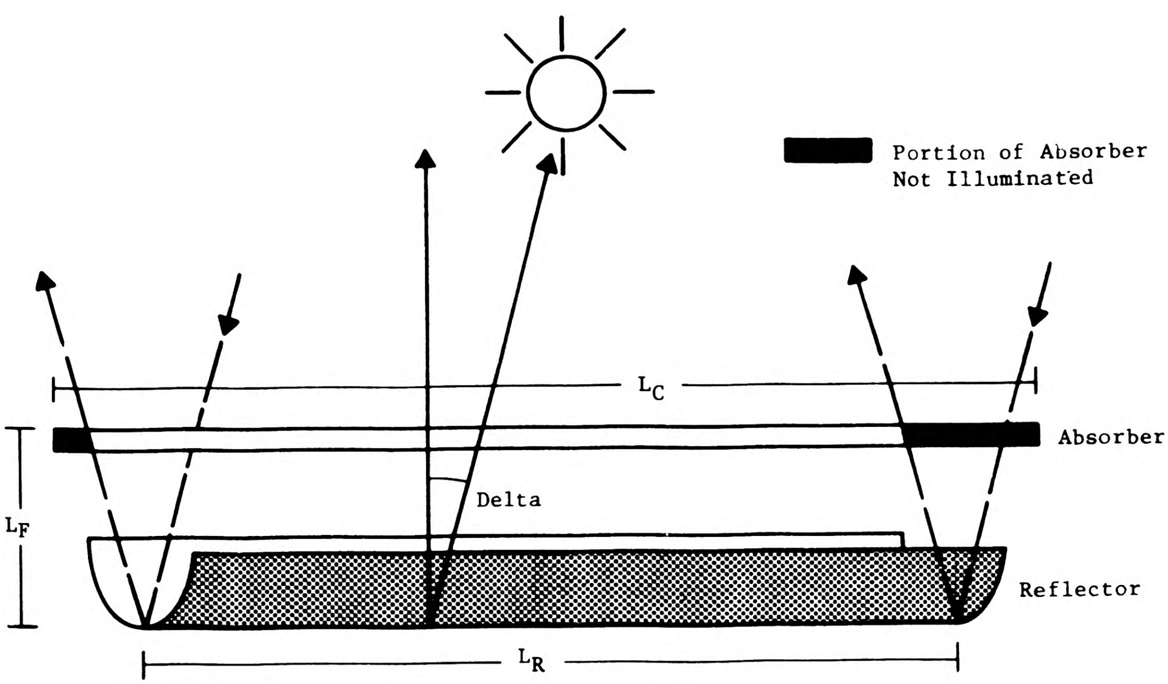

Figure 5. Side View of Parabolic Trough, Showing Parameters for End Loss Corrections

those requiring a relatively constant level of energy throughout the year. Figure 6 shows the available direct radiation for several collector orientations [12]:

(1) fixed horizontal surface

(2) east-west axis orientation (horizontal one-axis tracking)

(3) north-south axis orientation (horizontal one-axis tracking)

(4) two-axis tracking

One can easily see marked differences in available direct insolation from the various receiving surfaces. These differences should be kept in mind when designing the array for a specific seasonal load profile.

5. SUMMARY

This paper has developed a method to convert total horizontal radiation to radiation falling on the surface of horizontally mounted single axis tracking focusing collectors. The calculations can be summarized by the following equation:

$$HC = \frac{[\cos(Delta)]}{\cos \theta_z} \{HT-[HT(1.0045+((2.6313\ HT/HEX-3.5227)\ HT/HEX+0.04349)HT/HEX)]\} \quad (13)$$

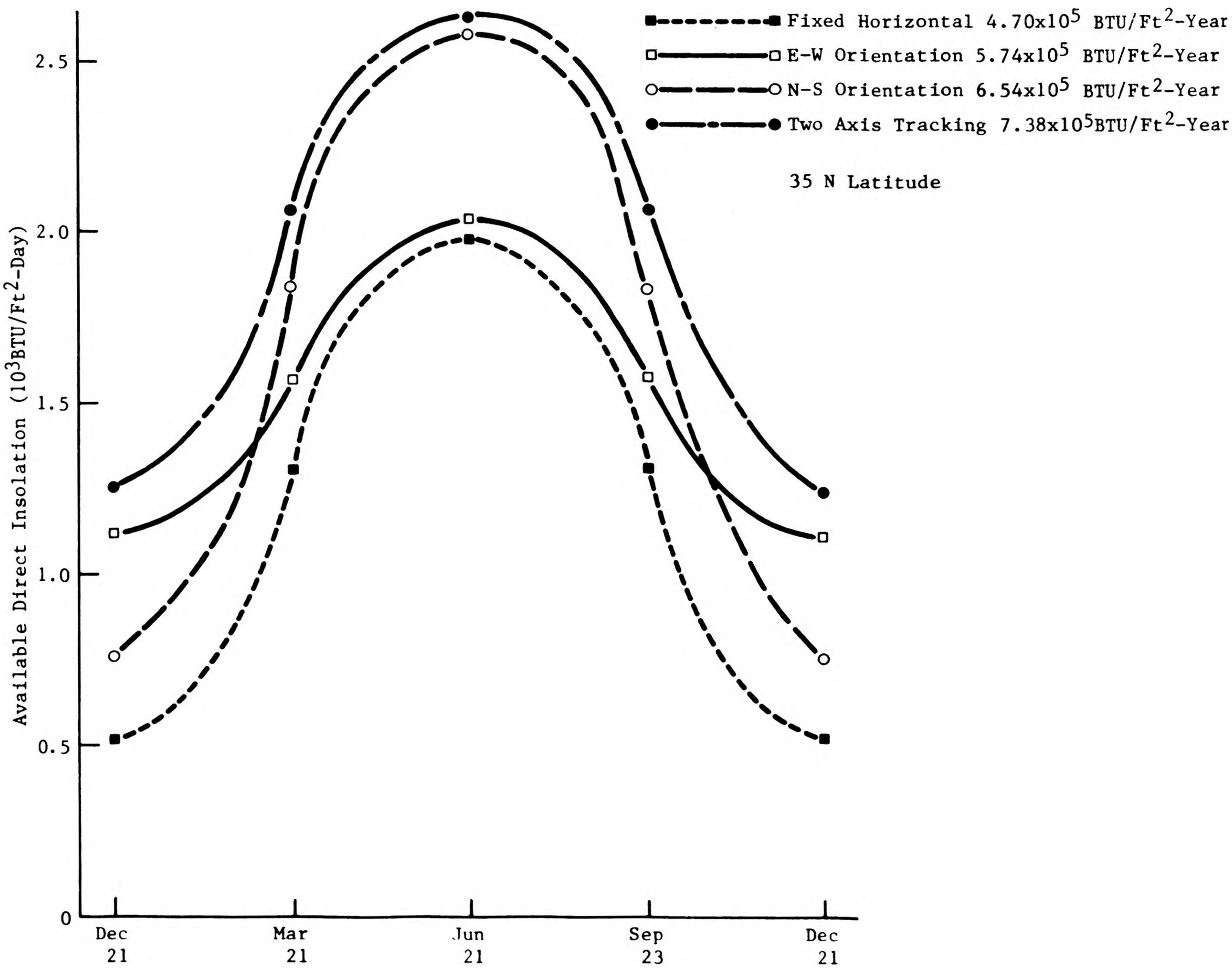

Figure 6. Effects of Collector Orientation and Tracking on Available Direct Insolation

where: Delta is as defined in (1) and (2)

HC = Radiation falling on the collector

θ_z = Zenith angle

HT = Total horizontal radiation

HEX = Exterrestrial radiation on horizontal surface

ϕ = latitude

δ = declination

ω = hour angle

The value of HC is subject to the limitations described in equation (10). When end losses due to collector geometry are considered, the result is a reasonable estimate of the hourly direct radiation falling on the horizontally mounted, single-axis tracking collector.

6. CONCLUDING REMARKS

The present network of data collection in the United States does not lend itself to the evaluation of focusing collectors. Only a handful of stations are instrumented with a pyrheliometer to compile direct normal insolation values on an hourly basis. The Liu and Jordan method has been used here, and elsewhere, to determine the diffuse component of the total horizontal radiation collected at many weather stations outfitted with pyranometers. The use of the Liu and Jordan relationship to estimate hourly values of direct insolation is subject to many criticisms. However, until a better relationship[13] is developed, or until more weather stations are equipped with pyrheliometers, we will have to accept these limitations in estimating direct radiation from total horizontal radiation on an hourly basis.

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