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SOLAR RADIATION AVAILABILITY TO VARIOUS COLLECTOR GEOMETRIES: A PRELIMINARY STUDY

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ABSTRACT

Solar energy collectors of various designs and installation oreientations are being built or used. Because most existing solar energy data consists of measurements of total radiation incident upon a horizontal surface, and because geometric conversion to radiation incident upon another surface is difficult, the amounts of solar energy available to various locations are not well known. This paper reports such solar energy availabilities to various collectors for both clear and average days in each of the four seasons at Albuquerque, Blue Hill, and Omaha. Unlike several similar previous studies, the amounts of solar energy given here are based directly on representative data samples consisting of simultaneous measurements of direct-normal and total-horizontal radiation at these three sites.

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I. Project Summary

One of the curious aspects of solar energy collection is its dependence on geometry; there is a higher solar energy density incident upon solar collectors which face the sun directly than on collectors which are not oriented perpendicular to the solar rays. This geometric dependence leads to a number of basic questions. For instance, if flat-plate collectors for space heating and cooling are tilted upward to the south at an angle equal to the local latitude, would the additional energy collected by a tracking collector justify the added cost of the tracking mechanism? Or, how much more energy is incident upon a surface tilted at (Lat $+20^{\circ}$) than upon a south vertical wall during the months November through March?

Although these questions are fundamental, they haven't been adequately answered. This is due principally to the lack of appropriate data. Nearly all existing solar radiation data consists of measurements of either total radiation on a horizontal surface or direct-normal radiation. Conversion to solar energy incident upon some other surface requires simultaneous measurements of both of these parameters, or the equivalent. For this reason, solar energy availabilities to other surfaces are generally based upon theoretical calculations (1,2) or clear day data with some sort of reduction factors to adjust for clouds (3).

Possession of a set of solar data samples consisting of simultaneous readings of direct-normal intensity and total-horizontal-intensity for different seasons and locations offered Sandia an opportunity to make some solar energy availability studies based upon actual data. These samples are described in Section II.

Using the readings of direct-normal intensity, time, date and simple geometry, it is possible to compute the intensity of direct radiation to any other collecting surface, fixed or tracking. Moreover, the simultaneous readings of total-horizontal radiation permitted the computation of the diffuse-horizontal radiation. This diffuse-horizontal radiation component was transformed to other surfaces using the blanket assumption that ground radiation is one-half of diffuse sky radiation. The various conversion formulas are presented in the Appendix.

The intensities of both direct radiation and total (direct + diffuse) radiation available to a wide variety of collector surfaces were calculated. For each of the three locations, seasonal means of daily sums of these intensities were computed. In addition, the daily totals for a single clear day for each season and location were computed. Tabulations of these clear day and average daily totals of both direct and total radiation are the subject of Section III.

Finally, Section IV is devoted to graphical presentations and discussion of some of the more interesting results.

II. Data Sources

The data samples were read from the 1962 solar strip chart records of the National Weather Service for Albuquerque, Blue Hill, and Omaha. (Direct-normal data is available for only two or three other U.S. locations.) For each location, the samples consist of four weeks of data which are representative of the four seasons in the following sense; the mean daily total-horizontal radiation in the sample week is very nearly equal to the long term daily average of total-horizontal radiation for that season and location. The actual readings consist of the simultaneous intensities of total-horizontal radiation and direct-normal radiation at 10-minute intervals. (Because of the incompleteness of records for Omaha, it was impossible to select four sample 'weeks'. Consequently, the Omaha sample consists of data for 28 days, seven selected in each season.)

The samples were selected as close to the solstices and equinoxes as possible. The actual dates of the samples are given in Table 2.1. These are especially important in the Spring or Fall when a shift of several days from the equinox results in a significant change in the solar declination which in turn will significantly affect the relative availabilities of solar radiation to certain collecting surface orientations.

	Albuquerque	Blue Hill	Omaha
Spring	Mar 17 - 23	Mar 27 - Apr 2	Feb 6,8 Mar 20,22,27 Apr 18,19
Summer	June 23 - 29	June 24 - 30	June 17,26 July 1,2,3,7,14
Fall	Sept 28 - Oct 4	Sept 2 - 8	Sept 9,10,12,13, 14,22,24
Winter	Dec 11 - 17	Dec 6 - 12	Dec 1,10,16,18, 23,29,30

Table 2.1 Dates of the Representative Samples
(Year is 1962)

The total-horizontal data in the samples were adjusted using the correction factors suggested by Hanson et. al. (4). In addition a linear adjustment was made to the data to correct for instrumental response drift if such a drift was indicated by a terminal calibration. The multiplication adjustment factors applied to the data are given in Table 2.2. The direct-normal data was not changed.

	Spring	Summer	Fall	Winter
Albuquerque	0.90	0.90	0.91	0.91
Blue Hill	1.00	1.00	1.00	0.90
Omaha	0.88	0.88 (June 17) 0.96 (Other 6 days)	0.96	0.96

Table 2.2 Multiplication Adjustment Factors Applied to the Total-Horizontal Data

III. Solar Radiation Availability Tables

The intensities at 10-minute intervals of direct radiation and diffuse radiation incident upon the various collector surfaces were calculated using the formulas given in the Appendix. Daily totals were gotten by simply summing; this assumes that no significant difference in daily totals is introduced by using instantaneous values instead of 10-minute average intensities.

For each season and location a typical clear day was selected. The daily totals of direct and total radiation available to various collectors for these clear days are given in Tables 3.1, 3.2, and 3.3. The definition of the radiation types are given in the Appendix. All radiation units are $kW \cdot hr \cdot m^{-2}$.

The daily averages of the solar radiation availabilities for the seasonal samples are given in Tables 3.4, 3.5, and 3.6. To the extent that the data samples are truly representative, these values should indicate the mean daily amounts of solar energy available to various collectors at these locations on a seasonal basis. It should be emphasized that these availabilities are based upon actual measurements of total-horizontal and direct-normal radiation.

IV. Results

The tables of the preceding section are valuable in two important ways. They provide designers with an estimate of seasonal solar energy availability to various collectors both for clear days and average conditions, and they allow the possibility of making many interesting comparisons. Some such comparisons are presented here. Note that all of the curves presented are based solely on the points shown, which come from the tables of the preceding section.

The amounts of energy available to flat-plate collectors tilted upward 40° from horizontal to the south are illustrated by the curves labeled TT(40°) in Figures 4.1, 4.2, and 4.3. Since the latitudes of the three locations are all close to 40°, very nearly the same amounts are available to collectors tilted upward at an angle equal to the local latitude. The amount of energy available to a flat-plate collector tilted at the same angle but allowed to track the sun through the day by rotating about its polar axis is illustrated by the curves labeled TNSP in Figures 4.1, 4.2, and 4.3. On an annual basis, a polar-mounted tracking flat-plate collector would receive 26%, 25%, and 20% more energy than a fixed, flat-plate collector filted upward 40° at Albuquerque, Blue Hill, and Omaha, respectively. Whether these increases are enough to offset the cost of tracking mechanism's and the penalty of additional shading seems to be very much an open question.

These Figures 4.1 - 4.3 also display curves labeled DNSP which represent the amount of direct radiation available to a parabolic trough collector tracking about a polar axis. At all three locations the amount of direct radiation available to such a focusing collector is about the same as the total radiation incident upon a flat-plate collector inclined 40°.

Figure 4.4 displays seasonal availabilities of diffuse radiation on a horizontal surface. The most notable feature of this plot is that there is little difference in the curves for the three locations. A comparison with the curves of total-horizontal radiation in Figure 4.5 shows that on a horizontal surface the diffuse component generally contributes less than half of the total. Thus, the solar radiation component of primary importance for comparing locations is the direct component. The seasonal availabilities of direct-normal radiation are exhibited in Figure 4.6; although Omaha receives somewhat more direct-normal radiation than Blue Hill, Albuquerque receives at least 50% more than either of these.

For winter heating applications, the optimum collector inclination angle is generally assumed to be about latitude + 25°. The tables confirm this. It is interesting to compare the availability of solar energy to such an optimally inclined collector with the architecturally common south vertical surface. These comparisons are shown in Figures 4.7, 4.8, and 4.9. Notice that for the winter season the percent reductions in available solar energy effected by conversion from optimum tilt to south-vertical surfaces range from about five to eleven.

A comparison of amounts of direct radiation available to various types of focusing collectors at Albuquerque is given in Figure 4.10. The curve labeled DEW indicates that an East-West horizontal collector receives amounts which tend to match the heating and cooling loads over the year. However, a horizontal collector tracking about a North-South axis through the day receives considerably more energy through the year.

Radiation Type	Spring	Summer	Fall	Winter
DN	3.34	5.32	5.23	3.05
DEW	2.36	3.96	3.82	2.70
DNSP	3.34	4.89	5.21	2.80
DNSH	2.95	5.17	4.66	1.68
DH	1.87	3.73	3.14	0.98
DT(10)	2.09	3.82	3.46	1.40
DT(20)	2.24	3.79	3.68	1.78
DT(30)	2.33	3.66	3.79	2.10
DT(40)	2.35	3.41	3.79	2.36
DT(50)	2.30	3.07	3.67	2.55
DT(60)	2.17	2.64	3.43	2.66
DT(70)	1.98	2.13	3.10	2.69
DT(80)	1.73	1.57	2.67	2.64
DV	1.43	0.97	2.16	2.50
TN	4.91	7.21	6.27	3.49
TEW	3.99	5.96	4.92	3.15
TNSP	4.97	6.76	6.28	3.32
TNSH	4.57	7.08	5.73	2.18
TH	3.59	5.76	4.29	1.52
TT(10)	3.81	5.84	4.61	1.94
TT(20)	3.94	5.79	4.82	2.31
TT(30)	4.00	5.62	4.91	2.62
TT(40)	3.97	5.32	4.87	2.87
TT(50)	3.87	4.92	4.72	3.04
TT(60)	3.68	4.41	4.44	3.13
TT(70)	3.42	3.82	4.06	3.14
TT(80)	3.10	3.18	3.58	3.06
TV	2.72	2.49	3.02	2.91

TABLE 3.5

Average Daily Solar Radiation Availabilities

for Blue Hill $(kW \cdot hr/m^2)$

Radiation Type	Spring	Summer	Fall	Winter
DN	3.45	5.47	4.75	3.95
DEW	2.69	4.08	3.64	3.46
DNSP	3.39	5.04	4.74	3.63
DNSH	2.87	5.33	4.08	2.24
DH	1.98	3.89	2.84	1.27
DT(10)	2.24	3.98	3.19	1.81
DT(20)	2.44	3.95	3.45	2.29
DT(30)	2.56	3.80	3.60	2.71
DT(40)	2.60	3.54	3.64	3.04
DT(50)	2.57	3.17	3.57	3.27
DT(60)	2.45	2.71	3.39	3.41
DT(70)	2.27	2.18	3.11	3.45
DT(80)	2.01	1.59	2.73	3.38
DV	1.70	0.96	2.27	3.21
TN	5.18	7.88	6.30	4.58
TEW	4.50	6.62	5.29	4.09
TNSP	5.21	7.43	6.37	4.36
TNSH	4.66	7.76	5.69	2.93
TH	3.91	6.46	4.58	2.03
TT(10)	4.16	6.54	4.93	2.56
TT(20)	4.34	6.48	5.16	3.03
TT(30)	4.42	6.29	5.28	3.43
TT(40)	4.42	5.96	5.28	3.74
TT(50)	4.33	5.51	5.15	3.96
TT(60)	4.14	4.96	4.91	4.07
TT(70)	3.88	4.32	4.56	4.08
TT(80)	3.54	3.63	4.11	3.97
TV	3.14	2.89	3.58	3.77

TABLE 3.6

Average Daily Solar Radiation Availabilities

for Omaha $(kW \cdot hr/m^2)$

Radiation Type	Spring	Summer	Fall	Winter
DN	6.39	9.56	9.09	6.18
DEW	5.44	7.03	6.68	5.41
DNSP	6.15	8.78	9.06	5.67
DNSH	4.23	9.33	8.04	3.49
DH	2.71	6.66	5.40	1.99
DT(10)	3.49	6.82	6.00	2.83
DT(20)	4.15	6.77	6.41	3.58
DT(30)	4.70	6.51	6.63	4.23
DT(40)	5.10	6.06	6.65	4.75
DT(50)	5.34	5.43	6.47	5.12
DT(60)	5.43	4.64	6.09	5.34
DT(70)	5.34	3.73	5.52	5.39
DT(80)	5.10	2.73	4.79	5.28
DV	4.70	1.67	3.91	5.01
TN	7.33	11.06	10.04	6.53
TEW	6.40	8.62	7.70	5.77
TNSP	7.20	10.26	10.05	6.08
TNSH	5.24	10.84	4.00	3.88
TH	3.81	8.27	6.47	2.41
TT(10)	4.58	8.42	7.06	3.25
TT(20)	5.24	8.35	7.47	4.00
TT(30)	5.76	8.07	7.67	4.64
TT(40)	6.14	7.57	7.66	5.14
TT(50)	6.35	6.89	7.44	5.50
TT(60)	6.39	6.05	7.02	5.71
TT(70)	6.27	5.08	6.41	5.75
TT(80)	5.97	4.01	5.64	5.62
TV	5.53	2.88	4.71	5.33
DATE	FEB 6	JUNE 26	SEPT 10	DEC 16

TABLE 3.3

Clear Day Solar Radiation Availabilities

for Omaha $(kW \cdot hr/m^2)$

Radiation Type	Spring	Summer	Fall	Winter
DN	6.22	8.25	6.27	7.23
DEW	4.54	6.30	4.75	6.18
DNSP	6.22	7.58	6.25	6.64
DNSH	5.53	8.13	5.37	4.63
DH	3.66	6.05	3.60	2.83
DT(10)	4.07	6.12	4.08	3.74
DT(20)	4.36	6.00	4.44	4.53
DT(30)	4.52	5.71	4.66	5.19
DT(40)	4.53	5.24	4.74	5.68
DT(50)	4.41	4.63	4.68	6.01
DT(60)	4.16	3.87	4.47	6.15
DT(70)	3.78	3.01	4.13	6.11
DT(80)	3.29	2.06	3.66	5.88
DV	2.69	1.07	3.08	5.47
TN	7.65	9.35	7.93	7.45
TEW	6.04	7.47	6.47	6.41
TNSP	7.70	8.65	8.00	6.89
TNSH	6.99	9.23	7.09	4.87
TH	5.23	7.25	5.44	[illegible]
TT(10)	5.64	7.31	5.92	4.00
TT(20)	5.91	7.18	6.25	4.79
TT(30)	6.03	6.87	6.44	5.44
TT(40)	6.01	6.37	6.47	5.93
TT(50)	5.84	5.72	6.35	6.25
TT(60)	5.54	4.92	6.08	6.38
TT(70)	5.09	4.01	5.67	6.33
TT(80)	4.53	3.01	5.12	[illegible]
TV	3.87	1.97	4.46	5.67

TABLE 3.4

Average Daily Solar Radiation Availabilities

for Albuquerque, $(kW \cdot hr/m^2)$

Radiation Type	Spring	Summer	Fall	Winter
DN	9.09	9.88	9.13	7.96
DEW	6.97	7.47	6.74	6.78
DNSP	9.08	9.06	9.11	7.31
DNSH	7.94	9.73	7.91	5.12
DH	5.53	7.16	5.14	3.10
DT(10)	6.18	7.20	5.82	4.09
DT(20)	6.65	7.02	6.32	4.96
DT(30)	6.91	6.63	6.63	5.68
DT(40)	6.96	6.05	6.73	6.23
DT(50)	6.80	5.29	6.64	6.59
DT(60)	6.43	4.39	6.33	6.74
DT(70)	5.87	3.37	5.84	6.70
DT(80)	5.13	2.28	5.17	6.44
DV	4.24	1.14	4.35	6.00
TN	9.68	10.57	10.13	8.07
TEW	7.60	8.22	7.78	6.90
TNSP	9.70	9.74	10.16	7.44
TNSH	8.55	10.42	8.94	5.24
TH	6.20	7.93	6.25	3.24
TT(10)	6.85	7.96	6.93	4.23
TT(20)	7.31	7.77	7.41	5.10
TT(30)	7.56	7.37	7.70	5.81
TT(40)	7.59	6.77	7.78	6.36
TT(50)	7.41	5.99	7.65	6.71
TT(60)	7.02	5.06	7.31	6.86
TT(70)	6.43	4.02	6.77	6.81
TT(80)	5.66	2.89	6.05	6.55
TV	4.74	1.72	5.18	6.10
DATE	MAR 17	JUNE 24	SEPT 30	DEC 12

TABLE 3.1

Clear Day Solar Radiation Availabilities

for Albuquerque, (kW · hr/m^2)

Radiation Type	Spring	Summer	Fall	Winter
DN	7.17	8.67	8.44	6.84
DEW	5.53	6.33	5.98	6.02
DNSP	7.16	7.97	8.41	6.29
DNSH	6.17	8.42	7.52	3.81
DH	4.33	5.91	4.86	2.17
DT(10)	4.86	6.05	5.38	3.11
DT(20)	5.24	6.01	5.75	3.96
DT(30)	5.47	5.80	5.94	4.68
DT(40)	5.53	5.41	5.94	5.26
DT(50)	5.42	4.87	5.77	5.69
DT(60)	5.14	4.19	5.42	5.94
DT(70)	4.71	3.40	4.91	6.00
DT(80)	4.14	2.51	4.25	5.89
DV	3.44	1.58	3.46	5.60
TN	8.53	9.98	9.22	7.10
TEW	6.97	7.72	6.81	6.28
TNSP	8.58	9.25	9.22	6.59
TNSH	7.57	9.74	8.32	4.08
TH	5.84	7.33	5.73	2.47
TT(10)	6.37	7.47	6.25	3.42
TT(20)	6.74	7.41	6.61	4.26
TT(30)	6.93	7.17	6.78	4.98
TT(40)	6.96	6.75	6.77	5.55
TT(50)	6.80	6.16	6.57	5.97
TT(60)	6.47	5.43	6.19	6.20
TT(70)	5.98	4.58	5.64	6.26
TT(80)	5.35	3.64	4.94	6.13
TV	4.58	2.64	4.11	5.83
DATE	MAR 29	JUNE 28	SEPT 8	DEC 11

TABLE 3.2

Clear Day Solar Radiation Availabilities

for Blue Hill (kW · hr/m^2)

FIGURES

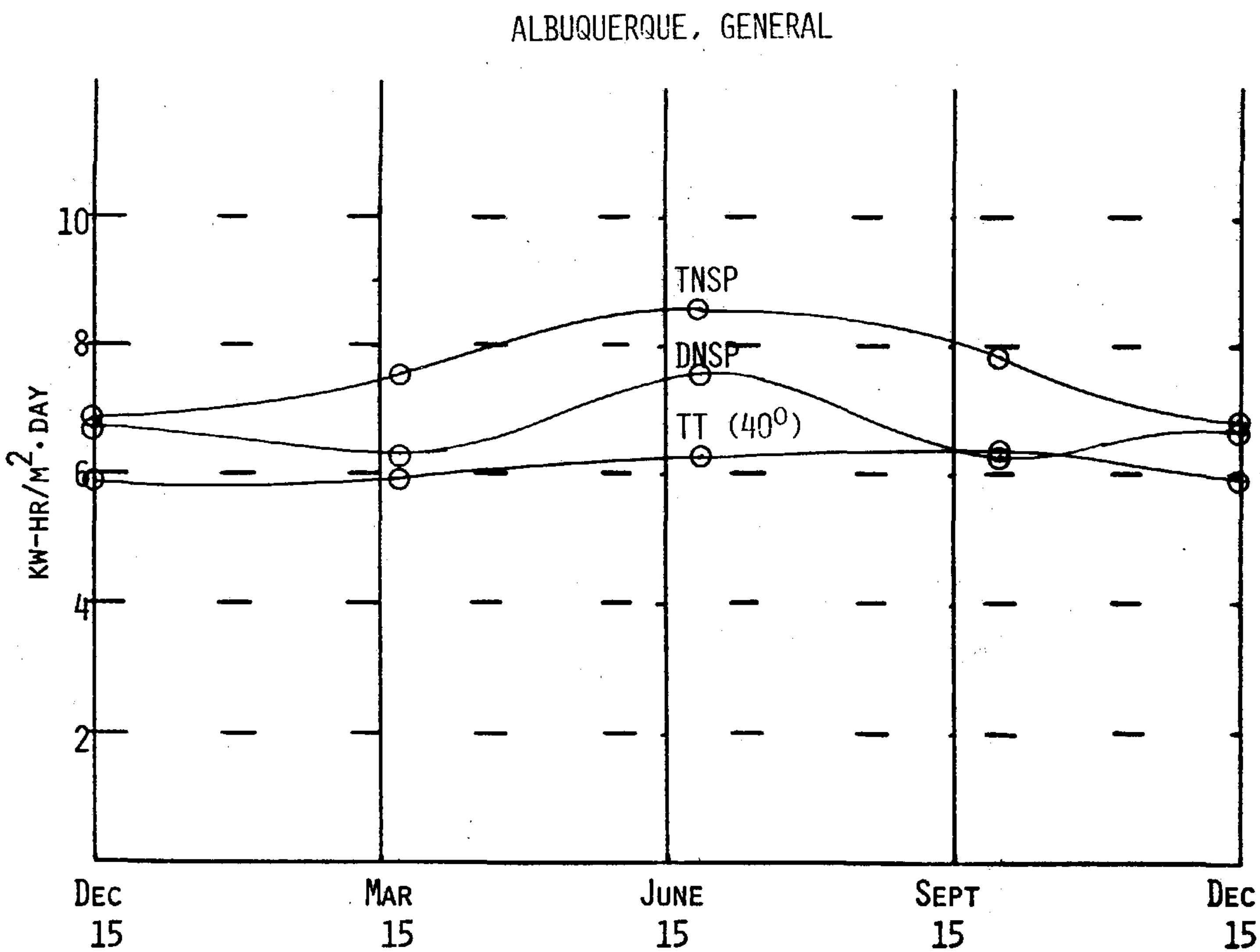

FIGURE 4.1

Mean daily energy available to a polar mounted tracking flat-plate (TNSP) and a fixed flat-plate inclined 40° (TT(40°)) at Albuquerque.

BLUE HILL, GENERAL

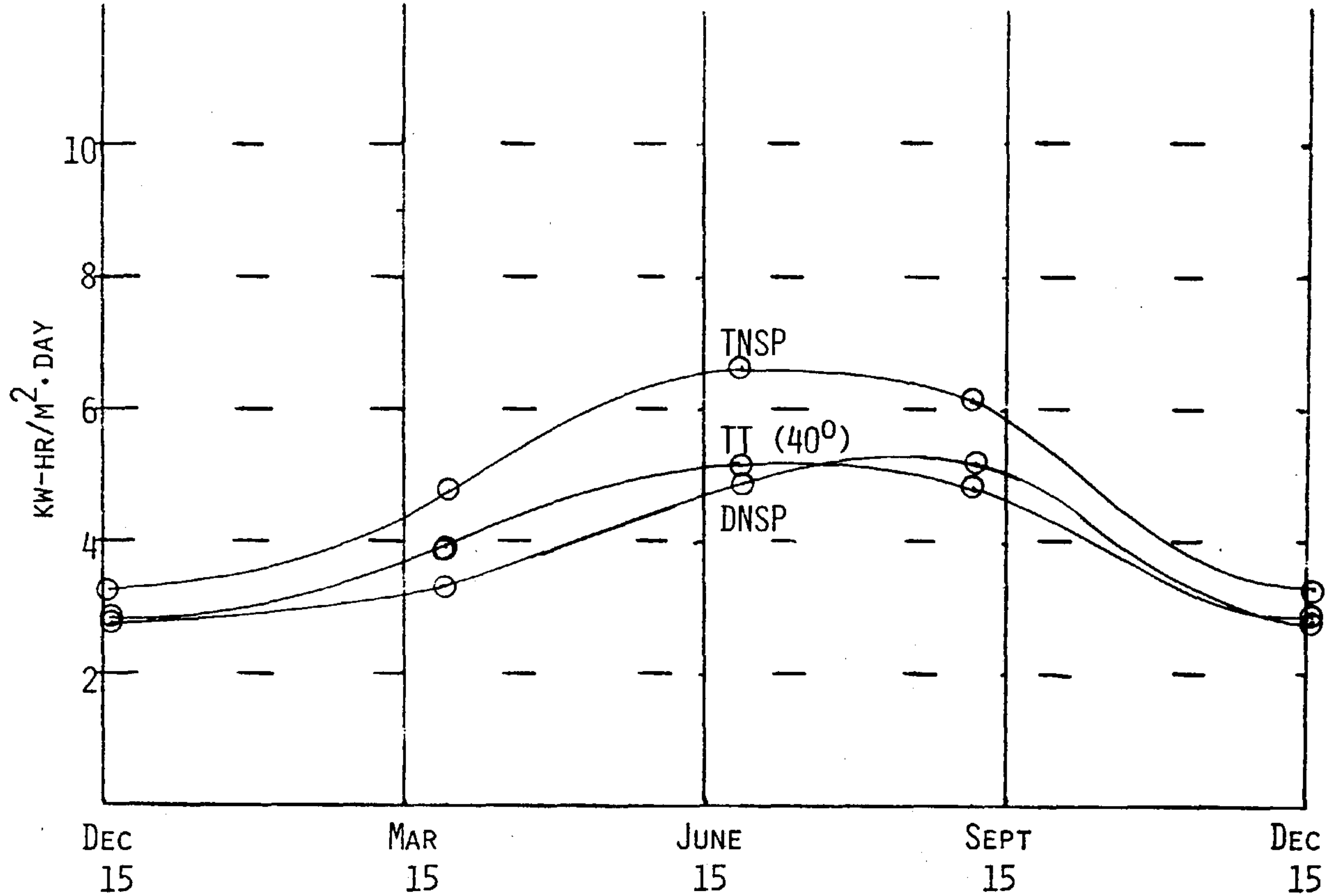

FIGURE 4.2

Mean daily energy available to a polar mounted tracking flat-plate (TNSP) and a fixed flat-plate inclined 40° (TT(40°)) at Blue Hill.

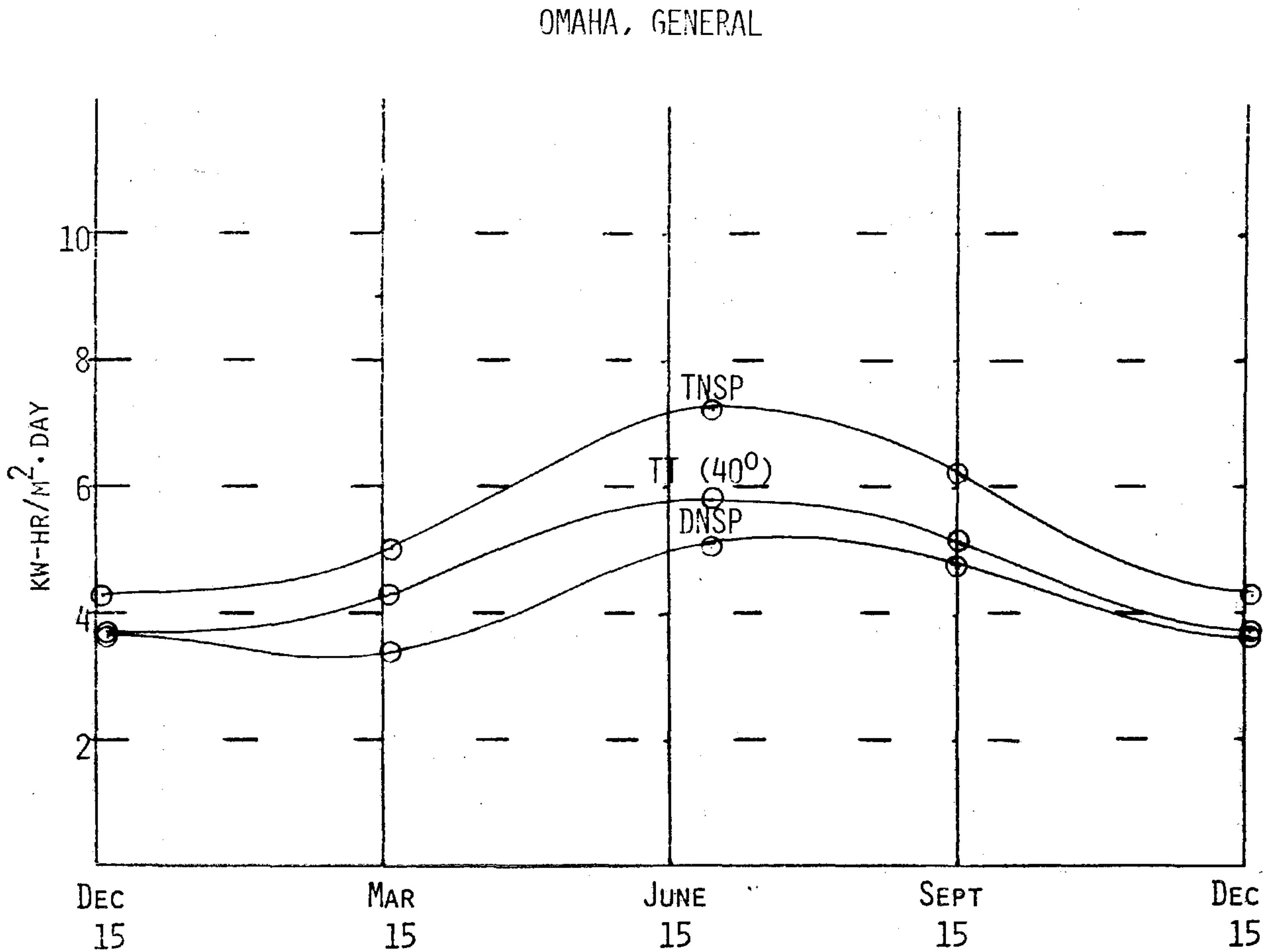

FIGURE 4.3

Mean daily energy available to a polar mounted tracking flat-plate (TNSP) and a fixed flat-plate inclined 40° (TT(40°)) at Omaha.

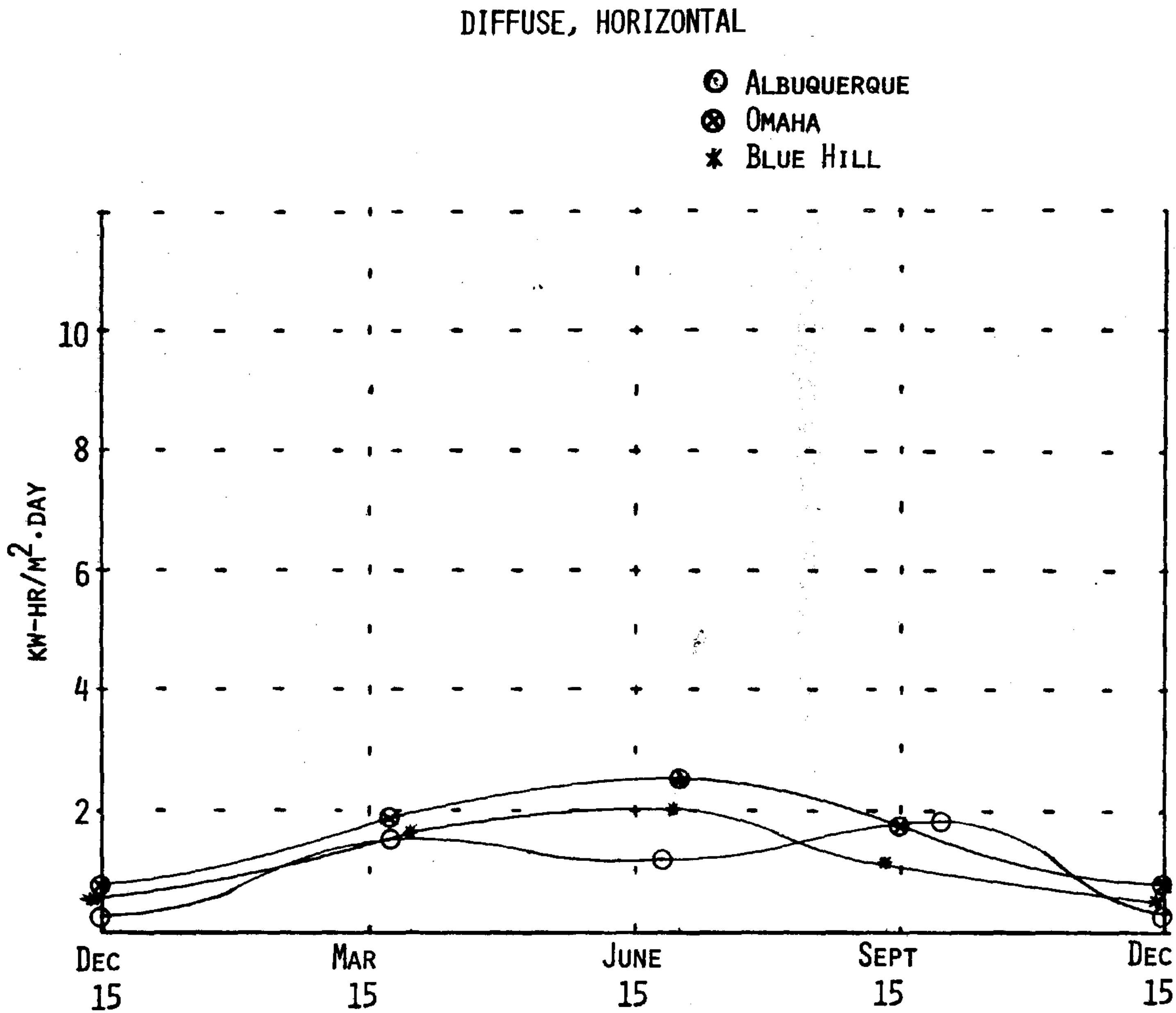

FIGURE 4.4 Mean daily diffuse radiation incident on a horizontal surface in Albuquerque, Omaha, and Blue Hill.

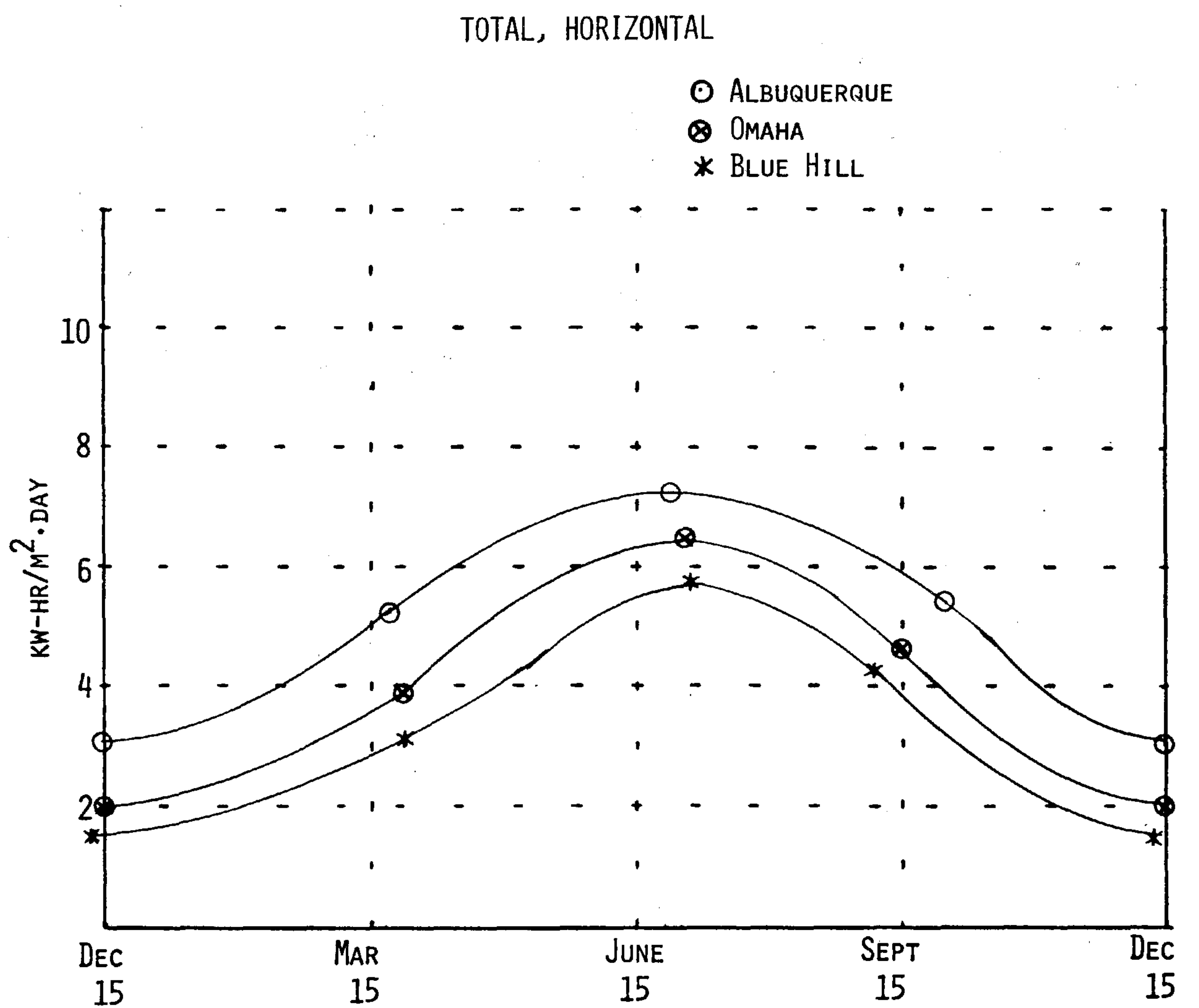

FIGURE 4.5 Mean daily total-horizontal radiation at Albuquerque, Blue Hill & Omaha.

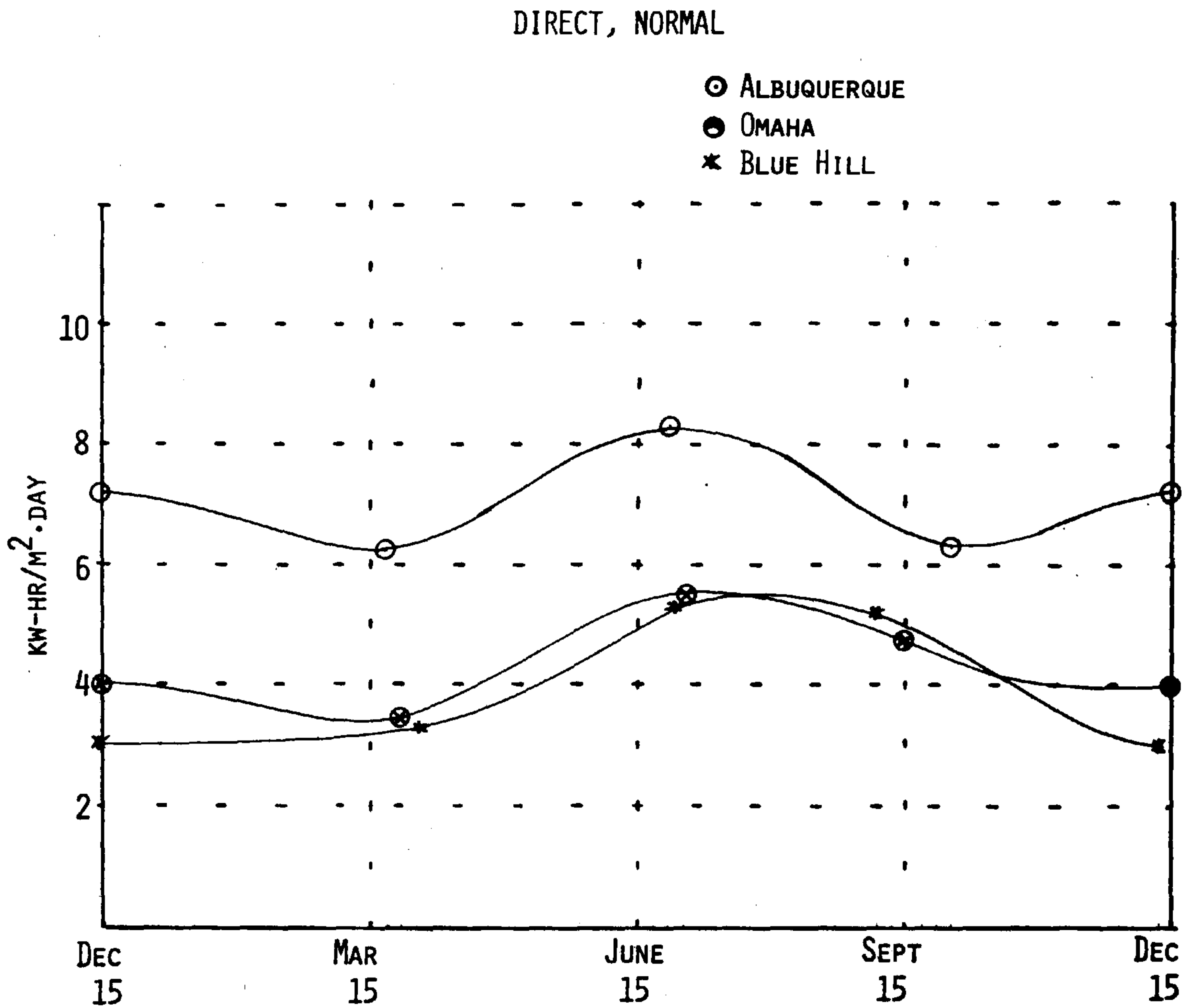

FIGURE 4.6 Daily means of direct normal radiation at Albuquerque, Omaha, and Blue Hill.

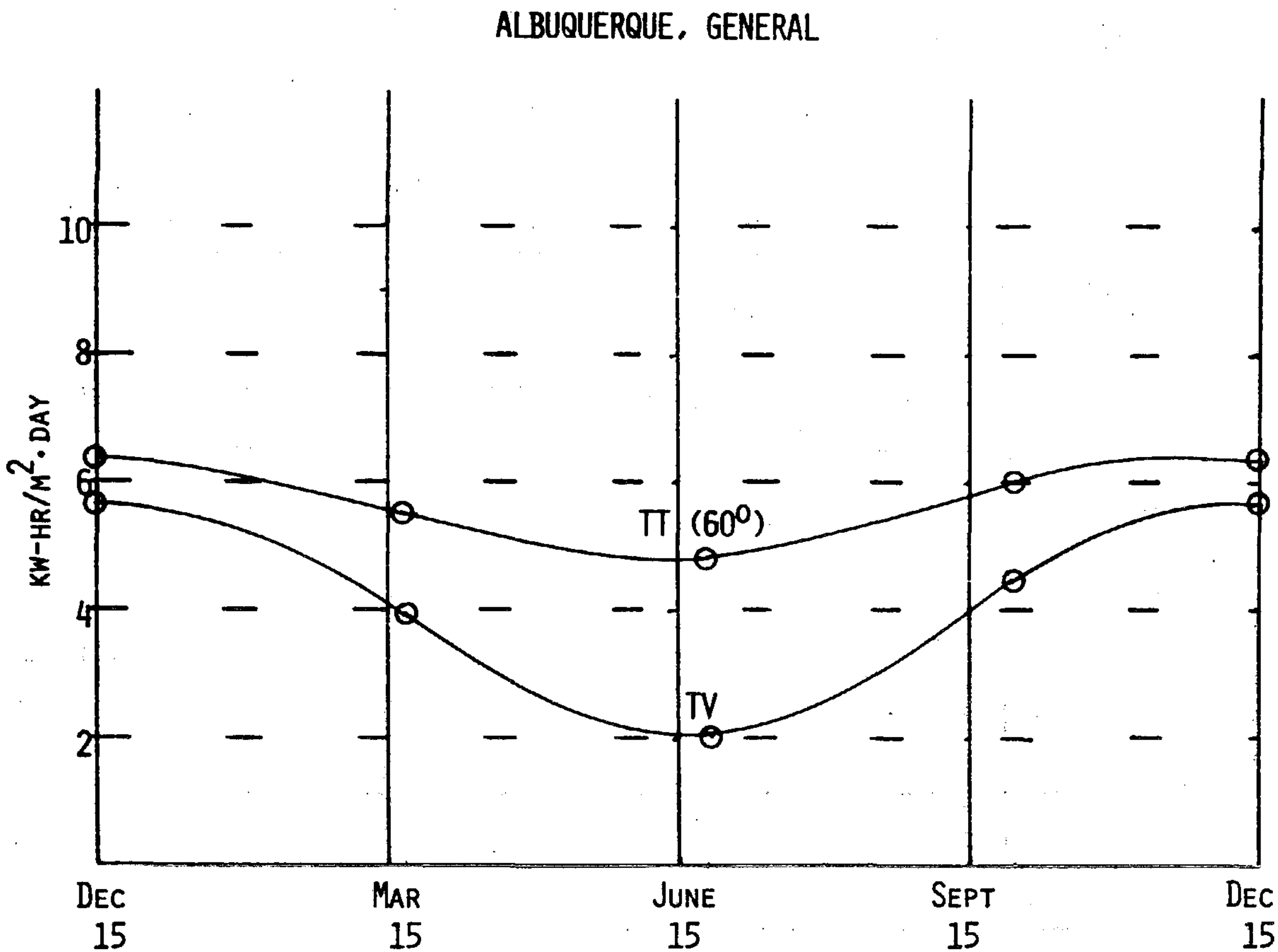

FIGURE 4.7

Comparison of the mean daily solar energy available to a south vertical surface (TV) and a surface inclined 60° from horizontal toward the south (TT(60°)) at Albuquerque.

BLUE HILL, GENERAL

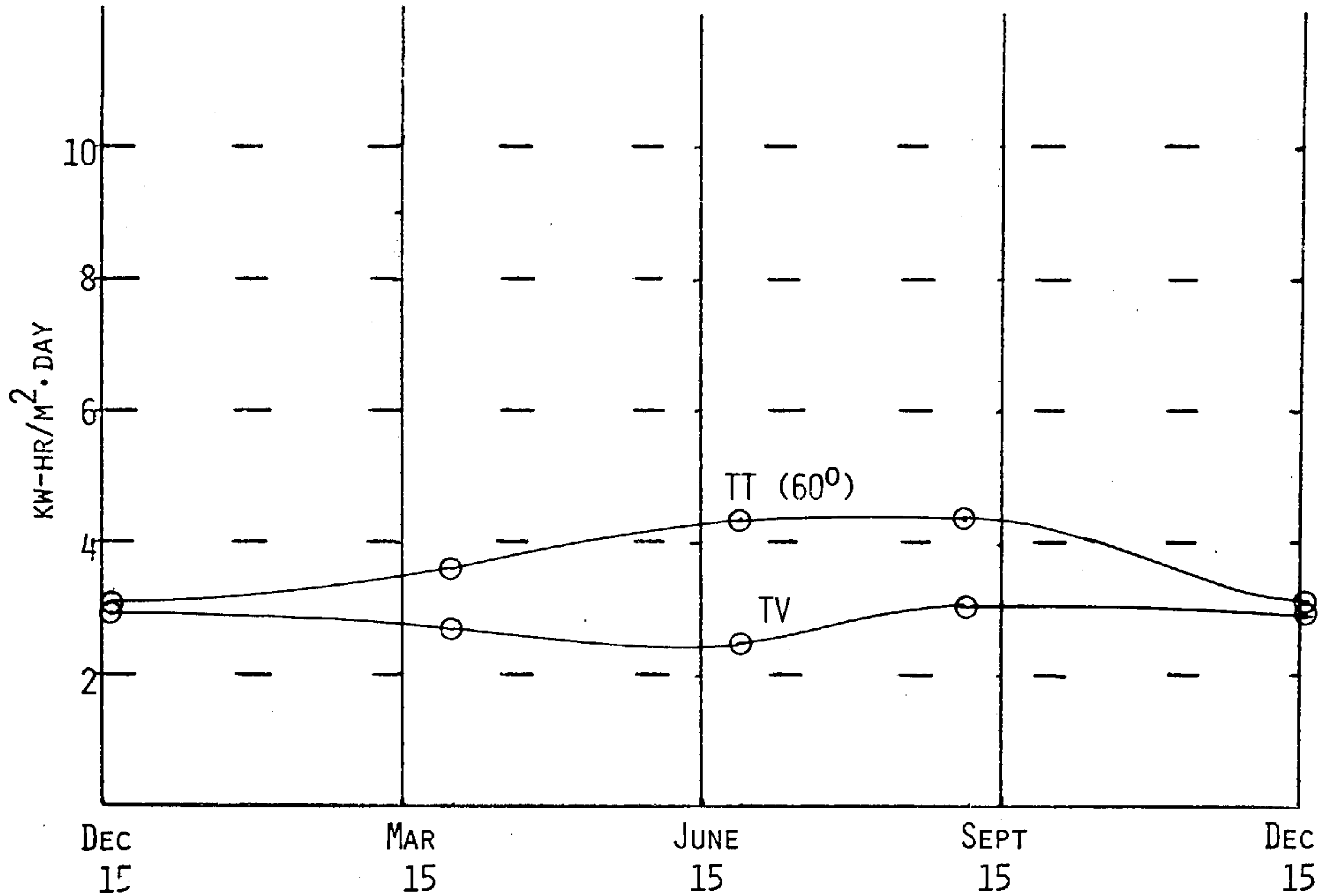

FIGURE 4.8

Comparison of the mean daily solar energy available to a south vertical surface (TV) and a surface inclined 60° from horizontal toward the south (TT(60°)) at Blue Hill.

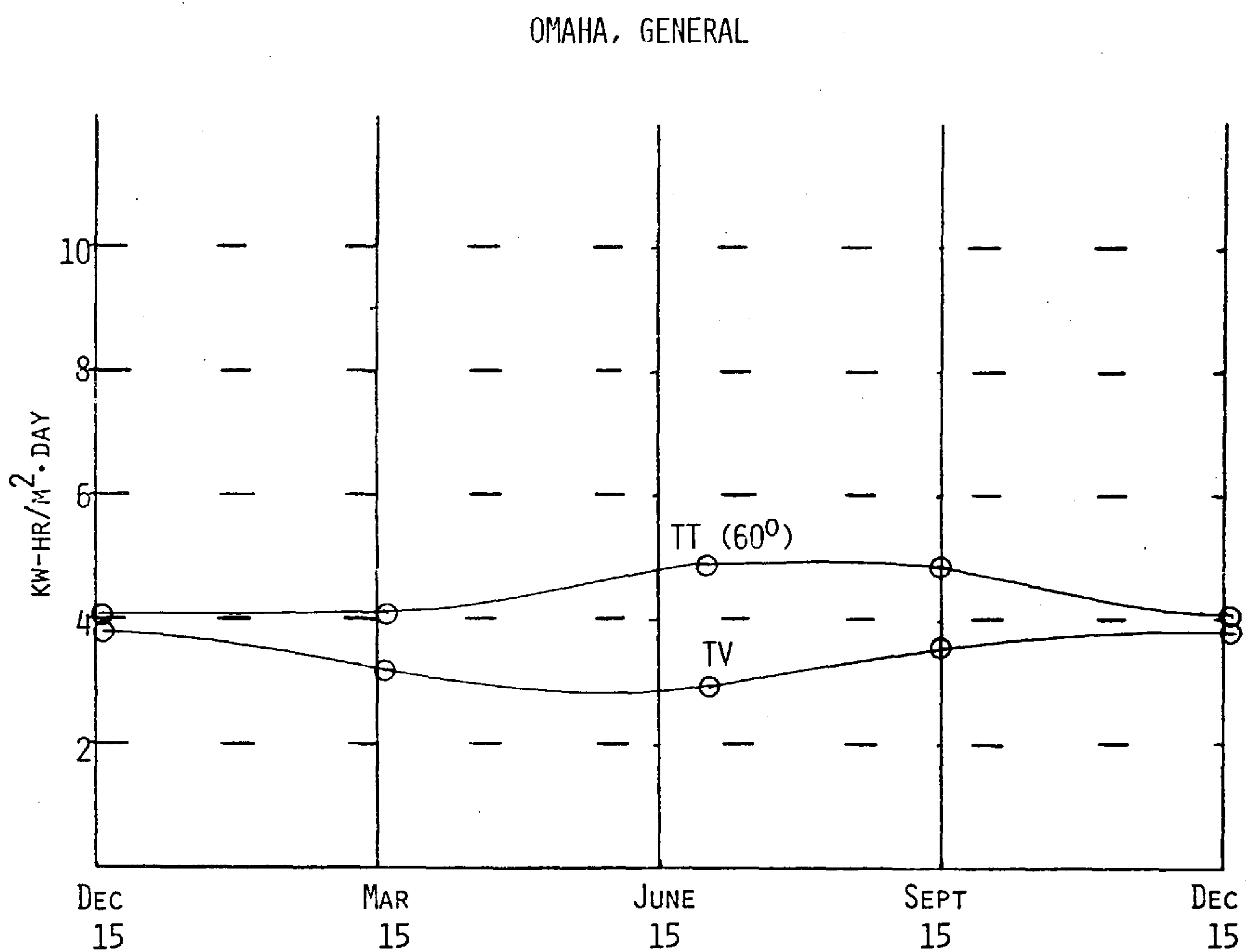

FIGURE 4.9

Comparison of the mean daily solar energy available to a south vertical surface (TV) and a surface inclined 60° from horizontal toward the south (TT(60°)) at Omaha.

ALBUQUERQUE, GENERAL

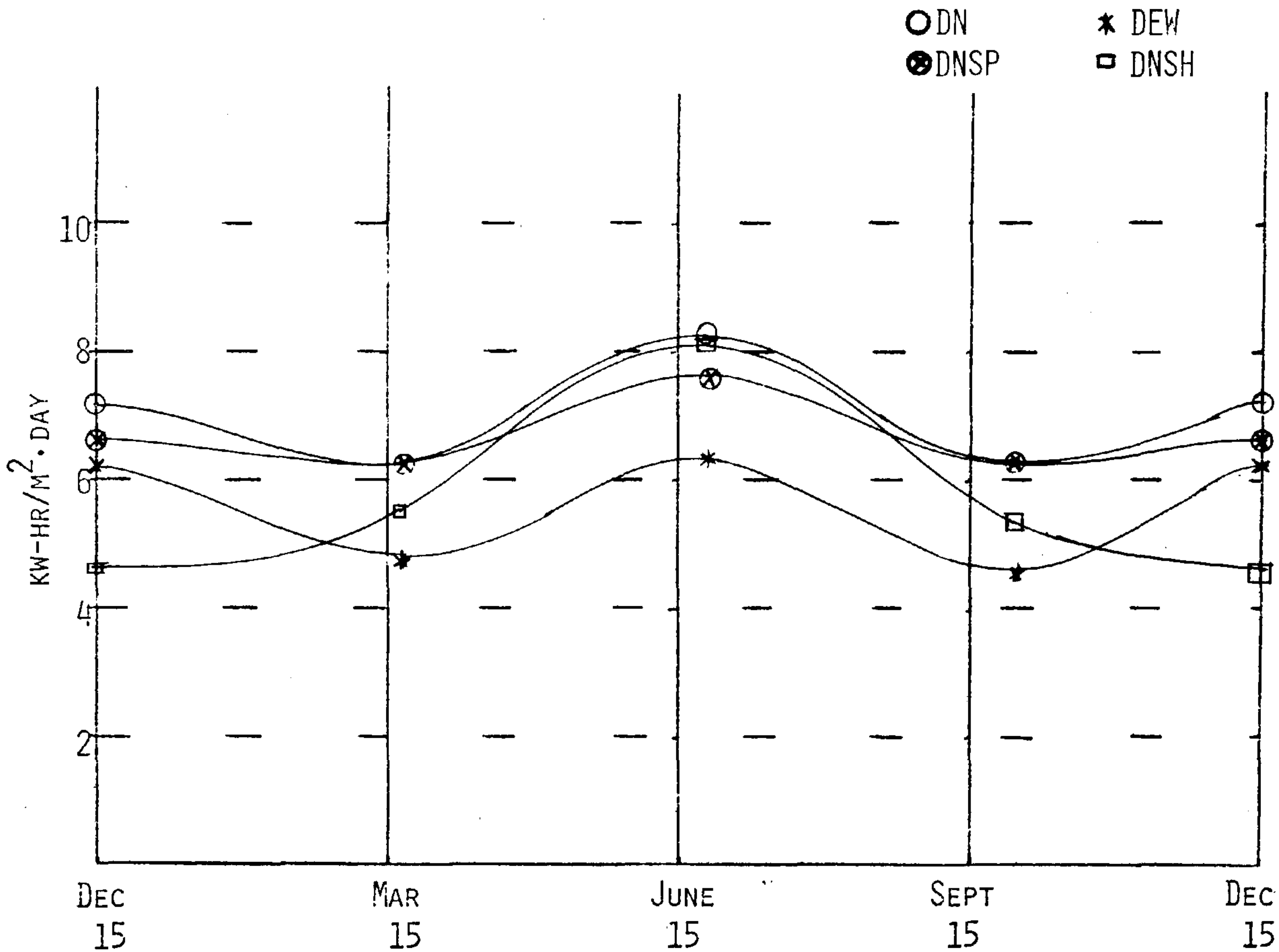

FIGURE 4.10 Daily means of direct radiation available to (a) a normal surface, DN, (b) a surface tracking about a polar axis, DNSP, (c) a surface tracking about an east-west horizontal axis, DEW, and (d) a surface tracking about a north-south horizontal axis, DNSH.

APPENDIX

The explanation of the "Radiation Types" used in Tables 3.1-3.6 are given here.

DN (TN)	Direct (total) radiation incident upon a normal surface.
DEW(TEW)	Direct (total) radiation incident upon a surface which rotates about a horizontal East-West axis through the day.
DNSP(TNSP)	Direct (total) radiation incident upon a surface which rotates about a North-South polar axis (an axis parallel to the earth's axis) through the day.
DNSH(TNSH)	Direct (total) radiation incident upon a surface which rotates about a North-South horizontal axis through the day.
DH(TH)	Direct (total) radiation incident upon a horizontal surface.
DT(t)TT(t)	Direct (total) radiation incident upon a surface tilted t° upward from horizontal toward the south, $t = 10,20, . . ., 80$.
DV(TV)	Direct (total) radiation incident upon a south-facing vertical surface.

The variables used in the formulas for these Radiation Types are as follows:

z = solar zenith angle (angle between sun and vertical).

α = solar elevation = complement of z.

β = solar azimuth, measured from south.

δ = solar declination.

θ = surface zenith angle (angle between vertical and surface-normal).

H = hour angle, in degrees = 1/4 (number of minutes from solar noon).

L = latitude

DFH = intensity of diffuse radiation incident upon a horizontal surface.

DN = intensity of direct normal radiation.

TH = intensity of total horizontal radiation.

The values of the first six of these variables are calculated from the time, date, and location. Two basic equations useful in these calculations are:

$$\cos\alpha \ \sin\beta = \cos\delta \ \sin H$$

and

$$\sin\alpha = \sin\delta \ \sin L + \cos\delta \ \cos L \cos H.$$

The values of the last two variables, DN and TH, were recorded measurements of direct-normal and total-horizontal intensities at 10 minute intervals.

The diffuse-horizontal radiation, DFH, was calculated from these using the formula

$$DFH = TH - (DN * \cos z).$$

The formulas for computing the intensities of direct radiation on the various surfaces are now given.

$$DEW = DN * \sqrt{1 - \cos^2\delta \ \sin^2 H}$$

$$DNSP = DN * \cos \delta$$

$$DNSH = DN * \sqrt{1 - \cos^2\alpha \ \cos^2\beta}$$

$$DH = DN * \cos z$$

$$DT(t) = \begin{cases} DN * (\cos(10t^\circ)\cos z + \sin(10t^\circ)\sin z \cos\beta, \text{ if this} \\ \text{number is positive} \\ 0, \text{ otherwise} \end{cases}$$

$$DV = \begin{cases} DN * (\sin z \cos\beta), \text{ if this number is positive} \\ 0, \text{ otherwise} \end{cases}$$

The above formulas were used to compute intensities at 10-minute intervals. Daily totals of direct radiation were obtained by summing.

Calculations of total radiation intensities on the various surfaces required a transformation of the diffuse-horizontal intensity, DFH, to a diffuse intensity incident upon each of the surfaces. For this task, the assumption was made that the ground is half as bright as the sky, and that both are uniform. The basic equation in every calculation then becomes

$$T = D + \tfrac{1}{2}(1 + \cos\theta)\ DFH + \tfrac{1}{2}(1 - \cos\theta)(\tfrac{1}{2}\ DFH)$$

$$= D + (.75 + .25 \cos\theta)\ DFH$$

where D is the direct radiation intensity on the surface in question, T is the total radiation intensity on that surface, and θ is the zenith for that surface. The formulas for $\cos\theta$ for the various surfaces are given in Table A.1.

Surface	Cosine of Surface Zenith, $\cos\theta$
N	$\cos z$
EW	$\dfrac{\sin\alpha}{\sqrt{1 - \cos^2\delta \ \sin^2 H}}$
NSP	$\cos L \cos H$
NSH	$\dfrac{\sin\alpha}{\sqrt{1 - \cos^2\alpha \ \cos^2\beta}}$
H	1
T(t)	$\cos (10t^{\circ})$
V	0

TABLE A.1

A listing of the surface zenith cosine factors required in the transformation of the diffuse radiation component.

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