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Deterministic Insolation Model Program Description and User's Guide

E. P. French

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DETERMINISTIC INSOLATION MODEL PROGRAM DESCRIPTION AND USER'S GUIDE

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FOREWORD

This is the computer program description and User's Guide for the Deterministic Insolation Model Program, developed under the Department of Energy (DOE) Contract EY-76-C-03-1210 [formerly, Energy Research and Development Administration (ERDA) Contract E(04-03)-1210]. The contract effort was performed by Rockwell International Corporation's Atomics International (AI) Division, and was monitored by Dr. R. W. Harrigan of Sandia Laboratories under the direction of Mr. J. E. Rannels, DOE Program Manager.

This documentation for the Deterministic Insolation Model was funded by Sandia Laboratories, Albuquerque, New Mexico, through Federal Agency Order (FAO) 07-6971 to AI. The AI program manager was Mr. S. J. Nalbandian. Dr. E. P. French developed the program at Rockwell's Space Division, in support of the above-mentioned contract effort, and is the author of this document.

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1.0 INTRODUCTION

This report describes a simple mathematical model for estimating the monthly average insolation experienced by a fixed or tracking collector. It was developed under ERDA Contract E(04-3)-1210 "Commercial Applications of Solar Total Energy Systems."[(1)*] It is designed to fulfill the need for a rapid, economical method of assessing the availability of solar radiation as a basis for site selection and system performance estimation. It attempts to make maximum use of predictable factors, introducing random factors associated with local weather in the simplest way possible.

The method lends itself to a formulation in terms of simple mathematical expressions and is suitable for use by hand calculators and small computers. It has been implemented by a three-module program written for the Texas Instruments SR-52 Programmable Slide-Rule Calculator, as described herein. The same mathematical model has been incorporated into the Fortran Program STESEP.[(2)]

The model described here is intended for the rapid, approximate analysis of solar systems. It does not take the place of the SOLMET data base[(3)] which provides, in a single FORTRAN compatible tape, quality controlled hourly insolation and meteorological data for representative sites throughout the United States.

*Numbers in superscript parenthesis refer to references

2.0 PROGRAM DESCRIPTION

2.1 EXTRATERRESTRIAL SOLAR RADIATION

Solar radiation reaching the top of the earth's atmosphere may be predicted quite accurately. Its intensity is a near constant (I_{SC}) modified only by a small correction (R) which takes into account the effect of seasonal variations in the earth-sun distance. According to Reference 4, this distance correction is approximately

$$R = 1.0 + 0.033 \cos (360\ n/365) \qquad \ldots(1)$$

where n is the day of the year. (See glossary for definition of symbols.)

The angle of incidence on a horizontal surface (zenith angle, θ_z) depends upon the geographic location (latitude, ϕ), the solar declination (δ) and the local solar time as measured by the hour angle (h).

$$\cos \theta_z = \sin \delta \sin \phi + \cos \delta \cos \phi \cos h \qquad \ldots(2)$$

The solar declination is a function of the day of the year (n) and is given approximately by

$$\delta = 23.45 \sin [284 + n\ (360/365)] \qquad \ldots(3)$$

Monthly values of R and δ are the declination given in Table 1.

2.2 ESTIMATION OF DIRECT (BEAM) RADIATION DURING NONCLOUDY TIMES

On noncloudy days most of the extraterrestrial radiation penetrates the atmosphere with small change in direction. A portion of the initial radiation is absorbed by molecular atmospheric constituents; another fraction is scattered out of the beam direction by molecules, droplets, and suspended solid particles. The attenuation, which depends upon the concentration of absorbers and scatterers in the atmosphere, can be considered to have a local component and a general component which exhibits systematic seasonal variations.

TABLE 1

SEASONALLY VARYING SOLAR RADIATION PARAMETERS

Date	R	δ (degree)	(A/I_{SC})	B
January 21	1.031	-20.0	0.909	0.142
February 21	1.021	-10.8	0.897	0.144
March 21	1.006	0.0	0.876	0.156
April 21	0.989	+11.6	0.839	0.180
May 21	0.975	+20.0	0.815	0.196
June 21	0.968	+23.45	0.804	0.205
July 21	0.969	+20.6	0.801	0.207
August 21	0.979	+12.3	0.818	0.201
September 21	0.999	0.0	0.850	0.177
October 21	1.011	-10.5	0.881	0.160
November 21	1.026	-19.8	0.902	0.149
December 21	1.033	-23.45	0.911	0.142

The ASHRAE Handbook of Fundamentals[5] presents a semitheoretical expression for direct normal radiation (I_{DN}) which follows this approach. It is expressed in terms of an apparent extraterrestrial irradiation (A) and an extinction coefficient (B) based on air mass.

$$I_{DN} = CN \cdot A \cdot \exp(-B/\cos\theta_z) \qquad \ldots(4)$$

where I_{DN} is the irradiation on a surface normal to the beam. The term (A) includes both the effects of upper atmosphere and of variable earth-sun distance. Table 1 gives monthly values of A, nondimensionalized by I_{SC}, and B, based upon empirical data from Reference 5. These values have been used in the numerical results reported here. The factor (CN) is a "clearness number" which characterizes the average local transmittance of the atmosphere. It may exhibit seasonal variations, but is considered constant during each individual day.

2.3 ESTIMATION OF DIFFUSE RADIATION

A certain amount of the radiation scattered by atmospheric constituents and cloud surfaces reaches ground level from directions other than that of the direct beam. The amount of this diffuse radiation received in a complicated function of the state of the atmosphere, the sun's position, ground reflectance, and surface orientation. The diffuse component is estimated by means of two simplifying assumptions: that the diffuse radiation is independent of the orientation of the receiving surface and that the direct normal radiation is linearly related to the "percent possible," the fraction of total (direct plus diffuse) radiation falling on a horizontal surface at ground level compared with the extraterrestrial value. These assumptions result in the following relationship between direct and diffuse radiation intensities:

$$I_{DN} = \alpha \frac{I_{DN} \cdot \cos \theta_z + I_{DF}}{I_{SC} \cdot R \cdot \cos \theta_z} + \beta \qquad \ldots(5)$$

The coefficients (α) and (β) are empirically determined by linear regression analysis of simultaneous measurements of both total and direct components. Although they are found to depend to some extent on site location and time of day, they are treated as constants in the present application.

2.4 EFFECT OF CLOUD COVER

Solar radiation exhibits periods of reduced intensity associated with the obscuration of sunlight by clouds. The effects range from long-term overcasts which may last for days, to broken cloud cover which may block the sun for only a fraction of an hour. The net effect of cloud cover is to reduce the average radiation measured at a given site below the unclouded values. Cloud effects are dependent on local atmospheric characteristics and vary seasonally. In the present method the effect of cloud cover is approximated very simply. On the average, for each hour of the day the proportion of unclouded time is assumed to be a constant (CF). During the remaining fraction (1 - CF), solar radiation is considered to be nil. Like CN, CF can have seasonal variations.

2.5 EVALUATION OF CLEARNESS NUMBERS AND CLOUD FACTORS

2.5.1 Application of the Model to Compute Daily Average Insolation

The foregoing model describes local insolation in terms of deterministic equations which contain the clearness number (CN) and the cloud factor (CF).

The average daily direct normal radiation (with cloud effects considered) is obtained by integrating Equation 4 over the full day.

$$\begin{aligned} H_{DN} &= \int CF \cdot I_{DN}\, dt \\ &= CF \cdot CN \cdot \int A \exp(-B/\cos\theta_z)\, dt \\ &= CF \cdot CN \cdot I_1 \end{aligned} \qquad \ldots(6)$$

Similarly, the daily total horizontal radiation is found by integrating Equation 5.

$$\begin{aligned} H_h &= CF\,(I_{DN} \cos\theta_z + I_{DF})\, dt \\ &= \frac{CF \cdot CN \cdot R \cdot I_{SC}}{\alpha} \int A \exp(-B/\cos\theta_z) \cos\theta_z\, dt \\ &\quad - \frac{CF \cdot R \cdot I_{SC}\, \beta}{\alpha} \int \cos\theta_z\, dt \end{aligned}$$

$$H_h = \frac{CF \cdot CN \cdot R \cdot I_2}{(\alpha/I_{SC})} - \frac{CF \cdot R \cdot \beta \cdot I_3}{(\alpha/I_{SC})} \qquad \ldots(7)$$

Equation 7 is more compactly written

$$\hat{H} = CF \cdot CN \cdot I_2 - CF \cdot \hat{\beta} \qquad \ldots(8)$$

where $\hat{\beta} = \beta \cdot I_3$

and $\hat{H} = \dfrac{H_h(\alpha/I_{SC})}{R}$.

The integrals (I_1, I_2, I_3, see Glossary) are obtained by numerical integration. (I_3 can be integrated in closed form, but is grouped with the others for programming convenience.) Because of the symmetry about solar noon all three can be expressed in the form

$$I = 2 \int_0^{t_s} F (\cos \theta_z) \, dt \qquad \ldots(9)$$

where t is the time measured in hours from solar noon, $t_s = \cos^{-1} (-\tan \delta/\tan \phi)/15$ is the sunset time, and $\cos \theta_z$ is a function of the hour angle, h = 15 t (see Equation 2). Equation 9 is evaluated by the trapezoidal rule, with ordinates evaluated at half-hour intervals. The numerical approximation becomes

$$I \approx 0.5 \, F_0 + \sum_{i=1}^{N} F_i \qquad \ldots(10)$$

where N is the integral part of $2t_s - 1$.

Equation 10 slightly overestimates the contribution of the "tail" whenever the sunset time is not an even half-hour. The error is insignificant in the present application.

2.5.2 CN Evaluation From Daily Averages of Total Horizontal and Direct Insolation

The first module of the deterministic insolation program evaluates the clearness number (CN) in one of two ways. If no cloud factor (CF) is specified, it solves Equations 6 and 8 simultaneously for both CF and CN. Substitution of Equation 6 into Equation 8 yields

$$\hat{H} = H_{DN}(I_2/I_1) - CF \cdot \hat{\beta}$$

which can then be solved for CF:

$$CF = (H_{DN} \cdot I_2/I_1 - \hat{H})/\hat{\beta} \qquad \ldots(11)$$

Equation 8 is then solved for CN in terms of CF:

$$CN = (\hat{H}/CF + \hat{\beta})/I_2 \qquad ...(12)$$

When CF and CN are calculated in this way, the results are sensitive to the relative values of the inputs, H_h and H_{DN}. It sometimes happens that, due to errors in the inputs or shortcomings in the model itself, the resulting value of CN is found to be unreasonably high. If so, a reasonable upper limit (say CN = 1.1) can be assigned and a revised value of CF can be calculated from Equation 8 as follows:

$$CF = \hat{H}/(CN \cdot I_2 - \hat{\beta}) \qquad ...(13)$$

Equation 13 is not part of the first module but can be implemented by means of a short key stroke sequence described in the User's Guide. This adjustment insures that the model will produce insolation values consistent with the average daily total radiation used as an input.

2.5.3 CN Evaluation From Total Horizontal Insolation and Assigned Cloud Factor

If a nonzero value is specified for the cloud factor, the first module computes a clearness number according to Equation 12. In this mode no value of H_{DN} is required and any value entered is ignored.

2.6 CALCULATION OF RADIATION INCIDENT ON A TILTED FLAT COLLECTOR

The second program module calculates the intensity of total (direct and diffuse) radiation falling on a flat collector tilted toward the south or north. It also integrates the intensity and applies a cloud factor to arrive at an average daily value. As a byproduct of these calculations the intensity of direct normal radiation and its average daily value are also computed. These quantities correspond to the energy incident on an ideal two-axis tracking collector.

The data storage locations for Module 2 have been made compatible with those for Module 1. This feature allows one to use Module 1 to compute a set of CN, CF output values and then proceed to use Module 2 without keying in either the outputs or the inputs common to the two modules.

Module 2 evaluates direct normal intensity (I_{DN}) from Equation 4 and the total intensity on a surface tilted at angle, T.

$$I_T = I_{DN} \cos \theta_i + I_{DF} \qquad \ldots(14)$$

where θ_i is the incidence angle of the direct radiation and I_{DF} is the diffuse intensity (assumed isotropic here). Cos θ_i is evaluated from Equation 2 with the "corrected" latitude (ϕ - T) used in place of ϕ. Diffuse intensity is obtained from Equation 5 in the form

$$I_{DF} = I_{DN} \cdot \cos \theta_z \cdot (I_{SC} \cdot R/\alpha - 1)$$

$$-\cos \theta_z \cdot R \cdot I_{SC} \cdot \beta/\alpha \qquad \ldots(15)$$

Daily average values of I_{DN} and I_T are computed from the general expression

$$H = CF \cdot 2 \int_0^{t_m} I \, dt \qquad \ldots(16)$$

where the upper limit is either the sunset hour or the time at which the incidence angle becomes zero, whichever is the smaller. The integral is evaluated numerically by Equation 10.

2.7 CALCULATION OF RADIATION INCIDENT ON SINGLE-AXIS TRACKING COLLECTORS

The third program module calculates the direct radiation incident on a single-axis tracking collector. The module operates in two modes. Mode 1 is for systems with the tracking axis in the east-west horizontal line. Mode 2 is for either a horizontal or a tilted axis, located in the north-south plane. Module III, like Module II, is designed to be used in sequence with Module I with retention of common data.

In either mode, incident intensity is evaluated from the direct normal intensity (Equation 4) and the incidence angle.

$$I = I_{DN} \cdot \cos \theta_i \qquad \text{...(17)}$$

For single-axis trackers with the axis in a north-south plane tilted above the horizontal at angle, T (Mode 2), the incidence angle is given by

$$\sin \theta_i = \cos \delta \sin (\phi - T) \cos h$$

$$- \sin \delta \cos (\phi - T) \qquad \text{...(18)}$$

An important special case is the polar axis orientation ($T = \phi$) in which $\cos \theta_i = \cos \delta$.

For Mode 1 where the axis is aligned east-west in the horizontal plane, the incidence angle is given by

$$\sin \theta_i = \cos \delta \sin h \qquad \text{...(19)}$$

For either mode, the daily average is computed from Equation 16.

3.0 USER'S GUIDE

3.1 INPUT REQUIREMENTS

Data for each month is entered into the SR-52 calculator by keystroke. It is retained in its designated storage location as long as the calculator power is left on unless modified by subsequent storage operations. In particular, data used or generated by one module can be retained for use by another module. This feature has been used to reduce data entry operations substantially. Table 2 shows the data storage structure of the three program modules. Permanent data (locations 98, 99, 19) need not be re-entered when running multiple cases. Recommended values are given in the Glossary. Data pertaining to the season (locations 05, 06, 07, 08) may be obtained from Table 1. It need not be re-entered when comparing locations at the same time of year.

TABLE 2

DATA STORAGE STRUCTURE

Data Location	Module I		Module II		Module III	
	Item	Category*	Item	Category*	Item	Category*
98	α/I_{SC}	I	α/I_{SC}	I	α/I_{SC}	I
99	β/I_{SC}	I	β/I_{SC}	I	β/I_{SC}	I
00	N		N		N	
01	ϕ	I	ϕ	I	ϕ	I
02	S	I	T	I	T	I
03	CN	O	CN	I	CN	I
04	CF	O	CF	I	CF	I
05	A/I_{SC}	I	A/I_{SC}	I	A/I_{SC}	I
06	B	I	B	I	B	I
07	δ	I	δ	I	δ	I
08	R	I	R	I	R	I
09	I_1		I_1		Mode	I,O
10	I_2		I_2		I_2	
11	I_3		-		h	
12	H_h	I	$\cos\Theta_i$		$\cos\Theta_i$	
13	H_{DN}	I	I_{DN}	O	I_{DN}	
14	$\hat{H}$		-		$\cos\delta$	
15	$\hat{\beta}$		$\phi,\ \phi - T$		$\phi - T$	
16	t		t	O	t	O
17	$\cos\Theta_z$		$\cos\Theta_z$		$\cos\Theta_z$	
18	Δt		Δt		Δt	
19	I_{SC}	I	I_{SC}	I	I_{SC}	I

*I = input; O = output; Additional outputs: I_T, H_{DN}, and H_T are printed but not stored.

Data pertaining to both the location and season (locations 01, 03, 04, 12, 13) need not be re-entered in order to compare collectors of different type or orientation.

3.1.1 Local Insolation Inputs for Module I

The inputs which characterize local insolation are the average daily total radiation on a horizontal surface (H_h) and one of the following: the average daily direct radiation (H_{DN}) or an assigned value (S) which is equated with the cloud factor. The daily total insolation values must be expressed in the units $I_{SC} \cdot hr \cdot day^{-1}$ (for example, $kW \cdot hr \cdot m^{-2} \cdot day^{-1}$).

The insolation data base which was used to develop and validate the present method was derived from the Aerospace solar tapes.[6]

Daily averages of both total and direct radiation on a monthly basis have been obtained for 33 sites by numerical integration of the Aerospace solar tapes.[7] These results, along with other climatological data have been summarized for 12 representative sites in Reference 1 and are included in the Appendix of this report.

The Climatic Atlas[8] contains daily average total insolation data for a much larger number of sites. In addition, the same information is presented in maps from which insolation can be estimated throughout the U.S. The Atlas also contains tables and maps giving average values of percent sunshine. This latter quantity may be used to estimate the cloud factor, CF. It has been found that the empirical relation

$$CF = \sqrt{\text{Percent Sunshine} \div 100} \qquad \ldots(20)$$

gives cloud factors fairly close to those computed from Equation 11. Equation 20 is therefore recommended whenever only total horizontal insolation is available, that is, for most sites. This definition was used for the CF values presented in the Appendix.

There are other sources of insolation data. Most recently, Sandia Laboratories, Albuquerque, New Mexico has summarized data from the SOLMET tapes[3] for 26 sites and also provided insolation maps. This data base is currently being reviewed but it appears that the results for many sites are substantially different from those obtained using the Aerospace data base. The implication of these differences is discussed under the section entitled "Program Limitations."

3.1.2 Other Inputs for Module I

The choice of the energy unit in which output quantities are expressed is set by the solar constant, (location 19) which can have any units as long as the time is in hours. Two convenient choices are 1.353 kW m^{-2} (kWh-m^{-2}-hr^{-1}) and 429.2 Btu-ft^{-2}-hr^{-1}. At present, recommended values for the two linear regression coefficients (Equation 5) are the average values given in Reference 3. Their nondimensionalized values are $(\alpha/I_{SC}) = 1.33$ and $(\beta/I_{SC}) = -0.384$. Later refinement of the deterministic model may require a revision of these values.

The general properties which vary seasonally can be obtained by interpolation from Table 1. All quantities except the declination are dimensionless; it must be expressed in degrees. The latitude (ϕ) must also be in degrees, with the northern hemisphere taken positive. The sign convention for latitude and collector tilt is illustrated in Figure 1.

3.1.3 Inputs for Module II

If Module I has been run just previously, only the collector tilt, T (in degrees), must be entered in location 02. Tilt is zero for a horizontal surface and is defined as positive toward the south. Collectors in the southern hemisphere would normally have negative tilt angles. If Module II is being run independently, all the inputs shown in Table 2 must be entered by keystroke.

3.1.4 Inputs for Module III

If Module I has been run just previously only the axis tilt, T (in degrees), and the mode number must be entered. The same sign convention is employed for axis tilt as that for flat collectors. For east-west trackers (Mode 1) axis tilt is not required and its value is ignored. For Mode 2, axis tilt is measured in the north-south plane. Tilt is zero for a horizontal axis and positive southward. If Module III is being run independently, all the inputs shown in Table 2 must be entered by keystroke.

3.2 OUTPUT OPTIONS

3.2.1 Operation With and Without Printer

The program modules have been recorded and listed in a form compatible with the use of the Texas Instruments PC 100A printer. If a printer is not available, the module must be modified by keystroke after being read into the calculator.

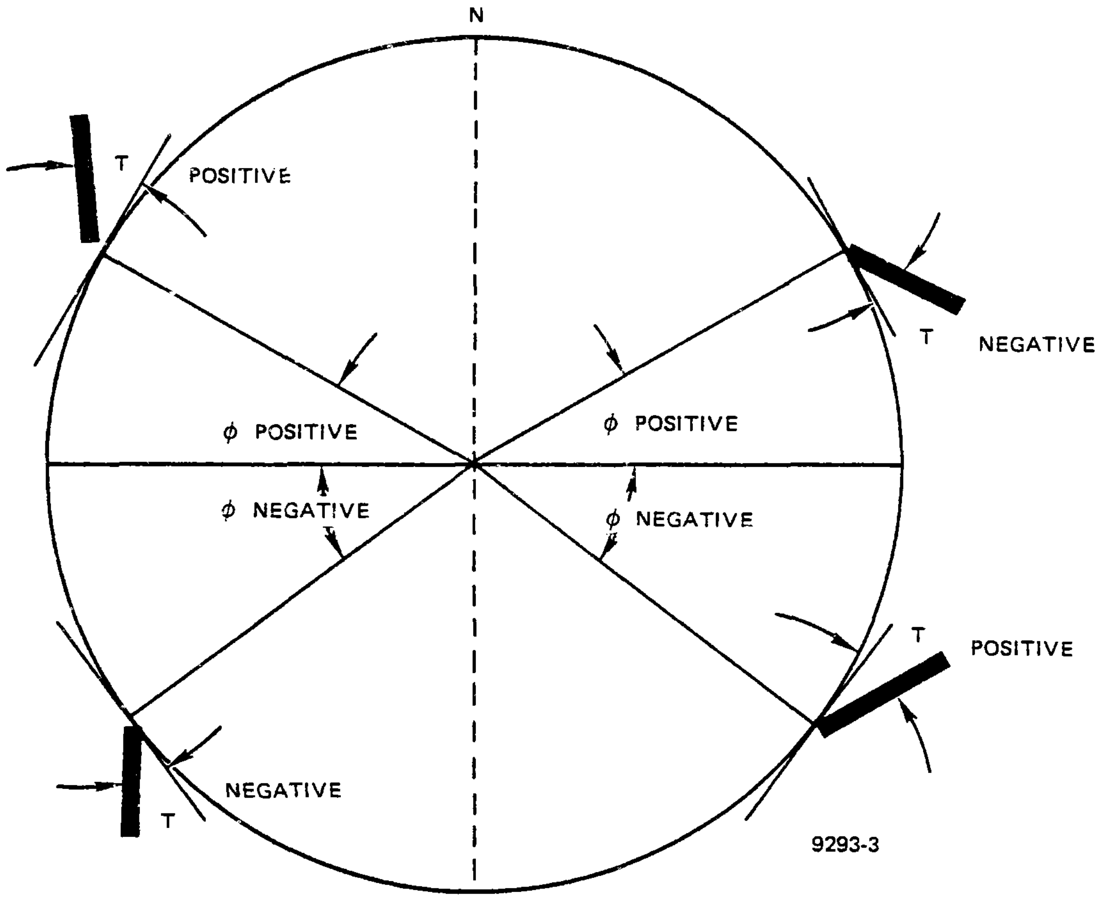


Figure 1. Sign Conventions for Latitude and Collector Tilt

This modification consists of changing PRINT commands to HALT commands. During execution without a printer the module displays each result rather than printing it. Execution is continued by pressing the RUN key after each stop.

Each location requiring change for nonprinter operation is identified in the module listings (Section 4) by an asterisk between the location number and the instruction code, thus: 203 * 98. Module change takes place after the magnetic card has been read into the calculator, starting in the "calculate" mode, as follows:

Keystroke Sequence	Display	Comment
1. GTO 203 LRN	203 98	Locate print instruction
2. HLT	204 20	Change print to halt; display next step
3. LRN	0.	Return to "calculate" mode

The above sequence is repeated for each print instruction requiring change. (Note: The last print instruction in each module is followed by a halt instruction and need not be changed.)

3.2.2 Output for Module I

Output for this module consists of two items, CF and CN. When the printer is used these outputs are printed one after the other. Without printer CF is displayed first; CN appears after the RUN key is pressed.

3.2.3 Output for Module II

Output for this module consists of a sequence of blocks which give the time variation of direct (I_{DN}) and total (I_T) intensities at half-hourly intervals. The first item is the time,t,in hours, measured from solar noon. Because of the symmetry about noon, each block corresponds to both a morning and afternoon time. For example, t = 2.500 refers to 9:30 am and 2:30 pm. In each block, the time is followed by I_{DN}, I_T and a space. Both intensities have the units of the solar constant.

Following the time-variation sequence, daily values of direct (H_{DN}) and total (H_T) incident radiation, including cloud effect, are printed. Units are (solar constant) · hr · day^{-1}.

3.2.4 Output for Module III

Output for this module starts with the printing of the mode number — 1. or 2. It is followed by a sequence of blocks giving the solar time in hours and the incident intensity (I) at half-hourly intervals beginning with solar noon (t = 0.000) corresponding to an average day of the month. Intensity units are those of the solar constant.

Following the time-variation sequence, the daily incident radiation (H) is printed in the units (solar constant) · hr · day^{-1}.

3.3 PROGRAM LIMITATIONS

3.3.1 Limitation on Input Values

The program is restricted to sun-earth-collector geometries in which the sun is above the horizon and falls on top of the collector during some part of the day. These considerations introduce the following limits:

$$|\phi| \leq 90° \text{ (by convention)}$$
$$|\phi-\delta| \leq 90° \text{ (finite daylight)}$$
$$|\phi-\delta-T| \leq 90° \text{ (top exposure)}$$

Because of its physical significance in the deterministic model, the cloud factor is restricted by logic to values of unity or less. As discussed in Section 2.5.2 CF,CN calculations are sensitive to input errors. It sometimes happens that Module I produces values of CF greater than one when the inputs are H_h and H_{DN}. The CF,CN pair of values can be revised by assigning the value, S = 1 and recomputing. The keystroke sequence required is as follows:

Keystroke Sequence	Display	Comment
1 STO 02	1.	(Assign S = 1)
B	1.000 0.823	(Enter module at B and recompute CF,CN)

Except at high altitudes, reasonable values of the clearness number should not be much greater than one. If Module I produces an unrealistic value, say CN > 1.1, the results can be revised by assigning the appropriate values, S, to yield CN = 1.1. The keystroke sequence required is as follows:

TABLE 3

DAILY INCIDENT ENERGY PREDICTIONS USING CONSTANTS DERIVED FROM AEROSPACE TAPES

Location	Month	CN	CF	Incident Energy (kWh/m^2-day)		
				45° Tilted Plate	NS Polar	EW Horizontal
Albuquerque	January	1.01	0.89	6.16 (6.20)*	6.35 (6.34)	5.68 (5.55)
	July	0.93	0.95	5.99 (5.89)	7.90 (7.61)	6.20 (6.26)
Madison	January	0.75	0.75	3.41 (3.45)	3.33 (3.29)	3.08 (3.10)
	July	0.99	0.84	5.87 (5.97)	7.62 (7.29)	5.89 (5.71)
Miami	January	0.77	0.84	5.45 (5.61)	5.20 (5.16)	4.52 (4.45)
	July	0.95	0.82	4.61 (4.52)	6.74 (6.45)	5.39 (5.26)
Nashville	January	0.70	0.63	3.24 (3.34)	3.06 (3.07)	2.74 (2.74)
	July	0.76	0.85	4.91 (4.81)	5.80 (5.68)	4.54 (4.68)
Omaha	January	1.10	0.76	4.90 (4.95)	5.18 (5.23)	4.75 (4.61)
	July	0.89	0.91	5.92 (5.82)	7.38 (7.10)	5.72 (5.68)
Seattle	January	0.75	0.64	2.51 (2.84)	2.50 (2.52)	2.35 (2.29)
	July	0.89	0.84	5.73 (5.68)	6.95 (6.65)	5.32 (5.32)

*First values obtained by deterministic method; values in brackets from hour-by-hour integration of Aerospace tapes.

TABLE 4

DAILY INCIDENT ENERGY PREDICTIONS BASED ON THE CLIMATIC ATLAS

Location	Month	CN	CF*	Incident Energy (kWh/m^2-day)		
				45° Tilted Plate	NS Polar	EW Horizontal
Albuquerque	January	1.09	0.84	6.17	6.47	5.78
	July	1.10	0.91	6.28	8.95	7.03
Madison	January	0.89	0.66	3.42	3.48	3.21
	July	0.87	0.84	5.46	6.70	5.17
Miami	January	0.91	0.81	5.92	5.93	5.15
	July	0.91	0.81	4.47	6.37	5.10
Nashville	January	0.51	0.65	2.69	2.30	2.06
	July	0.86	0.83	5.09	6.40	5.02
Omaha	January	0.95	0.67	4.36	4.47	4.10
	July	0.91	0.87	5.73	7.21	5.59
Seattle	January	0.61	0.52	1.75	1.65	1.55
	July	1.10	0.79	6.09	8.07	6.18

$*CF = \sqrt{\%\ Sunshine \times 100}$

Keystroke Sequence	Display	Comment
RCL 14 ÷ (1.1 x RCL 10 - RCL 15) =	0.793	(Compute S value)
STO 02	0.793	(Assign S)
B	0.793 1.100	(Enter module at B and recompute CF,CN)

If Module I yields too high values of both CF and CN simultaneously, they should be replaced by the limiting values or by an estimate drawn from a site with a similar climate.

The output of all modules is formatted with three places to the right of the decimal point. This is satisfactory for the intensity units suggested but may result in loss of significant figures for some other set of units. If the solar constant has a value <1 in the desired set, it should be multiplied by a suitable scale factor. The output intensities and daily energies will contain the same scale factor.

3.3.2 Availability and Consistency of Insolation Data

The deterministic method uses average insolation data to compute the empirical factors CN and CF for a given site. These factors, in turn, are used to predict the average energy incident on collectors of various orientations and tracking geometrices. The results depend upon the solar data base employed.

Table 3 shows sample results obtained using the Aerospace tapes. Average incident energy predictions are quite consistent with the values obtained by an analysis of the hourly tape data (rms deviation 3%). However, application to sites other than the locations for which average insolation data are given (Reference 7 or Appendix) involves interpolation or extrapolation and is subject to considerable uncertainty.

The Climatic Atlas[8] gives average total horizontal insolation and average percent sunshine for over 100 stations and in map form for the US as a whole. The data is drawn from a much longer time base than the 1962-63 period covered by the Aerospace tapes. Table 4 shows the results of applying the deterministic method to this data base. Here CF is estimated by Equation 20. In general, the results agree fairly well with those obtained from the Aerospace data base (rms deviation 15%). Because of their availability and broad coverage, the maps and tables from the Climatic Atlas are the most satisfactory source of input data at the present time.

More recently average total horizontal and direct insolation values based on the SOLMET tapes have been published(3) for 26 U.S. stations and in the form of maps. Many of the stations correspond to those in the Aerospace data base. However the time period covered by the SOLMET data is much longer and the results are frequently quite different. A substantial revision in the SOLMET data has also been made since Reference 3 was issued. As Table 5 shows, the deterministic predictions based on the SOLMET data base (as revised) differ considerably from those based on the Aerospace data base. Average incident energies are fairly consistent with the results of an hourly analysis of the SOLMET tapes (rms deviation 8%). However they are quite different from the Table 3 results (nms deviation 23%). The "permanent" constants α, β, A and B employed in the present deterministic model were chosen before the SOLMET data became available. While their use gave good results when compared with the earlier solar data (see Tables 3 and 4) it now appears that they require revision. Such a revision would involve

TABLE 5

DAILY INCIDENT ENERGY PREDICTIONS BASED ON SOLMET TAPES

Location	Month	CN	CF	Incident Energy (kWh/m^2-day) 45° Tilted Plate	NS Polar	EW Horizontal
Albuquerque	January	0.83	1.00	5.95 (5.54)*	5.86 (5.43)	5.24 (4.81)
	July	0.93	1.00	6.31 (6.45)	8.32 (7.65)	6.53 (6.02)
Madison	January	0.41	1.00	2.99 (2.89)	2.43 (2.34)	2.24 (2.10)
	July	0.56	1.00	5.26 (5.40)	5.13 (4.75)	3.97 (3.70)
Miami	January	0.49	1.00	4.83 (4.54)	3.94 (3.69)	3.42 (3.12)
	July	0.45	1.00	4.24 (4.46)	3.89 (3.25)	3.11 (2.60)
Nashville	January	0.38	0.85	2.93 (2.80)	2.24 (2.25)	2.01 (2.03)
	July	0.55	1.00	5.03 (5.12)	4.93 (4.35)	3.87 (3.48)
Omaha	January	0.48	1.00	4.90 (4.95)	5.18 (5.23)	4.75 (4.61)
	July	0.66	1.00	5.61 (5.68)	6.01 (5.64)	4.66 (4.23)
Seattle	January	-	-	- -	- -	- -
	July	-	-	- -	- -	- -

*First values obtained by deterministic method; values in brackets from hour-by-hour integration of the SOLMET tapes.

substantial numerical processing of the SOLMET data in order to obtain best-fit constants. It is a desirable future effort however, which would improve the accuracy and usefulness of the model.

3.3.3 Application to Transient Simulation

The deterministic method estimates the intensity of incident radiation in the absence of clouds and the long-term daily average of the incident energy with cloud effects included. It cannot simulate the random fluctuations in solar radiation typical of a given locality. Its use in a transient simulation is therefore limited to approximating the diurnal variations during a clear day.

3.4 SAMPLE PROBLEMS

All problems start with the calculator on in the "calculate" mode, with the D/R switch set on D (degrees). The following descriptions apply when the calculator is mounted on the printer. Without printer, the recorded programs must be modified by keystroke (see Section 3.2.1) and the RUN key must be used after each intermediate output is displayed.

3.4.1 Energy Incident on a Two-Axis Tracking Collector

Assume an ideal tracking collector intercepting all direct normal radiation, operating in Albuquerque on July 21st. Inputs are available from Table 1 and the Appendix, Table A-1. The operating steps and their results are tabulated in the following listing.

Note that the daily incident energy H_{DN} is equal to the input value as it should be.

Operation	Keystroke	Display	Print
Load "A" side of Module I	CLR *read	0	
Load "B" side of Module I	*read	0	
Enter: Ø	35.05 STO 01	35.05	
S	0 STO 02	0	
A/I_{SC}	.801 STO 05	0.801	
B	.207 STO 06	0.207	
δ	20.6 STO 07	20.6	
R	.969 STO 08	0.969	
H_h	7.39 STO 12	7.39	
H_{DN}	8.43 STO 13	8.43	
I_{SC}	1.353 STO 19	1.353	
α/I_{SC}	1.33 STO 99	1.33	
β/I_{SC}	.384+/-STO 98	-0.384	
Execute Module I	A		0.951 (CF)
		0.928	0.928 (CN)
Load "A" side of Module II	CLR *read	0	
Load "B" side of Module II	*read	0	
Enter T=0 (retain I/O from Module I)	0 STO 02	0.000	
Execute Module II	A		0.000 (t)
			0.812 (I_{DN})
			0.939 (I_h)
			⋮
			7.000 (t)
			0.000 (I_{DN})
			0.001 (I_h)
			8.430 (H_{DN})
			7.390 (H_h)

3.4.2 Energy Incident on an East-West Horizontal Tracker (Clear Air Estimate)

Assume month and location are the same (Albuquerque in July). Thus all general inputs will be the same and may be retained. The clearness number is retained but the cloud factor is set at one. The operating steps and their results are tabulated below.

Operation	Keystroke	Display	Print
Load "A" side of Module III	CLR *read	0	
Load "B" side of Module III	*read	0	
Enter: T = 0	0 STO 02	0.000	
CF = 1	1 STO 04	1.000	
MODE = 1	1 STO 09	1.000	
Execute Module III	A		1. (MODE)
			0.000 (t)
			0.812 (I)
			⋮
			7.000 (t)
			0.000 (I)
			6.513 (H)

3.4.3 Total Energy Incident on a Flat Collector

Assume a flat collector tilted at 45 degrees south, intercepting both direct and diffuse radiation. The location is Omaha and the time is January 21st. Determine performance from average daily total horizontal insolation and the average percent sunshine. Inputs are obtained from Table 1 and the Appendix, Table A-9. The operating steps and their results are tabulated in the following listing.

Operation	Keystroke	Display	Print
Load "A" side of Module I	CLR *read	0	
Load "B" side of Module I	*read	0	
Enter : Ø	41.37 STO 01	41.370	
$S = \sqrt{.57}$	.76 STO 02	0.760	
A/I_{SC}	.909 STO 05	0.909	
B	.142 STO 06	0.142	
δ	20+/-STO 07	- 20.000	
R	1.031 STO 08	1.031	
H_h	2.45 STO 12	2.450	
(I_{SC} α/I_{SC}, β/I_{SC} retained)			⋮
Execute Module I	A	1.090	0.760 (CF) 1.090 (CN)
Load "A" side of Module II	CLR *read	0	
Load "B" side of Module II	*read	0	
Enter T = 45 (Retain I/O from Module I)	45 STO 02	45.000	
Execute Module II	A		0.000 (t) 0.997 (I_{DN}) 1.042 (I_h) ⋮ 4.500 (t) 0.052 (I_{DN}) 0.037 (I_h) 5.461 (H_{DN}) 4.867 (H_h)

4.0 PROGRAMMERS INFORMATION

4.1 HARDWARE REQUIREMENTS

The SR-52 programmable calculator is battery operated and will execute the program modules without any additional equipment. For extended operating times, it may be necessary to plug the calculator into the AC9130 Adapter/Charger. In this configuration, batteries are recharged while calculations proceed. When the calculator is mounted on the PC100A printer, the battery pack is separately mounted and charged while calculations proceed.

4.2 EXECUTION TIME

Running time for each module is controlled primarily by the length of the solar day, being greatest for the summer months. When operating with the printer, Module I takes 1 to 1-1/2 min per case while Modules II and III take from 1-1/2 to 2-1/2 min.

4.3 PROGRAM CONVERSION

Since the modules were developed, a new programmable calculator, the TI59, has become available. The TI59 uses keystroke instructions very similar to the SR-52. The three modules could be readily adapted so as to become separate program segments in the newer calculator. The keystroke sequences would be essentially the same. Only the transfer instructions would require modification to reflect the altered memory storage pattern.

Because of differences in the way in which algebraic equations are evaluated in the Hewlett-Packard programmable calculators HP67/97, conversion would not be as simple. The same algorithms apply, but keystroke sequences would be altered significantly. The same remarks apply to other systems which may operate with different instruction languages.

4.4 PROGRAM LISTINGS AND FLOW CHARTS

Annotated listings and corresponding functional flow charts are provided for each module. When a module has been loaded on the calculator attached to the printer, a listing may be produced for comparison, using the following keystroke sequence:

```
CLR *reset (set to beginning of program memory)

*list      (list locations and instruction codes in sequence)
```

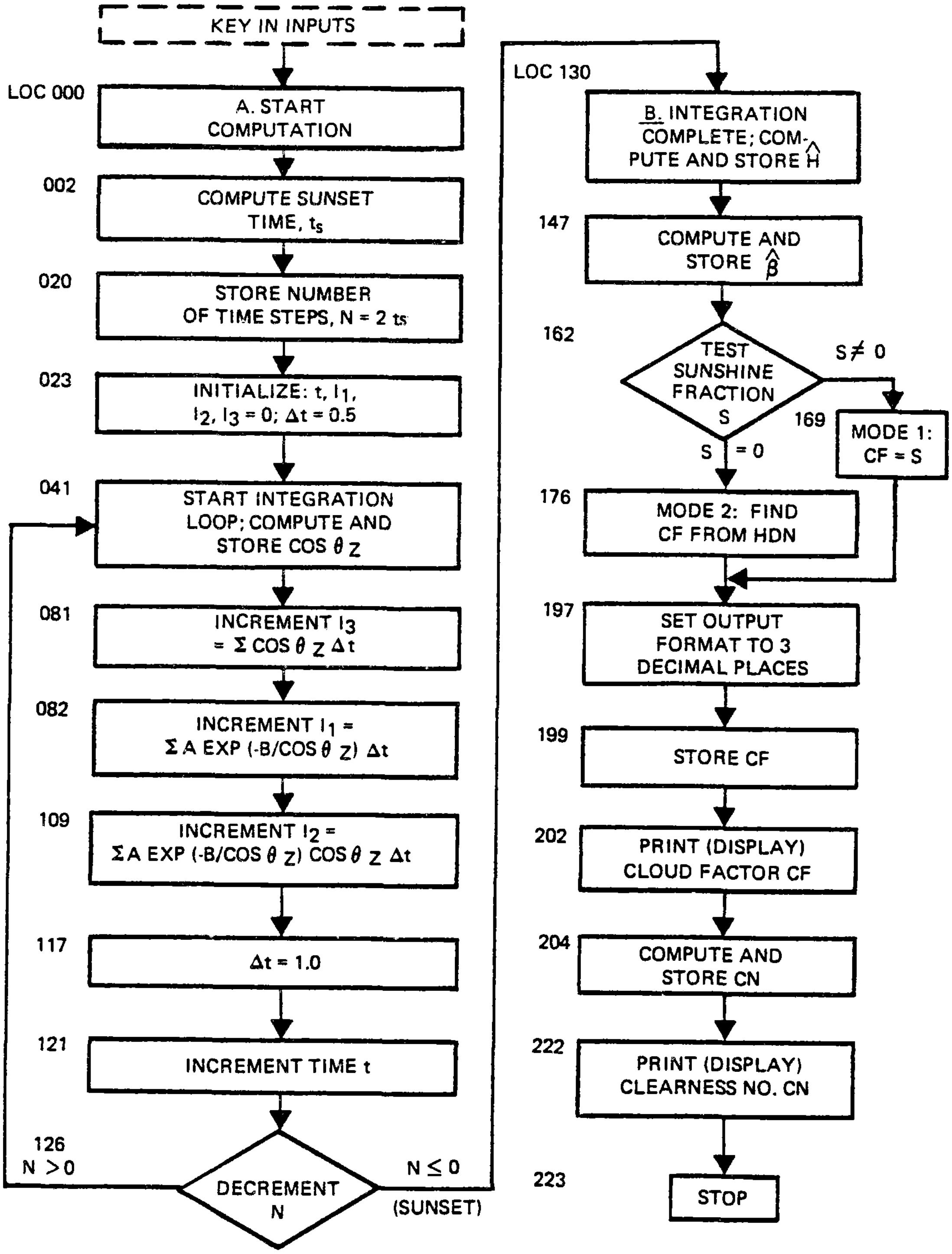
SR-52 PROGRAM LISTING
DETERMINISTIC INSOLATION ESTIMATES: 1. CLEARNESS NUMBER AND CLOUD FACTOR

LOC. CODE	KEY	COMMENT	LOC. CODE	KEY	COMMENT
000 46	*LBL	START	056 01	1	
001 11	A		057 06	6	
002 43	RCL	COMPUTE SUNSET TIME	058 54	)	HOUR ANGLE h
003 00	0		059 33	COS	COS h
004 07	7	DECLINATION δ	060 85	+	
005 34	TAN		061 43	RCL	
006 65	X		062 00	0	
007 43	RCL		063 01	1	
008 00	0		064 32	SIN	SIN ϕ
009 01	1	LATITUDE ϕ	065 65	X	
010 34	TAN		066 43	RCL	
011 95	=		067 00	0	
012 94	+/–		068 07	7	
013 22	INV		069 32	SIN	SIN δ
014 33	COS	SUNSET HOUR ANGLE h_s	070 95	=	
015 55	÷		071 42	STO	STORE COSINE OF
016 07	7		072 01	1	ZENITH ANGLE
017 93	.		073 07	7	COS θ_Z
018 05	5		074 65	X	
019 95	=	N= 2 x SUNSET HOUR	075 43	RCL	
020 42	STO	STORE ITERATION NO. N	076 01	1	
021 00	0	INITIALIZE t, I_1, I_2, I_3	077 08	8	Δt
022 00	0		078 95	=	
023 00	0		079 44	SUM	
024 42	STO		080 01	1	
025 01	1		081 01	1	INCREMENT I_3
026 06	6	t = 0	082 43	RCL	
027 42	STO		083 00	0	
028 00	0		084 06	6	B
029 09	9	$I_1 = 0$	085 55	÷	
030 42	STO		086 43	RCL	
031 01	1		087 01	1	
032 00	0	$I_2 = 0$	088 07	7	COS θ_Z
033 42	STO		089 95	=	
034 01	1		090 94	+/–	
035 01	1	$I_3 = 0$	091 22	INV	
036 93	.		092 23	LNX	EXP (–B/COS θ_Z)
037 05	5		093 65	X	
038 42	STO	$\Delta t = 0.5$	094 43	RCL	
039 01	1		095 00	0	
040 08	8		096 05	5	A/I_{SC}
041 43	RCL	START INTEGRATION LOOP	097 65	X	
042 00	0	COMPUTE COSINE OF	098 43	RCL	
043 01	1	ZENITH ANGLE	099 01	1	
044 33	COS	COS φ	100 09	9	SOLAR CONSTANT I_{SC}
045 65	X		101 65	X	
046 43	RCL		102 43	RCL	
047 00	0		103 01	1	
048 07	7		104 08	8	Δt
049 33	COS	COS δ	105 95	=	
050 65	X		106 44	SUM	
051 53	(		107 00	0	
052 01	1		108 09	9	INCREMENT I_1
053 05	5		109 65	X	
054 65	X		110 43	RCL	
055 43	RCL		111 01	1	

SR–52 PROGRAM LISTING
DETERMINISTIC INSOLATION ESTIMATES: 1. CLEARNESS NUMBER AND CLOUD FACTOR (CONTINUED)

LOC. CODE	KEY	COMMENT	LOC. CODE	KEY	COMMENT
112 07	7	cos θ_Z	168 06	6	
113 95	=		169 42	STO	MODE 1
114 44	SUM		170 00	0	
115 01	1		171 04	4	CF = S
116 00	0	INCREMENT I_2	172 41	GTO	
117 01	1		173 01	1	
118 42	STO		174 09	9	
119 01	1		175 07	7	
120 08	8	$\Delta t = 1.0$	176 43	RCL	MODE 2
121 93	·		177 01	1	
122 05	5		178 03	3	DAILY DIRECT H_{DN}
123 44	SUM		179 65	X	
124 01	1		180 43	RCL	
125 06	6	INCREMENT TIME	181 01	1	
126 58	*dsz		182 00	0	I_2
127 00	0		183 55	÷	
128 04	4	IF N > 0 GO TO LOC. 041	184 43	RCL	
129 01	1		185 00	0	
130 46	*LBL	INTEGRATION IS COMPLETE;	186 09	9	I_1
131 12	B	COMPUTE CF AND CN	187 75	−	
132 43	RCL		188 43	RCL	
133 01	1		189 01	1	∧
134 02	2	DAILY TOTAL, H_h	190 04	4	H
135 65	X		191 95	=	
136 43	RCL		192 55	÷	
137 09	9		193 43	RCL	
138 09	9	α/I_{SC}	194 01	1	∧
139 44	÷		195 01	5	β
140 43	RCL		196 95	=	CF
141 00	0		197 57	*FIX	SET OUTPUT FORMAT TO
142 08	8	R	198 03	3	3 DECIMAL PLACES
143 95	=		199 42	STO	
144 42	STO		200 00	0	
145 01	1		201 04	4	
146 04	4	$\hat{H}$	202 99	*PAP	SPACE
147 43	RCL		203*98	*PRT	PRINT (DISPLAY) CF
148 09	9		204 20	*1/X	
149 08	8	β/I_{SC}	205 65	X	
150 65	X		206 43	RCL	
151 43	RCL		207 01	1	∧
152 01	1		208 04	4	H
153 09	9	I_{SC}	209 85	+	
154 65	X		210 43	RCL	
155 43	RCL		211 01	1	∧
156 01	1		212 05	5	β
157 01	1	I_3	213 95	=	
158 95	=		214 55	÷	
159 42	STO		215 43	RCL	
160 01	1	∧	216 01	1	
161 05	5	β	217 00	0	I_2
162 43	RCL		218 95	=	
163 00	0		219 42	STO	
164 02	2	SUNSHINE FRACTION S	220 00	0	
165 90	*IF ZRO	TEST S FOR MODE	221 03	3	
166 01	1		222 98	*PRT	PRINT (DISPLAY) CN
167 07	7		223 81	HLT	STOP

SR-52 PROGRAM FLOW CHART
DETERMINISTIC INSOLATION ESTIMATES: 1. CLEARNESS NUMBER AND CLOUD FACTOR



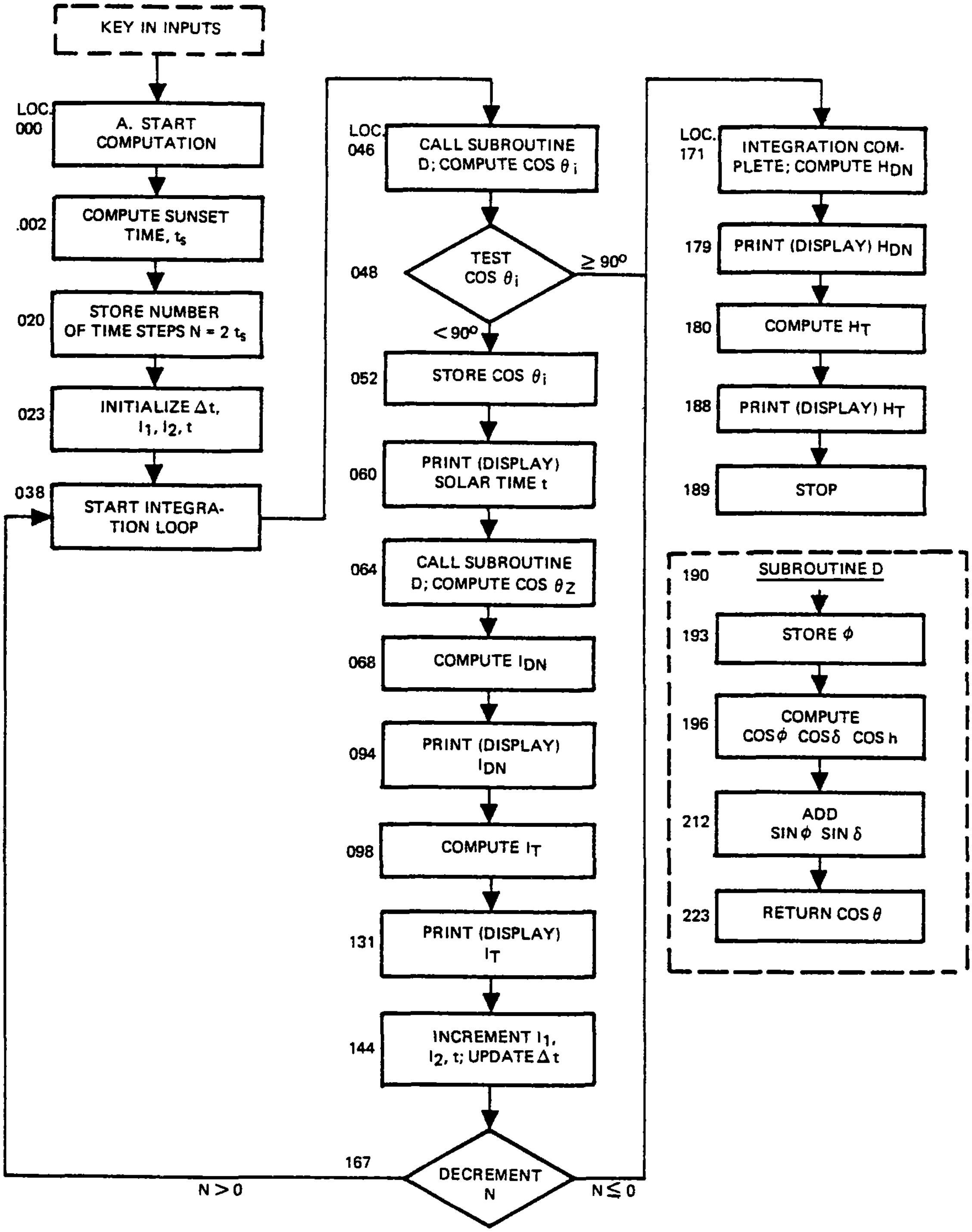
SR–52 PROGRAM LISTING
DETERMINISTIC INSOLATION ESTIMATES: 2. FLAT COLLECTORS AND TWO-AXIS TRACKERS

LOC. CODE	KEY	COMMENT	LOC. CODE	KEY	COMMENT
000 46	*LBL	START	056 01	1	
001 11	A		057 06	6	t
002 43	RCL	COMPUTE SUNSET TIME	058 57	*FIX	SET OUTPUT FORMAT
003 00	0		059 03	3	TO 3 DECIMAL PLACES
004 07	7	DECLINATION δ	060*98	*PRT	PRINT (DISPLAY) TIME
005 34	TAN		061 43	RCL	
006 65	X		062 00	0	
007 43	RCL		063 01	1	ϕ
008 00	0		064 14	D	COMPUTE COS θ_Z
009 01	1	LATITUDE ϕ	065 42	STO	
010 34	TAN		066 01	1	
011 95	=		067 07	7	
012 94	+/–		068 65	X	COMPUTE I_{DN}
013 22	INV		069 53	(	
014 33	COS	SUNSET HOUR ANGLE h	070 53	(	
015 55	÷		071 53	(	
016 07	7		072 20	*1/X	
017 93	.		073 94	+/–	
018 05	5		074 65	X	
019 95	=	N=2 X SUNSET HOUR	075 43	RCL	
020 42	STO	STORE ITERATION NO. N	076 00	0	
021 00	0		077 06	6	B
022 00	0		078 54	)	
023 93	.	INITIALIZE Δt, I_2	079 22	INV	
024 05	5	I_2, t	080 23	LUX	EXP $(-B/\text{COS}\,\theta_Z)$
025 42	STO		081 65	X	
026 01	1		082 43	RCL	
027 08	8	$\Delta t = .5$	083 00	0	
028 00	0		084 05	5	A/I_{SC}
029 42	STO		085 65	X	
030 00	0		086 43	RCL	
031 09	9	$I_1 = 0$	087 00	0	
032 42	STO		088 03	3	APPLY CLEARNESS NO. CN
033 01	1		089 65	X	
034 00	0	$I_2 = 0$	090 43	RCL	
035 42	STO		091 01	1	
036 01	1		092 09	9	SOLAR CONSTANT I_{SC}
037 06	6	t = 0	093 54	)	I_{DN}
038 43	RCL	START INTEGRATION LOOP	094*98	*PRT	PRINT (DISPLAY) I_{DN}
039 43	0		095 42	STO	
040 01	1		096 01	1	
041 75	–		097 03	3	
042 43	RCL		098 65	X	COMPUTE I_T
043 00	0		099 53	(	
044 02	2		100 43	RCL	
045 95	=	$\phi - T$	101 00	0	
046 14	D	COMPUTE COS θ_i	102 08	8	R
047 22	INV		103 55	÷	
048 80	*IF POS	IS $\theta_i > 90°$?	104 43	RCL	
049 01	1	YES, TRANSFER	105 09	9	
050 07	7		106 09	9	α/I_{SC}
051 01	1		107 75	–	
052 42	STO	NO, STORE COS θ_i	108 01	1	
053 01	1		109 54	)	
054 02	2		110 75	–	
055 43	RCL		112 43	RCL	

SR–52 PROGRAM LISTING
DETERMINISTIC INSOLATION ESTIMATES: 2. FLAT COLLECTORS AND TWO-AXIS TRACKERS (CONTINUED)

LOC.	CODE	KEY	COMMENT	LOC.	CODE	KEY	COMMENT
112	09	9		168	00	0	
113	08	8	β/I_{SC}	169	03	3	IF N > 0 GO TO
114	65	X		170	08	8	LOC. 038
115	43	RCL		171	43	RCL	INTEGRATION COMPLETE
116	01	1		172	00	0	
117	09	9	I_{SC}	173	09	9	I_1
118	65	X		174	65	X	
119	43	RCL		175	43	RCL	
120	00	0		176	00	0	
121	09	8	R	177	04	4	APPLY CLOUD FACTOR CF
122	55			178	95	=	
123	43	RCL		179*	98	*PRT	PRINT (DISPLAY) H_{DN}
124	09	9		180	43	RCL	
125	09	9	α/I_{SC}	181	01	1	
126	54	)		182	00	0	I_2
127	95	=	DIFFUSE RADIATION	183	65	X	
128	85	+		184	43	RCL	
129	43	RCL		185	00	0	
130	01	1		186	04	4	APPLY CLOUD FACTOR CF
131	02	2	$\cos\theta_i$	187	95	=	
132	65	X		188*	98	*PRT	PRINT (DISPLAY) H_T
133	43	RCL		189	81	HLT	END OF MAIN PROGRAM
134	01	1		190	46	*LBL	SUBROUTINE D
135	03	3	I_{DN}	191	14	D	
136	95	=	TOTAL RADIATION I_T	192	53	(	
137*	98	*PRT	PRINT (DISPLAY) I_T	193	42	STO	
138	99	*PAP	SPACE	194	01	1	
139	65	X		195	05	5	STORE ϕ, $\phi-T$
140	43	RCL		196	33	COS	$\cos\phi$, $\phi-T$
141	01	1		197	65	X	
142	08	8	Δt	198	43	RCL	
143	95	=		199	00	0	
144	44	SUM		200	07	7	
145	01	1		201	33	COS	$\cos\delta$
146	01	0	INCREMENT I_2	202	65	X	
147	43	RCL		203	53	(	
148	01	1		204	01	1	
149	03	3	I_{DN}	205	05	5	
150	65	X		206	65	X	
151	43	RCL		207	43	RCL	
152	01	1		208	01	1	
153	08	8	Δt	209	06	6	t
154	95	=		210	54	)	HOUR ANGLE h
155	44	SUM		211	33	COS	COS h
156	00	0		212	85	+	
157	09	9	INCREMENT I_1	213	43	RCL	
158	01	1	$\Delta t = 1$	214	01	1	
159	42	STO		215	05	5	
160	01	1		216	32	SIN	$\sin\phi$, $\phi-T$
161	08	8		217	65	X	
162	93	0		218	43	RCL	
163	05	5		219	00	0	
164	44	SUM		220	07	?	$\sin\delta$
165	01	1		221	32	SIN	
166	06	6	INCREMENT t	222	54	)	$\cos\theta_Z$, $\cos\theta_i$
167	58	*dsz		223	56	*VTN	END OF SUB D

SR-52 PROGRAM FLOW CHART
DETERMINISTIC INSOLATION ESTIMATES: 2. FLAT COLLECTORS AND TWO-AXIS TRACKERS



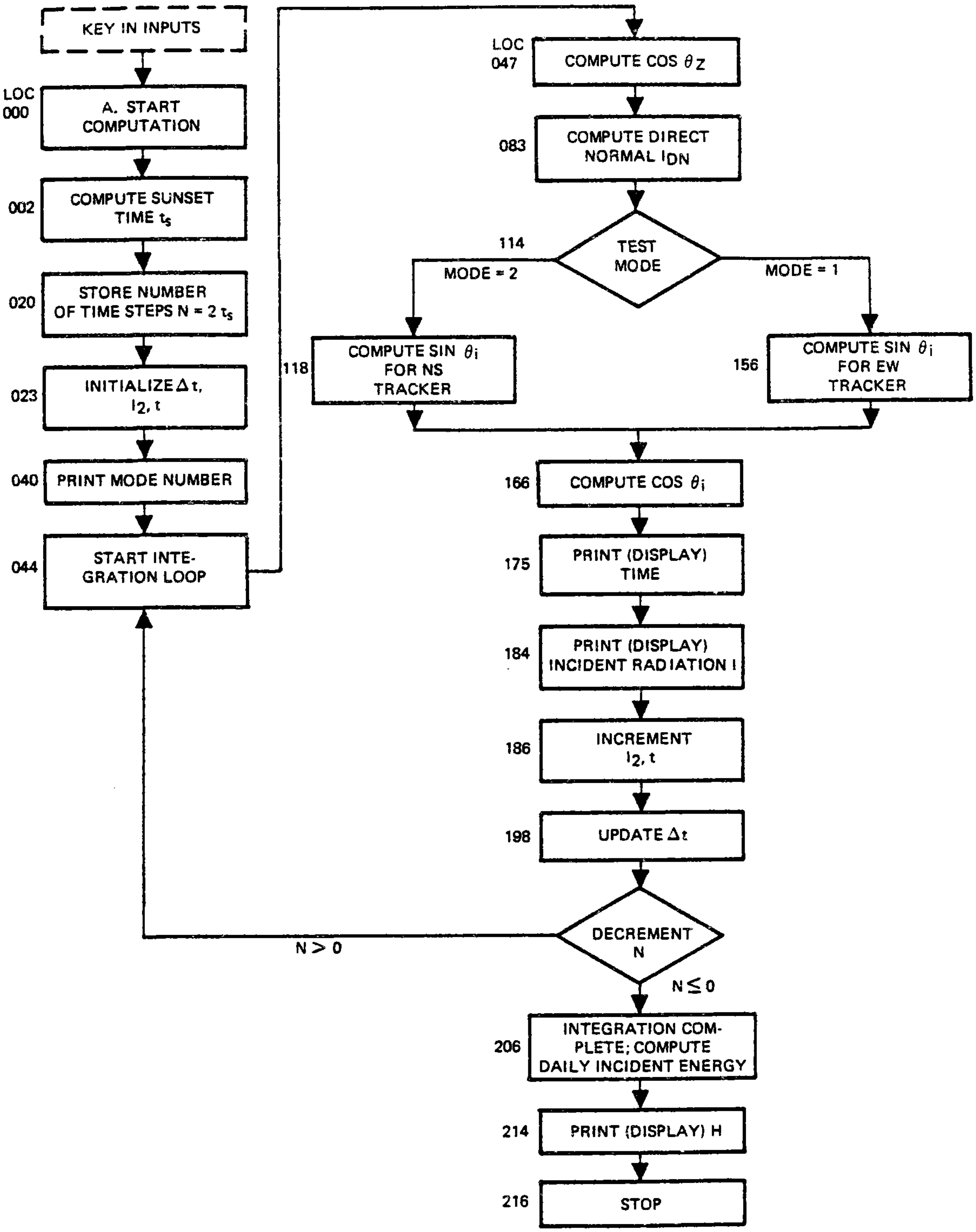
SR–52 PROGRAM LISTING
DETERMINISTIC INSOLATION ESTIMATES: 3. SINGLE-AXIS TRACKERS

LOC.	CODE	KEY	COMMENT	LOC.	CODE	KEY	COMMENT
000	46	*LBL	START	056	65	X	
001	11	A		057	53	(	
002	43	RCL	COMPUTE SUNSET TIME	058	01	1	
003	00	0		059	05	5	
004	07	7	DECLINATION δ	060	65	X	
005	34	TAN		061	43	RCL	
006	65	X		062	01	1	
007	43	RCL		063	06	6	
008	00	0		064	54	)	$h = 15\,t$
009	01	1	LATITUDE ϕ	065	42	STO	
010	34	TAN		066	01	1	
011	95	=		067	01	1	
012	94	+/–		068	33	COS	COS h
013	22	INV		069	85	+	
014	33	COS	SUNSET HOUR ANGLE h_s	070	43	RCL	
015	55	÷		071	00	0	
016	07	7		072	01	1	
017	93	.		073	32	SIN	SIN ϕ
018	05	5	N = 2 x SUNSET HOUR	074	65	X	
019	95	=		075	43	RCL	
020	42	STO		076	00	0	
021	00	0		077	07	7	
022	00	0	STORE INTERATION	078	32	SIN	SIN δ
023	93	.	NO. N	079	95	=	
024	05	5	INITIALIZE Δt, I_2, t	080	42	STO	
025	42	STO		081	01	1	
026	01	1		082	07	7	COSINE OF ZENITH ANGLE
027	08	8	$\Delta t = .5$	083	94	+/–	COMPUTE DIRECT NORMAL
028	00	0		084	20	*1/X	
029	42	STO		085	65	X	
030	01	1		086	43	RCL	
031	00	0	$I_2 = 0$	087	00	0	
032	42	STO		088	06	6	B
033	01	1		089	95	=	
034	06	6	t = 0	090	22	INV	
035	57	*FIX		091	23	LUX	EXP $(-B/\cos\theta_Z)$
036	00	0		092	65	X	
037	43	RCL		093	43	RCL	
038	00	0		094	00	0	
039	09	9		095	05	5	A/I_{SC}
040	98	*PRT	PRINT MODE NO.	096	65	X	
041	99	*PAP	SPACE	097	43	RCL	
042	57	*FIX	SET OUTPUT FORMAT TO	098	00	0	
043	03	3	3 DECIMAL PLACES	099	03	3	APPLY CLEARNESS NO. CN
044	43	RCL	START INTEGRATION LOOP	100	65	X	
045	00	0		101	43	RCL	
046	01	1		102	01	1	
047	33	COS	COS ϕ	103	09	9	SOLAR CONSTANT I_{SC}
048	65	X		104	95	=	
049	43	RCL		105	42	STO	
050	00	0		106	01	1	
051	07	7		107	03	3	DIRECT NORMAL I_{DN}
052	33	COS	COS δ	108	43	RCL	
053	42	STO		109	00	0	
054	01	1		110	09	9	
055	04	4		111	75	–	MODE NO.

SR–52 PROGRAM LISTING
DETERMINISTIC INSOLATION ESTIMATES: 3. SINGLE-AXIS TRACKERS (CONTINUED)

LOC.	CODE	KEY	COMMENT	LOC.	CODE	KEY	COMMENT
112	01	1		168	33	COS	
113	95	=		169	42	STO	
114	90	*IF ZRO	IF MODE = 1	170	01	1	
115	01	1	GO TO LOC. 156	171	02	2	COSINE OF INCIDENCE ANGLE
116	05	5		172	43	RCL	
117	06	6		173	01	1	
118	53	(	IF MODE = 2	174	06	6	
119	43	RCL	(NORTH-SOUTH TRACKER)	175*	98	*PRT	PRINT TIME
120	01	1		176	43	RCL	
121	01	1		177	01	1	
122	33	COS	COS h	178	02	2	COS θ_i
123	65	X		179	65	X	
124	53	(		180	43	RCL	
125	43	RCL		181	01	1	
126	00	0		182	03	3	I_{DN}
127	01	1	ϕ	183	65	X	
128	75	–		184*	98	*PRT	PRINT INCIDENT RADIATION
129	43	RCL		185	99	*PAP	
130	00	0		186	43	RCL	
131	02	2		187	01	1	
132	54	)	T	188	08	8	Δt
133	42	STO		189	95	=	
134	01	1		190	44	SUM	INCREMENT I_2
135	05	5	(ϕ –T)	191	01	1	
136	32	SIN	SIN (ϕ–T)	192	00	0	
137	65	X		193	93	.	
138	43	RCL		194	05	5	
139	01	1		195	44	SUM	INCREMENT t
140	04	4	COS δ	196	01	1	
141	75	–		197	06	6	
142	43	RCL		198	01	1	
143	00	0		199	42	STO	
144	07	7		200	01	1	
145	32	SIN	SIN δ	201	08	8	$\Delta t = 1$
146	65	X		202	58	*DEG	IF N>0 GO TO
147	43	RCL		203	00	0	LOC. 044
148	01	1		204	04	4	
149	05	5		205	04	4	
150	33	COS	COS (ϕ–T)	206	43	RCL	
151	54	)	SINE OF INCIDENCE ANGLE	207	01	1	
152	41	GTO		208	00	0	I_2
153	01	1	GO TO LOC. 166	209	65	X	
154	06	6		210	43	RCL	APPLY CLOUD FACTOR
155	06	6		211	00	0	
156	53	(	MODE = 1	212	04	4	CF
157	43	RCL	(EAST-WEST TRACKER)	213	95	=	
158	01	1		214	98	*PRT	PRINT DAILY INCIDENT ENERGY
159	01	1		215	99	*PAP	SPACE
160	32	SIN	SIN h	216	81	HLT	STOP
161	65	X					
162	43	RCL					
163	01	1					
164	04	4	COS δ				
165	54	)	SINE OF INCIDENCE ANGLE				
166	22	INV					
167	32	SIN					

SR–52 PROGRAM FLOW CHART
DETERMINISTIC INSOLATION ESTIMATES: 3. SINGLE-AXIS TRACKERS



5.0 INSTALLATION ENVIRONMENT

5.1 ELECTRIC POWER

The SR-52 calculator may be operated on batteries, independent of any external power source. If an inverter or printer is used, a standard 115 V ac/ 60 Hz outlet is required.

5.2 MAGNETIC CARDS

Program instructions are contained in the keystroke sequences given in the Program Listings (Section 4.3), and can be entered into the calculator directly using the following procedure:

Keystroke Sequence	Display	Comment
1. CLR *reset	0	Set calculator to beginning of memory
2. LRN	000 00	Enter "learn" mode
3. *LBL A, etc.	002 00	Begin keystroke sequence

It is more convenient to enter instructions by magnetic card. Each module is contained on both the A and B sides of a single card. The two sides are read in sequence by carrying out the keystroke operations described in the section on sample problems and inserting the appropriate end of the card into the slot on the right side of the calculator.

REFERENCES

1. AI-DOE-13230, "Commercial Applications of Solar Total Energy Systems," DOE Contract EY-76-C-03-1210 Final Report Volume 1 (July 1978)

2. AI-78-18, Solar Thermal, "Manual for the Solar Total Energy Systems Evaluation Program (STESEP)" (July 1978)

3. Eldon C. Boes, et al., "Availability of Direct, Total and Diffused Solar Radiation to Fixed and Tracking Collectors in the USA." Sandia Laboratories Energy Report, SAND 77-0885 (August 1977)

4. John A. Duffie and William A. Beckman, Solar Energy Processes, John Wiley, New York, 1974. pp 8-18

5. ASHRAE Handbook of Fundamentals, ASHRAE, pp 386-394 (1972)

6. "Solar Thermal Conversion Mission Analysis, Volume III. South-Western United States Insolation Climatology," Aerospace Corporation Report ATR - 74 (7417-16) - 2, Vol III (November 15, 1974)

7. "Terrestrial Photovoltaic Power Systems with Sunlight Concentration," Annual Progress Report for Period January 1, 1975, to December 31, 1975, ERDA Contract No. E(11-1)-2590, ERDA Report No. CDO-2590-1(2)

8. "Climatic Atlas of the United States," U.S. Department of Commerce, pp 69-70 (June 1968)

GLOSSARY

Symbol		Description
A	=	apparent extraterrestrial irradiation, kW/m^2
B	=	atmospheric extinction coefficient per air mass
CF	=	cloud factor
CN	=	clearness number
h	=	hour angle, degrees
H	=	daily average incident or net energy, kWh/m^2-day
$\hat{H}$	=	defined by Equation 8
H_{DN}	=	daily average of direct normal energy, kWh/m^2-day
H_h	=	daily average of total horizontal energy, kWh/m^2-day
I_1	=	first solar integral, $\int A \exp(-B/\cos\theta_z)dt$
I_2	=	second solar integral, $\int A \exp(-B/\cos\theta_z)\cos\theta_z\, dt$
I_3	=	third solar integral, $\int \cos\theta_z\, dt$
I_{DF}	=	diffuse radiation intensity, kW/m^2
I_{DN}	=	direct normal intensity, kW/m^2
I_{SC}	=	solar constant, 1.353 kW/m^2
N	=	number of integration time steps
n	=	day of year
R	=	earth-sun distance correction
T	=	tilt angle, degrees
t	=	time, hours
Δt	=	time increment, hours
α	=	first coefficient (Equation 5), kW/m^2; (α/I_{SC} = 1.33)
β	=	second coefficient (Equation 5), kW/m^2; (β/I_S = -0.384)
$\hat{\beta}$	=	defined by Equation 8
δ	=	solar declination, degrees
θ_i	=	solar incidence angle, degrees
θ_z	=	solar zenith angle, degrees
ϕ	=	latitude, degrees

APPENDIX – CLIMATE AND INSOLATION SUMMARIES

One-page summaries of the significant climatic and insolation parameters have been prepared for the twelve sites which are representative of the continental United States. The summaries are contained in Tables A-1 through A-12. In the following, the sources of the data and methods of presentations are discussed.

Geographical information is limited to the site (city) name and the latitude and longitude. The latter are generally associated with the reporting weather station. The ASHRAE design conditions are included (e.g., winter dry bulb and wind severity, summer dry bulb and wet bulb conditions).

Heating and cooling degree days based on long-term averages are included for each month of the year (65^{o}F base). Similar long-term averages of percent possible sunshine and average ambient temperature maxima and minima are also provided by month.

Both total horizontal and direct normal values of incident radiation are presented for each month. These values were obtained from two-year averages of the Aerospace Corporation tapes. In each case, only the horizontal values are directly measured. The direct normal values are inferred by means of correlations.

The clearness number and cloud factor parameters are obtained directly from the values of incident radiation, using the deterministic method. Cloud factors are obtained from average percent sunshine.

Table A-13 lists the sources used to supply the data presented in the climate and insolation summaries. In certain cases, it was necessary to substitute data from nearby sites of similar climatology. In such cases, the substitute is indicated in parenthesis. For dry bulb temperatures, a slight adjustment was sometimes made if the mean temperature at the substitute site differed significantly.

CLIMATE AND INSOLATION SUMMARY

TABLE A-1 ________.

SITE NAME ALBUQUERQUE, N.M. ________ LATITUDE 35.05° LONGITUDE 106.62°

ASHRAE DESIGN CONDITION:

WINTER – 97 1/2%

DRY BULB TEMP 8.3 °C, 94 °F;

WIND SPEED LOW

SUMMER – 2 1/2%

DRY BULB TEMP 34.4 °C, 94 °F;

WET BULB TEMP 18.3 °C, 65 °F

DESIGN RELATIVE HUMIDITY 20 %

DEGREE DAYS:

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
HEATING	°C	513	389	331	156	32	0	0	0	4	121	342	496
	°F	924	700	595	282	58	0	0	0	7	218	615	893
COOLING	°C	0	0	0	3	37	162	236	200	89	4	0	0
	°F	0	0	0	6	67	291	425	360	160	7	0	0

PERCENT POSSIBLE SUNSHINE:

70	72	72	76	79	84	76	75	81	80	79	70

AVERAGE AMBIENT TEMPERATURE RANGE:

MAX D.B.	°C	8.0	11.2	14.9	20.6	25.7	31.4	32.9	31.1	27.9	21.5	13.4	9.1
	°F	46.4	52.2	58.8	69.1	78.3	88.6	91.2	88.0	82.3	70.7	56.1	48.3
MIN D.B.	°C	-4.7	-2.5	0.4	5.7	11.1	16.2	18.8	17.9	14.2	7.4	-0.5	-3.6
	°F	23.5	27.5	32.7	42.2	51.5	61.1	65.8	64.3	57.6	45.3	31.1	25.6

AVERAGE DAILY INCIDENT RADIATION:

HORIZ	kWh/m2	3.58	4.50	6.00	7.30	8.29	8.63	7.39	7.23	5.87	6.23	3.80	3.48
	Btu/ft2	1136	1427	1903	2116	2630	2738	2343	2292	1861	1658	1205	1105
DIRECT	kWh/m2	6.77	7.11	8.48	9.10	10.00	10.40	8.43	8.90	7.37	8.19	6.90	7.23
	Btu/ft2	2149	2254	2591	2887	3172	3299	2691	2824	2337	2599	2189	2292

EFFECTIVE ATMOSPHERE FACTORS:

CLEARNESS NO.	0.96	0.87	0.99	0.92	1.17	1.17	1.03	1.10	0.93	1.05	0.97	1.14
CLOUD FACTOR	0.84	0.85	0.85	0.87	0.89	0.92	0.87	0.866	0.90	0.89	0.89	0.84

CLIMATE AND INSOLATION SUMMARY

TABLE A-2.

SITE NAME BLUE HILL, MASS. LATITUDE 42.22° LONGITUDE 71.02°

ASHRAE DESIGN CONDITION:

WINTER – 97 1/2%

DRY BULB TEMP -12.2 °C, 10 °F;

WIND SPEED HIGH

SUMMER – 2 1/2%

DRY BULB TEMP 31.1 °C, 88 °F; } DESIGN RELATIVE HUMIDITY 50 %

WET BULB TEMP 23.3 °C, 74 °F }

DEGREE DAYS:

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
HEATING	°C	668	583	513	312	151	30	3	8	62	203	378	608
	°F	1203	1050	924	561	271	54	6	14	111	366	681	1094
COOLING	°C	0	0	0	0	6	38	108	83	18	0	0	0
	°F	0	0	0	0	10	69	195	150	33	0	0	0

PERCENT POSSIBLE SUNSHINE:

47	56	57	56	59	62	64	63	61	58	48	48

AVERAGE AMBIENT TEMPERATURE RANGE:

MAX D.B.	°C	2.8	2.8	7.2	13.3	20.	24.4	27.8	26.7	22.8	17.2	11.1	4.4
	°F	37	37	45	56	68	76	82	80	73	63	52	40
MIN D.B.	°C	-5	-5	-.6	4.4	10	15	18.3	17.2	13.9	8.3	3.3	-2.8
	°F	23	23	31	40	50	59	65	63	57	47	38	27

AVERAGE DAILY INCIDENT RADIATION:

HORIZ	kWh/m^2	1.87	2.68	4.03	5.07	6.00	6.33	5.71	5.23	4.17	3.35	1.71	1.90
	Btu/ft^2	593	850	1278	1608	1903	2008	1811	1659	1323	1063	542	603
DIRECT	kWh/m^2	4.06	4.64	5.94	6.33	7.03	7.10	6.42	6.42	5.60	5.48	3.42	4.26
	Btu/ft^2	1288	1472	1884	2008	2230	2252	2036	2036	1776	1738	1085	1351

EFFECTIVE ATMOSPHERE FACTORS:

CLEARNESS NO.	0.74	0.61	0.75	0.82	0.91	0.92	0.79	0.81	0.81	0.92	0.62	1.05
CLOUD FACTOR	0.69	0.75	0.76	0.75	0.77	0.79	0.80	0.79	0.78	0.76	0.70	0.69

CLIMATE AND INSOLATION SUMMARY

TABLE A-3

SITE NAME FT. WORTH, TEXAS LATITUDE 32.83° LONGITUDE 97.05°

ASHRAE DESIGN CONDITION:

WINTER – 97 1/2%

DRY BULB TEMP -4.4 °C, 24 °F;

WIND SPEED HIGH

SUMMER – 2 1/2%

DRY BULB TEMP 37.8 °C, 100 °F;

WET BULB TEMP 25.6 °C, 78 °F

DESIGN RELATIVE HUMIDITY 40 %

DEGREE DAYS:

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
HEATING	°C	348	253	186	49	0	0	0	0	0	33	159	294
	°F	626	456	335	88	0	0	0	0	0	60	287	530
COOLING	°C	0	0	14	52	131	260	341	343	212	78	6	0
	°F	0	0	25	94	236	468	614	617	381	141	11	0

PERCENT POSSIBLE SUNSHINE:

56	57	65	66	67	75	78	78	74	70	63	58

AVERAGE AMBIENT TEMPERATURE RANGE:

MAX D.B.	°C	13.3	15.6	19.4	24.4	28.3	33.3	35.6	35.6	31.7	26.1	18.9	14.4
	°F	56	60	67	76	83	92	96	96	89	79	66	58
MIN D.B.	°C	1.7	3.9	6.7	12.2	17.2	21.7	23.9	23.9	20	13.3	6.7	2.8
	°F	35	39	44	54	63	71	75	75	68	56	44	37

AVERAGE DAILY INCIDENT RADIATION:

HORIZ	kWh/m2	3.06	3.86	5.19	5.20	6.81	6.81	7.42	7.10	5.27	4.39	2.94	2.61
	Btu/ft2	971	1224	1646	1649	2160	2160	2354	2252	1672	1393	933	828
DIRECT	kWh/m2	5.10	5.61	6.71	5.67	7.55	7.58	8.65	8.74	6.47	6.42	4.61	4.55
	Btu/ft2	1618	1779	2128	1799	2395	2404	2744	2772	2052	2052	1462	1443

EFFECTIVE ATMOSPHERE FACTORS:

CLEARNESS NO.	0.78	0.75	0.81	0.66	0.97	0.87	1.0	1.02	0.79	0.81	0.66	0.71
CLOUD FACTOR	0.75	0.76	0.81	0.81	0.82	0.87	0.88	0.88	0.86	0.84	0.79	0.76

CLIMATE AND INSOLATION SUMMARY

TABLE A-4

SITE NAME LAKE CHARLES, LA. LATITUDE 30.12° LONGITUDE 93.22°

ASHRAE DESIGN CONDITION:

WINTER – 97 1/2%

DRY BULB TEMP 0.6 °C, 33 °F;

WIND SPEED MEDIUM

SUMMER – 2 1/2%

DRY BULB TEMP 33.9 °C, 93 °F; } DESIGN RELATIVE HUMIDITY 60 %

WET BULB TEMP 26.1 °C, 79 °F }

DEGREE DAYS:

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
HEATING	°C	231	170	111	14	0	0	0	0	0	20	98	188
	°F	415	306	200	26	0	0	0	0	0	36	177	338
COOLING	°C	12	16	30	79	176	262	299	296	223	106	18	4
	°F	21	29	54	143	316	471	539	533	402	191	33	7

PERCENT POSSIBLE SUNSHINE:

49	50	57	63	66	64	58	60	64	70	60	46

AVERAGE AMBIENT TEMPERATURE RANGE:

MAX D.B.	°C	17.8	19.4	21.7	25.6	28.9	32.2	32.8	32.8	30.6	26.7	21.1	18.3
	°F	64	67	71	78	84	90	91	91	87	80	70	65
MIN D.B.	°C	7.2	8.9	11.1	14.4	17.8	21.7	22.8	22.8	20.6	16.1	10	7.8
	°F	45	48	52	58	64	71	73	73	69	61	50	46

AVERAGE DAILY INCIDENT RADIATION:

HORIZ	kWh/m2	2.42	3.68	4.55	5.29	6.48	5.87	6.23	5.68	5.00	4.48	3.06	2.52
	Btu/ft2	766	1167	1443	1649	2055	1862	1976	1802	1586	1421	971	799
DIRECT	kWh/m2	3.35	4.89	4.54	5.53	7.29	6.43	7.10	6.68	5.83	5.94	4.35	3.87
	Btu/ft2	1063	1551	1729	1754	2312	2040	2252	2119	1849	1884	1380	1228

EFFECTIVE ATMOSPHERE FACTORS:

CLEARNESS NO.	0.48	0.70	0.68	0.67	0.90	0.77	0.96	0.85	0.77	0.76	0.64	0.69
CLOUD FACTOR	0.70	0.71	0.76	0.79	0.81	0.80	0.76	0.78	0.80	0.84	0.78	0.68

CLIMATE AND INSOLATION SUMMARY

TABLE A-5

SITE NAME LOS ANGELES, CA. LATITUDE 34.05° LONGITUDE 118.23°

ASHRAE DESIGN CONDITION:

WINTER – 97 1/2%

DRY BULB TEMP 6.7 °C, 44. °F;

WIND SPEED VERY LOW

SUMMER – 2 1/2%

DRY BULB TEMP 32.2 °C, 90. °F;

WET BULB TEMP 21.1 °C, 79. °F

DESIGN RELATIVE HUMIDITY 36 %

DEGREE DAYS:

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
HEATING	°C	149	115	106	69	33	14	0	0	3	19	63	121
	°F	268	207	190	124	60	25	0	0	5	35	113	218
COOLING	°C	6	8	6	14	28	64	143	157	131	78	24	0
	°F	10	14	10	25	51	115	258	282	236	140	44	0

PERCENT POSSIBLE SUNSHINE:

70	69	70	67	68	69	80	81	80	76	79	72

AVERAGE AMBIENT TEMPERATURE RANGE:

MAX D.B.	°C	18.3	18.9	20.3	21.4	22.9	25.1	28.5	28.5	28.0	25.2	22.9	19.7
	°F	65.0	66.0	68.6	70.6	73.3	77.1	83.3	83.3	82.4	77.3	73.3	67.5
MIN D.B.	°C	8.1	9.0	10.1	11.7	13.3	14.9	17.0	17.2	16.3	14.1	11.2	9.3
	°F	46.6	48.2	50.2	53.0	56.0	58.9	62.6	62.9	61.4	57.4	52.1	48.8

AVERAGE DAILY INCIDENT RADIATION:

HORIZ	kWh/m2	2.94	3.32	5.23	6.57	6.23	6.27	8.13	7.49	5.87	4.19	3.27	3.03
	Btu/ft2	931	1054	1658	2083	1975	1988	2579	2353	1861	1330	1036	962
DIRECT	kWh/m2	5.32	4.86	7.32	8.00	7.03	6.73	9.32	8.84	7.50	6.23	5.63	5.16
	Btu/ft2	1688	1541	2323	2538	2231	2136	2957	2804	2379	1975	1787	1637

EFFECTIVE ATMOSPHERE FACTORS:

CLEARNESS NO.	0.64	0.49	0.79	0.99	0.82	0.81	1.15	1.07	0.92	0.73	0.70	0.83
CLOUD FACTOR	0.84	0.83	0.84	0.82	0.83	0.83	0.89	0.90	0.89	0.87	0.89	0.85

CLIMATE AND INSOLATION SUMMARY

TABLE A-6

SITE NAME MADISON, WIS. LATITUDE 43.13° LONGITUDE 89.33°

ASHRAE DESIGN CONDITION:

WINTER – 97 1/2%

DRY BULB TEMP -20.6 °C, -5 °F;

WIND SPEED MEDIUM

SUMMER – 2 1/2%

DRY BULB TEMP 31.1 °C, 88 °F;
WET BULB TEMP 23.9 °C, 75 °F } DESIGN RELATIVE HUMIDITY 53 %

DEGREE DAYS:

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
HEATING	°C	830	696	599	328	165	40	8	22	96	263	505	742
	°F	1494	1252	1079	591	297	72	14	39	173	474	909	1336
COOLING	°C	0	0	0	0	10	53	96	86	8	3	0	0
	°F	0	0	0	0	18	96	172	154	14	6	0	0

PERCENT POSSIBLE SUNSHINE:

44	49	52	53	58	64	70	66	60	56	41	38

AVERAGE AMBIENT TEMPERATURE RANGE:

MAX D.B.	°C	-3.3	-2.2	2.8	11.7	18.9	24.4	28.3	27.2	22.2	16.1	5.6	-1.1
	°F	26	28	37	53	66	76	83	81	72	61	42	30
MIN D.B.	°C	-12.2	-12.2	-6.1	1.7	7.2	13.9	15.6	15	10.6	4.4	-2.2	-8.9
	°F	10	10	21	35	45	57	60	59	41	40	28	16

AVERAGE DAILY INCIDENT RADIATION:

HORIZ	kWh/m^2	1.77	2.46	3.68	5.47	6.03	7.13	6.71	6.16	4.50	3.26	1.80	1.56
	Btu/ft^2	563	780	1167	1734	1912	2260	2127	1953	1427	1033	571	495
DIRECT	kWh/m^2	3.52	4.18	5.10	6.90	7.29	8.67	8.19	7.97	6.30	5.26	3.43	3.35
	Btu/ft^2	1116	1325	1617	2187	2311	2448	2596	2526	1997	1667	1087	1062

EFFECTIVE ATMOSPHERE FACTORS:

CLEARNESS NO.	0.78	0.62	0.72	1.00	0.94	1.09	0.98	1.04	0.96	0.94	0.86	1.00
CLOUD FACTOR	0.66	0.70	0.72	0.73	0.76	0.80	0.84	0.81	0.78	0.75	0.64	0.62

CLIMATE AND INSOLATION SUMMARY

TABLE A-7

SITE NAME MIAMI, FLA. LATITUDE 25.80° LONGITUDE 80.27°

ASHRAE DESIGN CONDITION:

WINTER – 97 1/2%

DRY BULB TEMP 8.3 °C, 47 °F;

WIND SPEED MEDIUM

SUMMER – 2 1/2%

DRY BULB TEMP 32.2 °C, 90 °F;

WET BULB TEMP 26.1 °C, 79 °F

DESIGN RELATIVE HUMIDITY 65 %

DEGREE DAYS:

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
HEATING	°C	29	37	9	0	0	0	0	0	0	0	7	31
	°F	53	67	17	0	0	0	0	0	0	0	13	56
COOLING	°C	67	81	118	167	224	267	298	308	278	221	127	88
	°F	121	145	212	300	403	480	536	555	501	397	229	159

PERCENT POSSIBLE SUNSHINE:

66	72	73	73	68	62	65	67	62	62	65	65

AVERAGE AMBIENT TEMPERATURE RANGE:

MAX D.B.	°C	24.4	25.	26.7	28.3	29.4	31.1	31.7	32.2	31.1	29.4	26.7	25
	°F	76	77	80	83	85	88	89	90	88	85	80	77
MIN D.B.	°C	14.4	15.	16.1	18.9	21.1	23.3	23.9	23.9	23.9	21.7	18.3	15
	°F	58	59	61	66	70	74	75	75	75	71	65	59

AVERAGE DAILY INCIDENT RADIATION:

HORIZ	kWh/m2	3.81	4.79	5.90	6.67	6.68	5.97	6.42	5.71	4.80	4.90	3.80	3.65
	Btu/ft2	1205	1518	1870	2114	2118	1892	2035	1810	1522	1553	1205	1157
DIRECT	kWh/m2	5.52	6.50	7.32	7.47	7.55	6.63	7.19	6.10	5.27	6.48	5.20	5.58
	Btu/ft2	1750	2061	2320	2368	2393	2102	2279	1934	1671	2054	1648	1769

EFFECTIVE ATMOSPHERE FACTORS:

CLEARNESS NO.	0.69	0.70	0.80	0.89	0.93	0.83	0.92	0.76	0.68	0.86	0.71	0.76
CLOUD FACTOR	0.81	0.85	0.85	0.85	0.83	0.79	0.81	0.82	0.79	0.79	0.81	0.81

CLIMATE AND INSOLATION SUMMARY

TABLE A-8

SITE NAME NASHVILLE, TENN. LATITUDE 36.12° LONGITUDE 86.68°

ASHRAE DESIGN CONDITION:

WINTER – 97 1/2%

DRY BULB TEMP -8.9 °C, 16 °F;

WIND SPEED LOW

SUMMER – 2 1/2%

DRY BULB TEMP 35 °C, 95 °F;

WET BULB TEMP 25.6 °C, 78 °F

DESIGN RELATIVE HUMIDITY 50 %

DEGREE DAYS:

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
HEATING	°C	460	373	291	98	25	0	0	0	6	100	277	424
	°F	828	672	524	176	45	0	0	0	10	180	498	763
COOLING	°C	0	0	11	16	85	193	252	233	122	29	0	0
	°F	0	0	19	29	153	348	453	419	220	53	0	0

PERCENT POSSIBLE SUNSHINE:

42	47	54	60	65	69	69	68	69	65	55	42

AVERAGE AMBIENT TEMPERATURE RANGE:

MAX D.B.	°C	9.4	10.6	15	21.7	26.7	31.1	32.8	32.2	29.4	23.3	15	10
	°F	49	51	59	71	80	88	91	90	85	74	59	50
MIN D.B.	°C	-0.6	0.6	3.9	8.9	13.9	18.9	21.1	20.0	16.1	9.4	3.3	0
	°F	31	33	39	48	57	66	70	68	61	49	38	32

AVERAGE DAILY INCIDENT RADIATION:

HORIZ	kWh/m^2	1.97	2.89	3.71	5.07	6.13	5.77	5.90	5.61	4.37	3.87	1.94	1.84
	Btu/ft^2	625	917	1177	1608	1944	1830	1871	1779	1386	1228	615	584
DIRECT	kWh/m^2	3.26	4.04	4.48	5.63	6.68	5.90	6.19	6.23	5.03	5.39	2.90	3.06
	Btu/ft^2	1034	1281	1421	1786	2119	1871	1963	1976	1596	1710	920	971

EFFECTIVE ATMOSPHERE FACTORS:

CLEARNESS NO.	0.56	0.61	0.56	0.71	0.84	0.69	0.76	0.79	0.65	0.80	0.40	0.64
CLOUD FACTOR	0.65	0.69	0.74	0.78	0.81	0.83	0.83	0.83	0.83	0.81	0.74	0.65

CLIMATE AND INSOLATION SUMMARY

TABLE A-9

SITE NAME OMAHA, NEB. LATITUDE 41.37° LONGITUDE 96.02°

ASHRAE DESIGN CONDITION:

WINTER – 97 1/2%

DRY BULB TEMP -18.3 °C, -1 °F;

WIND SPEED MEDIUM

SUMMER – 2 1/2%

DRY BULB TEMP 34.4 °C, 94 °F;

WET BULB TEMP 25.6 °C, 78 °F

DESIGN RELATIVE HUMIDITY 53 %

DEGREE DAYS:

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
HEATING	°C	730	576	481	217	82	11	0	3	39	167	417	637
	°F	1314	1036	865	391	148	20	0	6	71	301	750	1147
COOLING	°C	0	0	0	6	48	131	210	186	61	11	0	0
	°F	0	0	0	10	86	236	378	334	110	19	0	0

PERCENT POSSIBLE SUNSHINE:

57	59	60	60	63	69	76	71	67	66	59	55

AVERAGE AMBIENT TEMPERATURE RANGE:

MAX D.B.	°C	1.7	3.9	9.4	17.8	23.9	29.4	33.9	32.2	27.8	21.1	11.1	5
	°F	35	39	49	64	75	85	93	90	82	70	52	41
MIN D.B.	°C	-8.3	-6.7	-1.7	5	11.1	17.2	20.6	19.4	13.9	7.2	-0.6	-5.
	°F	17	20	29	41	52	63	69	67	57	45	31	23

AVERAGE DAILY INCIDENT RADIATION:

HORIZ	kWh/m2	2.45	2.89	4.19	5.33	5.84	6.90	6.84	5.94	4.67	3.84	2.40	2.10
	Btu/ft2	777	916	1328	1690	1851	2187	2168	1883	1480	1217	761	666
DIRECT	kWh/m2	5.58	4.68	5.90	6.60	6.55	7.83	7.90	7.32	6.10	6.29	4.77	4.81
	Btu/ft2	1769	1484	1870	2092	2076	2482	2504	2320	1934	1994	1512	1525

EFFECTIVE ATMOSPHERE FACTORS:

CLEARNESS NO.	0.94	0.64	0.75	0.84	0.81	0.97	0.93	0.90	0.88	0.99	0.89	1.02
CLOUD FACTOR	0.76	0.77	0.78	0.78	0.79	0.83	0.87	0.84	0.82	0.81	0.77	0.74

CLIMATE AND INSOLATION SUMMARY

TABLE A-10

SITE NAME PHOENIX, ARIZ. LATITUDE 33.43° LONGITUDE 112.02°

ASHRAE DESIGN CONDITION:

WINTER – 97 1/2%

DRY BULB TEMP 1.1 °C, 34 °F;

WIND SPEED VERY LOW

SUMMER – 2 1/2%

DRY BULB TEMP 41.1 °C, 106 °F;

WET BULB TEMP 24.4 °C, 76 °F

DESIGN RELATIVE HUMIDITY 27 %

DEGREE DAYS:

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
HEATING	°C	238	162	103	33	0	0	0	0	0	9	101	216
	°F	428	292	185	60	0	0	0	0	0	17	182	388
COOLING	°C	0	8	12	78	197	327	451	415	313	133	14	0
	°F	0	14	21	141	355	588	812	747	564	240	26	0

PERCENT POSSIBLE SUNSHINE:

76	79	83	88	93	94	84	84	89	88	84	77

AVERAGE AMBIENT TEMPERATURE RANGE:

MAX D.B.	°C	17.8	20	23.9	28.9	33.9	38.9	40.6	38.9	36.7	30.6	23.3	18.9
	°F	64	68	75	84	93	102	105	102	98	87	74	66
MIN D.B.	°C	1.7	3.9	6.1	10	13.9	18.9	23.9	22.8	19.4	12.8	5.6	2.8
	°F	35	39	43	50	57	66	75	73	67	55	42	37

AVERAGE DAILY INCIDENT RADIATION:

HORIZ	kWh/m^2	3.61	4.50	5.97	7.23	8.00	8.10	7.74	6.87	5.93	5.13	3.74	3.42
	Btu/ft^2	1145	1427	1894	2293	2538	2569	2455	2179	1881	1627	1186	1085
DIRECT	kWh/m^2	6.42	6.86	8.16	8.97	9.65	9.67	9.19	8.26	7.43	7.81	6.39	6.65
	Btu/ft^2	2036	2176	2588	2845	3061	3067	2915	2620	2357	2477	2027	2109

EFFECTIVE ATMOSPHERE FACTORS:

CLEARNESS NO.	0.83	0.76	0.85	0.92	0.96	0.96	1.02	0.91	0.84	0.89	0.82	0.92
CLOUD FACTOR	0.87	0.89	0.91	0.94	0.96	0.97	0.92	0.92	0.94	0.94	0.92	0.88

CLIMATE AND INSOLATION SUMMARY

TABLE A-11

SITE NAME SEATTLE, WASH. LATITUDE 47.45° LONGITUDE 122.30°

ASHRAE DESIGN CONDITION:

WINTER – 97 1/2%

DRY BULB TEMP 0 °C, 32 °F;

WIND SPEED LOW

SUMMER – 2 1/2%

DRY BULB TEMP 26.1 °C, 79 °F;

WET BULB TEMP 18.3 °C, 65 °F

DESIGN RELATIVE HUMIDITY 47 %

DEGREE DAYS:

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
HEATING	°C	410	319	329	238	143	69	31	32	68	184	297	372
	°F	738	574	592	429	258	124	56	57	123	332	534	670
COOLING	°C	0	0	0	0	0	12	50	38	10	0	0	0
	°F	0	0	0	0	0	22	90	69	18	0	0	0

PERCENT POSSIBLE SUNSHINE:

27	34	42	48	53	48	62	56	53	36	28	24

AVERAGE AMBIENT TEMPERATURE RANGE:

MAX D.B.	°C	6.7	8.3	10.6	14.4	18.9	21.1	24.4	23.9	22.8	15.6	10.0	7.8
	°F	44.	47.	51.	58.	66.	70.	76.	75.	73.	60.	50.	46.
MIN D.B.	°C	0.6	1.7	2.2	5.0	7.2	10.0	12.2	12.2	8.3	6.7	3.3	2.2
	°F	33.	35.	36.	41.	45.	50.	54.	54.	47.	44.	38.	36.

AVERAGE DAILY INCIDENT RADIATION:

HORIZ	kWh/m2	1.19	1.96	3.10	4.20	5.94	6.00	6.19	5.13	4.03	2.19	1.10	0.84
	Btu/ft2	379	623	982	1332	1883	1903	1965	1627	1279	696	349	266
DIRECT	kWh/m2	2.68	3.46	4.52	5.10	7.00	6.97	7.45	6.45	5.70	3.48	2.20	1.90
	Btu/ft2	849	1099	1433	1618	2220	2210	2364	2046	1808	1105	698	604

EFFECTIVE ATMOSPHERE FACTORS:

CLEARNESS NO.	0.93	0.76	0.75	0.74	1.02	1.08	0.98	0.95	1.03	0.91	0.78	0.87
CLOUD FACTOR	0.52	0.58	0.65	0.69	0.73	0.69	0.79	0.75	0.73	0.60	0.53	0.49

CLIMATE AND INSOLATION SUMMARY

TABLE A-12

SITE NAME WASHINGTON, D.C. LATITUDE 38.89° LONGITUDE 77.03°

ASHRAE DESIGN CONDITION:

WINTER – 97 1/2%

DRY BULB TEMP -7.2 °C, 19 °F;

WIND SPEED MEDIUM

SUMMER – 2 1/2%

DRY BULB TEMP 33.3 °C, 92 °F;

WET BULB TEMP 25.0 °C, 77 °F

DESIGN RELATIVE HUMIDITY 55 %

DEGREE DAYS:

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
HEATING	°C	506	431	343	147	40	0	0	0	8	106	283	476
	°F	911	776	617	265	72	0	0	0	14	190	510	856
COOLING	°C	0		4	5	62	148	216	191	101	21	0	0
	°F	0	0	8	9	111	267	388	344	181	37	0	0

PERCENT POSSIBLE SUNSHINE:

JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
46	53	56	57	61	64	64	62	62	61	54	47

AVERAGE AMBIENT TEMPERATURE RANGE:

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
MAX D.B.	°C	6.7	7.8	12.2	18.9	24.4	28.3	30.6	29.4	26.1	20.	13.9	7.8
	°F	44	46	54	66	76	83	87	85	79	68	57	46
MIN D.B.	°C	-1.1	-1.7	2.2	7.8	13.3	18.3	20.6	20	16.1	10.	3.9	-0.6
	°F	30	29	36	46	56	65	69	68	61	50	39	31

AVERAGE DAILY INCIDENT RADIATION:

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
HORIZ	kWh/m2	2.20	2.90	4.20	5.20	5.70	6.40	5.90	5.40	4.60	3.50	2.30	2.00
	Btu/ft2	699	919	1331	1648	1807	2029	1870	1712	1458	1110	729	634
DIRECT	kWh/m2	3.80	4.10	5.00	5.70	5.60	6.40	5.50	5.50	5.20	4.70	3.60	3.60
	Btu/ft2	1205	1300	1585	1807	1775	2029	1744	1744	1648	1490	1141	1141

EFFECTIVE ATMOSPHERE FACTORS:

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
CLEARNESS NO.	0.78	0.62	0.74	0.81	0.79	0.90	0.82	0.83	0.85	0.80	0.73	0.85
CLOUD FACTOR	0.68	0.73	0.75	0.76	0.78	0.80	0.80	0.79	0.79	0.78	0.73	0.69

TABLE A-13

DATA SOURCES FOR CLIMATE AND INSOLATION SUMMARY DATA

Site	ASHRAE Design Conditions	Degree Days	Percent Sunshine	Dry Bulb Temperatures	Average Daily Incident Radiation
Lake Charles, La.	4*	2	1(New Orleans)	1(New Orleans)	5
Miami, Fla.	4	2	1	1	5
Nashville, Tenn.	4	2	1	1	5
Washington, D.C.	4	2	1	1	6
Albuquerque, N.M.	4	2	1	3	5
Ft. Worth, Texas	4	2	1		5
Los Angeles, Ca.	4	2	1	3	5
Phoenix, Ariz.	4	2	1	3	5
Blue Hill, Mass.	4(Boston)	2	1(Boston)	1(Boston)	5
Madison, Wis.	4	2	1	1(Green Bay + 1.2°F)	5
Omaha, Neb.	4	2	1(Lincoln)	1(Lincoln + 0.5°F)	5
Seattle, Wash.	4	2	1	1	5

*Data Source Legend References:

1. "Climatic Atlas of the United States," U.S. Department of Commerce (June 1968)
2. Climatography of the U.S., No.81 (By State), U.S. Department of Commerce (August 1973)
3. Local Climatological Data, U.S. Department of Commerce (1972)
4. ASHRAE Handbook of Fundamentals, ASHRAE (1972)
5. ERDA Report No. ERC-R-76005, "Terrestrial Photovoltaic Power Systems with Sunlight Concentration," Contract E(11-1)-2590 Arizona State U., Spectrolab, Inc.
6. Eldon C. Boes, et al, "Distribution of Direct and Total Solar Radiation Availabilities for the U.S.A," Sandia Laboratories Energy Report, SAND 76-0411 (1976)