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LAWRENCE LIVERMORE LABORATORY

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GUIDE FOR CALCULATING COLLECTION EFFICIENCY FOR THE SHALLOW SOLAR POND
(Applicable for Any Horizontal Flat Plate Solar Collector)

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DISCLAIMER

CONTENTS

I. Introduction

The collection efficiency, η_c, of a solar collector system is defined as the useful heat collected divided by the solar radiation incident on the top surface. For a particular collector geometry it will be dependent on the position of the sun during the day, the amount of cloudiness, the ambient air temperature, as well as the cleanliness of the top surface.

There are several methods described in the literature for the calculation of η_c. One method is to calculate η_c for a clear equinoxial day and solstice day[1]. Another method is to make the calculation for a set of selected clear days each month[2]. We have followed the method of Hottel and Whillier[3] and Liu and Jordan[4]. [Hereafter referred to as HW and LJI respectively.] They present a method of calculating the hourly rate of energy collection but also, more importantly, the long term monthly average collection efficiency based upon monthly average daily solar insolation data and day-time temperatures obtained from Weather Bureau data. This data is appended to LJI for some eighty localities in the U.S. and Canada. We feel that this method provides the most realistic values of collection efficiency which can be obtained for a given collector system in a given location. Not only is the monthly variation taken into account but also the statistical effect of bad weather. The description presented below is necessarily concise and one is referred to the references for additional discussion.

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[1] H. Tabor, Transactions of the Conference on the Use of Solar Energy — The Scientific Basis, II, Part I, Section A, 1955, pp. 1-23.

[2] E. R. G. Eckert, et al., Semi-Annual Progress Report prepared by University of Minnesota and Honeywell, supported by NSF (RANN). July 31, 1973. Report: NSF/RANN/SE/GI-34871/PR/73/2.

[3] H. C. Hottel and A. Whillier, Transactions of the Conference on the Use of Solar Energy — The Scientific Basis, II, Part I, Section A, 1955, pp. 74-104.

[4] B. Y. H. Liu and R. C. Jordan, Solar Energy 7 (2), 53 (1962). Also see article by same authors in Low Temperature Engineering Application of Solar Energy, published by American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., New York, N. Y., 1967

II. Solar Geometry

If θ is the solar angle of incidence (also called the zenith angle), δ the solar declination, ω the solar hour angle from solar noon (15° per hour), and L the latitude, then it can be shown by spherical trigonometry that,

$$\cos\theta = \cos L \cos\delta \cos\omega + \sin L \sin\delta \quad (1)$$

The sunset angle, ω_s, is obtained by setting $\cos\theta = 0$ in Eq. (1):

$$\cos\omega_s = -\tan L \tan\delta \quad (2)$$

The number of hours between sunrise and sunset is $2\,\omega_s{}^\circ\,(24/360) = 0.1333\,\omega_s{}^\circ$.

In the method of LJI the direct and diffuse solar radiation on the earth's surface are expressed as fractions of the radiation on a horizontal surface outside the earth's atmosphere. If I_{sc} is the solar constant; i.e., the intensity on a unit area normal to the sun's rays and at mean distance of the earth from the sun, then the intensity on a horizontal surface outside the atmosphere is

$$I_o = r\, I_{sc} \cos\theta \quad (3)$$

where r is the square of the ratio of the mean distance to the actual distance between earth and sun. The best present value of I_{sc} is 1353 w/m^2. Values of r and δ for the 15th of each month are given in Table I.

The average daily radiation* on a horizontal surface outside the earth's atmosphere is obtained by integrating Eq. (3), using the expression for $\cos\theta$ from Eq. (1):

*For all radiation values; instantaneous, average hourly, average daily, etc., we will use units of $watts/m^2$. LJI and most others use units of $BTU/hr\text{-}ft^2$ and $BTU/day\text{-}ft^2$. 1 $BTU/hr\text{-}ft^2$ = 3.153 w/m^2, 1 $BTU/day\text{-}ft^2$ = 0.1314 w/m^2.

$$H_o = \frac{r I_{sc}}{2\pi} \int_{-\omega_s}^{\omega_s} (\cos L \cos \delta \cos \omega + \sin L \sin \delta) d\omega$$

$$= \frac{r}{\pi} I_{sc} (\cos L \cos\delta \sin \omega_s + \omega_s \sin L \sin \delta) \quad (4)$$

Table I. Values of r and δ for the 15th of each month[a].

	r	δ
JANUARY	1.0336	-21°09'
FEBRUARY	1.0250	-12°43'
MARCH	1.0110	- 2°11'
APRIL	0.9934	9°44'
MAY	0.9785	18°51'
JUNE	0.9691	23°18'
JULY	0.9679	21°33'
AUGUST	0.9750	14°05'
SEPTEMBER	0.9889	3°01'
OCTOBER	1.0058	- 8°32'
NOVEMBER	1.0222	-18°28'
DECEMBER	1.0323	-23°16'

a. From the 1974 Nautical Almanac.

III. Performance Equation (Collector Output)

If the total solar insolation (direct and diffuse) per unit horizontal area is I_T then the instantaneous rate of useful heat collection per unit area of pond is*:

*There should be an additional multiplicative term, F_R, which is the heat extraction efficiency for the particular collector. According to LJI, when water is used to remove the heat from the collector, $F_R \approx 0.9$, and when air is used, it is ≈ 0.8. We are particularly interested in the case of a shallow solar pond collector module where the water itself serves as the collector and $F_R = 1$.

$$q = I_T\,(\overline{\tau\alpha}) - U\,(T_c - T_a) \quad \text{watts/m}^2 \tag{5}$$

where $\overline{\tau\alpha}$ is the transmissivity-absorptivity product (fraction of I_T absorbed by pond water), suitably averaged for direct and diffuse radiation components, U is the overall heat loss coefficient (in w/m²°C) which will depend weakly on both T_c and T_a where T_c is the average water temperature of the pond and T_a is the ambient air temperature (°C). Evaluation of $\overline{\tau\alpha}$ and U will be discussed below.

From Eq. (5), the instantaneous value of the collection efficiency is

$$\eta_{ci} = \overline{\tau\alpha} - \frac{U\,(T_c - T_a)}{I_T} \tag{6}$$

If the solar insolation is so weak that it can just make up for the heat losses, then the collector pumping system will be turned off and there will be no heat collection. This critical intensity, I_c, is obtained by setting q = o in Eq. (5):

$$I = \frac{U\,(T_c - T_a)}{\overline{\tau\alpha}} \tag{7}$$

The critical intensity ratio is defined for later use as,

$$X_c = I_c/\bar{I}_T \tag{8}$$

where $\bar{I}_T$ is the average hourly total radiation*. Eq. (5) can now be written as

$$q = \overline{\tau\alpha}\,\left[I_T - I_c\right]^+ \tag{9}$$

Clearly, when I_T falls to I_c or below, no useful heat output is available.

To determine the long-term performance of the pond we need average hourly values of $\overline{\tau\alpha}$, I_T, I_c, and T_a. Then we can calculate the average hourly useful heat collection, $\bar{q}$, for any hour of any month. Weather

*In the statistical method described here, average values are usually understood to be "long-term", that is, averages taken over 3 to 5 years.

Bureau data is normally presented as monthly average daily total radiation on a horizontal surface, $\overline{H}$. From values of $\overline{H}$ it is possible to obtain, as discussed below, values of $\overline{I}_T$, the average hourly total radiation, for any hour of the day from solar noon. Hence we take one month as a period during which the mean air temperature and mean position of the sun, at a particular hour of day, do not vary excessively. Hence $(\overline{\tau\alpha})$ and I_c can be assumed to have the same average value during the same hour throughout the month. Then the value of $\overline{q}$ [for a particular hour of day from solar noon in a given month] is given by

$$\overline{q} = \overline{\tau\alpha}\,\overline{I}_T \left[(1/n) \sum_n \left(\frac{I_T}{\overline{I}_T} - \frac{I_c}{\overline{I}_T}\right)^+\right] \qquad (10)$$

where n is the total number of mornings and afternoons in the month and the + sign indicates that only positive values are used in the summation. (The two hours symmetrical with solar noon are assumed to be identical.)

Hottel and Whillier[3] first introduced this approach. They named the bracketed term "utilizability", ϕ. Hence,

$$\phi = (1/n) \sum_n \left[\frac{I_T}{\overline{I}_T} - \frac{I_c}{\overline{I}_T}\right]^+ \qquad (11)$$

If measured values of T_a, I_T (and hence $\overline{I}_T$) are available for every hour of a particular month, than a value of I_c can be calculated for each hour and hence values of ϕ can be determined for each hour. Note that ϕ is just the fraction of the total month's incidence on a horizontal surface, for one particular hour from solar noon, which arrives with sufficient intensity to justify collection. The average hourly heat collection can now be written

$$\overline{q} = \overline{\tau\alpha}\,\overline{I}_T\,\phi \qquad (12)$$

Note that the quantity $\overline{\tau\alpha}$ is a characteristic of the collector geometry and materials whereas the other two quantities are characteristics of the "solar weather".

If a graph of ϕ vs. $I_c/\bar{I}_T$ can be obtained for a particular month at a particular location, then for every hour a value of I_c can be calculated and, if $\bar{I}_T$ is known, then ϕ can be determined. For example, if we hypothesize a month of identical days, then $I_T \equiv \bar{I}_T$ and the ϕ vs. $I_c/\bar{I}_T$ is a straight line as shown below in Figure 1. For a month of variable weather the curve would lie above the straight line, as illustrated in the same figure.

Thus, for a month of identical days, if $I_c = I_T = \bar{I}_T$, then $\phi = 0$. However, for an actual month of variable weather, if $I_c/\bar{I}_T = 1$, there will be some days where the summation of Eq. (11) for the particular hour has a positive value as well as some days where it has a negative value (and hence not counted). So there will be a net positive value of ϕ. The more constant the weather is, the closer the curve will approach the straight line limit.

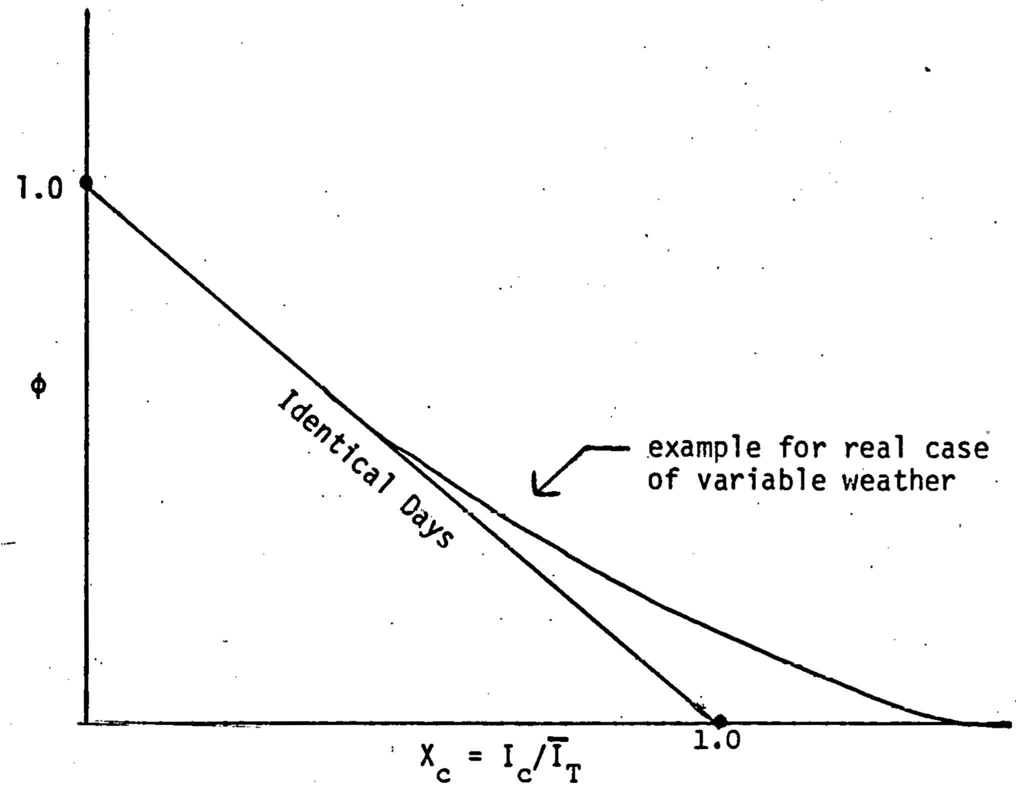

Figure 1. Examples of shape of ϕ function.

IV. Construction of ϕ Curves

Weather Bureau data generally consist of daily total radiation values only as well as average daily temperatures*. HW and LJI give a procedure for constructing generalized ϕ vs. I_c/I_T curves which are applicable to any locality where monthly average daily total radiation data are available. This procedure will be briefly outlined here. For more detail one is referred to the above listed papers plus a paper on solar weather by Liu and Jordan[5]. (LJ2)

LJ2 show that a well-defined empirical relationship exists between the average daily diffuse radiation, $\overline{D}$, and the average total radiation, $\overline{H}$. Defining $\overline{K}_T = \overline{H}/H_o$ and $\overline{K}_d = \overline{D}/H_o$, the relation between $\overline{K}_T$ and $\overline{K}_d$ is given in Table II. The value of $\overline{K}_T$ is a sort of "cloudiness index". A locality may be considered to be extremely cloudy if $\overline{K}_T = 0.30$. On the other hand, it is a very sunny locality that has $\overline{K}_T \geq 0.70$.

Table II. Relation between $\overline{K}_T$ and $\overline{K}_d$

$\overline{K}_T$	0.3	0.4	0.5	0.6	0.7	0.75
$\overline{K}_d$	0.179	0.183	0.188	0.174	0.149	0.125

Hence if we are given values of the monthly average daily total radiation, $\overline{H}$, we can calculate $\overline{K}_T = \overline{H}/H_o$ and from Table II we can then determine $\overline{K}_d = \overline{D}/H_o$. From this we can determine $\overline{D}$. (This will be required later in the calculation of $\overline{\tau\alpha}$.)

Next, it is necessary to obtain relationships between hourly total and daily total radiation and between hourly diffuse and daily diffuse radiation. These have been established, on the basis of long-term weather

*For a few communities in the U.S., hourly total insolation data and hourly temperature data are available over a period of several years.

[5] B. Y. H. Liu and R. C. Jordan, Solar Energy 4 (3), 1, July 1960.

data by LJ2 and HW. LJ2 assume that, just as $\overline{D} = \overline{K}_d H_o$, so also $\overline{I}_d = \overline{K}_d I_o$. Therefore $r_d = \overline{I}_d/\overline{D} = I_o/H_o$. The expression for H_o is given in Eq. (4) and by a similar integration we can obtain

$$I_o = \frac{rI_{sc}}{24} (\cos L \cos \delta \cos \omega + \sin L \sin \delta) \tag{13}$$

which gives

$$r_d = \frac{\overline{I}_d}{\overline{D}} = \frac{I_o}{H_o} = \frac{\pi}{24} \frac{\cos \omega - \cos \omega_s}{\sin \omega_s - \omega_s \cos \omega_s} \tag{14}$$

where $\cos \omega_s$ is given by Eq. (2).

In Figure 2 from LJ2 the solid curves are Eq. (14) and the experimental data points are from the two weather stations listed. Agreement is seen to be good so that either Eq. (14) or Figure 2 can be used.

Unfortunately, Eq. (14) is not a good representation of $r_T = \overline{I}_T/\overline{H}$. HW obtained experimental values of r_T from several widely separated localities and the mean curves shown in Figure 3 are a good representation of the experimental data (deviation < ± 5%).

To summarize the procedure up to this point:

1) For a given latitude, calculate H_o for the 15th day of each month, using Eq. (4) and Table I.
2) For the given location, look in tables at back of LJ1 for values of $\overline{H}$ for each month.
3) Calculate values of $\overline{H}/H_o = \overline{K}_T$ for each month.
4) Use Table II to determine $\overline{K}_d = \overline{D}/H_o$. From this determine $\overline{D}$.
5) Use Eq. (14) or Figure 2 to determine r_d (and hence $\overline{I}_d$) for the middle of each hour from solar noon. This must be done for each month. Sunset hour angle given in Eq. (2).
6) Use Figure 3 to determine r_T (and hence $\overline{I}_T$) for the middle of each hour from solar noon and each month.

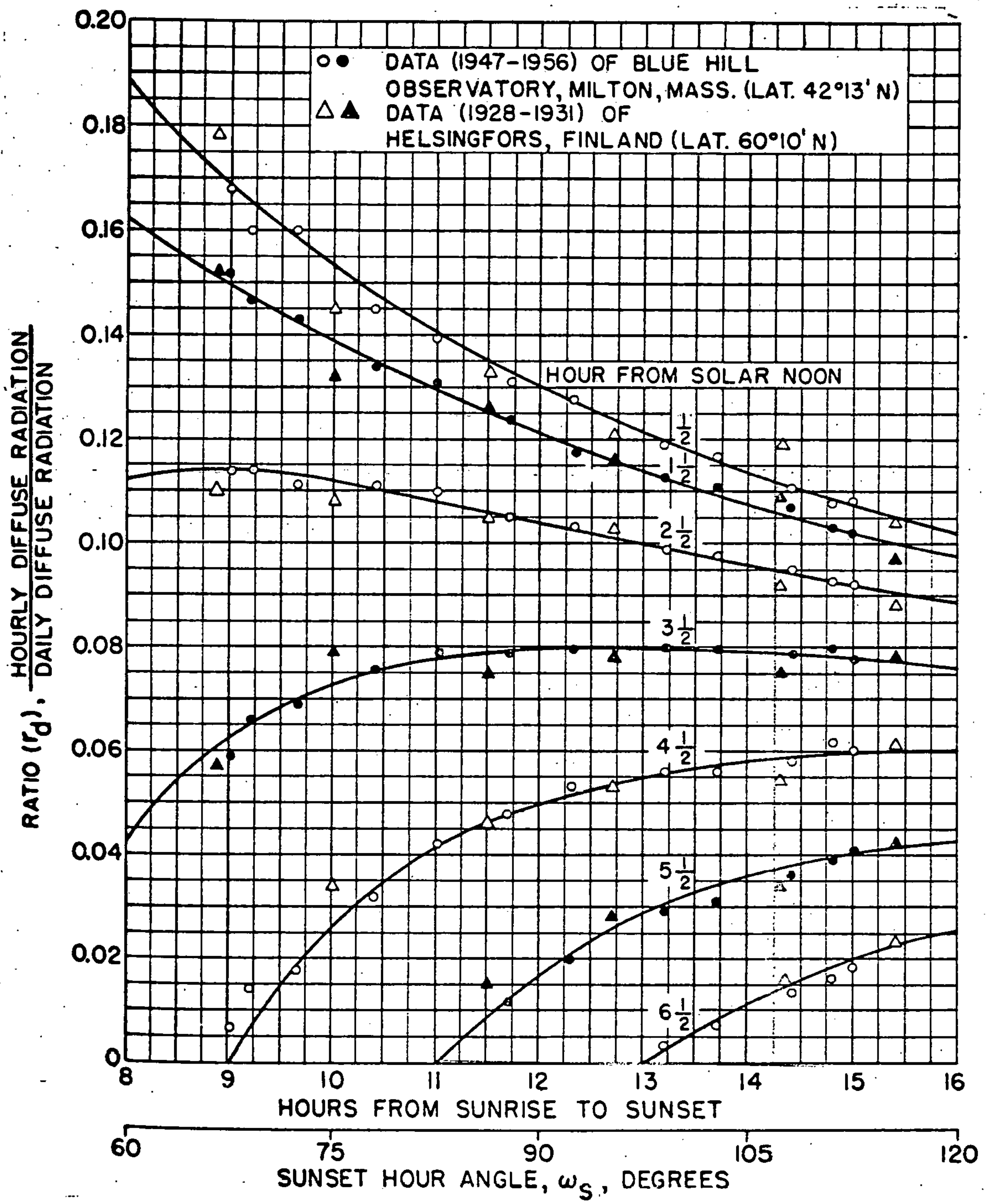

Figure 2. Theoretical and experimental ratio of the hourly diffuse radiation to the daily diffuse radiation. (Figure 15 from our reference 5)

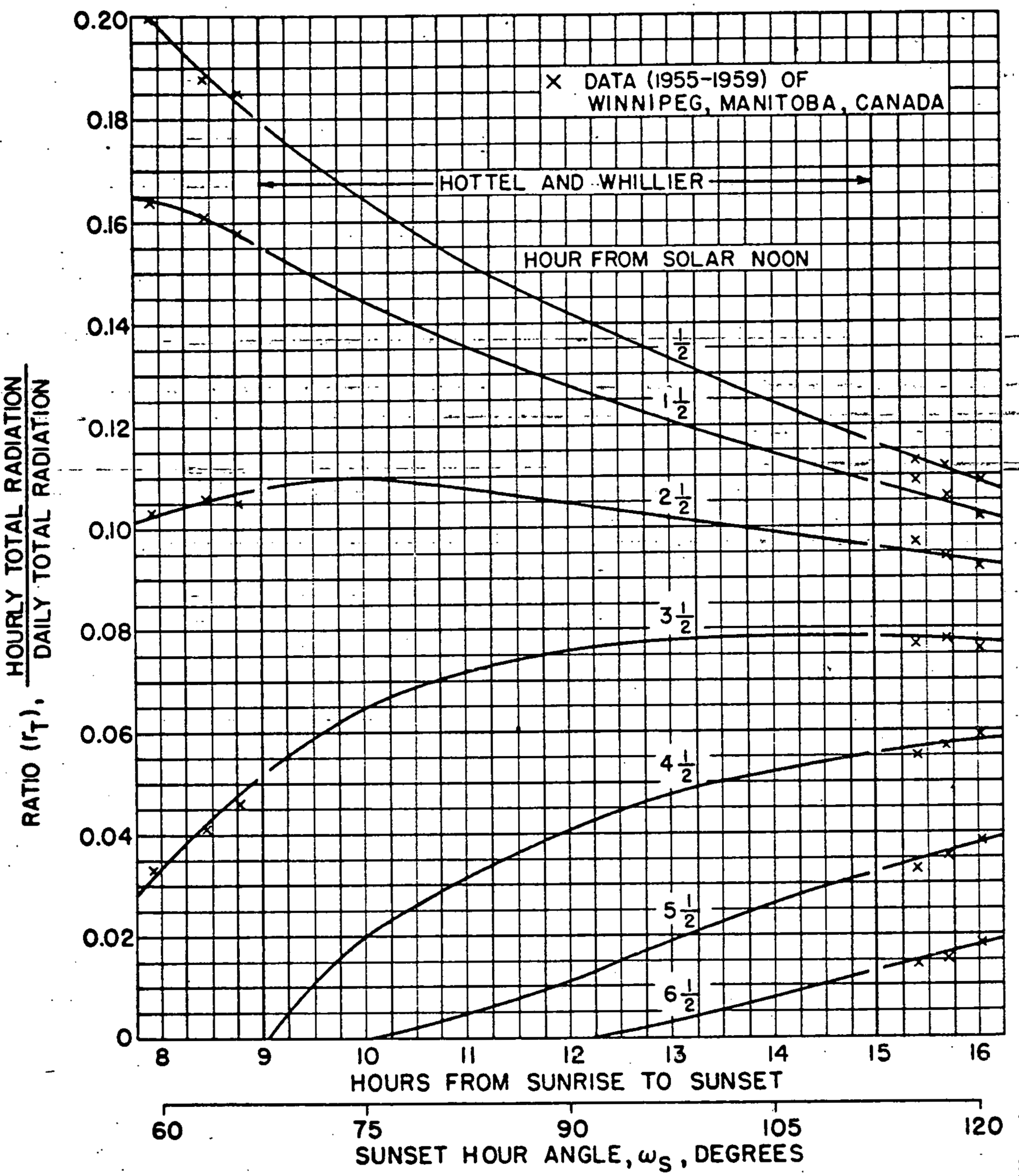

Figure 3. Experimental ratio of the hourly total radiation to the daily total radiation. (Figure 16 from our reference.5)

Now to proceed with determining the utilizability function, ϕ, LJ2 show that for widely different localities with about the same cloudiness index, $\overline{K}_T$, the statistical distribution over a month of daily total radiation, H, is very similar. From extensive experimental data of 27 localities, LJ2 construct a set of generalized radiation distribution curves shown in Figure 4. For each curve, representing a given value of the cloudiness factor $\overline{K}_T$, the ordinate gives $H/\overline{H}$ and the abscissae gives the fractional time f during the month for which the daily radiation is less than H. LJ2 find that, independent of the locality, as long as $\overline{K}_T$ has a given value, the appropriate curve from Figure 4 is an excellent representation of the statistical distribution of daily radiation.

It has been shown by HW that the distribution curves for hourly radiation are closely similar to those for daily data. Hence in Figure 4 the ordinate can also stand for $I_T/\overline{I}_T$ and the abscissae for fractional time f during the month for which the hourly radiation is less than I_T.

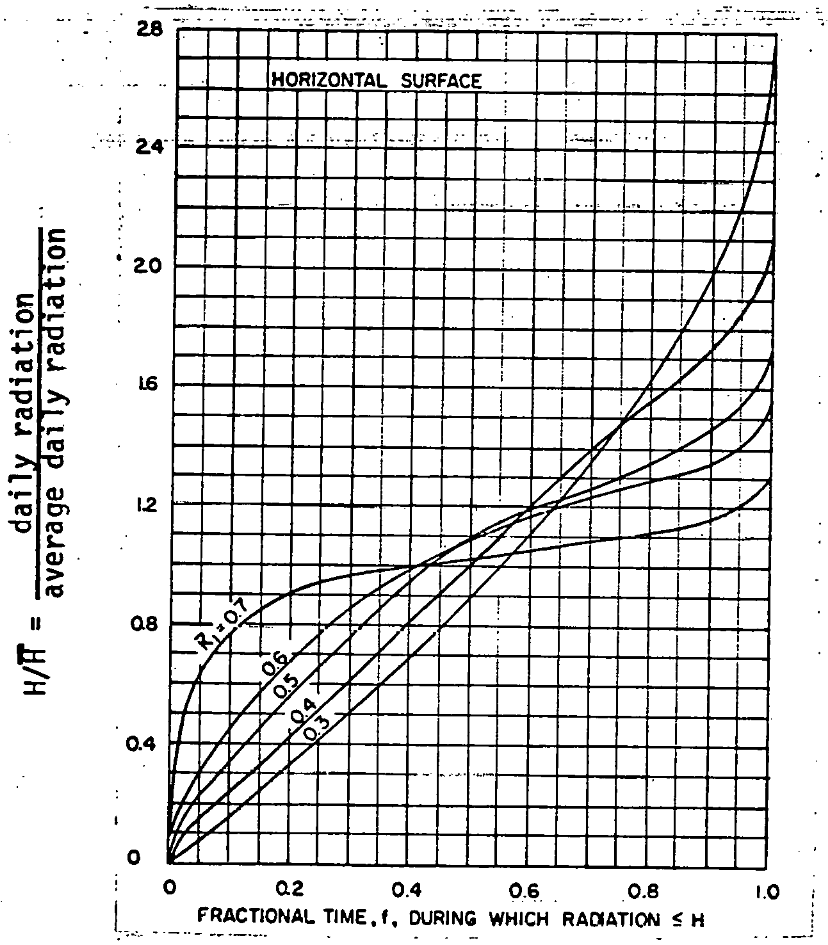

Figure 4. The generalized radiation distribution curves for a horizontal surface. (Figure 11 from our reference 4)

Defining f_c as the fractional time during the month for which the hourly radiation is less than I_c, the critical radiation intensity defined in Eq. (7), then we have

$$\phi = \int_{f_c}^{1} \left[\frac{I_T}{\overline{I}_T} - \frac{I_c}{\overline{I}_T}\right] df = \int_{f_c}^{1} \left[\frac{I_T}{\overline{I}_T} - X_c\right] df \qquad (15)$$

and hence ϕ vs. X_c curves can be constructed for various value of $\overline{K}_T$ using the distribution curves of Figure 4. These generalized utilizability curves are shown in Figure 5 for values of $\overline{K}_T$ from 0.3 through 0.7.

It must be emphasized that this use of generalized ϕ curves will give only the long-term average performance of the solar pond for a given month at a given location. LJ2 claim that the results of this technique will be quite reliable for localities where $\overline{K}_T$ is high (say 0.6 to 0.7). These are very sunny localities where the divergence of the ϕ curve from the straight line for a climate of identical days is small. It is in such localities where solar systems will be situated. In localities with extremely cloudy weather (low $\overline{K}_T$) the fluctuations from year to year about the generalized ϕ curve will be larger, hence introducing larger errors. However, these localities are of much less interest to us.

V. Calculation of $\overline{\tau\alpha}$

Assume that there are n layers of plastic or glass constituting the thermal blanket over the pond. The layers may be of different thickness but they must all have the same index of refraction. Then the transmittance of the cover is given by[6)]:

$$\tau = e^{-KL/\cos\theta}\left[(1 - r)/(1 + (2n - 1)r)\right] \qquad (16)$$

where K is the extinction coefficient of the material for the solar spectrum, L is the total thickness of the plastic or glass layers and r is

[6)] A. Whillier, Low Temperature Engineering Application of Solar Energy. See reference 4).

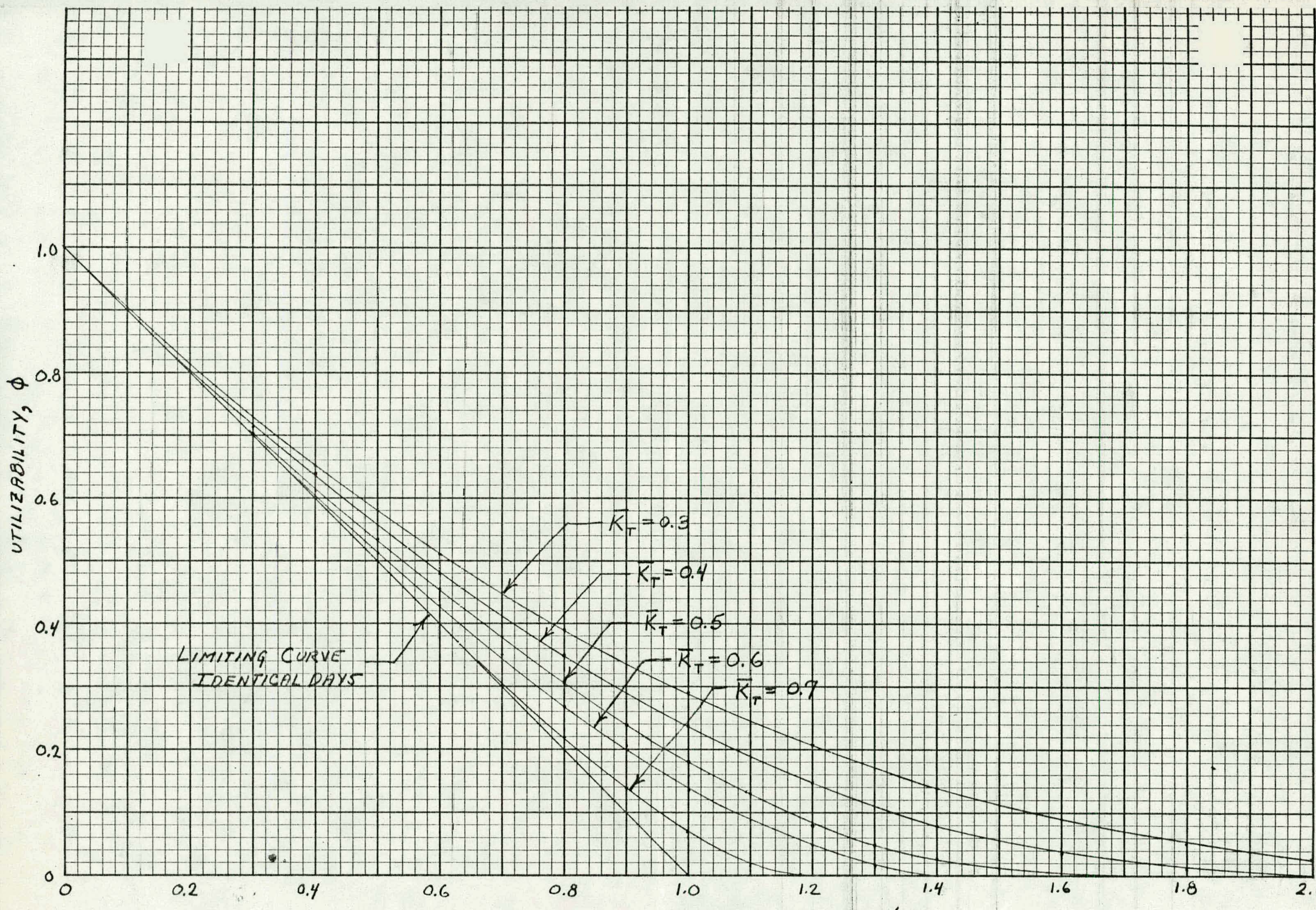

Fig. 5. Generalized utilizability curves for various values of $\bar{K}_T$.

the reflectivity of a single plastic or glass surface. The expression for r is derived from the Fresnel equations[6]:

$$r = \frac{1}{2}\left[\frac{\sin^2(\theta - \theta')}{\sin^2(\theta + \theta')} + \frac{\tan^2(\theta - \theta')}{\tan^2(\theta + \theta')}\right] \tag{17}$$

where θ and θ' are the incident and refracted angles, respectively, and $\sin\theta' = \sin\theta/n'$, where n' is the index of refraction of the plastic or glass. For normal incidence, $\theta = 0°$, Eq. (17) does not apply but rather

$$r_0 = \left[(n' - 1)/(n' + 1)\right]^2 \tag{18}$$

(Of course for latitude greater than 23½° N or S we never have normal solar incidence.)

To obtain the absorptivity of the water-black bottom collector, consider a light beam incident on the water at angle θ. A fraction, r, of the beam will be reflected from the top surface. (If there is a layer of plastic or glass lying on the water surface, the index of refraction used in Eq. (17) will be that of the layer rather than of the water. We can neglect any reflection from the layer-water interface since the indices of refraction are not very different.)

The fraction, $(1 - r)$, will pass into the water. Since water is almost completely opaque to the infrared and since about half of the energy in solar radiation lies in the infrared ($\geq 0.7\ \mu$), only about half of the beam reaches the black bottom. A typical emissivity for a black surface is 0.96. Hence about 98% of the beam entering the water will be absorbed as heat in the water. We can then write for α:

$$\alpha = 0.98\,(1 - r) \tag{19}$$

Finally, the $\tau\alpha$ product has to be suitably weighted for the direct and diffuse solar components. We follow the generally accepted convention[6] of assuming the diffuse radiation has an average angle of incidence for a horizontal collector of 58°. For the middle of each hour from solar noon, the following expression must be evaluated:

$$\overline{\tau\alpha} = \frac{(\overline{I}_T - \overline{I}_d)\,(\tau\alpha) + \overline{I}_d\,(\tau\alpha)_{58°}}{\overline{I}_T} \qquad (20)$$

VI. Calculation of U

For a given collector geometry and given materials it is possible to calculate the overall heat loss coefficient, U, defined in Eq. (5). Comparison between calculated and measured values of U usually show agreement[7,8] within about 10%.

There is a vast literature in heat transfer and English units are used almost exclusively in English language publications. Therefore we have found it more convenient here to use English units; BTU, hour, feet, °F and °R. Hence our calculated values of U will be in BTU/ft^2 hr °F. They can be converted to metric units for use in Eq. (5) by:

$$1\ \frac{\text{BTU}}{\text{ft}^2\ \text{hr}\ °\text{F}} = 5.678\ \frac{\text{watts}}{\text{m}^2\ °\text{C}}$$

Although we are concerned with the case of a layer of water covered by two, or possibly three, plastic glazings, it is simpler to first consider the case of two or three glass glazings. (This is because glass is totally opaque to thermal radiation whereas plastics are not.) The difference in U for the two cases turns out to be 20% or less[9].

The theory of heat convection and conduction through a gas (air in our case) involves several dimensionless numbers which we define below[10]:

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[7] H. C. Hottel and B. B. Woertz, ASME Trans., V. 64, p. 91-104, 1942.

[8] Carl N. Hodges, et al., Solar Distillation Utilizing Multiple-Effect Humidification, Final Report. The University of Arizona Solar Energy Laboratory of the Institute of Atmospheric Physics. 31 Jan., 1966.

[9] A. Whillier, Solar Energy 7, #3, p. 148, 1963.

[10] An excellent overall reference is: W. H. McAdams, Heat Transmission, McGraw-Hill, 3rd edition, 1954.

Prandtl number: $Pr = c_p\mu/k$

Grashof number: $Gr = (L^3\rho^2 g/\mu^2)(\beta\ \Delta t)$

Nusselt number: $Nu = hL/k$

Stanton number: $St = h/c_pV\rho$

Reynolds number: $Re = LV\rho/\mu$

It is also convenient to define a dimensional parameter, a:

$$a = \rho^2\ g\ \beta\ c_p/\mu k = (Gr\ Pr)/L^3\ \Delta t \quad [ft^{-3}\ °F^{-1}] \tag{21}$$

The definitions of the quantities in the above expression are:

c_p = specific heat of air [BTU/lb °F]

μ = viscosity of air [lb/hr ft]

k = thermal conductivity of air [BTU/hr ft °F]

L = characteristic dimension [ft]

ρ = density of air [lb/ft^3]

g = acceleration of gravity = $4.17 \times 10^8\ ft/hr^2$

β = coefficient of volumetric expansion of air [$°F^{-1}$]

Δt = temperature difference between two layers or between layer and adjoining air [°F]

h = convection heat transfer coefficient [$BTU/hr\ ft^2\ °F$]

V = wind velocity [$ft\ hr^{-1}$ or mph]

q_c = rate of convection heat transfer [$BTU/hr\ ft^2$]

$Gr \cdot Pr = aL^3\Delta t$ (dimensionless)

Some useful values of these quantities for air at temperatures of interest to us are listed in Table III below:

Table III. Some useful physical quantities for air.

Mean Temp °F	80°	100°	150°	200°
c_p	.240	.240	.241	.241
μ	.0446	.0459	.0484	.0519
k	.0151	.0157	.0167	.0181
ρ	.0735	.0710	.0649	.0602
β	.00200	.00200	.00200	.00200
10^{-6} a	1.605	1.400	1.047	0.775
$ka^{1/4}$	.537	.540	.534	.537
Pr	0.71	0.70	0.70	0.69

For two horizontal plates separated by distance L (ft), the heat transfer coefficient (including convection and conduction but not radiation) is defined by:

$$q_c = h_c \, \Delta t \tag{22}$$

where Δt is the °F temperature difference between the plates. From considerations of dimensional analysis[10], it is customary to write h_c in the form:

$$Nu = \frac{h_c L}{k} = C \, (Gr \cdot Pr)^n = C \, (aL^3 \, \Delta t)^n \tag{23}$$

where experimental data is needed to determine C and n. McAdams gives the expressions

$$\begin{aligned} Nu &= 0.192 \, Gr^{1/4} \quad \text{for} \quad 10^4 < Gr < 3.2 \times 10^5 \\ Nu &= 0.067 \, Gr^{1/3} \quad \text{for} \quad 3.2 \times 10^5 < Gr < 10^7 \end{aligned} \tag{24}$$

which fits one set of experiments quite well. Tabor[11] has made a careful survey of a number of experiments and concludes that work done by NBS give results which are probably most reliable, particularly when applied to large plates as in our case. He gives:

$$Nu = 0.168\ (Gr \cdot Pr)^{0.281} = 0.152\ Gr^{0.281} \qquad 10^4 < Gr < 10^7 \qquad (25)$$

which can be written as,

$$h_c = 0.168\ \frac{k}{L}\ (aL^3\ \Delta t)^{0.281} \qquad (26)$$

In Figure 6 we show both the Tabor and McAdams values of h_c plotted against plate spacing L for a Δt = 50°F and an average temperature between plates of 125°F. These values of h_c will be quite insensitive to average temperature (notice in Table III that $ka^{1/4}$ is essentially independent of temperature.) Also a 20% change in Δt will only change h_c by about 5%. For L = 1" the conduction heat loss is about half the convection heat loss and for smaller L, conduction increases inversely with L, explaining the rise in h_c.

Convection heat loss from the top glass plate in the absence of any wind will be characterized by a $Gr \cdot Pr \approx 3 \times 10^{10}$ which is in the turbulent range. McAdams[10] gives for this case:

$$h_c = 0.22\ \Delta t^{1/3} \qquad (27)$$

where now Δt is the temperature difference between the top plate and ambient air. In our case, $\Delta t \approx 15$ to 25°F, so that $h_c \approx 0.6$.

If there is a wind the convection heat loss will be increased. For a 10 mph wind the Reynolds number in our case is about 10^6. McAdams[10] recommends the Colburn relation:

$$St\ (Pr)^{2/3} = \frac{0.036}{(Re)^{0.2}} \qquad (28)$$

[11] H. Tabor, Bull. Res. Counc. of Israel, Vol. 6C, pp. 155-176, 1958.

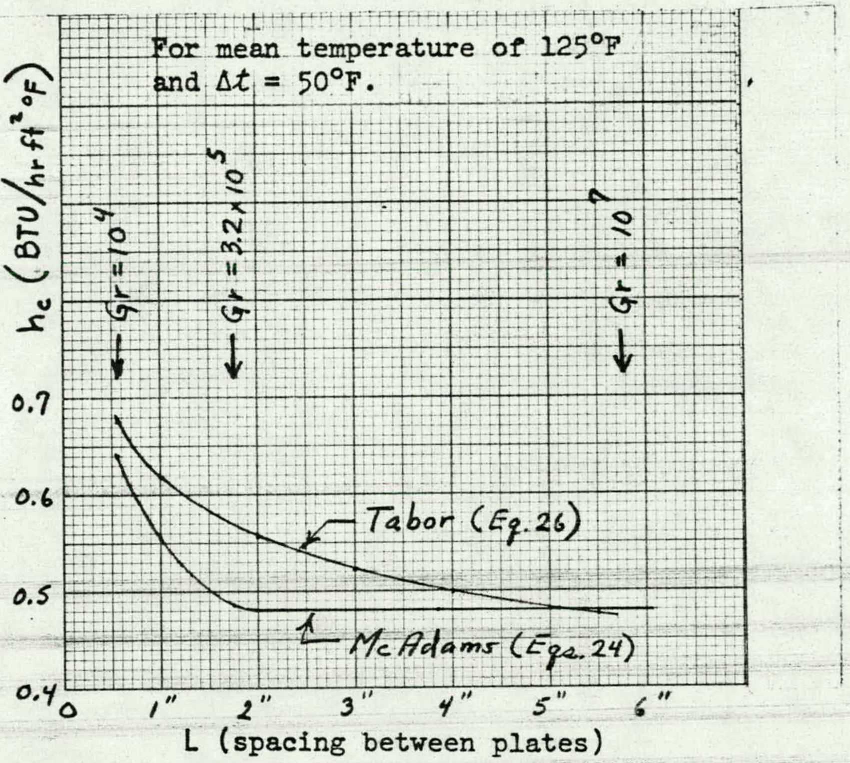


Figure 6. Convection heat transfer coefficient vs. plate spacing.

From Eq. (28) we can derive the following expression for the wind coefficient:

$$h_w = 0.40\ V_{mph}^{0.8} \tag{29}$$

Eqs. (27) and (29) can be closely approximated by:

$$h_{top} = 0.6 + 0.18\ V_{mph} \tag{30}$$

The other form of heat loss between the plates and from the top plate is from radiation. In fact, for the case of two plates over the water, the radiation loss between water and first plate and between first and second plate is about a factor of 2 to 3 greater than the respective convection losses for our temperature domain. For the top plate in a 10 mph wind the radiation and convection losses will be comparable.

For two infinite parallel plates with emissivities ε_1 and ε_2 and absolute temperatures T_1 and T_2 (in °R = °F + 460), McAdams[10] shows that the net radiation heat loss from the hotter to the colder plate is:

$$q_r = \frac{\sigma\,(T_1^4 - T_2^4)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1} \qquad (31)$$

where the Stefan-Boltzmann constant is 0.1716×10^{-8} BTU/hr ft² °R⁴.

The net radiation loss from the top plate to the atmosphere depends not only on the temperature T of the top plate but also on the water and CO_2 content of the atmosphere since thermal radiation from the atmosphere orginates chiefly from these two components. The higher the ambient air temperature, T_a, the greater amount of water vapor usually contained in the air and hence the greater the return atmospheric radiation.

In a recent paper[12] it is shown that experimental data for clear days can be fit well in several different localities from Alaska to Arizona by the following expression for the apparent emissivity of the atmosphere:

$$\varepsilon_a = 1 - 0.261 \exp\left[-7.77 \times 10^{-4}\,(273 - T_a)^2\right] \qquad (32)$$

where T_a is the ambient air temperature <u>in °K</u>. Hence the net radiation loss from the top plate at temperature T can be written as:

$$q_r = \varepsilon_g \sigma\,(T^4 - \varepsilon_a T_a^4) \qquad (33)$$

where T and T_a are in °R as before. In the temperature range from 60° to 110°F the apparent atmospheric emissivity can be well represented by:

$$\varepsilon_a = 0.574 + 0.0035\, t_a \ (°F) \qquad (34)$$

We are now ready to solve for the total upward heat loss q_{up} from the system. From the water at temperature T_o to the first glass plate at temperature T_1 (°R):

$$q_{up} = c\,(T_0 - T_1)^{1.28} + \frac{\sigma\,(T_0^4 - T_1^4)}{\frac{1}{\varepsilon_c} + \frac{1}{\varepsilon_g} - 1} \qquad (35)$$

---

[12] S. B. Idso and R. D. Jackson, Jour. of Geophysical Research <u>74</u>, #23, p. 5397, 1969.

From 1st glass plate to 2nd glass plate:

$$q_{up} = c\,(T_1 - T_2)^{1.28} + \frac{\sigma\,(T_1^4 - T_2^4)}{2/\varepsilon_g - 1} \tag{36}$$

and from 2nd glass plate to sky:

$$q_{up} = h_{top}\,(T_2 - T_a) + \sigma\,\varepsilon_g\,(T_2^4 - \varepsilon_a T_a^4) \tag{37}$$

This is a system of three equations in three unknowns; q_{up}, T_1, and T_2 with the plate spacing, T_0, T_a, and the emissivities of the water, ε_c, and glass, ε_g, all given. Tabor[11] points out that one should use the hemispherical values for ε_c and ε_g rather than the values for normal emittance as used by Hottel and Woertz[7]. Hence for glass, H and W used $\varepsilon_g = 0.96$ whereas, according to Tabor, the hemispherical value is 0.90[13].

The above equations can be solved relatively quickly by trial and error. For example, let t_o = 185°F, $\varepsilon_c = \varepsilon_g = 0.90$, and plate spacing = 2". Also assume a 10 mph wind giving h_{top} = 2.4. From Eq. (26) we obtain c = 0.18. After a couple of trials one obtains:

$$t_o = 185°\text{F} = \text{water temperature}$$

$$t_1 = 150°\text{F},\ q_{up} = 17.05 + 48.62 = 65.7 \tag{38}$$

$$t_2 = 110.5°\text{F},\ q_{up} = 19.90 + 45.68 = 65.6 \tag{39}$$

$$t_a = 95.5°\text{F},\ q_{up} = 36.00 + 29.81 = 65.8 \tag{40}$$

The upward heat loss coefficient, U_{up}, is now obtained* from:

$$U_{up} = q_{up}/(t_o - t_a) = \frac{65.7}{89.5} = 0.73$$

[13] J. I. Yellott (Solar Energy, 7, #4, p. 167 (1963) quotes a value of hemispherical emittance for "ordinary" glass of 0.84, based on spectral emittance data.

*For no wind this value of U_{up} decreases from 0.73 to 0.63 (about 15%).

(The simplified approximate expression for q_{up}, given as Eq. (13) in Hottel and Woertz[7], gives essentially the same result providing we use our values of c, ε_c, ε_g, and h_{top} and that we replace T_a^4 in their Eq. (13) by $\varepsilon_a T_a^4$.)

To obtain the overall heat coefficient, U, we must add the heat loss from the bottom of the water into the earth. With about a 2" layer of good insulation such as a plastic foam, this can easily be reduced to 10% or less of the upward heat loss. Hence we can write

$$U = 1.1\ q_{up}/(t_o - t_a) \simeq 0.80$$

The addition of a third glass plate will reduce U_{up} to 0.49 and U to about 0.54. However the incident solar transmission will also be reduced so the net percentage gain in collection efficiency may be only about half the percentage reduction in U.

If plastic glazings are used over the pond rather than glass, the calculation of heat loss through the plastic is more difficult because of the partial transparency of plastic to heat radiation. One must have measured values of monochromatic spectral absorptivity, reflectivity, and transmissivity for the particular plastic. These values must then be integrated over the entire wavelength range.

Hodges[8] has treated this case in general and made numerical evaluations of heat loss for Tedlar. For a water temperature of t_c = 185°F and with one Tedlar glazing on the water surface and two above the surface he obtains U_{up} = 0.91 BTU/ft^2 hr °F. Adding a third glazing above the surface reduces U_{up} to 0.65. Both of these values are for a 10 mph wind.

Experimental measurements of heat loss through 1, 2, and 3 Tedlar glazings have recently been made[14]. For 2 glazings above the water they obtain (at t_c = 185°F) U_{up} = 1.03 and for 3 glazings, U_{up} = 0.78. Whillier[9] calculates U_{up} for 2 Tedlar glazings (at t_c = 190°F) to be 0.87.

From the above data we can use an average of U_{up} = 0.93 for 2 Tedlar glazings above the water. This is to be compared with our value of U_{up} = 0.73 for 2 glass glazings. Whillier states[9] that the increased

[14] W. H. Gopffarth, et al., Solar Energy 12, 183, 1968.

upward heat loss for Tedlar covered collectors is "more or less fully compensated by the improved solar transmittance of the Tedlar". Let us check his statement by considering a 2 glass glazing covering with $\tau = 0.75$ versus a 2 Tedlar glazing cover with $\tau \approx 0.85$. (Both at normal incidence.) For a solar insolation of 750 watts/m^2 = 238 BTU/ft^2 hr, and assuming $\alpha = 0.96$, $t_c = 185°F$, $t_a = 90°F$, we have for the collection efficiencies:

$$\text{2 Glass:} \quad \eta_c = 0.72 - \frac{0.73 \times 95}{238} = 0.72 - 0.29 = 0.43$$

$$\text{2 Tedlar:} \quad \eta_c = 0.82 - \frac{0.93 \times 95}{238} = 0.82 - 0.37 = 0.45$$

and we see that Whillier's statement seems to be justified.

As seen in Hottel and Woertz[7], the heat loss coefficient is a function of both t_c and t_a. Hence, if Eqs. (35), (36), and (37) are solved to find a value of U for a particular set of values for t_c and t_a, it would be convenient to be able to calculate U for any other values of t_c and t_a. Using the U curves in Figure 16 of Hottel and Woertz we obtain the following experssion relating a value of $U = U_o$ at $t_c = t_{co}$ and $t_a = t_{ao}$ to a value U at t_c and t_a:

$$U = U_o \frac{1 + .00512\, t_c + .00219\, t_a}{1 + .00512\, t_{co} + .00219\, t_{ao}} \quad \text{[temperature in °F]} \qquad (41)$$

and

$$U = U_o \frac{1 + .00746\, T_c + .00320\, T_a}{1 + .00746\, T_{co} + .00320\, T_{ao}} \quad \text{[temperature in °C]} \qquad (42)$$

These expressions are quite accurate for one, two, or three glass plates and for collection temperatures equal to or greater than about 110°F (43°C). They also give fairly good agreement with the heat loss vs. collector temperatures calculated by Hodges[8] for Tedlar (see his Figure 16).

VII. Computer Program and Sample Results

We include in this section the computer prgram "Solar", which was written to calculate average hourly values of collected heat and average daily values of collection efficiency - the averages taken over each month of the year. Also included is the print-out of a sample problem: A solar pond in Phoenix, Arizona with two 0.125" glass plates, average water temperature = 60°C.

In Figure 7 is shown the collection efficiency for 2 and 3 Tedlar covers (0.004") at two collection temperatures, T_c = 140°F (60°C) and 185°F (85°C). Note that at 140°F there is little improvement in using a third layer of Tedlar whereas at the higher collector temperature of 185°F it makes a large improvement, particularly in winter. This is because the heat losses are greater at the higher temperature and the additional optical loss of the third layer is more than compensated by the decreased heat loss.

In Figure 8 are shown similar curves for glass. (Sample problem gives top curve.) Note that at 140°F, two layers of glass are better than three for all except the months of January and February. Also, except for the 2 layer, 185°F case, Tedlar always results in a higher collection efficiency for equivalent collector temperatures and number of layers.

Figure 7. Collection efficiencies for 2 and 3 layers of Tedlar at 2 water temperatures.

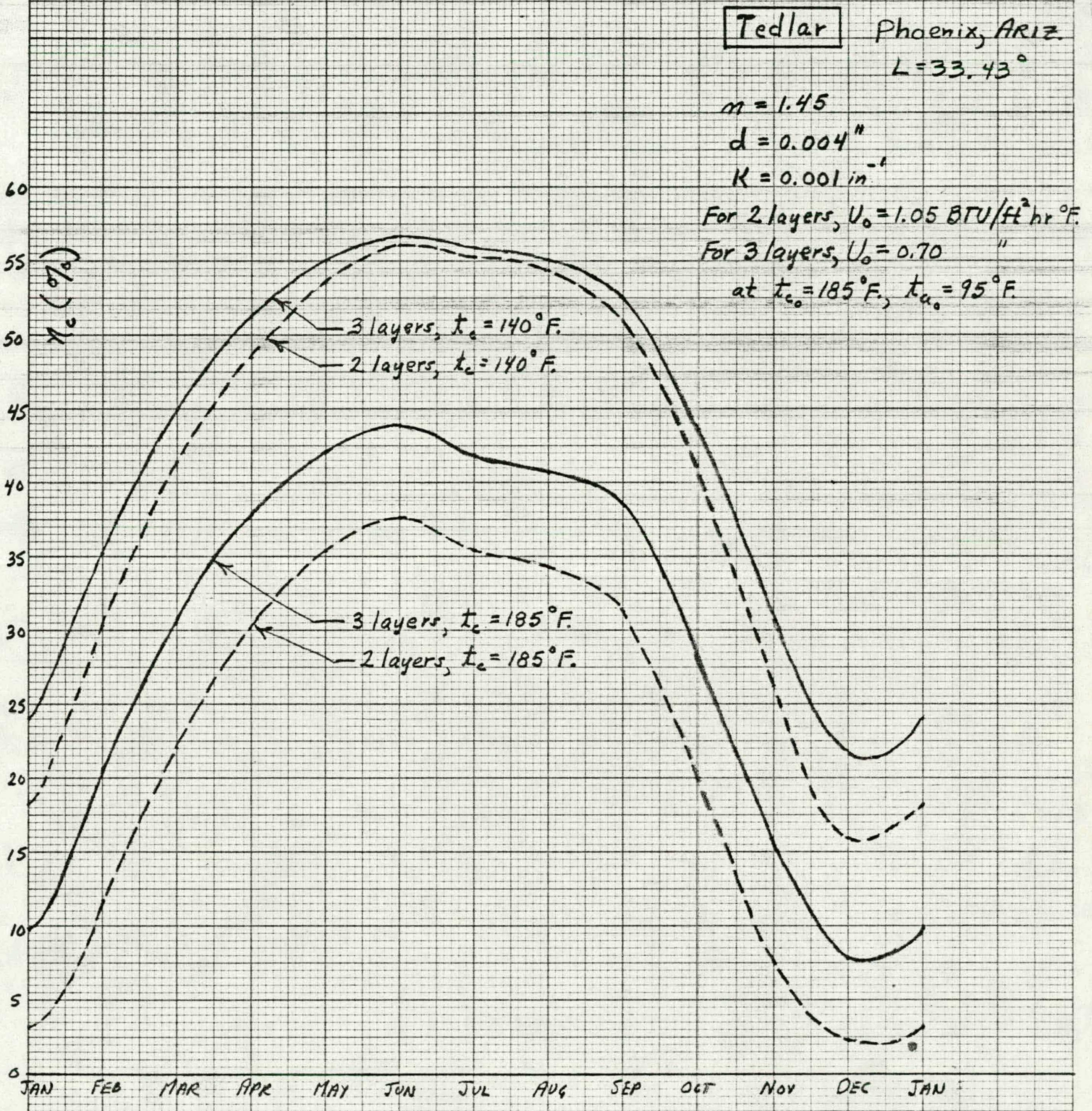
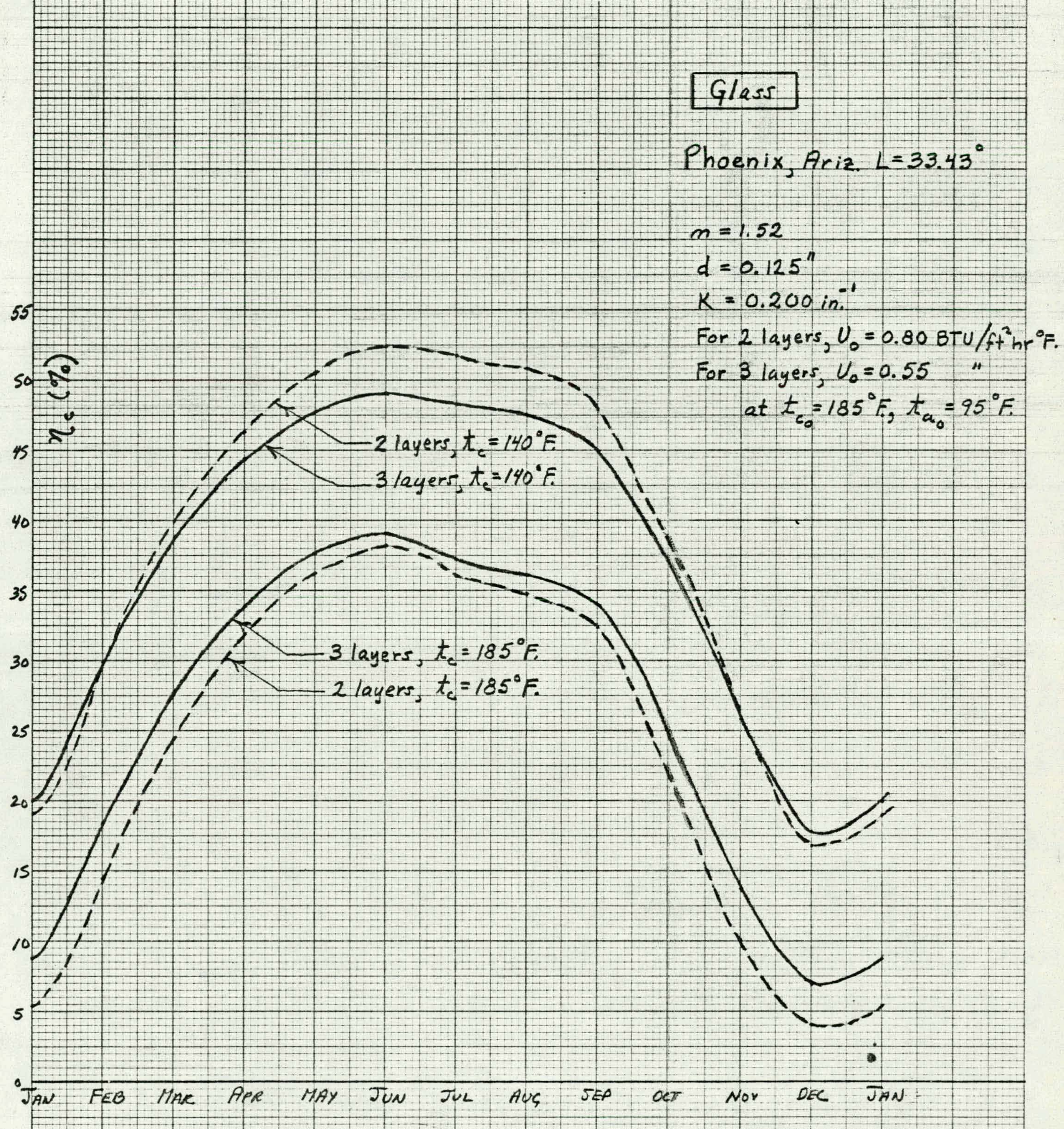


Figure 8. Collection efficiencies for 2 and 3 layers of glass at 2 water temperatures.



```
*ID   290MLP               SOLAR POND                  NEIFERT             BOXH20
* PRINT RDN
* CONTROLLEE 0,SOLAR
* DUMP OCT DEC
* CARDS DBUG
* LOD SUNSYM↑
* LIST8
* FORTRAN
      PROGRAM SOLAR(OUTIT,TAPE3=OUTIT,TAPE2,TAPE63)
C
C
C* * * * * * * * IDENTIFICATION* * * * * * * * * * * *
C
C
C          PROGRAM NAME:   SOLAR
C            ORIGINATED:   DECEMBER 1973
C          VERSION/DATE:   1/24 JANUARY 1974
C            PROGRAMMER:   R. NEIFERT
C
C
C* * * * * * * * CODE DESCRIPTION * * * * * * * * * *
C
C          THIS CODE CALCULATES THE LONG TERM COLLECTION EFFICIENCY
C          OF A HORIZONTAL PLATE SOLAR ENERGY COLLECTOR.  THE ASSUMPTIONS
C          AND APPROXIMATIONS USED CLOSELY PARALLEL THE METHOD
C          DESCRIBED BY HOTTEL AND WHILLIER, "TRANSACTIONS OF THE
C          CONFERENCE ON THE USE OF SOLAR ENERGY: THE SCIENTIFIC
C          BASIS," II, PART I, SECTION A, 1955, PAGES 74-104 AND
C          LIU AND JORDAN, SOLAR ENERGY, VOL. 7, NO. 2, 1963.
C
C* * * * * * * * VARIABLE DEFINITIONS * * * * * * * *
C
C    THETA=ANGLE OF INCIDENCE(ZENITH ANGLE)  RADIANS
C    LAT=LATITUDE  DEGREES
C    DELTA=SOLAR DECLINATION  DEGREES
C    OMEGA=SOLAR HOUR ANGLE FROM SOLAR NOON  DEGREES
C    OMEGAS=SUNSET HOUR ANGLE  RADIANS
C    OMEGAH=SUNSET HOUR ANGLE  HOURS
C    ISC=SOLAR CONSTANT
C    RATIO=SQUARE OF RATIO OF MEAN DISTANCE TO ACTUAL DISTANCE
C          BETWEEN EARTH AND SUN
C    HOURS=24
C    PI=3.14159
C    CONV1=3.153 W/M**2 PER BTU/HR-FT**2
C    CONV2=.1314 W/M**2 PER BTU/DAY-FT**2
C    HZERO=AVERAGE DAILY RADIATION ON HORIZONTAL SURFACE
C          OUTSIDE ATMOSPHERE
C    HBAR=MONTHLY AVERAGE DAILY TOTAL RADIATION ON A
C         HORIZONTAL SURFACE
C    KTBAR=HBAR/HZERO
C    DBAR=MONTHLY AVERAGE DAILY DIFFUSE RADIATION ON A
C        HORIZONTAL SURFACE
C    KDBAR=DBAR/HZERO
C    IBARTH=AVERAGE HOURLY TOTAL RADIATION ON A HORIZONTAL
C           SURFACE
C    IBARDH=AVERAGE HOURLY DIFFUSE RADIATION ON A HORIZONTAL
C           SURFACE
C    RTOT=IBARTH/HBAR
C    RDIF=IBARDH/DBAR
C    IC=CRITICAL INTENSITY OF RADIATION
```

```
C     XC=IC/IBARTH   CRITICAL INTENSITY RATIO
C     R=REFLECTIVITY OF A SINGLE SURFACE USING FRESNEL EQUATIONS
C     K1=EXTINCTION COEFFICIENT OF THE REFLECTING SURFACE
C     L1=THICKNESS OF REFLECTING SURFACE
C     N=NUMBER OF REFLECTING SURFACES
C     CTH=COSINE OF THE ANGLE OF INCIDENCE
C     TAU=TRANSMITTANCE OF REFLECTING SURFACE
C     ALPHA=ABSORPTIVITY OF THE COLLECTOR
C     TABAR=AVERAGE VALUE OF TAU*ALPHA
C     NPRIME=INDEX OF REFRACTION OF REFLECTING SURFACE
C     TC=COLLECTOR TEMPERATURE  DEGREES CENTIGRADE
C     T0=AMBIENT AIR TEMPERATURE  DEGREES FAHRENHEIT
C     DCEFF=DAILY COLLECTION EFFICIENCY
C     U=OVERALL HEAT LOSS COEFFICIENT  W/M**2-DEGREE C
C     U0=HEAT LOSS COEFFICIENT AT INITIAL CONDITIONS
C        OF TC AND T0   W/M**2-DEGREE C
C
C
      CLICHE SET
      REAL ISC,KTBAR,KDBAR,LAT,KTBARX,KDBARY,IBARDH,IBARTH
      REAL N,NPRIME,L1,K1,IC
      COMMON ISC,HOURS,PI,CONV1,CONV2,LAT,ID(2),RADIAN,
     1TAUD,ALPHAD,N,NPRIME,L1,K1,TC,U0
      COMMON RATIO(12),DELTA(12),HZERO(12),HBAR(12),
     1KTBARX(12),KDBARY(12),DBAR(12),OMEGAS(12),DCEFF(12),
     2OMEGAH(12),KDBAR(12),KTBAR(12),MONTH(12),T0(12),U(12)
      COMMON RDIF(12,7),RTOT(12,7),IBARDH(12,7),
     1IBARTH(12,7),IC(12,7),XC(12,7),
     2PHI(12,7),Q(12,7),THETA(12,7),TAU(12,7),ALPHA(12,7),
     3TABAR(12,7),CTH(12,7)
      COMMON OMEGA(8),HRS(9),XCX(11),PHIY(11,7),RT(9,7)
      ENDCLICHE
      USE SET
      ISC=1400.
      HOURS=24.
      PI=3.14159
      CONV1=3.153
      CONV2=0.1314
      RADIAN=6.28318/360.
      CALL TABLE
      CALL DATAIN
      CALL CALC1
      CALL CALC2
      CALL CALC3
      CALL TAUALF
      CALL CALC4
      CALL OUTPUT
      CALL QUIT
      END
      SUBROUTINE TABLE
C
C* * * * * * * * CODE DESCRIPTION * * * * * * * * * *
C
C          THIS SUBROUTINE SETS UP THE VARIOUS TABLES THAT ARE USED
C          IN THE EFFICIENCY CALCULATION.
C
      USE SET
      DATA RATIO/1.0315,1.0235,1.0103,.9913,.9757,
     1.9680,.9680,.9757,.9898,1.0087,1.0238,1.0318/
      DATA DELTA/-21.27,-12.93,-2.43,9.50,18.68,
```

```
123.28,21.65,14.30,3.33,-8.23,-18.30,-23.23/
 DATA KTBARX/.3,.4,.5,.6,.7,.75,1.0/
 DATA KDBARY/.179,.183,.188,.174,.149,.125,.120/
 DATA OMEGA/7.5,22.5,37.5,52.5,67.5,82.5,97.5/
 DATA HRS/8.,9.,10.,11.,12.,13.,14.,15.,16./
 DATA(((RT(I,J),I=1,9),J=1,7)=
1.198,.179,.165,.152,.142,.133,.124,.116,.107,
2.164,.155,.145,.136,.128,.121,.114,.108,.102,
3.103,.108,.110,.108,.105,.102,.099,.096,.092,
4.033,.053,.064,.072,.076,.078,.079,.078,.077,
5.000,.000,.020,.032,.041,.048,.052,.056,.058,
6.000,.000,.000,.005,.011,.019,.026,.032,.038,
7.000,.000,.000,.003,.000,.003,.008,.013,.018)
 DATA XCX/0.,.2,.4,.6,.8,1.0,1.2,1.4,1.6,1.8,2.0/
 DATA(((PHIY(I,J),I=1,11),J=1,7)=
11.0,.815,.655,.510,.390,.290,.207,.140,.090,.055,.025,
21.0,.905,.635,.480,.350,.235,.145,.080,.040,.015,.000,
31.0,.900,.615,.455,.305,.180,.085,.025,.005,.000,.000,
41.0,.900,.605,.427,.267,.137,.049,.000,.000,.000,.000,
51.0,.900,.600,.400,.217,.070,.000,.000,.000,.000,.000,
61.0,.800,.600,.400,.214,.058,.000,.000,.000,.000,.000,
71.0,.800,.600,.400,.200,.000,.000,.000,.000,.000,.000)
 MONTH(1)=3HJAN
 MONTH(2)=3HFEB
 MONTH(3)=3HMAR
 MONTH(4)=3HAPR
 MONTH(5)=3HMAY
 MONTH(6)=3HJUN
 MONTH(7)=3HJUL
 MONTH(8)=3HAUG
 MONTH(9)=3HSEP
 MONTH(10)=3HOCT
 MONTH(11)=3HNOV
 MONTH(12)=3HDEC
 RETURN
 END
 SUBROUTINE DATAIN
C
C* * * * * * * * CODE DESCRIPTION * * * * * * * * * *
C
C         THIS IS THE INPUT SUBROUTINE FOR SOLAR. A DISK FILE NAMED
C         SOLARIN ASSIGNED TO LOGICAL UNIT 2 IS REQUIRED AS THE
C         INPUT DATA FILE.
C
 USE SET
 CALL ASSIGN(2,0,7RSOLARIN,0)
 RIT 2,1,(ID(I),I=1,2)
 RIT 2,3,LAT
 RIT 2,3,N,NPRIME,L1,K1
 RIT 2,3,TC,U0
 RIT 2,3,(HBAR(I),I=1,12)
 RIT 2,3,(T0(I),I=1,12)
 DO 4 I=1,12
C         CONVERT INPUT AMBIENT TEMPERATURE TO DEGREES CENTIGRADE
 T0(I)=(T0(I)-32.0)*5.0/9.0
C         CONVERT INPUT AVERAGE DAILY TOTAL RADIATION TO WATTS/M**2
 HBAR(I)=HBAR(I)*CONV2
4 CONTINUE
1 FORMAT(2A10)
3 FORMAT(6E10.3)
```

```
      RETURN
      END
      SUBROUTINE CALC1
C
C* * * * * * * * CODE DESCRIPTION * * * * * * * * * *
C
C          THIS SUBROUTINE CALCULATES HZERO, THE AVERAGE DAILY
C          RADIATION ON A HORIZONTAL SURFACE OUTSIDE THE ATMOSPHERE.
C
      USE SET
      DO 1 I=1,12
      OMEGAS(I)=ACOS(-(TAN(LAT*RADIAN)*TAN(DELTA(I)*RADIAN)))
      A=RATIO(I)*ISC/PI
      B=COS(LAT*RADIAN)*COS(DELTA(I)*RADIAN)*SIN(OMEGAS(I))
      C=OMEGAS(I)*SIN(LAT*RADIAN)*SIN(DELTA(I)*RADIAN)
      HZERO(I)=A*(B+C)
    1 CONTINUE
      RETURN
      END
      SUBROUTINE CALC2
C
C* * * * * * * * CODE DESCRIPTION * * * * * * * * * *
C
C          THIS SUBROUTINE CAACULATES THE VALUES OF KTBAR, KDBAR
C          AND DBAR.  INTERPOLATED VALUES OF KDBAR ARE CALCULATED
C          FROM AN INPLT DATA ARRAY IN SUBROUTINE TABLE.
C
      USE SET
      DO 1 I=1,12
      KTBAR(I)=HBAR(I)/HZERO(I)
      CALL TERP(KTBARX,KDBARY,7,KTBAR(I),KDBAR(I),0)
      DBAR(I)=KDBAR(I)*HZERO(I)
    1 CONTINUE
      RETURN
      END
      SUBROUTINE CALC3
C
C* * * * * * * * CODE DESCRIPTION * * * * * * * * * *
C
C          THIS SUBROUTINE CALCULATES THE VALUES OF RDIF,IBARDH AND
C          RTOT,IBARTH.  RDIF IS CALCULATED FROM AN ANALYTIC
C          EXPRESSION GIVEN IN THE PREVIOUS REFERENCES. INTERPOLATED
C          VALUES OF RTOT ARE CALCULATED FROM INPUT DATA ARRAYS
C          IN SUBROUTINE TABLE.
C
      USE SET
      DO 1 J=1,12
      DO 1 I=1,7
      A=COS(OMEGA(I)*RADIAN)-COS(OMEGAS(J))
      B=SIN(OMEGAS(J))-OMEGAS(J)*COS(OMEGAS(J))
      IF(A)2,2,
      RDIF(J,I)=(PI*A)/(B*HOURS)
      GO TO 3
    2 RDIF(J,I)=0.
    3 OMEGAH(J)=OMEGAS(J)*HOURS/PI
      CALL TERP(HRS,RT(1,I),9,OMEGAH(J),RTOT(J,I),0)
      IBARDH(J,I)=RDIF(J,I)*DBAR(J)*HOURS
      IBARTH(J,I)=RTOT(J,I)*HBAR(J)*HOURS
    1 CONTINUE
      RETURN
```

```
      END
      SUBROUTINE CALC4
C
C* * * * * * * * CODE DESCRIPTION * * * * * * * * * *
C
C           THIS SUBROUTINE CALCULATES THE VALUES OF U,IC,XC,PHI
C           AND DCEFF.
C
      USE SET
C     CALCULATE PHI=UTILIZABILITY
      DO A1 I=1,12
      SUM=0.
      DO 1 J=1,7
      IF(TABAR(I,J)),,4
      IC(I,J)=XC(I,J)=PHI(I,J)=Q(I,J)=0.
      GO TO 1
    4 TC0=85.0
      TA0=35.0
      A=(1.0+.00746*TC+.0032*T0(I))
      B=(1.0+.00746*TC0+.0032*TA0)
      U(I)=U0*(A/B)
      IC(I,J)=U(I)*(TC-T0(I))/TABAR(I,J)
      XC(I,J)=IC(I,J)/IBARTH(I,J)
      DO 2 K=1,7
      JA=K
      IF(KTBAR(I)-KTBARX(K))3,,
    2 CONTINUE
    3 K=JA-1
      CALL TERP(XCX,PHIY(1,K),11,XC(I,J),PHI1,0)
      CALL TERP(XCX,PHIY(1,K+1),11,XC(I,J),PHI2,0)
      PHI(I,J)=PHI1+(((PHI2-PHI1)/(KTBARX(K+1)-KTBARX(K)))*
     1(KTBAR(I)-KTBARX(K)))
      Q(I,J)=PHI(I,J)*TABAR(I,J)*IBARTH(I,J)
      SUM=SUM+Q(I,J)
    1 CONTINUE
      DCEFF(I)=SUM/(12.*HBAR(I))
   A1 CONTINUE
      RETURN
      END
      SUBROUTINE TAUALF
C
C* * * * * * * * CODE DESCRIPTION * * * * * * * * * *
C
C          THIS SUBROUTINE CALCULATES THE AVERAGE OF TAU*ALPHA
C          USING DIRECT AND DIFFUSE SOLAR RADIATION
C
      USE SET
C     DIFFUSE RADIATION ASSUMING EFFECTIVE ANGLE OF
C     INCIDENCE IS 58 DEGREES
      THETAD=58.0*RADIAN
      CALL FRESNL(THETAD,NPRIME,RD)
      A=EXP(-K1*N*L1/COS (THETAD))
      B=1-RD
      C=1+(2*N-1)*RD
      TAUD=A*(B/C)
      ALPHAD=.98*B
C
C     DIRECT RADIATION
      ARAD=LAT*RADIAN
      DO 1 I=1,12
```

```
      DO 1 J=1,7
      CTH(I,J)=(COS (ARAD) *COS(DELTA(I)*RADIAN)*
     1COS(OMEGA(J)*RADIAN))+(SIN (ARAD)*SIN(DELTA(I)*RADIAN))
      IF(CTH(I,J)),,2
      CTH(I,J)=0.
    2 THETA(I,J)=ACOS(CTH(I,J))
      CALL FRESNL(THETA(I,J),NPRIME,R)
      IF(CTH(I,J)),,4
      A=0.
      GO TO 5
    4 A=EXP(-K1*N*L1/CTH(I,J))
    5 B=1-R
      C=1+(2*N-1)*R
      TAU(I,J)=A*(B/C)
      ALPHA(I,J)=.98*B
      TABAR(I,J)=((IBARTH(I,J)-IBARDH(I,J))*
     1TAU(I,J)*ALPHA(I,J))+(IBARDH(I,J)*TAUD*ALPHAD)
      IF(IBARTH(I,J)),,3
      TABAR(I,J)=0.
      GO TO 1
    3 TABAR(I,J)=TABAR(I,J)/IBARTH(I,J)
    1 CONTINUE
      RETURN
      END
      SUBROUTINE FRESNL(ANGL1,NPRIM,REFL)
C
C* * * * * * * * CODE DESCRIPTION * * * * * * * * * *
C
C          THIS SUBROUTINE CALCULATES THE REFLECTIVITY OF A SURFACE
C          USING THE FRESNEL EQUATIONS.
C
C
C* * * * * * * * VARIABLE DEFINITIONS * * * * * * * *
C
C          ANGL1=INCIDENT ANGLE IN RADIANS
C          ANGL2=REFRACTED ANGLE IN RADIANS
C          REFL=REFLECTIVITY OF THE SURFACE
C          NPRIM=INDEX OF REFRACTION OF THE SURFACE
C
      REAL NPRIM
      IF(ANGL1-1.57)1,,
      REFL=1.
      GO TO 2
    1 ANGL2=ASIN((SIN(ANGL1))/NPRIM)
      DIFA=ANGL1-ANGL2
      SUMA=ANGL1+ANGL2
      R1=((SIN (DIFA))**2)/((SIN (SUMA))**2)
      R2=((TAN (DIFA))**2)/((TAN (SUMA))**2)
      REFL=.5*(R1+R2)
    2 RETURN
      END
      SUBROUTINE OUTPUT
      USE SET
      NN=3
      WOT 3,1,(ID(I),I=1,2)
      WOT 3,2,LAT
      WOT 3,A1,N
      WOT 3,A2,NPRIME
      WOT 3,A3,L1
      WOT 3,A4,K1
```

```
      WOT 3,A5,TC
      WOT 3,A6,U0
      WOT 3,A7
      WOT 3,3,(MONTH(I),HBAR(I),T0(I),I=1,12)
      WOT 3,4
      WOT 3,5,(MONTH(I),DELTA(I),RATIO(I),OMEGAS(I),OMEGAH(I),
     1HZERO(I),HBAR(I),KTBAR(I),KDBAR(I),DBAR(I),I=1,12)
      WOT 3,6
      WOT 3,7
      DO 20 J=1,12
      IF((J-1).NE.NN) GO TO B1
      WOT 3,6
      WOT 3,7
      NN=NN+3
   B1 CONTINUE
      OMEGAS(J)=OMEGAS(J)/RADIAN
      WOT 3,8,MONTH(J),OMEGAS(J),OMEGAH(J)
      WOT 3,9,(RTOT(J,I),I=1,7)
      WOT 3,10,(IBARTH(J,I),I=1,7)
      WOT 3,11,(RDIF(J,I),I=1,7)
      WOT 3,12,(IBARDH(J,I),I=1,7)
      WOT 3,13,(CTH(J,I),I=1,7)
      WOT 3,14,(THETA(J,I),I=1,7)
      WOT 3,15,(TABAR(J,I),I=1,7)
      WOT 3,16,(IC(J,I),I=1,7)
      WOT 3,17,(XC(J,I),I=1,7)
      WOT 3,18,(PHI(J,I),I=1,7)
      WOT 3,19,(Q(J,I),I=1,7)
      WOT 3,A19,U(J)
      WOT 3,A20,DCEFF(J)
   20 CONTINUE
      WOT 3,6
    1 FORMAT(5X,2A10)
    2 FORMAT(21X,9HLATITUDE=,F10.3,2X,7HDEGREES)
   A1 FORMAT(21X,9HSURFACES=,F10.3)
   A2 FORMAT(13X,17HREFRACTIVE INDEX=,F10.3)
   A3 FORMAT(20X,10HTHICKNESS=,F10.3)
   A4 FORMAT(7X,23HEXTINCTION COEFFICIENT=,F10.3)
   A5 FORMAT(8X,22HCOLLECTOR TEMPERATURE=,F10.3)
   A6 FORMAT(8X,22HHEAT LOSS COEFFICIENT=,F10.3///)
    3 FORMAT(10X,A10,F10.3,6X,F10.3)
   A7 FORMAT(10X,5HMONTH,10X,4HHBAR,5X,19HAMBIENT TEMPERATURE)
    4 FORMAT(///2X,5HMONTH,7X,5HDELTA,5X,5HRATIO,5X,6HOMEGAS,4X,
     16HOMEGAH,4X,5HHZERO,6X,4HHBAR,6X,5HKTBAR,5X,5HKDBAR,5X,4HDBAR//)
    5 FORMAT(A10,F10.3,F10.5,7F10.3)
    6 FORMAT(1H1)
    7 FORMAT(14X,3H1/2,5X,5H1 1/2,5X,5H2 1/2,5X,5H3 1/2,
     15X,5H4 1/2,5X,5H5 1/2,5X,5H6 1/2//)
    8 FORMAT(1X,A10/1X,13HSUNSET ANGLE=,F10.3,2X,7HDEGREES/,
     11X,18HSUNRISE TO SUNSET=,F10.3,2X,5HHOURS/)
    9 FORMAT(3X,4HRTOT,3X,7F10.3)
   10 FORMAT(1X,6HIBARTH,3X,7F10.3)
   11 FORMAT(3X,4HRDIF,3X,7F10.3)
   12 FORMAT(1X,6HIBARDH,3X,7F10.3)
   13 FORMAT(4X,3HCTH,3X,7F10.3)
   14 FORMAT(2X,5HTHETA,3X,7F10.3)
   15 FORMAT(2X,5HTABAR,3X,7F10.3)
   16 FORMAT(5X,2HIC,3X,7F10.3)
   17 FORMAT(5X,2HXC,3X,7F10.3)
   18 FORMAT(4X,3HPHI,3X,7F10.3)
```

```
 13 FORMAT(6X,1HQ,3X,7F10.3)
A13 FORMAT(//15X,23HHEAT LOSS COEFFICIENT =,F10.3)
A23 FORMAT(10X,28HDAILY COLLECTION EFFICIENCY=,F10.3//)
    RETURN
    END
    SUBROUTINE TERP (X,Y,N,XA,YA,IT)
    DIMENSION X(1),Y(1)
C
C* * * * * * * * CODE DESCRIPTION * * * * * * * * * *
C
C
C        THIS SUBROUTINE PERFORMS A STRAIGHT LINE INTERPOLATION
C        IF THE INPUT VALUE XA IS OUTSIDE THE TABLE VALUES OF X THEN
C        A STRAIGHT LINE EXTRAPOLATION IS DONE TO OBTAIN THE
C        VALUE OF YA
C
C   REVISED 1 JAN 1974
C
C
C* * * * * * * * VARIABLE DEFINITIONS * * * * * * * *
C
C        X=TABLE OF X VALUES
C        Y=TABLE OF Y VALUES
C        N=NUMBER OF (X,Y) VALUES IN TABLES
C        XA=INPUT VALUE OF X
C        YA=INTERPOLATED VALUE OF Y
C        IT=TYPE OF INTERPOLATION
C          0  X LINEAR,Y LINEAR
C          1  X LOG, Y LOG
C          2  X LINEAR, Y LOG
C          3  X LOG, Y LINEAR
C
C
    IL = 0
    IE=0
    DO 5 I=2,N
    IF(XA-X(I)) 7,6,5
  5 CONTINUE
    I=I-1
    IE=1
    IF(IT-1)10,14,10
  6 YA = Y(I)
    GO TO 50
  7 I = I
    IF(IT-1) 10,14,10
 10 XV = XA
    XVA = X(I-1)
    XVB = X(I)
 12 IF(IT-2) 19,16,14

 14 XV = LOGF(XA)
    XVA = LOGF(X(I-1))
    XVB = LOGF(X(I))
 15 IF(IT-2) 16,16,19
 16 IF(Y(I-1))60,60,17
 17 IF(Y(I)) 60,60,18
 60 YA= 0
    GO TO 50
 18 YVA = LOGF(Y(I-1))
    YVB = LOGF(Y(I))
```

```
      IL = 1
      GO TO 20
   19 YVA = Y(I-1)
      YVB = Y(I)
C     DO INTERPOLATION
   20 CONTINUE
      IF(IE.EQ.0) GO TO 21
      YA=YVB+(YVB-YVA)*(XV-XVB)/(XVB-XVA)
      GO TO 23
   21 YA = YVA + (YVB-YVA) * (XV-XVA) / (XVB - XVA)
   23 IF(IL) 50,50,22
   22 YA = EXPF(YA)
   50 RETURN
      END
```

SAMPLE PROBLEM

CARD INPUT FOR PROGRAM SOLAR

CARD 1	ID(1), ID(2) ID(1), ID(2) = IDENTIFICATION	(2A10)
CARD 2	LAT LAT = LATITUDE IN DEGREES	(E10.3)
CARD 3	N, NPRIME, L1, K1 N = NUMBER OF COVER SURFACES NPRIME = INDEX OF REFRACTION L1 = THICKNESS OF A SINGLE SURFACE K1 = EXTINCTION COEFFICIENT	(4E10.3)
CARD 4	TC, UØ TC = COLLECTOR TEMPERATURE IN DEGREES CENTIGRADE UØ = HEAT LOSS COEFFICIENT AT INITIAL CONDITIONS OF TC AND TØ	(2E10.3)
CARD 5	HBAR(I), I = 1, 6 HBAR = MONTHLY AVERAGE DAILY TOTAL RADIATION ON A HORIZONTAL SURFACE	(6E10.3)
CARD 6	HBAR(I), I = 7, 12	(6E10.3)
CARD 7	TØ(I), I = 1, 6 TØ = AMBIENT AIR TEMPERATURE IN DEGREES FAHRENHEIT	(6E10.3)
CARD 8	TØ(I), I = 7, 12	(6E10.3)

SAMPLE INPUT

```
1    PHOENIX,ARIZONA
2    33.43
3    2.,1.52,.125,.200,
4    60.,4.54,
5    1126.6,1514.7,1967.1,2388.2,2709.6,2781.5,
6    2450.5,2299.6,2131.3,1688.9,1290.0,1040.9,
7    54.2,58.8,64.7,72.2,80.8,89.2,
8    94.6,92.5,87.4,75.8,63.6,56.7,
```

PHOENIX,ARIZONA

LATITUDE=	33.430	DEGREES
SURFACES=	2.000	
REFRACTIVE INDEX=	1.520	
THICKNESS=	0.125	
EXTINCTION COEFFICIENT=	0.200	
COLLECTOR TEMPERATURE=	60.000	
HEAT LOSS COEFFICIENT=	4.540	

MONTH	HEAR	AMBIENT TEMPERATURE
JAN	148.035	12.333
FEB	199.032	14.889
MAR	258.477	18.167
APR	313.809	22.333
MAY	356.041	27.111
JUN	365.489	31.778
JUL	321.996	34.778
AUG	302.167	33.611
SEP	280.053	30.778
OCT	221.921	24.333
NOV	169.506	17.556
DEC	136.774	13.722

MONTH	DELTA	RATIO	OMEGAS	OMEGAH	HZERO	HBAR	KTBAR	KDBAR	DBAR
JAN	-21.270	1.03150	1.311	10.015	225.058	148.035	0.658	0.160	35.910
FEB	-12.930	1.02350	1.419	10.838	286.946	199.032	0.694	0.151	43.213
MAR	-2.430	1.01030	1.543	11.786	359.029	258.477	0.720	0.139	50.060
APR	9.500	0.99130	1.681	12.846	428.933	313.809	0.732	0.134	57.404
MAY	18.680	0.97570	1.796	13.719	472.866	356.041	0.753	0.125	59.080
JUN	23.280	0.96800	1.859	14.200	491.666	365.489	0.743	0.128	63.023
JUL	21.650	0.96800	1.836	14.025	483.889	321.996	0.665	0.158	76.281
AUG	14.300	0.97570	1.740	13.292	449.556	302.167	0.672	0.156	70.114
SEP	3.330	0.98980	1.609	12.294	389.937	280.053	0.718	0.140	54.694
OCT	-8.230	1.00870	1.475	11.269	317.290	221.921	0.699	0.149	47.322
NOV	-18.300	1.02380	1.351	10.319	246.182	169.506	0.689	0.152	37.387
DEC	-23.230	1.03180	1.284	9.805	209.934	136.774	0.652	0.161	33.825

1

JAN

SUNSET ANGLE= 75.109 DEGREES

SUNRISE TO SUNSET= 10.015 HOURS

	1/2	1 1/2	2 1/2	3 1/2	4 1/2	5 1/2	6 1/2
RTOT	0.165	0.145	0.110	0.064	0.020	0.000	0.
IBARTH	585.546	514.696	390.709	227.797	71.679	0.259	0.
RDIF	0.153	0.139	0.112	0.073	0.026	0.	0.
IBARDH	131.616	119.509	96.119	63.040	22.527	0.	0.
CTH	0.571	0.519	0.417	0.274	0.098	0.	0.
THETA	0.963	1.026	1.140	1.294	1.473	1.571	1.571
TABAR	0.625	0.591	0.509	0.365	0.214	0.	0.
IC	295.090	311.638	361.798	505.406	860.920	0.	0.
XC	0.504	0.605	0.926	2.219	12.011	0.	0.
PHI	0.503	0.407	0.150	0.	0.	0.	0.
Q	183.947	123.783	29.861	0.	0.	0.	0.

HEAT LOSS COEFFICIENT = 3.866

DAILY COLLECTION EFFICIENCY= 0.190

FEB

SUNSET ANGLE= 81.283 DEGREES

SUNRISE TO SUNSET= 10.838 HOURS

	1/2	1 1/2	2 1/2	3 1/2	4 1/2	5 1/2	6 1/2
RTOT	0.154	0.137	0.108	0.071	0.030	0.004	0.
IBARTH	736.143	656.614	517.440	337.726	143.556	20.009	0.
RDIF	0.142	0.131	0.109	0.077	0.039	0.	0.
IBARDH	147.419	135.560	112.650	80.250	40.568	0.	0.
CTH	0.683	0.628	0.522	0.372	0.188	0.	0.
THETA	0.819	0.892	1.022	1.190	1.382	1.571	1.571
TABAR	0.677	0.655	0.594	0.463	0.274	0.	0.
IC	259.045	267.937	295.440	378.709	640.805	0.	0.
XC	0.352	0.408	0.571	1.121	4.464	0.	0.
PHI	0.648	0.592	0.431	0.031	0.	0.	0.
Q	323.130	254.574	132.251	4.865	0.	0.	0.

HEAT LOSS COEFFICIENT = 3.888

DAILY COLLECTION EFFICIENCY= 0.299

MAR

SUNSET ANGLE= 88.395 DEGREES

SUNRISE TO SUNSET= 11.786 HOURS

	1/2	1 1/2	2 1/2	3 1/2	4 1/2	5 1/2	6 1/2
RTOT	0.144	0.130	0.106	0.075	0.039	0.010	0.
IBARTH	894.167	804.663	655.345	466.151	242.392	60.272	0.
RDIF	0.132	0.123	0.105	0.079	0.049	0.014	0.
IBARDH	158.427	147.317	125.853	95.498	58.322	16.857	0.
CTH	0.803	0.747	0.638	0.484	0.296	0.085	0.
THETA	0.638	0.727	0.879	1.065	1.271	1.485	1.571
TABAR	0.711	0.698	0.660	0.565	0.379	0.187	0.
IC	230.374	234.636	248.134	289.938	432.308	874.257	0.
XC	0.258	0.292	0.379	0.622	1.784	14.505	0.
PHI	0.742	0.708	0.621	0.380	0.	0.	0.
Q	471.908	397.885	268.777	99.935	0.	0.	0.

HEAT LOSS COEFFICIENT = 3.915

DAILY COLLECTION EFFICIENCY= 0.399

1

APR
SUNSET ANGLE= 96.342 DEGREES
SUNRISE TO SUNSET= 12.846 HOURS

	1/2	1 1/2	2 1/2	3 1/2	4 1/2	5 1/2	6 1/2
RTOT	0.134	0.122	0.102	0.078	0.047	0.018	0.003
IBARTH	1012.142	919.440	771.693	585.126	353.371	133.797	19.107
RDIF	0.122	0.115	0.100	0.080	0.055	0.027	0.
IBARDH	168.459	158.129	138.175	109.955	75.392	36.843	0.
CTH	0.907	0.851	0.744	0.592	0.406	0.198	0.
THETA	0.435	0.552	0.732	0.937	1.153	1.371	1.571
TABAR	0.726	0.719	0.698	0.638	0.494	0.281	0.
IC	204.917	206.871	213.225	233.318	300.921	528.984	0.
XC	0.202	0.225	0.276	0.399	0.852	3.954	0.
PHI	0.798	0.775	0.724	0.601	0.176	0.	0.
Q	586.053	512.447	389.655	224.325	30.700	0.	0.

HEAT LOSS COEFFICIENT = 3.950
DAILY COLLECTION EFFICIENCY= 0.463

MAY
SUNSET ANGLE= 102.896 DEGREES
SUNRISE TO SUNSET= 13.719 HOURS

	1/2	1 1/2	2 1/2	3 1/2	4 1/2	5 1/2	6 1/2
RTOT	0.127	0.116	0.100	0.079	0.051	0.024	0.007
IBARTH	1081.151	990.908	853.145	672.658	434.752	205.392	56.375
RDIF	0.116	0.109	0.097	0.079	0.058	0.034	0.009
IBARDH	163.889	154.772	137.160	112.254	81.749	47.726	12.502
CTH	0.960	0.907	0.804	0.658	0.479	0.280	0.073
THETA	0.293	0.435	0.637	0.853	1.071	1.287	1.497
TABAR	0.732	0.728	0.713	0.670	0.560	0.357	0.147
IC	179.250	180.341	183.966	195.710	234.390	367.051	889.630
XC	0.156	0.182	0.216	0.291	0.539	1.787	15.780
PHI	0.834	0.818	0.784	0.709	0.461	0.	0.
Q	660.180	589.734	477.274	319.756	112.160	0.	0.

HEAT LOSS COEFFICIENT = 3.989
DAILY COLLECTION EFFICIENCY= 0.505

JUN
SUNSET ANGLE= 106.501 DEGREES
SUNRISE TO SUNSET= 14.200 HOURS

	1/2	1 1/2	2 1/2	3 1/2	4 1/2	5 1/2	6 1/2
RTOT	0.122	0.113	0.098	0.079	0.053	0.027	0.009
IBARTH	1073.656	989.448	863.137	691.212	463.150	238.595	78.949
RDIF	0.112	0.106	0.095	0.079	0.059	0.036	0.014
IBARDH	169.855	160.858	143.475	118.893	88.786	55.206	20.442
CTH	0.978	0.926	0.826	0.684	0.511	0.318	0.118
THETA	0.211	0.387	0.599	0.817	1.034	1.247	1.453
TABAR	0.732	0.728	0.716	0.680	0.585	0.402	0.197
IC	155.356	156.138	158.718	167.129	194.197	282.868	576.298
XC	0.145	0.158	0.184	0.242	0.419	1.186	7.300
PHI	0.855	0.842	0.816	0.758	0.581	0.004	0.
Q	671.998	606.750	504.563	356.501	157.451	0.413	0.

HEAT LOSS COEFFICIENT = 4.028
DAILY COLLECTION EFFICIENCY= 0.524

1

JUL

SUNSET ANGLE= 105.191 DEGREES

SUNRISE TO SUNSET= 14.025 HOURS

	1/2	1 1/2	2 1/2	3 1/2	4 1/2	5 1/2	6 1/2
RTOT	0.124	0.114	0.099	0.079	0.052	0.026	0.008
IBARTH	956.688	879.802	764.472	610.307	402.636	202.104	62.805
RDIF	0.113	0.107	0.096	0.079	0.058	0.036	0.012
IEARDH	207.719	196.523	174.892	144.303	106.839	65.052	21.792
CTH	0.972	0.920	0.819	0.675	0.500	0.305	0.102
THETA	0.236	0.403	0.612	0.829	1.047	1.261	1.469
TABAR	0.722	0.718	0.706	0.671	0.579	0.411	0.235
IC	141.543	142.320	144.724	152.384	176.561	248.443	435.147
XC	0.148	0.162	0.189	0.250	0.439	1.229	6.929
PHI	0.852	0.838	0.811	0.751	0.565	0.014	0.
Q	588.752	529.747	437.785	307.388	131.645	1.202	0.

HEAT LOSS COEFFICIENT = 4.053

DAILY COLLECTION EFFICIENCY= 0.517

AUG

SUNSET ANGLE= 99.687 DEGREES

SUNRISE TO SUNSET= 13.292 HOURS

	1/2	1 1/2	2 1/2	3 1/2	4 1/2	5 1/2	6 1/2
RTOT	0.130	0.119	0.101	0.078	0.049	0.021	0.004
IEARTH	945.466	862.691	733.362	567.772	356.556	152.591	32.330
RDIF	0.119	0.112	0.098	0.080	0.056	0.031	0.004
IEARDH	199.804	188.164	165.675	133.872	94.922	51.478	6.502
CTH	0.938	0.883	0.778	0.628	0.446	0.242	0.031
THETA	0.354	0.488	0.680	0.891	1.109	1.327	1.540
TABAR	0.721	0.716	0.700	0.653	0.537	0.352	0.122
IC	147.916	149.027	152.533	163.511	198.795	303.496	877.632
XC	0.156	0.173	0.208	0.288	0.558	1.989	27.146
PHI	0.844	0.827	0.792	0.713	0.449	0.	0.
Q	575.353	510.988	406.348	264.041	85.869	0.	0.

HEAT LOSS COEFFICIENT = 4.044

DAILY COLLECTION EFFICIENCY= 0.508

SEP

SUNSET ANGLE= 92.201 DEGREES

SUNRISE TO SUNSET= 12.294 HOURS

	1/2	1 1/2	2 1/2	3 1/2	4 1/2	5 1/2	6 1/2
RTOT	0.139	0.126	0.104	0.077	0.043	0.013	0.001
IBARTH	936.665	846.513	699.815	514.762	289.381	89.716	5.918
RDIF	0.127	0.119	0.103	0.080	0.052	0.021	0.
IBARDH	166.771	155.830	134.693	104.801	68.190	27.357	0.
CTH	0.858	0.802	0.693	0.539	0.351	0.141	0.
THETA	0.539	0.641	0.805	1.001	1.212	1.430	1.571
TABAR	0.719	0.710	0.681	0.605	0.440	0.240	0.
IC	163.354	165.523	172.458	194.072	266.921	488.855	0.
XC	0.174	0.196	0.246	0.377	0.922	5.449	0.
PHI	0.826	0.804	0.754	0.623	0.124	0.	0.
Q	556.107	483.298	359.215	194.114	15.786	0.	0.

HEAT LOSS COEFFICIENT = 4.020

DAILY COLLECTION EFFICIENCY= 0.479

1

OCT
SUNSET ANGLE= 84.521 DEGREES
SUNRISE TO SUNSET= 11.269 HOURS

	1/2	1 1/2	2 1/2	3 1/2	4 1/2	5 1/2	6 1/2
RTOT	0.149	0.134	0.107	0.073	0.034	0.007	0.
IBARTH	795.216	712.869	570.914	389.222	183.354	35.243	0.
RDIF	0.137	0.127	0.107	0.079	0.044	0.005	0.
IBARDH	155.864	144.111	121.404	89.292	49.963	6.097	0.
CTH	0.740	0.684	0.576	0.424	0.237	0.029	0.
THETA	0.738	0.817	0.956	1.133	1.331	1.542	1.571
TABAR	0.695	0.677	0.628	0.514	0.322	0.105	0.
IC	203.641	208.894	225.285	275.280	438.747	1352.712	0.
XC	0.256	0.293	0.395	0.707	2.393	38.383	0.
PHI	0.744	0.707	0.605	0.302	0.	0.	0.
Q	410.962	341.304	217.045	60.423	0.	0.	0.

HEAT LOSS COEFFICIENT = 3.966
DAILY COLLECTION EFFICIENCY= 0.387

NOV
SUNSET ANGLE= 77.390 DEGREES
SUNRISE TO SUNSET= 10.319 HOURS

	1/2	1 1/2	2 1/2	3 1/2	4 1/2	5 1/2	6 1/2
RTOT	0.161	0.142	0.109	0.067	0.024	0.002	0.
IBARTH	654.392	578.214	444.903	270.732	96.919	6.482	0.
RDIF	0.149	0.136	0.111	0.075	0.032	0.	0.
IBARDH	133.343	121.690	99.178	67.341	28.349	0.	0.
CTH	0.613	0.559	0.456	0.309	0.130	0.	0.
THETA	0.911	0.978	1.098	1.256	1.440	1.571	1.571
TABAR	0.647	0.618	0.542	0.397	0.225	0.	0.
IC	256.344	268.612	306.220	418.222	736.980	0.	0.
XC	0.392	0.465	0.688	1.545	7.604	0.	0.
PHI	0.609	0.537	0.323	0.	0.	0.	0.
Q	257.927	191.775	77.995	0.	0.	0.	0.

HEAT LOSS COEFFICIENT = 3.910
DAILY COLLECTION EFFICIENCY= 0.259

DEC
SUNSET ANGLE= 73.540 DEGREES
SUNRISE TO SUNSET= 9.805 HOURS

	1/2	1 1/2	2 1/2	3 1/2	4 1/2	5 1/2	6 1/2
RTOT	0.168	0.147	0.110	0.062	0.016	0.	0.
IBARTH	550.570	482.363	359.806	203.058	52.875	0.	0.
RDIF	0.156	0.141	0.112	0.072	0.022	0.	0.
IBARDH	126.391	114.331	91.033	58.085	17.732	0.	0.
CTH	0.543	0.491	0.391	0.250	0.076	0.	0.
THETA	0.997	1.057	1.169	1.319	1.495	1.571	1.571
TABAR	0.608	0.572	0.485	0.341	0.215	0.	0.
IC	295.393	313.961	369.824	526.064	835.967	0.	0.
XC	0.537	0.651	1.028	2.591	15.810	0.	0.
PHI	0.473	0.369	0.092	0.	0.	0.	0.
Q	158.281	101.847	15.981	0.	0.	0.	0.

HEAT LOSS COEFFICIENT = 3.878
DAILY COLLECTION EFFICIENCY= 0.168

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