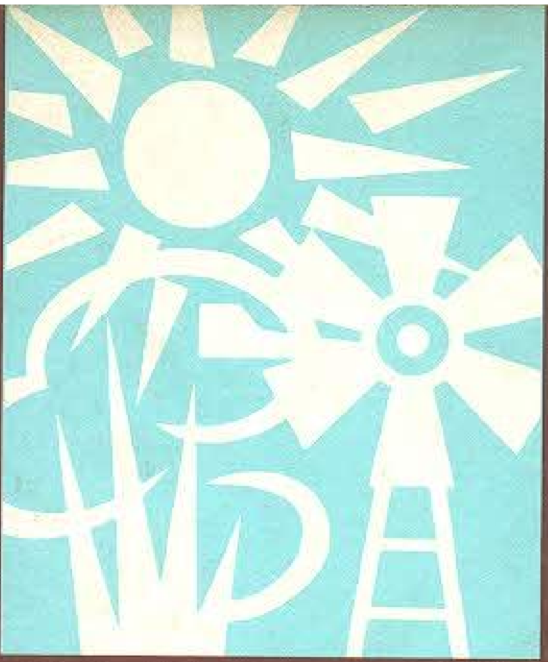

NEW SOURCES OF ENERGY

PROCEEDINGS OF THE CONFERENCE

Rome, 21 – 31 August 1961

VOLUME 4

SOURCES NOUVELLES D'ÉNERGIE

ACTES OFFICIELS DE LA CONFÉRENCE

Rome, 21 – 31 août 1961

UNITED NATIONS
NATIONS UNIES

PROCEEDINGS OF THE UNITED NATIONS CONFERENCE ON NEW SOURCES OF ENERGY

SOLAR ENERGY, WIND POWER AND GEOTHERMAL ENERGY
Rome, 21-31 August 1961

VOLUME 4. SOLAR ENERGY: I

ACTES OFFICIELS DE LA CONFÉRENCE DES NATIONS UNIES SUR LES SOURCES NOUVELLES D'ÉNERGIE

ÉNERGIE SOLAIRE, ÉNERGIE ÉOLIENNE ET ÉNERGIE GÉOTHERMIQUE
Rome, 21-31 août 1961

VOLUME 4. ÉNERGIE SOLAIRE : I

UNITED NATIONS / NATIONS UNIES
New York, 1964

E/CONF.35/5

UNITED NATIONS PUBLICATION

Sales No. : 63. I. 38

Price : $ U.S. 20.00
(or equivalent in other currencies)

PUBLICATION DES NATIONS UNIES

Numéro de vente : 63. I. 38

Prix : 20. dollars (USA)
(ou l'équivalent en monnaie du pays)

INTRODUCTION

The United Nations Conference on New Sources of Energy was held in Rome from 21 to 31 August 1961. A brief review of the proceedings, of the papers submitted to the Conference and of the related discussions has been printed in *New Sources of Energy and Energy Development: Report on the United Nations Conference on New Sources of Energy.*[1] The same publication also contains the agenda and the lists of participants and conference officers, as well as lists of all the papers and reports.

The Proceedings of the Conference comprise seven volumes as follows:

Volume 1. General sessions.
Volume 2. Geothermal energy: I.
Volume 3. Geothermal energy: II.
Volume 4. Solar energy: I.
Volume 5. Solar energy: II.
Volume 6. Solar energy: III.
Volume 7. Wind power.

The present volume, "Solar energy: I", contains the papers and reports relating to the following agenda items: II.C.1. Use of solar energy for mechanical power and electricity production: (*a*) by means of piston engines and turbines; (*b*) by direct conversion to electricity: (*i*) by means of thermoelectric converters; (*ii*) by means of photo-electric cells; III.A. Solar energy availability and instruments for measurement; III.B. New materials in solar energy utilization.

The rapporteurs' general reports and their summations of the proceedings in connexion with each agenda item or sub-item are given in full in both English and French, as are those individual papers that were submitted to the Conference in both languages. With a few exceptions, all the papers are summarized in both English and French.

Within each agenda item or sub-item, the papers are printed in the alphabetical order of the authors' names. References supplied by the authors are listed after the text. As a rule, they are numbered consecutively throughout each paper and are indicated by Arabic figures in parentheses.

The reports and papers are printed in the form in which they were presented to the Conference, and the affiliations of the participants are those in effect at the time. Corrections to the papers have been incorporated; some of the figures have been rearranged; and minor editorial changes have been made.

The views and opinions expressed are those of the individual authors and do not imply the expression of any opinion on the part of the Secretariat of the United Nations.

The symbols appearing after the titles of the papers and reports, and in reference to them in the text, correspond to the symbols under which they were presented at the Conference. They have been abbreviated by the elimination of the prefix "E/CONF.35/", which should be included in all full references.

---

[1] United Nations publication, Sales No.: 62.I.21.

S/98

THE ESTIMATION OF MONTHLY MEAN VALUES OF DAILY TOTAL SHORT WAVE RADIATION ON VERTICAL AND INCLINED SURFACES FROM SUNSHINE RECORDS FOR LATITUDES 40°N-40°S

John K. Page *

One of the first problems in the design of flat plate collectors is to decide the amount of energy actually available at any locality and the best orientation for optimum efficiency. Techniques for calculating the total radiation on cloudless days on inclined surfaces are well known. In practice, however, the problem is to determine rather the radiation received on surfaces with different orientations under average conditions.

Few observations of radiation intensities have been made in many parts of the tropics, particularly on a long-term climatological basis. Records of sunshine, however, are often available over relatively long periods. It was decided any prediction technique of widespread engineering interest must therefore be based on the use of sunshine data. The order of accuracy sought was of the order ± 10 per cent, and the technique developed below appears to give results somewhat better than this where it has been possible to check it.

The average amount of radiation received can be calculated only for inclined and vertical surfaces, if the diffuse radiation component can be assessed with reasonable accuracy. The paper sets out to provide a rapid method of carrying out such computations which can be used by persons relatively unacquainted with either the complexities of the solar radiation climate at different centres or the detailed movements of the sun. It enables the monthly mean daily values of the direct and diffuse radiation to be estimated separately for certain vertical and inclined surfaces using sunshine data.

Part I

THE USE OF ÅNGSTRÖM TYPE FORMULAE FOR THE ESTIMATION OF MEAN VALUES OF GLOBAL RADIATION FROM SUNSHINE RECORDS

Regression equations of the Ångström type have been used for many years for estimating mean values of the total daily radiation falling on horizontal surfaces from sunshine records.

The original Ångström formula $\frac{n}{N}$ was written in the form:

$$Q = Qo' \left(a + b\,\frac{n}{N}\right) \qquad [1]$$

where Q = mean global daily radiation on the horizontal plane for the period under consideration.
Qo' = the global daily radiation on the horizontal plane on cloudless days for the period under consideration.
n = mean daily amount of bright sunshine hours during period under consideration.
N = maximum possible amount of sunshine hours during period under consideration.
a and b = constants depending on locality and climate of station.

The climatological period adopted varies; usually it is one month or ten days. The value of Qo' at high latitudes, however, changes very rapidly from day to day during the winter and a ten day period is better in such regions.

It was often inferred that $a + b = 1$, because on cloudless days $Q = Qo'$ and $\frac{n}{N} = 1$. Such regression equations are based on climatological means, and they cannot necessarily be expected to apply to extreme values for particular days. Several investigations have, in fact, shown that the relationship between the daily global radiation and the percentage of possible sunshine considered on the basis of individual daily values is not linear (2, 12). Ångström type equations usually give an over estimate of total radiation on cloudless days, and on overcast days. This does not mean, however, that it is not possible to derive satisfactory linear equations for calculating mean monthly values of total radiation. It is, however, necessary to relax the condition $a + b = 1$ first.

There are two important practical difficulties in using the original form of the Ångström equation.

(*a*) The definition of possible bright sunshine is ambiguous. Some investigations have applied corrections to allow for the fact that the sunshine recorder

---

* Professor of Building Science, University of Sheffield, United Kingdom.

does not turn the card until the sun's rays reach a certain critical intensity, and others do not. It is not in fact possible to assess the correction without detailed knowledge of the radiation climate of a particular area.

(*b*) The precise value of Qo' to adopt cannot be determined in the absence of local radiation measurements.

The use of the modified form of Ångström type formula gets round the second difficulty (1). If the formula is written in the following form:

$$Q = Q_o \left(a + b \frac{n}{N_o} \right) \qquad [2]$$

where Q now represents the total radiation per unit area falling on a horizontal plane *outside the atmosphere*, and where the other symbols have the same meaning as before, Q_o can be determined unambiguously for any particular value of the solar constant. Black, Bonython and Prescott obtained the following over-all regression equation for the stations they studied:

$$Q = Q_o \left(0.23 + 0.48 \frac{n}{N} \right) \qquad [3]$$

It appears, however, that no attempt was made to reduce records to a common pyrheliometric scale. In addition, the basis on which the percentage of possible sunshine was calculated is not stated. Attention must be drawn to the fact that results of both American measurements based on the Mervin recorder and results obtained in other parts of the world by the Campbell Stokes recorder are grouped together in their calculations. As corrections for the length of day are always applied in American practice, it is clear that the studies of Black *et al.* are based, as they were aware, on an ambiguous definition of percentage of possible sunshine, as well as on imprecisely defined pyrheliometric scales (1).

In this paper an attempt has been made to avoid some of these criticisms by adopting the following procedure:

(*a*) All observed values of Q were reduced to the International Pyrheliometric Scale involving a correction of —2.0 per cent to all values measured on the Smithsonian (1913) scale, and of +1.5 per cent to all values measured on the Ångström scale.

(*b*) The recorded sunshine was expressed as a percentage of the possible sunshine between sunrise and sunset. No attempt was made to correct for the fact that the trace is not burned until the intensity reaches a given critical value because this correction depends on a number of indeterminable factors like the water and dust content of the air, the humidity content of the card, etc. Such corrections cannot be accurate unless based on extensive local studies. Besides, it seems illogical to give a lot of attention to attempting to correct one limitation of sunshine recorders as a radiation recording instrument while ignoring others like the burning of the card through this high cloud, etc. Attention was confined to records made with the Campbell Stokes type of sunshine recorder.

(*c*) Black, Bonython and Prescott's form of the Ångström formula was adopted so that Q_o would be determined unambiguously.

The relationship between the monthly means of total daily radiation on the horizontal plane and the percentage of possible bright sunshine for a number of centres, mainly in the tropics and subtropics, has been studied and the results given in table 2. The original regression equations published by Black, Bonython and Prescott have also been included together with other recently published values for low latitudes.

A solar constant of 2.00 cals. cm.$^{-2}$ min.$^{-1}$ has been used throughout as a result of Johnson's recommendations for the stations studied by the author (7). In practice, the reduction procedure used by Drummond was adopted (4), the correction (for the Ångström scale being too low) being applied to the computed radiation outside the atmosphere Q_o instead of to the surface data Q recorded on the Ångström scale to cut down the amount of computation. Q_o was determined for latitudes 10° N - 60° N by using the tables of radiation outside the atmosphere for given dates at different latitudes based on the work of Milanovitch given in the Smithsonian Meteorological Tables (15). The original values in the tables were increased by the ratio $\frac{2.00}{1.94}$ to allow for the changed value of the solar constant. These adjusted values for individual days were plotted on an extended scale. A smooth curve was drawn, and the mean monthly values were obtained by planimetry. The values for latitudes 0° - 40° S were taken from Drummond's paper, which followed a procedure essentially similar to that described above for the southern hemisphere. The values adopted based on a solar constant of 2.00 gm. cal. cm.$^{-2}$ min.$^{-1}$ are given in table 1. From the values given in table 1, smoothed curves can be drawn for different months giving the variation of the monthly mean value of Q_o outside the atmosphere with latitude. The values adopted for the possible sunshine were taken from the table given by Brooks (3), and no adjustment was applied for failure to record at low solar altitudes. (Suitable tables may also be found in the Smithsonian Meteorological Tables, 15.)

The regression equations were calculated by the method of least squares as a regression of Q/Q_o on $\frac{n}{N}$. The advantage of adopting the above procedure is that all variations between different climates and latitudes appear in the regression coefficients a and b. It is then possible to explore systematically their variation from place to place. It will be shown in a future paper by the author that it is possible to place the Ångström formula on a reasonably sound climatological basis, by selecting the constants according to latitude and the transmission characteristics of the atmosphere for any particular season of

Table 1. Mean values for calendar months of total daily radiation on a horizontal plane outside the earth's atmosphere, latitudes 40°N-40°S. (Solar constant 2.00 cals. cm^{-2} $min.^{-1}$.) Units: cals. cm^{-2}, day^{-1}

Latitude	*40°N.*	*30°N.*	*20°N.*	*10°N.*	*0°*	*10°S.*	*20°S.*	*30°S.*	*40°S.*
January	373	521	659	780	884	967	1 020	1 049	1 049
February	500	632	747	844	915	961	974	964	925
March	674	772	848	899	923	918	884	825	741
April	839	899	924	924	893	839	761	658	536
May	970	977	959	916	846	758	648	520	382
June	1 017	1 003	965	902	817	713	589	456	312
July	996	987	959	905	827	729	614	483	344
August	895	927	934	913	867	801	706	591	465
September	740	822	877	904	905	880	826	748	648
October	564	683	784	860	911	937	931	903	841
November	412	558	687	799	888	958	1 001	1 016	1 001
December	332	487	631	760	869	961	1 026	1 067	1 084

the year in any given locality. The author's work on this subject is not yet ready for publication, but his preliminary investigations show little confidence can be placed on the formula suggested by Glover and McCulloch (6).

$$Q/Q_o = 0.29 \cos. \phi + 0.52 \frac{n}{N} \qquad [4]$$

Where ϕ is the latitude.

The author prefers to use monthly mean values of total radiation and sunshine, for this will be the data normally available for calculating climatological mean values of total radiation. The consequent regression formulae cannot be used for predicting daily values of total radiation from daily sunshine values with accuracy, but they were not derived for this purpose. This paper deals only with climatological mean values.

The mean values of a and b were found to be 0.23 and 0.52 respectively. These values are identical with the mean values suggested by Glover and McCulloch for latitude 32 (6) and differ very little from the mean values of 0.23 and 0.48 found by Black *et al.* (1). In practice it is better, however, to try to select climatologically appropriate values of a and b than to use mean values. These can be best established by study of radiation data and sunshine data from other stations in the same type of climate.

Examination of the results so far computed shows:

(*a*) If low percentage of possible sunshine coincides with the season of high turbidity, the value of a will be low, and the value of b high, for example, Kew and Dakar; also, modified by height, Windhoek.

(*b*) If season of high turbidity falls in period with intermediate amount of possible sunshine, the correlation coefficient falls, for the points in the turbid months fall off the curve, for example, Leopoldville.

(*c*) In places where there is little variation in possible sunshine but turbidity variations due to movement of the Intertropical Convergence Zone, the points will be very scattered, and it may become impossible to find a significant regression equation from monthly mean values.

(*d*) If season of high turbidity coincides with season of greatest percentage of possible sunshine, a tends to be high and b low, for example, Pretoria and Stanleyville. This often occurs when dust is responsible for the increased turbidity during the dry season.

(*e*) In places with high values of possible sunshine a tends to be high and b low; the opposite holds for places of very low possible sunshine, where a tends to be low and b high. This effect results because the actual curve is not strictly linear but has an upward curvature if considered over a wide enough range of values of $\frac{n}{N}$. Hence the slope is greater at low values than at medium values of possible sunshine, and vice versa at high levels of possible sunshine.

(*f*) There appears to be a latitudinal effect but it tends to be swamped by variations in turbidity. It follows that the constants a and b must be selected with considerable meteorological intelligence, in the absence of local records which would enable them to be determined satisfactorily for a particular region. The most important factor to consider is the variation of the transmission characteristics of the atmosphere above the site in question at different times of the year.

Part II

THE SEPARATION OF DIRECT RADIATION FROM DIFFUSE RADIATION

The second step in the problem of calculating the monthly mean total daily radiation incident on inclined surfaces from sunshine data is to separate the diffuse radiation from the direct radiation.

Examination of the records of ten selected stations where observations of both total and diffuse radiation have been made immediately revealed that a linear regression equation could be derived from

Table 2. Values of a and b in regression equation $Q/Q = (a + b\ n/N)$

Station	*Latitude*	*Height above sea level (metres)*	*Period*	*No. of months*	*Value of a*	*Value of b*	*r*	*Range of monthly mean values of n/N*	*Annual mean values*		*Source of regression equation*
									Q/Q	*n/N*	
Stanleyville	0° 31′ N	437	Sept. 1952-Aug. 1953	12	.28	.40	.89	.28 — .55	.47	.47	Page
Nairobi	1° 16′ S	1 959	Jan. 1948-Apr. 1943	66	.24	.56	.97	.34 — .81	.56	.57	Page
Singapore	1° 18′ N	120	Aug. 1952-July 1953	12	.21	.48	.45	.32 — .56	.44	.48	Page
Leopoldville	4° 22′ S	450	Jan. 1951-Dec. 1951	12	.21	.52	.65	.31 — .52	.42	.41	Page
Trinidad	10° 38′ N	Not known	Aug. 1957-Aug. 1958	12	(.27)*	(.49)*	N. K.	Not known	Not known		Smith
Dakar	14° 43′ N	Not known	Jan. 1953-Dec. 1953	12	.10	.70	.86	.54 — .84	.60	.70	Page
Jamaica	18° N	Not known	Not known	12	(.31)*	(.49)*	N. K.	Not known	Not known		Cowan
Tananarive	18° 54′S	1 310	Mar. 1953-Feb. 1954	12	.30	.48	.96	.41 — .75	.57	.56	Page
Windhoek	22° 34′ S	1 728	Aug. 1951-Feb. 1954	31	.23	.55	.98	.61 — .95	.69	.81	Page
Pretoria	25° 45′ S	1 369	Jan. 1951-Feb. 1954	38	.27	.46	.97	.61 — .88	.61	.74	Page
Bloomfontein	29° S	1 422	Not known	24	(.25)*	(.50)*	N. K.	Not known	Not knwon		Glover *et al.*
Durban	29°50′ S	5	July. 1951-Feb. 1954	32	.33	.35	.99	.36 — .81	.52	.56	Page
Capetown	33° 54′ S	17	Sept. 1951-Feb. 1954	30	.20	.59	.99	.60 — .82	.62	.71	Page
Dry Creek	34.8 S	Not known	1947-1950	48	(.30)	(.50)	.95	Not known	.60	.59	Black *et al.*
Mount Stromlo	35.3 S	770	1928-1939	144	(.25)	(.54)	.89	Not known		.63	Black *et al.*
Versailles	48.8 N	Not known	1935-1951	99	(.23)	(.50)	.90	Not known	.44	.42	Black *et al.*
Gembloux	50.6 N	Not known	1939-1950	60	(.15)	(.54)	.83	Not known	.33	.33	Black *et al.*
Kew	51.5 N	19	1947-1951	60	.14	.66	.99	.17 — .46	.35	.33	Page
Rothamsted	51.8 N	Not known	1931-1940	84	(.18)	(.55)	.79	Not known	.37	.36	Black *et al.*

NOTES:

(i) Values in parentheses known not to be corrected to International Pyrhetrometric Scale or to solar constant of 2.00 gm. cals. cm^{-2}. min^{-1}.

(ii) * Values based on daily and not monthly values of n/N.

(iii) The following uncorrected alternative values are given by Glover & McCulloch based on daily values of n/N.

Nairobi	$a = 0.26$	$b = 0.57$	Windhoek	$a = 0.26$	$b = 0.52$	Pretoria	$a = 0.25$	$b = 0.50$
Durban	$a = 0.26$	$b = 0.50$	Capetown	$a = 0.29$	$b = 0.50$	Kew	$a = 0.17$	$b = 0.52$

Table 3. Value of constants *c* and *d* in regression equation $\frac{D}{Q} = c + d\,\frac{Q}{Q}$ for ten stations

Station	*Latitude*	*Height above sea level in metres*	*Length of record*	*Period*	*Value of c*	*Value of d*	*Correlation coefficient*	*Range of monthly mean values %*	*Comments*
Stanleyville	0° 31′ N	437	12 months	Sept. 1952-Aug. 1953	1.07	— 1.16	.93	39 — 53	Hot humid climate
Leopoldville	4° 22′ S	450	23 months	Feb. 1951 -Dec. 1952	1.08	— 1.21	.96	32 — 52	Hot humid climate
Windhoek	22° 34′ S	1 728	31 months	Aug. 1951-Feb. 1954	0.88	— 0.95	.95	57 — 78	Hot dry climate — high
Pretoria	25° 45′ S	1 369	38 months	Jan. 1951-Feb. 1954	0.98	— 1.16	.93	55 — 69	Hot dry climate — high
Tananarive	18° 53′ S	1 310	13 months	Feb. 1953-Feb. 1954	1.20	— 1.39	.89	48 — 65	Hot humid climate — high
Durban	29° 50′ S	5	32 months	July 1951-Feb. 1954	1.10	— 1.43	.97	46 — 61	Hot humid climate
Capetown	33° 54′ S	17	30 months	Sept. 1951-Feb. 1954	1.07	— 1.26	.93	56 — 68	Mediterranean type climate
Blee Hill	42° 13′ N	205	48 months	Nov. 1945-Oct. 1949	0.72	— 0.67	.75	37 — 63	Temperate climate. Based on weekly values
Uccle	50° 49′ N	120	24 months	Jan. 1949-Dec. 1950	0.96	— 1.01	Fitted by eye	9 — 68	Temperate climate. Mean value for March, June and September
Kew	51° 28′ N	19	60 months	Jan. 1947-Dec. 1951	.94	— 1.03	.98	24 — 45	Temperate climate

the published observations, linking the ratio of diffuse radiation on a horizontal plane to the total radiation with the atmospheric transmission Q/Q_o. Thus we have the relationship

$$D_H/Q = c + d\,Q/Q_o \qquad [5]$$

where D_H is the monthly mean daily diffuse radiation on a horizontal plane, c and d are constants, climatologically determined. Q and Q_o have the same meaning as before.

This equation, like the typical Ångström formula, does not hold for daily values. It is reasonably valid, however, even under these daily conditions except when the weather is overcast or nearly overcast and on completely clear days when the regression equation leads to an underestimate of the value of D_H/Q. This ratio reaches a value of 1.00 on overcast days for a value of Q/Q_o approximately equal to 0.20. However, this paper is concerned with climatological mean values, and not with daily values.

The regression constants derived for the ten stations so far studied are given in table 3. All values are based on the International Pyrheliometric Scale and a value of the solar constant of 2.00 gm. cals. cm.$^{-2}$ min.$^{-1}$. There is some variation from station to station, but a full climatological explanation of these variations has not been found yet. One difficulty was to discover whether the appropriate correction had been applied for the shading ring, and if the correction was properly determined climatologically. This was known to be the case for the South African stations (5) and for the Congo stations. A correction was applied to the Kew observations but this was based on isotropic distribution of diffuse radiation, and was not climatologically determined.

Clearly low values of D_H/Q are normally associated with regions of great clarity, and high values of D_H/Q with regions of high turbidity. It is therefore possible to select from table 3 values of c and d which appear reasonable for a particular area, by considering the characteristics of the atmosphere in that region. The mean regression equation for the ten stations is

$$D_H/Q = 1.00 - 1.13\,Q/Q_o \qquad [6]$$

Thus the values of D_H can be easily calculated using the values of Q/Q_o previously obtained by use of the Ångström type formula. Calculations for humid tropical regions immediately show that about half the mean daily total radiation on horizontal surfaces is diffuse scattered radiation.

The monthly mean direct radiation on the horizontal plane (i.e., $\Sigma I_D \sin\theta$ where I_D is the direct radiation intensity normal to the sun's rays and θ is the solar altitude) can now be found by difference:

$$\Sigma I_D \sin\theta = Q - D_H \qquad [7]$$

The regression equation for the diffuse radiation is, of course, of parabolical form for, rearranging the equation, we have

$$D_H = cQ + \frac{dQ^2}{Qo} \qquad [8]$$

The maximum value of D_H which is equal to $-\dfrac{c^2\,Q_o}{4\,d}$ occurs when $Q/Q_o = \dfrac{c}{2\,d}$. Since $Q/Qo = a + b\,\dfrac{n}{N}$, it follows that the corresponding value of $\dfrac{n}{N}$ is $\left(\dfrac{-c}{2\,d\,b} - \dfrac{a}{b}\right)$. Using the mean values of a, b, c, and d obtained from tables 2 and 3, we have max. $=$ 0.221 Qo. It occurs when $Q/Qo = 0.44$ or $\dfrac{n}{N} = .40$. The maximum diffuse radiation thus occurs on partly clouded days and not on clear or overcast days.

All the observations confirm the fact that linear interpolation between diffuse radiation on clear days and overcast days gives completely erroneous results, and that this theoretical parabolical relationship does actually represent the observations with reasonable accuracy. Certain European studies have been based on the assumption that D_H is not a function of $\dfrac{n}{N_o}$ (16, 17). This assumption happens to be approximately true, if one is concerned with that part of the parabolic curve near the maximum which is often the case in European centres where $\dfrac{n}{N}$ approximates to 35 - 50 per cent. The assumption is certainly not sound in the hot dry arid regions of the world.

Part III

THE ESTIMATION OF DIRECT RADIATION ON INCLINED SURFACES

The third stage in the problem is to convert the climatological mean values obtained for horizontal incidence to appropriate values for inclined planes. The direct and the diffuse radiation must be handled separately at this stage.

The method proposed in this paper to convert the mean daily radiation on the horizontal plane to mean daily direct radiation on inclined planes is based on the use of conversion factors derived in the following way:

(*a*) A standard direct radiation curve representative of tropical conditions was selected. This curve is given in table 4. Values slightly lower than Moon's standard curve (11) were adopted, which it was hoped would be more representative of general tropical conditions at stations reasonably close to sea level. The turbidity of the tropical atmosphere is often high, either because of the high moisture or high dust content of the air.

(*b*) Using the standard astronomical formulae, tables of incidence factors were prepared at hourly

Table 4. Values of the direct intensity of the solar beam on a surface normal to the sun's rays with altitude of the sun used to construct table 5

Units: Cals. cm^{-2} min^{-1}, International Pyrheliometric Scale

Solar altitude	*Direct intensity* I_D
0°	.00
5°	.28
10°	.57
15°	.72
20°	.84
25°	.96
30°	1.04
40°	1.15
50°	1.21
60°	1.25
70°	1.27
80°	1.28
90°	1.28

intervals for latitudes 0 - 60° for declinations 0, ± 10°, ± 20°, ± 23°27′ for vertical north south surfaces, vertical east west surfaces and horizontal surfaces. From these basic tables of incidence factors on three planes at right angles, factors for any other surfaces could be rapidly obtained with little further calculation by simple trignometrical methods.

(*c*) The following surfaces were selected for detailed study:

1. Vertical facing equator.
2. Vertical facing away from equator.
3. Vertical east or west.
4. Inclined at 45° to horizontal facing equator.
5. Inclined at tilt equal to latitude facing the equator.

Using the standard radiation curve given in table 4, calculations were made of the direct radiation intensities at hourly intervals on the above five surfaces. The hourly values were plotted graphically, and the daily totals were found by planimetry, together with the daily totals for the horizontal plane.

(*d*) These daily totals were smoothed by use of difference tables as a check against graphical errors in integration. The ratios of the daily direct radiation on the selected planes to the corresponding daily direct radiation on a horizontal plane was calculated for different latitudes at suitable values of the declination. The conversion factors were plotted against declination, and appropriate values for each month were found from the curves. In this way, a series of conversion factors was obtained to convert daily values of ΣI_D sin θ to corresponding values for the inclined surfaces in question.

The results of this very extended and tedious series of calculations are given in table 5, which covers latitudes 0°-40°. (Conversion factors are available up to 60°.) The conversion factors are given for each month at suitable intervals of latitude for different surfaces. The computed value of ΣI_D sin θ is merely multiplied by the appropriate factor obtained from the table to find the monthly mean daily direct radiation on the plane in question.

Factors for surfaces other than those actually given in table 5 may sometimes be derived by simple trigonometrical resolution. The essential condition is whether the direct radiation will reach the collector throughout the day at a particular time of year or not, for radiation falling behind the collector must not be considered as negative, but zero. Thus, if we consider an inclined surface facing the equator, in the winter half of the year, normal trigonometrical resolution can be used, for the sun will always reach the surface and can never be behind. This will not be true in summer when the sun will move on the poleward side of the surface for at least part of the day. For example, the factor for a south facing inclined surface at 40°N. tilted at 60° to the horizontal is equal to (1 × cos. 60 + .93 × sin (60) on March 15. However, on June 15th, the factor is *not* equal to (1 × cos. 60 + 0.19 × sin) because the northwards component has been ignored, and the integration condition makes it impossible to take account of the correction from table 5.

The validity of this method of computation depends on the following assumptions:

(*a*) That the sunshine is evenly distributed throughout the day, and is not markedly asymmetrical about noon. This is not always so.

(*b*) That the standard radiation curves are appropriate for average conditions.

The advantages from the computional point of view in working with ratios of radiation values are:

(*a*) The same values of the ratios are obtained for both hemispheres, and no correction for variations in solar distance are required. All the necessary corrections are already incorporated in table 1.

(*b*) Since the Ångström type formulae suggested can make some allowance in variations of transparency according to local conditions, and the values of the conversion factors being ratios are relatively insensitive to change of turbidity, the computed values obtained for inclined surfaces are likely to be more reliable than might be expected from the conventional use of standard radiation curves.

Part IV

ESTIMATION OF THE DIFFUSE RADIATION INCIDENT ON VERTICAL AND INCLINED PLANES

The diffuse short wave radiation on inclined planes is made up of two parts, radiation diffusely scattered from the sky and radiation diffusely

Table 5. Ratio of direct radiation on inclined surfaces to direct radiation on a horizontal surface at different times of the year for latitudes 40° N-40° S, based on standard radiation curve given in table 3

Column 1. Vertical surface facing equator: horizontal surface; Column 2. Vertical surface facing pole: horizontal surface; Column 3. Vertical surface facing east or west: horizontal surface; Column 4. Vertical surface facing equator tilted at 45° to horizontal: horizontal surface; Column 5. Vertical surface facing equator tilted at angle to horizontal equal to latitude: horizontal surface

Date		*Approx. declination*	*Latitude 0°*					*Latitude 10°*					*Latitude 20°*					*Latitude 30°*					*Latitude 40°*				
N. Hemi.	*S. Hemi.*		*1*	*2 →*	*3 →*	*4 →*	*5 →*	*1*	*2*	*3*	*4*	*5*	*1*	*2 →*	*3 →*	*4 →*	*5 →*	*1*	*2*	*3*	*4*	*5*	*1*	*2 →*	*3*	*4*	*5*
Jan. 15	July 17 . . .	— 21.3	.53	—	.39	1.09	1.00	.76	—	.40	1.24	1.12	1.07	—	.43→	1.47	1.31	1.49	—	.49	1.75	1.61	2.11	—	.57	2.22	2.15
Feb. 15	Aug 19 . . .	— 13.0	.31	—	.39	.94	1.00	.51	—	.40	1.07	1.07	.75	—	.42→	1.23	1.20	1.06	—	.46	1.44	1.40	1.50	—	.53	1.75	1.72
Mar. 15	Sept 18 . .	— 2.5	.04	—	.39	.74	1.00	.23		.39	.86	1.02	.43	—	.41→	1.00	1.08	.64	—	.44	1.16	1.18	.93	—	.49	1.36	1.35
Apr. 15	Oct. 18 . . .	+ 9.5	—	.25	.39	.53	1.00	—	.14	.39	.65	.96	.16	.06	.39→	.78	.97	.29	.02	.42	.91	.99	.48	.01	.46	1.04	1.07
May 15	Nov. 17 . . .	+ 18.7	—	.48	.39	.40	1.00	—	.31	.38	.52	.93	.02	.16	.39→	.64	.90	.13	.07	.41	.75	.89	.27	.06	.44	.87	.90
June 15	Dec. 17 . . .	+ 23.3	—	.58	.38	.33	1.00	—	.39	.38	.45	.92	—	.21	.38	.57	.87	.06	.12	.40	.68	.84	.19	.09	.43	.80	.84
June 21	Dec. 22 . . .	+ 23.5	—	.59	.38	.31	1.00	—	.40	.38	.45	.91	—	.22	.38	.56	.87	.05	.12	.40	.67	.84	.18	.09	.42	.79	.83
July 15	Jan. 13 . . .	+ 21.6	—	.55	.38	.35	1.00	—	.37	.38	.47	.92	—	.20	.38	.59	.87	.09	.10	.40	.70	.85	.22	.08	.43	.82	.85
Aug. 15	Feb. 11 . . .	+ 14.2	—	.35	.39	.46	1.00	—	.22	.38	.58	.94	.09	.10	.39	.71	.93	.21	.04	.41	.82	.94	.37	.03	.45	.95	.98
Sept. 15	Mar. 12 . . .	+ 3.4	—	.09	.39	.64	1.00	.11	.05	.39	.76	.99	.28	.02	.40	.90	1.02	.45	Tr.	.43	1.03	1.09	.69	Tr.	.48	1.20	1.20
Oct. 15	Apr. 11 . . .	— 8.2	.20	—	.39	.86	1.00	.40	—	.39	.99	1.05	.62	—	.42	1.14	1.16	.88	—	.46	1.33	1.30	1.24	—	.52	1.57	1.57
Nov. 15	May 13 . . .	— 18.3	.46	—	.39	1.04	1.00	.67	—	.40	1.18	1.10	.95	—	.43	1.39	1.27	1.33	—	.48	1.63	1.53	1.86	—	.56	2.03	1.98
Dec. 15	June 13 . . .	— 23.2	.58	—	.38	1.12	1.00	.81	—	.40	1.27	1.12	1.13	—	.44	1.52	1.33	1.58	—	.49	1.83	1.65	2.28	—	.58	2.34	2.26
Dec. 22	June 21 . . .	— 23.5	.59	—	.38	1.13	1.00	.83	—	.40	1.29	1.13	1.16	—	.44	1.53	1.34	1.61	—	.49	1.84	1.67	2.36	—	.59	2.38	2.30

NOTE: This table is based on graphical interpretations and the order of accuracy is about ≠ ±1 per cent.

reflected from the ground. If we assume that the diffuse radiation is isotropically distributed, the total radiation on a plane S will be given by the formula:

$$\Sigma\,(I + D + r)^{\alpha}_{s} = \Sigma\, I_s + \left(\frac{1 + \cos\alpha}{2}\right) D_H + \left(\frac{1 - \cos\alpha}{2}\right) r_H$$

$$= f_s\, \Sigma\, I_D \sin\theta + \cos^2\frac{\alpha}{2}\, D_H + \sin^2\frac{\alpha}{2}\, r_H \qquad [9]$$

where f_s is the slope conversion factor for slope S for a particular month, where ΣI_D sin θ and D_H are the monthly mean daily values of the direct and diffuse radiation on a horizontal plane, where α is the angle of inclination of the slope to the horizontal plane, and where r_H is the diffuse flux reflected from the ground.

The reflected flux will be equal to YQ where Y is the albedo of the surface to short wave radiation and Q is the monthly mean daily total radiation, provided that the ground is not overshadowed. This will normally be the case for the majority of solar energy collectors which are orientated to face the equator for maximum collection efficiency.

Equation [9] gives the incoming monthly mean daily total radiation correctly, provided the isotropic approximation is valid. This assumption must now be examined in detail for it is well known that the diffuse radiation is not isotropic. Unfortunately, average conditions have never been studied in detail, though it is believed that work is going on now in this direction in Russia under the control of Kondratiev. Considerable attention has, however, been given to cloudless conditions, and among the more useful studies in this field may be mentioned the studies of Kondratiev and Manolova in Russia (8) and the work of Parmelee in America (13). Parmelee's work is confined to instantaneous values on vertical surfaces while Kondratiev's work deals with instantaneous values on inclined surfaces as well. Parmelee's work shows the great importance of atmospheric turbidity in determining the diffuse radiation on cloudless days. A decrease in the intensity of the direct beam is accompanied by an appreciable increase in the amount of diffuse radiation available. Kondratiev's work shows that there are certain compensating effects which may make the isotropic approximation more reliable for average conditions than would at first sight appear. An important factor influencing the radiation balance of inclined surfaces is the change of albedo of the ground surface with the angle of incidence. The albedo increases very appreciably at low angles of incidence. Another important factor is that appreciably higher diffuse radiation is received from the quadrant of the sky facing the sun than from the quadrant of the sky facing away from the sun. The isotropic approximation is not satisfactory on cloudless days, overestimating the radiation on surfaces away from the sun, and underestimating the radiation on surfaces facing the sun and on surfaces at right angles to the sun's azimuth as well. On overcast days, on the other hand, Kondratiev shows that the diffuse radiation balance of slopes can be estimated satisfactorily by the isotropic approximation.

There appears to be no published information about partly clouded days, but qualitative observation shows that there are two main factors influencing the diffuse radiation distribution:

(*a*) A tendency to find regions of high brightness of clouds close to the sun.

(*b*) A tendency to find regions of high brightness on clouds which stand opposite the sun giving significant back reflection, particularly to steeply inclined slopes, when the clouds are vertically deep, e.g., cumulus clouds.

The various factors mentioned above are to some degree compensatory. The author has made a preliminary study of the mean diffuse illumination values recorded by quadrants at Kew represented by McDermott and Gordon Smith (10). This study indicates, *for vertical surfaces* ($\alpha = 90°$) empirical correction factors might be applied to the daily diffuse radiation as calculated by the isotropic approximation as follows:

(*a*) Vertical or steeply inclined north-south surfaces facing the predominant direction of the sun, if the sun is reasonably low, i.e. $fs \geqslant 0.4$ multiply D_H by a factor of 1.2 before using in equation [9]. If sun is moderately high $fs \leqslant 0.4$ multiply by 1.1 before using in equation [9].

(*b*) Vertical or steeply inclined surfaces facing east or west. Morning excess tends to balance afternoon deficiency on east side and vice versa on west side. Apply no correction.

(*c*) Vertical or steeply inclined surfaces facing away from predominant direction of sun, multiply D_H by 0.8 before using in equation [9].

These corrections are extremely arbitrary, but it is difficult to see how more reliable corrections could be proposed in the light of existing knowledge. These corrections would not appear to be out of line with diffuse radiation data obtained by Tonne (16) for latitude 53°N by careful consideration of the directional characteristics of the sky hour by hour. Their only justification is that they appear to give acceptable results wherever it has been possible to check theoretical predictions against observed results. There are, of course, remarkably few observations of radiation on vertical and inclined surfaces, and most of these have been made in high latitudes.

For sloping north-south surfaces inclined between 30° and 60°, the same factor of 1.2 might be appropriate for surfaces facing the predominant direction of the sun (provided $fs \geqslant 0.5$) and no correction be applied otherwise, nor to surfaces facing east or west. The factor for inclined surfaces facing away from the sun is likely on the evidence of Kondratiev and Manolova (8) to be somewhat lower than that for vertical surfaces facing away from the sun. This is a result of the fact that the region of the clear sky of lowest brightness is found at a point opposite the sun such that the angle between the altitude of this point and the sun's altitude is 90°. It might be reasonable to adopt a value of $0.75\ D_H$ for such inclined surfaces in light of present knowledge. The whole matter obviously requires far more detailed exploration, however, than the author has been able to give to it.

For surfaces of low tilt, the isotropic approximation is likely to be satisfactory except for north-south surfaces facing the predominant direction of the sun when it might be reasonable to assume that the monthly mean daily diffuse radiation is invariant for tilts between 0°-30° and equal to D_H. In equatorial regions it should be remembered that the predominant direction of the sun changes from north to south according to the time of the year.

The albedo of the ground surface should, if at all possible, be determined locally in view of the wide variations which occur with different types of ground, covered or not as the case may be, with vegetation of different reflection having characteristics which will vary according to season and rainfall. In making such measurements it is essential that the total albedo should be measured by suitable instruments which record over the whole short wave spectrum. The correlation between the visual albedo and the total albedo is often poor, because most plants have a relatively high reflectivity in the infra-red region, and often a relatively low one in the visible. Typical values by Kondratiev, Mironova, and Daeva (9) show reflectivities for gross of the order of 10-15 per cent in the visible region and 40-50 per cent in the infra-red. A summary of the earlier measurements of albedo may be found in the Smithsonian Meteorological Tables (15). Typical values of the total albedo for green vegetation are 25 per cent, for dark soils 10 per cent, for desert sands 20-25 per cent, for dry grass 30 per cent. If detailed information is not available about ground albedo, it would appear reasonable to adopt values of the order of 20-25 per cent on rural sites covered with vegetation and 10-15 per cent on central urban sites, where building and road surfaces may predominate.

Conclusion

A method of calculating mean values of the total radiation on inclined planes from sunshine records has been given which can be used to calculate the optimum orientation of flat plate solar energy collectors. The technique proposed has been checked against the limited number of available meteorological observations of the mean monthly daily radiation on inclined surfaces and reasonable agreement between prediction and measurement has been achieved. The average error of the estimated radiation appears to be of the order of ± 10 per cent. The technique proposed for calculating the mean daily radiation is thus quite satisfactory for general engineering purposes and has the advantage of giving, with very little computation, the relative amounts of direct or diffuse radiation on the plane in question. In many parts of the humid tropics, diffuse radiation predominates. The optimum orientation of a collecting device is thus influenced very much by this factor. At latitude 40°N, for example, the optimum tilt for a collector to collect maximum energy in December is about 57° if the percentage of possible sunshine is 40 per cent and 64° if the percentage of possible sunshine is 75 per cent. The maximum mean daily total radiation available with 40 per cent possible sunshine is 180 cals. cm^2 day compared with 440 cals. cm^2 with 75 per cent possible sunshine. In the first case 45 per cent of the available energy is diffuse, in the second only 14 per cent is diffuse. Solar collectors must therefore be designed to take proper account of the radiation climate in which they are to be used. Efficient use of diffuse radiation is essential in the humid tropics where much cloud is often found. The author would particularly welcome any available information about measured mean values of short wave radiation on inclined surfaces in order to make a more systematic check on the validity of the method of analysis proposed.

References

1. Black, J. N., Bonython, C. W. and Prescott, J. A., *Quart. J. Roy. Met. Soc.*, 84, p. 231, 1954.
2. Blackwell, M. J., Five years' continuous recording of total and diffuse radiation at Kew Observatory, *M.R.P. 895*, Met. Off., London, 1954.
3. Brooks, C. E. P., Relation between the duration of bright sunshine registered by a Campbell-Stokes sunshine recorder and the estimated amount of cloud, *Met. Off. Prof. Notes No. 53*, H.M.S.O., London, 1929.
4. Drummond, A. J., The atmospheric transmission of solar energy over southern Africa, Notes, 3, pp. 272-286, 1954.
5. Drummond, A. J., On the measurement of sky radiation, *Arch. Met. Geoph.*, Serie B, 7, 413-436, 1956.
6. Glover, J. and McCulloch, J. S. G., *Quart. J. Roy. Met. Soc.*, 84, pp. 172-175, 1958.
7. Johnson, F. S., *J. Met.*, 2 (6), p. 131, 1954.
8. Kondratiev, K. J. and Manolova, M. P., Slopes radiation balance, *Reports at the Symposium on Radiation in Oxford*, Leningrad University, pp. 3-19, 1959.
9. Kondratiev, K. J., Mironova, Z. F. and Dava, L. V., Spectral Albedo of Snow and Vegetation Covers, International Geographical Year, University of Leningrad, 1960.

10. McDermott, L. M. and Gordon-Smith, G. W., Daylight illumination recorded at Teddington, Proc. Building Research Congress, London, 1951, Div. 3, pp. 156-161, 1951.

11. Moon, P., *Journ. Franklin Inst.*, 230, p. 583, 1940.

12. Nicolet, M. and Dogniaux, R., Étude de la radiation globale du soleil, *Inst. Roy. Met. Belg. Memoires*, 47, 50 pp, 1951.

13. Parmelee, G. V., Irradiation of vertical and horizontal surfaces by diffuse solar radiation from cloudless skies, *Heating, Piping and Air Conditioning*, Aug. 1954, pp. 129-135, 1954.

14. Smith, G. W., *Quart. J. Roy. Met. Soc.*, 86, p. 415, 1960.

15. *Smithsonian Meteorological Tables*, 6th. Ed., Smithsonian Inst., Washington, 1951.

16. Tonne, F, and Norman, W., Die berechnung der Sonnenwarmestrahlung auf senkrechte und beliebig geneigte Flachen unter Berücksichtigung. Meteorologischer Messungen, Institut für Tageslicht-technik, Stuttgart, 1956.

17. Pleijel, G., The computation of natural radiation in architecture and town planning, *Statens namnd for byggnadsforskning No. 25*, 1954.

Summary

A technique for calculating monthly mean values of total daily radiation on inclined surfaces from sunshine data has been proposed.

The first part deals with the calculation of mean values of total radiation on horizontal planes, using the conventional type of regression equation.

$$Q/Q_o = a + b\,\frac{n}{N}$$

where Q is the monthly mean daily total radiation, Q_o is the corresponding monthly mean daily radiation outside the atmosphere; a and b are constants which are climatologically determined; $\frac{n}{N}$ is the percentage of possible sunshine.

Values of a and b for various tropical stations are given in table 2, while values of Q_o may be found in table 1. It is suggested that the values of a and b should be selected that are representative of the transmission characteristics of the atmosphere in the locality under study.

The second part deals with the separation of the mean horizontal diffuse radiation from the total radiation, using a regression equation of the form

$$D_H/Q = c + d\,Q/Q_o$$

where D_H is the monthly mean daily diffuse radiation on a horizontal plane, where c and d are climatologically determined constants and where Q and Q_o have the same meaning as before.

The monthly mean value of the daily direct radiation on the horizontal plane $\Sigma I_D \sin\theta$ may be found from the relation

$$\Sigma\, I_D \sin\theta = Q - D_H$$

Values of c and d for various localities may be found in table 3. It is shown that maximum diffuse radiation occurs when $\frac{n}{N} = 40\text{-}50$ per cent.

The third part of this paper deals with the conversion of direct radiation on the horizontal plane to direct radiation on inclined planes. Table 5 contains a series of conversion factors f_s for latitudes 0-40° to convert values of $\Sigma I_D \sin\theta$ into values of I_s, the direct radiation on slope S.

Factors are given for the following surfaces

(1) Vertical facing equator,
(2) Vertical facing pole,
(3) Vertical facing east or west,
(4) Vertical facing equator tilted at 45° to horizon,
(5) Vertical facing equator tilted at angle to horizontal equal to latitude.

These factors are based on radiation curves drawn using standard radiation curve given in table 4.

The fourth part of this paper deals with the estimation of diffuse radiation on inclined surfaces using the isotropic approximation.

The total radiation on slope S is given by:

$$\Sigma\,(I + D + r)_s = \Sigma\, I_s + \left(\frac{1 + \cos\alpha}{2}\right) D_H + \left(\frac{1 - \cos\alpha}{2}\right) r_H$$

$$= f_s\, \Sigma\, I_D \sin\theta + \cos^2\frac{\alpha}{2}\, D_H + \sin^2\frac{\alpha}{2}\, \pi_H$$

where $f_s\, \Sigma I_D \sin\theta$ is the direct radiation on the slope of inclination

$\cos^2\frac{\alpha}{2}\, D_H$ is the diffuse radiation from the sky on the slope

$\sin^2\frac{\alpha}{2}\, r_H$ is the diffuse radiation from the ground.

The value of r_H will be equal to YQ, if the ground is not overshadowed, where Y is the total short wave albedo (not visual albedo).

The limitations of the isotropic approximation are discussed and certain empirical correction factors are proposed to take account of orientation.

The need for further field observations is stressed as well as the fact that the method of analysis is restricted to monthly mean values of possible

sunshine and so is not applicable to daily values of sunshine. The accuracy of prediction appears to be of the order of ± 5 per cent for monthly means. It is shown that collector orientation for maximum efficiency is influenced very much by the diffuse radiation climate in any locality and it is suggested that attention must be given to the problem of properly utilising this diffuse energy in flat plate collectors, particularly in the humid tropics where half the available energy may be diffuse.

ÉVALUATION DES VALEURS MOYENNES MENSUELLES DU RAYONNEMENT TOTAL A ONDES COURTES SUR LES SURFACES VERTICALES ET INCLINÉES, D'APRÈS LES RELEVÉS D'ENSOLEILLEMENT POUR LES LATITUDES 40° N ET 40° S

Résumé

On a proposé une technique de calcul des valeurs moyennes mensuelles du rayonnement quotidien total pour les surfaces inclinées, à partir des données d'ensoleillement.

La première partie du mémoire porte sur le calcul des valeurs moyennes du rayonnement total sur des plans horizontaux, en se servant de l'équation classique de régression :

$$Q/Q_o = a + b\,\frac{n}{N}$$

dans laquelle Q est la moyenne quotidienne du rayonnement total sur un mois, Q_o la moyenne quotidienne extra-atmosphérique correspondante, et a et b des constantes climatologiques, $\frac{n}{N}$ étant le pourcentage d'ensoleillement possible.

Le tableau 2 donne les valeurs de a et b pour les divers postes tropicaux, et le tableau 1 donne les valeurs de Q_o. L'auteur suggère que les valeurs de a et b soient choisies pour bien représenter les caractéristiques de transmission de l'atmosphère dans la localité à l'étude.

La deuxième partie du mémoire porte sur la séparation du rayonnement moyen horizontal diffus et du rayonnement total, en se servant d'une équation de régression de la forme :

$$D_H/Q = c + d\,Q/Q_o$$

dans laquelle D_H est le rayonnement diffus quotidien moyen sur un plan horizontal, c et d sont des constantes déterminées climatologiquement, et Q et Q_o ont la même signification qu'auparavant.

La valeur moyenne mensuelle du rayonnement quotidien direct sur le plan horizontal, $\Sigma I_D \sin\theta$, peut être tirée du rapport $\Sigma I_D \sin\theta = Q - D_H$.

Le tableau 3 donne les valeurs de c et d pour diverses localités. L'auteur montre que le rayonnement diffus maximum se produit quand $\frac{n}{N} = 40$ à 50 p. 100.

La troisième partie de ce mémoire porte sur la conversion du rayonnement direct sur le plan horizontal en rayonnement indirect sur les plans inclinés. Le tableau 5 contient une série de facteurs de conversion, correspondant aux latitudes 0-40°, pour transformer les valeurs de $\Sigma I_D \sin\theta$ en valeurs de I_s, rayonnement direct sur la pente S.

Le mémoire donne les facteurs pour les surfaces suivantes :

1) Verticale, tournée vers l'équateur;

2) Verticale, tournée vers le pôle;

3) Verticale, faisant face à l'est ou à l'ouest;

4) Verticale, faisant face à l'équateur et inclinée à 45° sur l'horizontale;

5) Verticale, faisant face à l'équateur et inclinée sur l'horizontale d'un angle égal à la latitude.

Ces facteurs sont basés sur des courbes de rayonnement établies en se servant de la courbe de rayonnement standard du tableau 4.

La quatrième partie de la communication porte sur les évaluations du rayonnement diffus sur les surfaces inclinées, en se servant de l'approximation isotropique.

Le rayonnement total sur la pente S est donné par :

$$\Sigma\,(I + D + r)_s = \Sigma\, I_s + \left(\frac{1 + \cos\alpha}{2}\right) D_H + \left(\frac{1 - \cos\alpha}{2}\right) r_H$$

$$= f_s\, \Sigma\, I_D \sin\theta + \cos^2\frac{\alpha}{2}\, D_H + \sin^2\frac{\alpha}{2}\, r_H$$

expression dans laquelle

$f_s\, \Sigma I_D \sin\theta$ est le rayonnement direct sur la pente d'inclinaison,

$\cos^2\frac{\alpha}{2}\, D_H$ est le rayonnement diffus du ciel sur la pente,

$\sin^2\frac{\alpha}{2}\, r_H$ est le rayonnement diffus du sol.

La valeur de r_H sera égale à YQ si le sol n'est pas ombragé, Y étant l'albédo total ondes courtes (et non pas l'albédo visuel).

Les limitations de l'approximation isotropique sont passées en revue et certaines corrections empiriques sont proposées pour tenir compte de l'orientation.

L'auteur souligne le besoin d'autres observations sur place, ainsi que le fait que la méthode d'analyse est limitée à des valeurs moyennes mensuelles de l'ensoleillement possible, et ne peut donc pas s'appliquer à des valeurs quotidiennes. L'exactitude des prédictions semble être de l'ordre de ± 5 p. 100 pour des moyennes mensuelles. L'auteur montre que l'orientation du collecteur, pour avoir le maximum de rendement, dépend beaucoup du climat de rayonnement diffus en tous lieux, et ce mémoire suggère qu'on doit s'attacher au problème d'utiliser convenablement cette énergie diffuse sur des collecteurs à plaque, particulièrement dans les tropiques humides où la moitié de l'énergie disponible peut être diffuse.