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Meteorological Aspects of the Daylighting of Buildings

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METEOROLOGICAL ASPECTS OF THE DAYLIGHTING OF BUILDINGS*

Abstract

The paper describes the way in which data on such meteorological factors as outdoor illumination and sky luminance distribution have been used in order to obtain a better understanding of the daylighting of building interiors.

Probable levels of outdoor illumination have been utilised in order to convert Daylight Factors into corresponding levels of indoor illumination and hence to determine the probable duration of artificial lighting.

A knowledge of sky luminance distributions, particularly that of the densely overcast sky, has been used to enable more accurate assessments of levels of indoor daylighting to be made than is possible by assuming a uniform sky. New measurement techniques have been devised based on an empirical sky luminance distribution.

Measurements of total solar radiation have been converted into equivalent illumination levels in order that some knowledge might be gained of the outdoor illumination obtainable in those parts of the world for which actual illumination measurements are not available but for which solar radiation data already exist.

Two new instruments are described whereby the daylighting, sun penetration and solar radiation in actual buildings can be conveniently studied.

Details are given of an investigation of the daylighting obtainable in a building by reflection of sunlight from the ground and from an opposite building.

Introduction

An illuminating engineer designing the artificial lighting of a building interior has available a wide range of different light sources from which to select the lamps he wishes to use. To assist him in his choice there usually exist photometric data on the light output, both initially and during life, of these lamps.

It is therefore possible for the illuminating engineer to design artificial lighting installations to meet precise specifications in respect of levels of illumination and luminance. The only influence which meteorological factors are likely to have on these levels is that due to load shedding in extremely cold weather.

On the other hand, an architect engaged in designing the lighting of a building interior by daylighting has available only two sources of light, the sun and the sky. Furthermore these sources are continually varying in their illuminating properties both with the time of day and year and with changes in the weather and geographical location.

It would seem at first that the architect's task must be insuperable, since the expression of interior daylighting in terms of the units of illumination and luminance used by the illuminating engineer can become very misleading. Fortunately the architect has not been discouraged by this fact, and many fine buildings exist to demonstrate the mastery which he has obtained over this vagary of Nature. This mastery has, however, in the past been to a large extent due to the architect's ability to evolve pleasing patterns of light and shade without necessarily being able to interpret those patterns in terms of lumens per sq. ft. or foot-lamberts.

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The first steps towards measuring the daylighting obtainable indoors were instigated by the increasing crowding together of the buildings in our larger towns and cities. The amount of daylight available was generally small and had to be jealously guarded. In order to enforce the legal protection which had been devised for this purpose it was necessary to be able to measure the daylighting in a way which would take account of the prevailing outdoor conditions.

The simplest, and possibly the obvious way of doing this, is to express the daylight in a room in terms of the daylight simultaneously occurring outdoors. By this means the wide and continuous variations in the outdoor conditions can, to a large extent, be allowed for. A further merit for expressing the daylighting in this way is that it accords more closely with subjective reactions to the daylighting than do absolute levels of illumination.

In 1928 the Daylight Factor was internationally defined as a measure of the daylight available in a building (1). It is most commonly obtained by expressing the indoor illumination as a ratio or percentage of that simultaneously occurring outdoors from a completely unobstructed sky.

The chief use of the daylight factor in the early days of its conception was as a gauge by which to judge the relative amounts of daylight available in a building before and after a proposed obstructing building had been erected. It was really little more than a matter of finding out whether one daylight factor was larger or smaller than another.

It was only at a later date that the daylight factor was used as a measure whereby minimum levels of daylighting could be specified in building regulations. The values of daylight factor given in the earlier of these regulations were to a large extent arbitrarily chosen since little or no data were then available whereby visual tasks of varying complexity could be related to the levels of illumination resulting from given values of daylight factor.

Various researches in the past twenty or so years have provided the data that were required to enable minimum levels of daylighting to be specified with some degree of engineering precision. The visual aspect of these researches comprised studies relating illumination with visual performance, of which the work of WESTON (2), culminating in the Code of recommended levels of illumination of the British Illuminating Engineering Society (3), should be mentioned. The meteorological aspect of these researches comprised very extensive measurements of sky illumination and luminance, the observations made by the National Physical Laboratory, Teddington (4), (5) on the frequency of occurrence of levels of daylight illumination being of particular use in the interpretation of daylight factors in terms of absolute levels of illumination.

It is consequently now possible to analyse a visual task and so determine the minimum level of illumination necessary for the efficient performance of the task. Then, from a knowledge of the meteorological data on probable levels of outdoor illumination, it is possible to specify the daylight factor required.

Probable levels of outdoor illumination are, however, only one small aspect of photometric meteorology which are necessary in order to determine completely the daylighting of a building interior. Not only is detailed information required on the illumination and luminance of the sky in different parts of the world, but also equally comprehensive data on the lighting and heating characteristics of direct sunlight. The purpose of this paper is to review some of the meteorological factors which influence the natural lighting of a building and the ways in which they are taken account of in the prediction of interior daylighting.

Total Outdoor Illumination

It will already be clear that a knowledge of the illumination obtainable from an unobstructed sky is necessary in order to interpret daylight factors in terms of absolute levels of illumination. The measurements of total sky illumination made by the National Physical Laboratory are probably among the more well-known of this type of work.

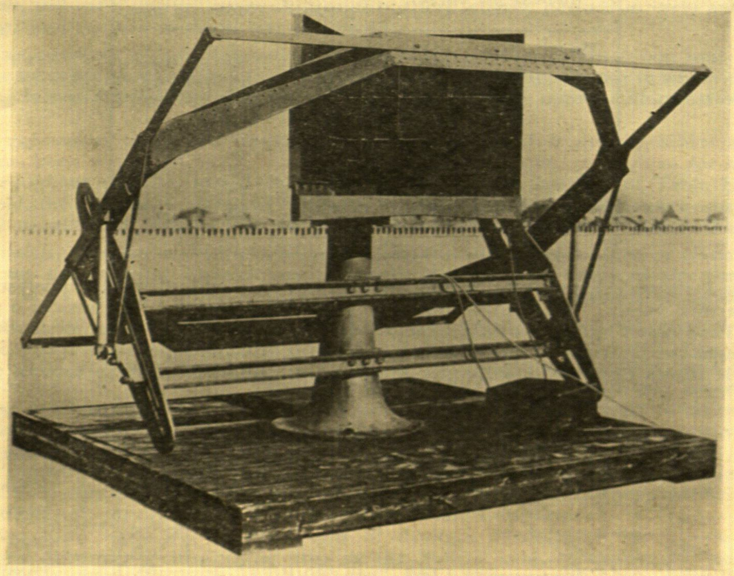

Fig. 1 — N.P.L. octant apparatus for daylight illumination measurements (McDermott and Gordon-Smith)

The measurements comprised the illumination on a horizontal surface exposed to octants of the sky orientated towards the four cardinal points (Fig. 1). By combining the readings from the four octants it was possible to derive the total horizontal illumination from the sky. Precautions were taken to exclude direct sunlight from the measurements, but other measurements of the illumination from direct sunlight, both on a horizontal plane and on a plane orientated normal to the sun's rays, were separately obtained.

The measurements were commenced in 1923 and for ten years were obtained three times a day with a visual photometer (4). Later a continuously recording photo-electric photometer was substituted and the measurements continued until 1939 (5).

Typical results obtained from the measurements are given in Table I (6) and Fig. 2.

Table I

Frequency with which the outdoor illumination falls below specified levels at given times of the day at Teddington

Illumination (lumens per sq. ft.)		Number of days in year		
		9 a.m.	Noon	3 p.m.
Below	100	6	3	14
	200	21	9	35
	300	36	16	53
	400	54	25	77
	500	67	33	94
	600	83	43	110
	700	97	55	121
	800	111	68	135
	900	125	80	146
	1000	141	93	157
Above	1000	224	272	208

Table I shows the probable frequency with which the outdoor illumination will fall below specified values. As a simple example of the use of this Table, consider a point in a room at Teddington having a daylight factor of 2 per cent. When the outdoor illumination is 500 lumens per sq. ft. the illumination at this point is 10 lumens per sq. ft. ($500 \times 0 \cdot 02 = 10$). The Table shows that the illumination at this point will fall below 10 lumens per sq. ft.

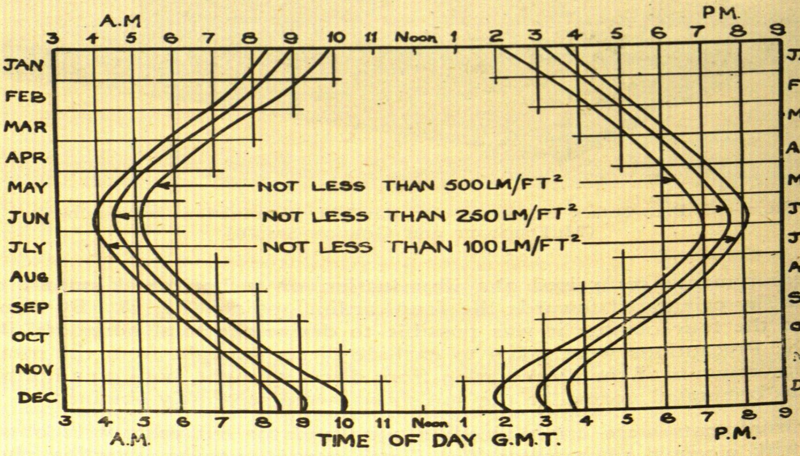

Fig. 2 — Curves showing times at which the average whole sky illumination at Teddington reaches certain levels (McDermott and Gordon-Smith)

(*i.e.* the outdoor illumination will fall below 500 lumens per sq. ft.) on 67 days of the year at 9 a.m., on 33 days at noon and on 94 days at 3 p.m.

The level of 500 lumens per sq. ft. has been chosen for the outdoor illumination in this example as representing average sky conditions in Great Britain. It was determined from the National Physical Laboratory measurements and was found, in fact, to correspond to average conditions in England over the greater part of winter days, over long periods in late autumn and early spring, over substantial but less lengthy periods in early autumn and late spring, and on wet days in late spring (7).

The approximate metric equivalent of this outdoor illumination (5 000 lux) has been used as the basis for an alternative form of the definition of daylight factor in which the indoor daylighting is expressed as the illumination obtained when the outdoor illumination is 5 000 lux.

The expression of natural daylighting data in terms of frequency tables similar to Table I has been widely adopted. In cases where the data have been given for hourly intervals throughout the day, rather than for the three hourly intervals of Table I, such as, for example, the frequency tables of FOURNOL (8), it is possible to determine quite closely the yearly duration of artificial lighting required to maintain a given illumination level.

An alternative form in which the illumination data can be expressed is given in Fig. 2 which shows the probable illumination to be obtained at Teddington at any time during the year. Such a diagram can also be used to compute the yearly duration of artificial lighting.

An application of this diagram is given in Fig. 3, which shows the lighting-up times for two levels of indoor daylighting (*viz.* minimum daylight factors of 2 per cent. and 5 per cent.) (9). The curves indicate that the lower level of daylighting requires three times the duration of artificial lighting of the higher level. Furthermore, with the lower level of daylighting, artificial lighting is required, on an average, for all the afternoon and part of the morning in winter whereas, with the higher level, artificial lighting is only required during the latter part of the afternoon and not at all in the morning.

Two factors have to be borne in mind when using the N.P.L. measurements in daylight design. First, they relate to only one measuring station. The question therefore arises whether they are applicable to locations other than Teddington.

Unfortunately very few measurements of daylight illumination have been made at other places, even in so compact an area as the British Isles, to enable this point to be checked on. Some data are, however, available for Edinburgh and Plymouth. The Edinburgh measurements have been published in a form similar to that of Table I and show that in general there is less daylight at Edinburgh at 9 a.m. than there is at Teddington. At noon the conditions are reversed. At 3 p.m. there is little difference in the daylight at the two locations.

Some measurements obtained at Plymouth between 1947 and 1949 have been reported by ATKINS and JENKINS (10). These showed that on an average the daylight illumination at Plymouth is the same as that at Kew (*i.e.* adjacent to Teddington). The explanation for this interesting finding is thought to be that at Plymouth there is a higher incidence of cloud cover and a greater frequency of sea mists than at Kew whereas at Kew there is a greater degree of atmospheric pollution than at Plymouth due to the close proximity of Kew to London.

The second factor to be borne in mind when using the N.P.L. illumination data is that they have been averaged for all types of sky. If daylight factor regulations are based on these measurements then they will apply to average outdoor conditions.

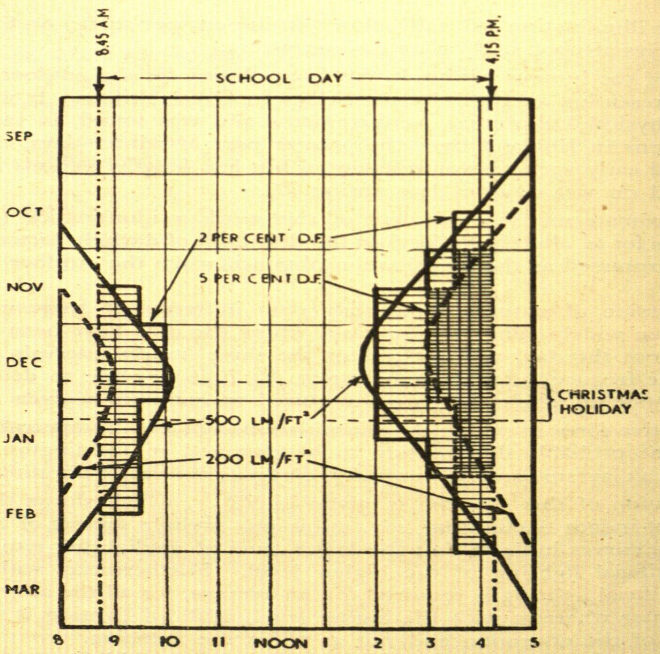

FIG. 3 — Proposed switching times for artificial lighting superimposed on curves showing variation with month of year of the time of day at which the outdoor illumination falls below 500 (———) and 200 (– – – –) lumens per sq. ft. (Building Research Station, Ref. No. (9))

One such regulation is the School Building Regulation of 1954 (11) which specifies that the daylight factor in the useful working area of school classrooms in England and Wales should not fall below 2 per cent. This Regulation was based on (i) a decision that the minimum level of illumination, whether natural or artificial, for performing visual tasks in schools should be 10 lumens per sq. ft. and (ii) an assumption that the yearly average of outdoor illumination in England and Wales for all types of sky was 500 lumens per sq. ft.

The question inevitably arises whether daylight factors should be based on average conditions, on the most adverse conditions or on the most frequently occurring conditions. Obviously if the most adverse conditions of outdoor illumination are taken as a basis for daylighting design, then there is no limit to the size of the windows that have to be provided.

However, a given level of outdoor illumination can be produced by widely differing types of sky, some of which have luminance distributions which are more favourable for lighting the interior of a room than others. In Great Britain a compromise has therefore been adopted, the design of a building for daylighting being based on the most adverse sky conditions producing an average level of outdoor illumination, on the assumption that more than a minimum amount of indoor illumination will be obtained with any other sky condition.

Sky Luminance Distribution

The fact that the daylighting of a building interior is dependent not only on the illumination from the sky but also on the distribution of luminance over the sky vault can be very simply demonstrated by considering a point remote from the window in a deep room. This point receives direct light from that part of the sky which is close to the horizon. The illumination at the point is therefore dependent on the luminance of the horizon sky.

The daylight factor, however, relates this indoor illumination to the total outdoor illumination. This, in turn, is numerically equal to the mean sky luminance. If the sky luminance distribution is non-uniform then it is possible for the horizon sky luminance to be greater or smaller than the mean sky luminance and hence for the daylight factor to have varying values.

It is therefore important that our knowledge of the meteorological factors which govern the daylighting of a building interior should include information not only on the outdoor illumination but also on the luminance distribution of the different types of sky producing this illumination. To this end studies of sky luminance distribution have been made in various parts of the world.

Probably the most extensive of these studies, and certainly the one most often referred to, is that made by Kimball and Hand in the U.S.A. in the early 1920's (12). Their measurements covered the whole sky vault and were averaged for five different types of sky. These were :

1. Clear sky
2. Sky covered with thin clouds or dense haze
3. Sky covered with dense clouds or fog
4. Sky covered with clouds from which rain was falling
5. Sky partly covered with clouds

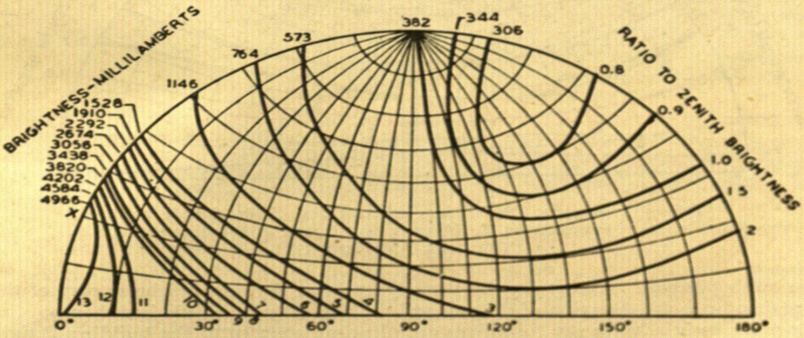

Fig. 4 — Luminance distribution, clear sky. Solar altitude 20°. Sun's position indicated by X. Measurements taken at Washington, U.S.A. (Kimball and Hand)

Figs. 4, 5 and 6 show luminance distributions corresponding to a blue sky (type 1) with the sun at two different altitudes and to a densely overcast sky (type 3). The distributions were assumed to be symmetrical on the two sides of the vertical circle through the observer

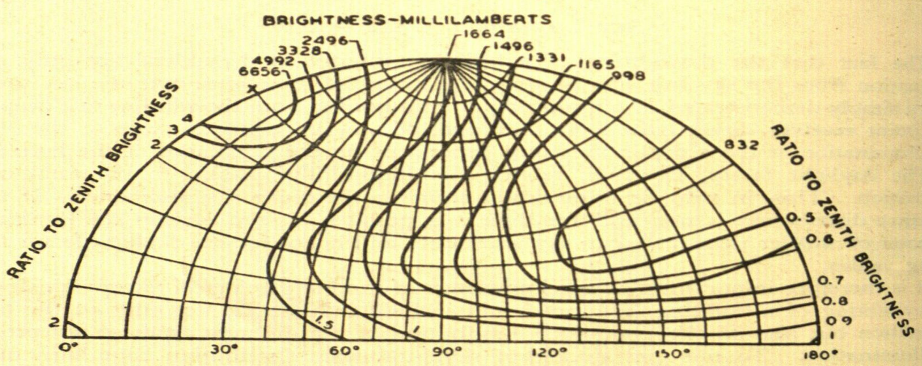

FIG. 5 — Luminance distribution, clear sky. Solar altitude 60°. Sun's position indicated by X. Measurements taken at Washington, U.S.A. (KIMBALL and HAND)

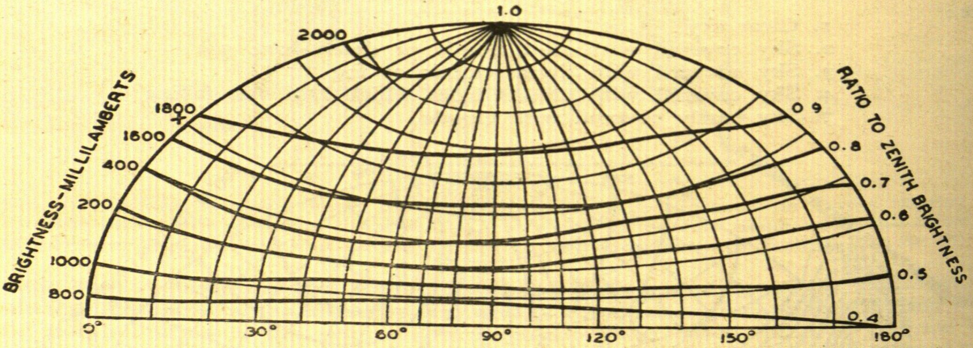

FIG. 6 — Luminance distribution, overcast sky. Solar altitude 40°. Sun's position indicated by X. Measurements taken at Washington, U.S.A. (KIMBALL and HAND)

and the sun's position. Except for the densely overcast sky, the brightest part of the sky was found to be in the direction of the sun and the darkest part a little less than 90° from it.

Since the most adverse sky conditions are of prime concern to the building designer in Great Britain it is natural that the greatest interest should be shown in the luminance distribution of the densely overcast sky (type 3 — Fig. 6) since this sky not only produces the lowest levels of outdoor illumination but also its luminance distribution is such that for any given level of outdoor illumination the least amount of light is obtained at the back of deep rooms. This type of sky has a number of characteristics of which the following should be mentioned :

1. The luminance distribution is virtually independent of the sun's position.
2. The distribution is symmetrical about the zenith in great circles through the sky vault.
3. The horizon luminance is about one third of the zenith luminance and one half of the mean sky luminance.

The employment of the luminance distribution of the overcast sky in daylighting design was greatly facilitated when MOON and SPENCER proposed an empirical formula whereby the distribution could be simply expressed (13). This formula is as follows:

$$B_\theta = B_z \frac{1 + 2 \sin\theta}{3} \qquad \text{......(1)}$$

where B_θ = luminance of sky at an altitude θ

and B_z = luminance of zenith sky

The formula was made to give good agreement with sky luminance measurements obtained by KIMBALL and HAND in Washington and Chicago, and by KÖHLER in Kiel. Before applying the formula to the design of buildings in temperate zones in countries other than the U.S.A. and Germany it was felt advisable to check on the applicability of this luminance distribution in these other countries.

Two series of comparison measurements were made at the Building Research Station to see whether the MOON and SPENCER distribution applied to southern England. The results of the second and more detailed of these comparisons is given in Fig. 7 from which it is seen that the empirical distribution gives good agreement with the measurements despite a difference of approximately 10 degrees between the latitudes at which the measurements were made.

Comparison measurements have also recently been made in Stockholm by HOPKINSON (14) and are also shown in Fig. 7. Other recent comparisons have been made by BÜNING in Berlin (15). The net result of all these comparisons is to show that the MOON and SPENCER formula specifies with reasonable accuracy the luminance distribution of densely overcast skies in those parts of the world bounded by latitudes of 40 degrees and 60 degrees North.

The luminance distribution of the densely overcast sky is such that at points remote from the window in a deep room the direct light from the sky is almost half what it would be if the sky were of a uniform luminance. This fact is of some considerable significance since in contemporary daylighting design the available daylight (*i.e.* the daylight factor) is usually calculated as that received directly from a sky of uniform luminance (referred to as the "sky factor"). In practice the direct sky light is supplemented by light received after reflections from the interior surfaces (*i.e.* the walls, ceiling, floor, etc.).

Until very recently it has been impracticable to calculate this "indirect" component, with the result that it has been treated as bonus light and regarded as a factor of safety in the prediction of the direct component. In the instance quoted above, however, the direct light received from the low-luminance horizon of a densely overcast sky (*i.e.* the direct component of daylight factor) may be so much less than that calculated for a uniform sky that the reflected component may barely make up the difference. In such a case the daylight factor (the sum of the direct and reflected components) may be less than the calculated direct component.

Examples of the effect which the luminance distribution of a densely overcast sky has on the penetration of daylight into buildings have been examined at the Building Research Station both in field and laboratory studies.

A typical field study was of the daylighting of a wide cross-lighted classroom with a low ceiling and internal decorations having reflection factors somewhat less than the average. An examination of the drawings showed that the worst – lit parts of the classroom had a sky factor (*i.e.* direct component – uniform sky) complying with the regulation value of 2 per cent. The addition of the reflected component should have ensured that the daylight factor exceeded this value.

Measurements showed, however, that on an overcast day, the daylight factor only just met the regulation minimum value, indicating that the true direct component of

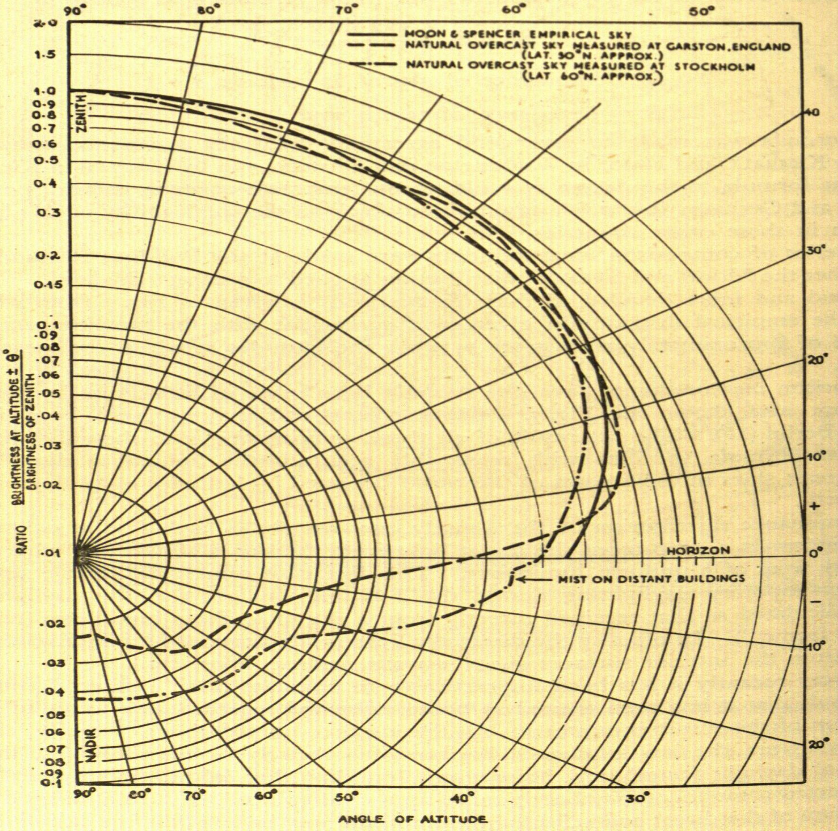

FIG. 7 — Cross-section through East sky showing comparison between luminance distributions of natural overcast skies measured in England and Sweden and the MOON and SPENCER empirical formula. Measurements of ground luminance also shown (HOPKINSON)

illumination from the low-luminance horizon sky must have been significantly lower than was indicated by the computed sky factor.

Rather similar findings have been obtained from model-scale laboratory studies of the penetration of daylight into a deep classroom lighted from one side only (**16**). For example, the sky factor (*i.e.* direct component – uniform sky) at a point on the working plane in this classroom was calculated to be 2·1 per cent. when the ceiling height was 8 ft. If the luminance distribution of an overcast sky had no effect on the penetration of daylight into a building, then it would be expected that the daylight factor at this particular point would be significantly greater than 2·1 per cent., due to the contribution of light reflected from the interior surfaces (whose average reflection factor was approximately 40 per cent.). The measured daylight factor, using an artificial sky conforming to the Moon and Spencer luminance distribution, was in fact, found to be almost exactly the same as the calculated direct component of daylight factor (uniform sky) — *i.e.* 2·2 per cent. (measured) as compared with 2·1 per cent. (calculated). This unexpected agreement was found to be due to the true direct component (*i.e.* for a non-uniform sky) being actually 1·2 per cent. and not 2·1 per cent.

It is of interest to note that in this example almost half the total daylight reaching the point being considered (actually 1·0 per cent. daylight factor, *i.e.* 2·2 – 1·2 per cent.) was due to reflections from the interior surfaces of the room.

An analysis of the Moon and Spencer sky luminance distribution formula was made at the Building Research Station and showed that the luminance of an overcast sky at an altitude of 40 to 45 degrees (more precisely 42 degrees) is numerically equal (in foot-lamberts) to the illumination of the whole sky (in lumens per sq. ft.). Furthermore a relationship was obtained whereby it is possible to derive the total outdoor illumination from luminance measurements on an overcast sky not merely at one specific altitude but at any known altitude. In Table II is given the factor (K), dependent on the sky altitude, by which the sky luminance (in foot-lamberts) has to be multiplied to obtain the total outdoor illumination (in lumens per sq. ft.).

TABLE II

Values of K by which to convert sky luminance at altitude θ into total outdoor illumination (Moon and Spencer sky)

Sky altitude (θ)	K
0 (Horizon)	2·32
10	1·72
20	1·39
30	1·16
40	1·02
42	1·00
45	0·96
50	0·92
60	0·85
70	0·81
80	0·79
90 (Zenith)	0·78

where Total outdoor illumination (lumens per sq. ft.) = K × sky luminance at altitude $\theta°$ (ft.-lamberts)

The fact that the luminance distribution of a densely overcast sky consistently repeats itself in a known manner enables the luminance/illumination relationships to be used in the design of new techniques for measuring daylight factor.

Older techniques require access to a completely unobstructed sky from which to measure the total outdoor illumination (*i.e.* the denominator of the daylight factor ratio). This can be a considerable handicap when making measurements in built-up areas where it may be difficult, if not impossible, to obtain the necessary freedom from obstructions. However, from a knowledge of the sky luminance distribution it is possible to obtain the total illumination of an overcast sky from measurements on only a restricted portion of the sky, provided the altitude of that portion is known.

One of the new techniques of daylight factor measurement involves measuring the luminance of the sky at a known altitude (17). If any obstructions that may be present are such as do not prevent access to a 42-degree sky then a numerical measure of the total outdoor illumination is obtained directly from the sky luminance measurements.

If the measurements are made at some other angle above the horizon then a correction

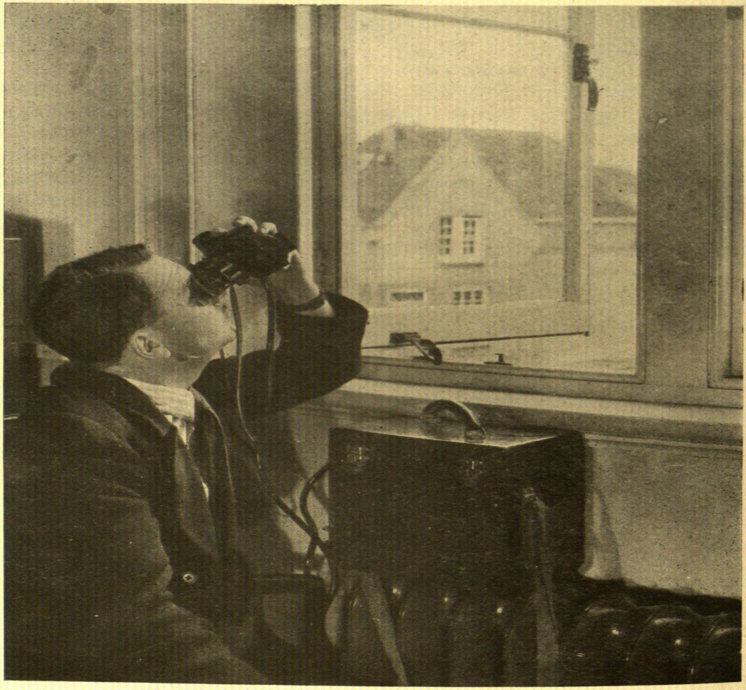

FIG. 8 — Sky luminance measurements being made at 42° through an open window with a SCHUIL telephotometer (PETHERBRIDGE)

has to be made to the luminance readings. For example, if the readings are made on a 20-degree sky then they will be numerically lower than the outdoor illumination and will have to be corrected by a multiplying factor of $\times 1 \cdot 39$ (see Table II).

In Fig. 8 is shown an observer measuring the luminance of a 42-degree sky through an open window using a luminance meter known as a Schuil telephotometer. An advantage of this particular instrument for this type of work is that it incorporates a built-in inclinometer whereby the altitude of the patch of sky whose luminance is being measured can be ascertained.

The complete technique for the measurement of daylight factor involves the almost simultaneous measurement of the sky luminance and the indoor illumination, in order that the quotient expressing daylight factor can be determined. This second measurement can be obtained with the same instrument as is used for measuring the sky luminance. Alternatively a photocell corrected for cosine error can be used for the indoor measurements.

A further application of the known luminance distribution of an overcast sky to daylight factor measurement is the development at the Building Research Station of a portable direct-reading daylight factor meter (18). The prototype of this instrument was based on a small commercially-available light meter to which was added a hinged mask to restrict the light reaching the photocell to a zone of sky at 42 degrees altitude.

With the mask in place the meter is exposed to the sky through a window (Fig. 9) and its sensitivity adjusted to match the prevailing sky luminance. The meter is then placed at the indoor position and the mask folded back (Fig. 10) when the daylight factor is read directly.

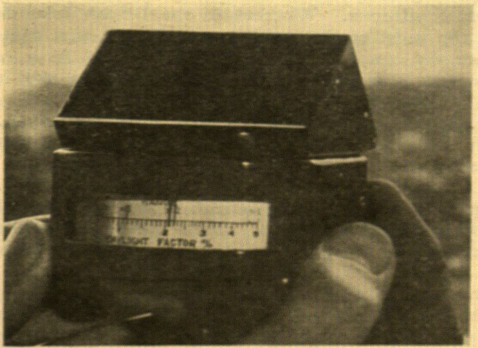

Fig. 9 — Portable daylight factor meter exposed to the sky through a window (Longmore and Hopkinson)

This instrument has been designed to meet the need for a simple means of measuring daylight factor which can be used by a person such as an architect or school inspector who is normally unskilled in more complex measuring techniques. The meter used to illustrate Figs. 9 and 10 is one which has now become commercially available.

Reference has already been made to the fact that the design of a building for daylighting can be as equally based on the average or the most frequently occurring outdoor conditions,

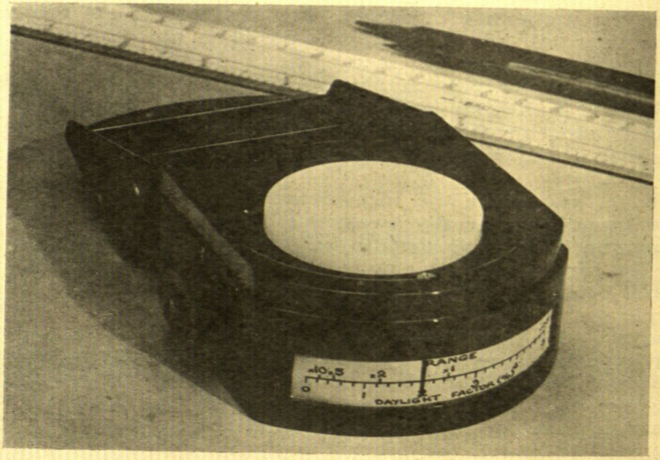

FIG. 10 — Portable daylight factor meter at the indoor position with the mask folded back (LONGMORE and HOPKINSON)

as on the most adverse conditions. Whereas in the British Isles design criteria for daylighting are based on the most severe outdoor conditions (*i.e.* the densely overcast sky), in other countries other sky conditions have been adopted. As a consequence it has not yet been possible to standardise the MOON and SPENCER sky luminance distribution internationally.

An example of a different approach to the subject is that taken by building designers in Sweden. Although the MOON and SPENCER sky is experienced in Sweden (see Fig. 7), it is felt that the densely overcast sky occurs too infrequently to be considered for design purposes.

The Swedish approach to daylighting design is that it should be based on the most frequently occurring type of sky condition. With this in mind, HOPKINSON has recently made sky luminance distribution measurements of a number of representative skies in the vicinity of Stockholm (14).

One of the types of sky which is typical of overcast conditions in the Stockholm area has a luminance distribution not unlike that given by MOON and SPENCER except for a marked inversion (*i.e.* brightening) in the immediate vicinity of the horizon. This inversion has been attributed to the presence of large areas of water around Stockholm. If this surmise is correct then it would be an advantage to study the effect of the presence of the sea or lakes on sky luminance distribution, since enquiries have been received by the Building Research Station in the past which would seem to indicate that the daylighting of schools built near the sea may be different from those built well inland.

Another type of sky which is characteristic of Sweden is the clear blue sky. A particular interest has been shown in this sky as it is another type having a repeatable luminance distribution for which it has been possible to derive a relationship similar to the MOON and SPENCER formula.

The relationship, which was derived by POKROWSKI (19) from first principles of atmospheric scattering by small particles, is as follows :

$$B_\theta \propto \left[\frac{1+\cos^2\alpha}{1-\cos\alpha}\right]\left[1-\exp\left(-\frac{P}{\sin\theta}\right)\right] \quad \ldots\ldots(2)$$

where B_θ = sky luminance at an angular distance θ from the horizon (*i.e.* altitude $\theta°$)
α = angular distance of measuring point from the sun
P = primary scattering coefficient

This formula enables the luminance distribution of the whole sky to be determined and not merely that of a great circle through the sun.

POKROWSKI found, however, that in order to obtain satisfactory agreement with measurements made in Moscow and Davos it was necessary to introduce an empirical correction to allow for secondary scattering of the light by large particles in the atmosphere. The modified formula is :

$$B_\theta \propto \left[\frac{1+\cos^2\alpha}{1-\cos\alpha}+K\right]\left[1-\exp\left(-\frac{P}{\sin\theta}\right)\right] \quad \ldots\ldots(3)$$

where K = secondary scattering coefficient.

POKROWSKI's original and modified luminance distributions have been compared by HOPKINSON with his own measurements in Stockholm (Fig. 11), and with KIMBALL and HAND's measurements in Washington and PEYRE's measurements in Montpellier, France (Fig. 12). The Stockholm measurements are seen to give better agreement with POKROWSKI's unmodified formula than with his modified formula. The best values of the scattering coefficients to give agreement with the Stockholm measurements were found to be $P = 0{\cdot}32$ and $K = 0$.

The references which have so far been made to studies of sky luminance have been concerned with the *relative* distributions of luminance of different types of sky. The MOON and SPENCER empirical distribution is an example of this. Provided the distributions can be related to the mean sky luminances and hence to the total outdoor illuminations there is not normally any need when considering the *illumination* of a building interior to know absolute levels of luminance over the sky vault.

One aspect of the *daylighting* of a building, as opposed to the mere provision of illumination, for which it is required to know absolute levels of sky luminance is in the assessment of visual comfort. An example of this is the assessment of the glare discomfort caused by the view of bright sky through a large window in a school classroom. Fig. 13 shows such an assessment being made by an observer in a model-scale classroom, while Fig. 14 shows the observer's view of the chalkboard wall and the adjacent window.

The degree of glare discomfort caused to the observer when looking towards the chalkboard is due, in part, to the luminance of the visible sky and its relationship to the luminance of the surfaces in the room which surround the window. It is therefore important to know what these luminances are in terms of absolute levels. These levels are usually available in the published data (see, for example, Figs. 4, 5 and 6) or can be derived from the relationship between the sky luminance distribution and total sky illumination.

SUPPLEMENTING PHOTOMETRIC DATA WITH SOLAR RADIATION DATA

It has already been mentioned that the number of places in the world at which regular measurements of outdoor illumination have been taken is exceedingly limited. In order to overcome this deficiency it has been suggested that the scant amount of available photometric data should be supplemented by other data obtained from continuous recordings

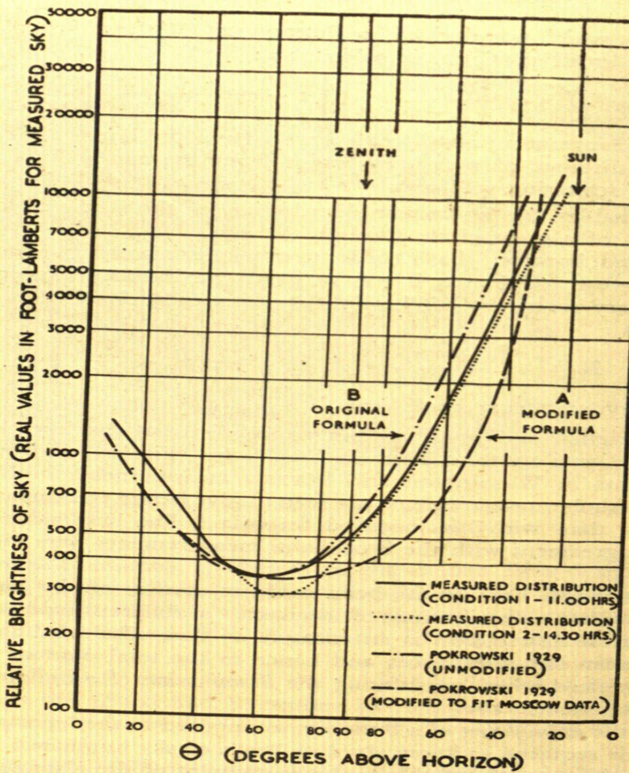

FIG. 11 — Comparison of blue-sky luminance measurements at Stockholm along a great circle through zenith and sun with values calculated from POKROWSKI, 1929 (HOPKINSON)

of total solar and sky radiation, since these measurements form part of standard meteorological observation programmes in many parts of the world.

Such a technique would be of considerable help to the Building Research Station when advising on the daylighting of buildings to be erected in those countries for which any sort of photometric data is at the moment completely lacking but for which solar radiation data may already be available.

There is, unfortunately, no simple and constant relationship between radiation intensity and illumination, since the relationship is dependent on the spectral distribution of the radiation, which is by no means constant but is itself dependent among other things on the sun's altitude. This is demonstrated by the fact that the illumination equivalent of 1 grm. cal. per sq. cm. per sec. of direct solar radiation varies between 7 040 lumens per sq. ft. when the sun is at an altitude of 70 degrees and 6 320 lumens per sq. ft. when the sun is at an altitude of about 10 degrees.

The derivation of the appropriate conversion factors from radiation intensity to illumination has involved the use of both semi-empirical studies and the direct simultaneous comparison of radiation intensity and illumination. The radiation measurements are, however, usually those of total radiation (*i.e.* sun and sky) on a horizontal surface. The illumination levels derived from these measurements may not, therefore, be comparable with, say, those obtained at the National Physical Laboratory, which are for sky illumination alone.

Among the most frequently quoted of the "illumination equivalent" data are those published by Kimball (20) in 1924. These equivalents have been derived from simultaneous measurements made with a photometer and a thermo-electric pyrheliometer and are given both for direct sunlight (measured normal to the sun's rays) and for total radiation (sun and sky) on a horizontal surface, the sky being cloudless. The results are given in Table III.

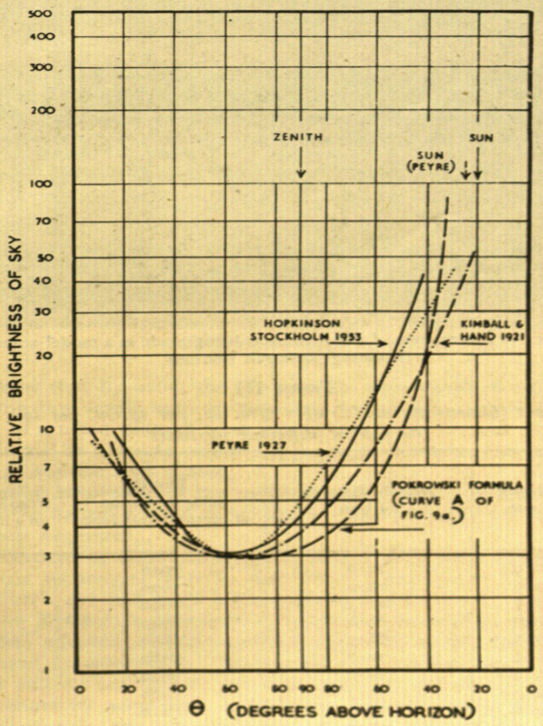

Fig. 12—Comparison of blue-sky luminance measurements along a great circle through zenith and sun made by Kimball and Hand, 1921, Peyre, 1927 and Hopkinson, 1953 (Hopkinson)

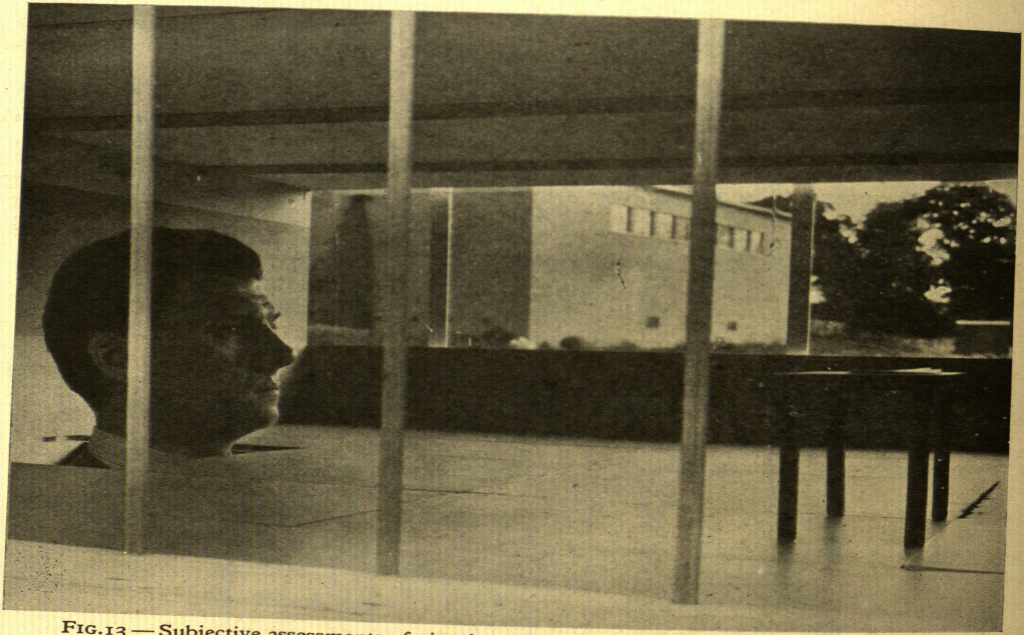

FIG. 13 — Subjective assessments of visual comfort being made in a model-scale classroom (Building Research Station)

TABLE III

Illumination equivalent (lumens per sq. ft.) of 1 grm. cal. per sq. cm. per sec. of radiation with the sun at different altitudes

Air Mass	Altitude of sun	Zenith distance of sun	Direct solar radiation at normal incidence	Radiation from sun and clear sky on a horizontal surface
1·06	70·0	20·0	7040	—
1·10	65·0	25·0	7020	7000
1·50	41·7	48·3	6880	6740
2·00	30·0	60·0	6740	6470
2·50	23·5	66·5	6650	6320
3·00	19·3	70·7	6580	6260
3·50	16·4	73·6	6520	6220
4·00	14·3	75·7	6460	6200
4·50	12·6	77·4	6410	6200
5·00	11·3	78·7	6370	6200
5·50	10·2	79·8	6320	—

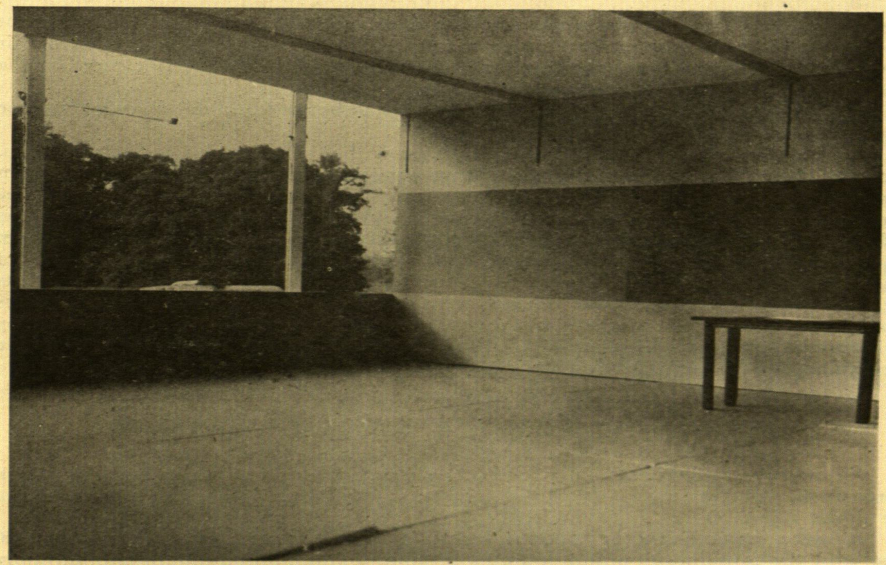

FIG. 14 — Observer's view of chalkboard wall and adjacent window in model-scale classroom (Building Research Station)

KIMBALL claims that by using the illumination equivalents in this table it is possible to calculate illumination levels with an accuracy comparable with that of ordinary photometric readings. If a mean value of 6700 lumens per sq. ft. is used for cloudless skies, the illumination levels will be accurate within ± 5 per cent, being too low near noon in summer and too high near sunrise and sunset.

The illumination equivalent of the radiation from a sky covered with clouds is somewhat higher than the figures quoted above and a value probably not far from 7000 lumens per sq. ft. has been suggested.

A possible criticism of KIMBALL's results is that they were obtained at a time when reliable photometric techniques were in their infancy and before the spectral response of the average observer's eye had been internationally standardised. As a consequence it is difficult to compare KIMBALL's photometric measurements with more recent data.

MOON (21) has adopted a semi-empirical approach to the derivation of illumination levels from radiation measurements. His results are, however, applicable solely to direct solar illumination and do not include the component of diffuse sky illumination.

MOON commences by adopting a mean curve for the relative spectral distribution of solar radiation outside the earth's atmosphere. A mean value of the solar constant is then adopted in order to convert this relative distribution into absolute values of radiation intensity on a surface normal to the sun's rays. Corrections are then applied for such factors as atmospheric scattering and absorption by dust, ozone and water vapour. The resultant curves, which give the spectral distribution of solar radiation at sea level for six values of air mass are then converted into equivalent levels of illumination using the C.I.E. curve for the spectral sensitivity of an average observer's eye.

The agreement with measured values was found to be good. Unfortunately the same method cannot be used to predict sky illumination.

Some interesting applications have been made of the "illumination equivalent" data. Richards (22) used Kimball's results to derive daylight illumination measurements from solar radiation data already available for two observing stations in South Africa. The information was required in order to assist in the better daylighting of building interiors and in the better understanding of the physiology of growth and reproduction in plants.

The study was confined to cloudless and overcast skies, an illumination equivalent (of 1 grm. cal. per sq. cm. per sec.) of 6700 lumens per sq. ft. being used for measurements with the cloudless skies and 7000 lumens per sq. ft. with the overcast skies. Observations were also obtained of the proportion of diffuse sky radiation to total sun and sky radiation on horizontal surfaces on cloudless days. From all these data it was possible to determine for each hour of the day and each month of the year the mean horizontal illumination from :

(a) Sun and cloudless sky
(b) A cloudless sky alone
(c) An overcast sky alone.

An estimation of the minimum outdoor illumination to be used for building design purposes showed that a level of 500 lumens per sq. ft. would be a reasonable design minimum for South Africa.

A further application of the "illumination equivalent" data has been that of Fournol (8) who used the solar radiation measurements obtained at the Paris–Saint-Maur observatory to give curves of mean levels of horizontal illumination similar to those of Fig. 2 and tables of frequencies of occurrence of daylight illumination similar to that of Table I. The illumination equivalent used for the derivation of the curves was 6870 lumens per sq. ft. (74000 lux) while for the tables a value of 7020 lumens per sq. ft. (75600 lux) obtained by Harff (23) was used.

The Commission Internationale de l'Eclairage (C.I.E.) is at present engaged in considering whether a single value of the illumination equivalent is sufficiently accurate for international use or whether it is preferable to have a series of conversion factors whose values are dependent on the sun's altitude and the state of the sky.

The Measurement of Sun and Sky Illumination and Radiation by "Graphical" Methods

Graphical methods for predicting the amount of illumination received directly from the sky have been established for a considerable number of years and various simple optical devices have been constructed whereby measurements of this direct illumination can be made in buildings, usually by counting squares on a graduated glass screen or, after exposure, on a photographic film or plate.

The Waldram sky-factor gauge (24) and the Beckett and Dufton pin-hole camera (25) are examples of these devices. The Waldram gauge can account for light received from only a relatively limited part of the complete sky vault at any one time, while the pin-hole camera, although having a more extensive field, has blind-spots at the zenith and horizon.

The pin-hole camera has a particular advantage, however, in that it can be used for studying sun-paths as well as sky illumination.

More recently alternative solutions have been proposed in which a parabolic reflecting surface is used such that the hemisphere of sky to which the observing position is exposed can be viewed in its entirety. On this view of the sky is then superimposed charts whereby the sky illumination, the instantaneous position of the sun or the integrated solar energy can be determined.

Two examples of this solution are PLEIJEL's Globoscope (26) and TONNE's Horizontoscope (27). The essential difference between the two instruments is that the former takes a photographic record of the outline of the sky which can be studied later in conjunction with interpretative diagrams whereas the latter is intended for visual observation.

The Globoscope (Fig. 15) comprises a convex parabolically-shaped polished metal dome, the reflections from which are focussed by a lens on to a miniature (35 mm.) camera. The mirror enables a complete hemisphere of environment about the measuring position

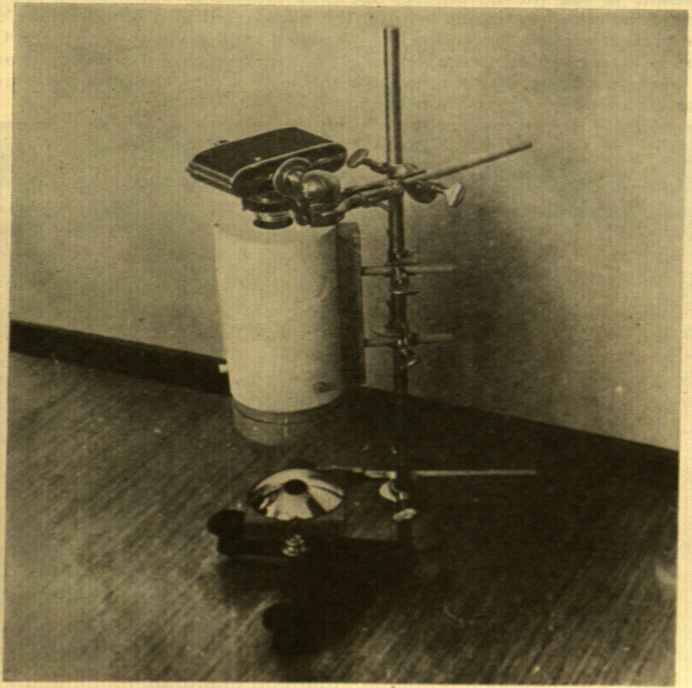

FIG. 15 — PLEIJEL's Globoscope (PLEIJEL)

to be observed at one time except for a small blind-spot at the zenith occupied by the reflection of the camera.

Photographs taken with the Globoscope are interpreted with a series of charts which are superimposed on the photographs at the printing stage.

For daylight studies the chart comprises a series of dots, each one of which represents approximately 0·1 per cent. sky factor. The number of dots covering the area of visible sky represents the sky factor for the observing position. The distribution of dots on the chart is such as to give sky factors corresponding to a sky of uniform luminance.

For insolation studies with the Globoscope a sun-path chart is used. This chart has marked on it the sun's positions for representative times of the day at different months of the year.

For heat radiation studies three charts are available, two giving the *x* and *y* components of radiation from the sun and one giving the *y* component (*i.e.* component on a horizontal plane) of radiation from any part of the sky vault.

It is possible to use the Globoscope for such studies as determining the percentage of possible total radiation obtainable in, say, the playground of a school where obstructing buildings are present around the perimeter. Another application to which the Globoscope has been put is in correlating photographs of the sky showing the cloud formation with photometric surveys of the sky luminance distribution. One such correlation is shown in Fig. 16 for a clear-blue sky in Stockholm.

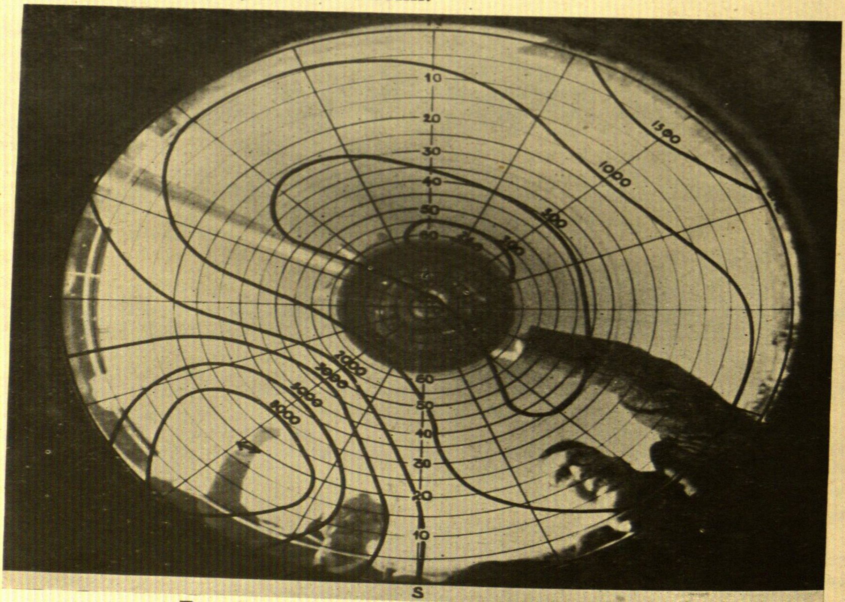

FIG. 16 — Photograph taken with Globoscope showing superimposed sky luminance contours (HOPKINSON)

The Horizontoscope (Fig. 17) comprises a convex hemispherically-shaped clear plastic dome, the reflections in which are viewed from a fixed distance. With this instrument a somewhat larger blind-spot occurs, due to the reflection of the observer's head and body.

Under the dome is placed one of three charts, the markings of which appear superimposed on the reflections of the outlines of windows, obstructing buildings, etc.

The chart for sky illumination is divided into a series of approximately rectangular areas, each one of which represents 0·1 per cent. of the total sky illumination. The number of rectangles covering the area of sky visible by reflection in the plastic dome gives a measure of the available percentage of outdoor illumination. The size and distribution of the rectangles have been adjusted so as to allow for a Moon and Spencer sky luminance distribution.

The chart for sun position is of almost identical form to that used with the Globoscope.

The chart for solar radiation is marked with contours of radiation intensity on horizontal and vertical surfaces. No provision is made in this instrument for assessing sky radiation.

When using the sun position and solar radiation charts the Horizontoscope has to be correctly orientated relative to the cardinal points and a small magnetic compass has been provided to facilitate this.

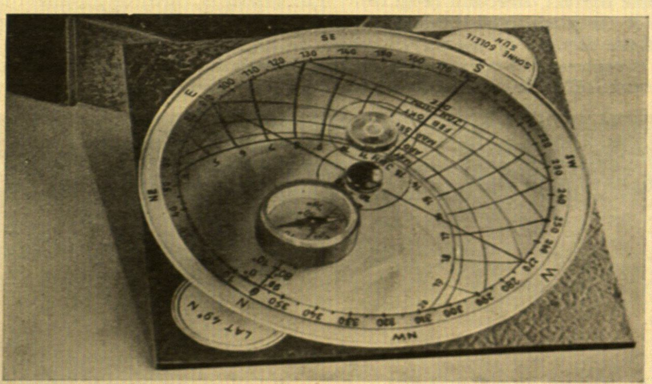

Fig. 17 — Tonne's Horizontoscope (Tonne)

Assessment of Daylighting due to Reflected Sunlight

The references to the daylighting of building interiors which have so far been made in this paper have been primarily concerned with the illumination from the sky. This is because in the temperate zones of the world, for which most of the studies of daylighting have so far been made, the sun is too unreliable to be used as an illuminant.

In other parts of the world, however, the sun is not only much more reliable but also occurs in conjunction with deep blue skies of a comparatively low luminance (250 foot-lamberts and less). In such localities a major change has to be made in the approach to building design since insufficient light is received from the sky alone to enable the same daylighting techniques to be used as in the temperate zones.

Although the architecture of tropical and sub-tropical countries shows that the use of reflected sunlight as an illuminant has been an established technique for centuries, few, if any, measurements have been published which indicate the effectiveness of this form of interior lighting in terms of levels of illumination. Furthermore, little or no data appear to exist whereby to assess with any degree of engineering precision the advantages to be gained by planning adjacent buildings so that deliberate use could be made of sunlight reflected into a building from an opposite facade.

In order to provide some initial data on this subject a study has been made at the Building Research Station (28) to see what levels of illumination could be obtained in a building by sunlight reflected from the ground and from an opposite building. Because of the continuous variation of this illumination with time of day and time of year it was decided that rather than calculate the probable illumination it would be simpler to measure the illumination in a model when a parallel beam of light of appropriate intensity and direction was shone upon it.

A Heliodon (29) was used to reproduce the relative motions of the earth and sun. This instrument comprises a board representing the earth's surface on which is placed the model orientated in the correct direction (Fig. 18). The board is tilted to an angle corresponding to the latitude of the place to be investigated and rotates about a vertical axis to give variations in the time of the day.

The sun is represented by a projector lamp which can be set at positions on a vertical scale to represent different times of the year. The scale and board are located at such a

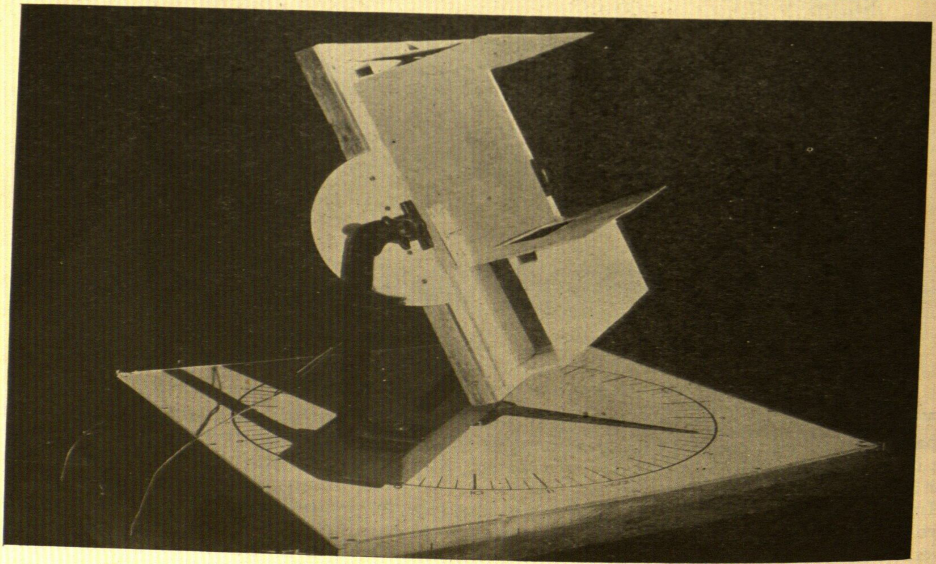

FIG. 18 — Heliodon with model building for reflected sunlight studies (HOPKINSON and PETHERBRIDGE)

distance relative to one another that the light from the lamp, which is considered as a " point " source, always strikes the centre of the board at the correct angle.

The model comprised a room on the ground floor of a two-storey building with a similar parallel building facing it. The buildings were assumed to be orientated first East-West and then North West-South East at the Tropic of Cancer (latitude 23½°N.) with the window of the room facing North.

Illumination measurements were made at a single observation point near the back of the room at times corresponding to hourly intervals between sunrise and sunset on five occasions during the year. These measurements were corrected to an assumed constant illumination of 10 000 lumens per sq. ft. normal to the sun's rays.

Fig. 19 shows the levels of illumination obtained in the room with time of day and time of year when the buildings were orientated East-West. It will be seen that over most of the day these levels fall between 100 and 200 lumens per sq. ft. When the sill height was raised from 2 ft. 6 ins. to 6 ft. (a height common to some buildings in tropical countries) the illumination levels were decreased to about half. Even so they were still fully adequate for all normal indoor visual tasks.

When the buildings were orientated North West–South East, it was then possible for the sun to shine directly through the window at certain hours of the day. This is indicated in Fig. 20 by the peaks in the illumination curves occurring during the early hours of the day.

The measurements in Figs. 19 and 20 are related to interior and exterior surfaces having reflection factors of average value. Additional measurements were made to find out the effects of varying the reflection factors of the ground, the facades and the room interior. These showed that the ground reflection factor had its greatest effect on the indoor illumination in Midsummer while the facade reflection factor had its greatest effect in Midwinter.

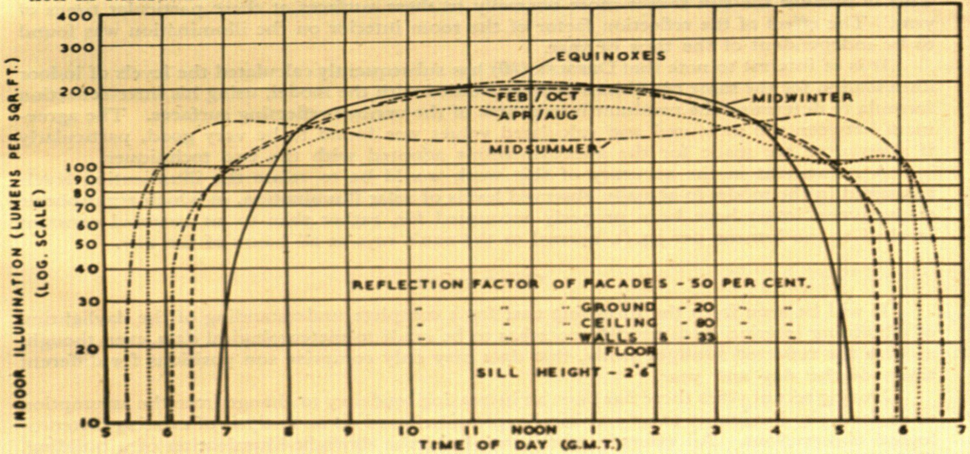

FIG. 19 — Variations of indoor illumination due to reflected sunlight when buildings are orientated East-West (HOPKINSON and PETHERBRIDGE)

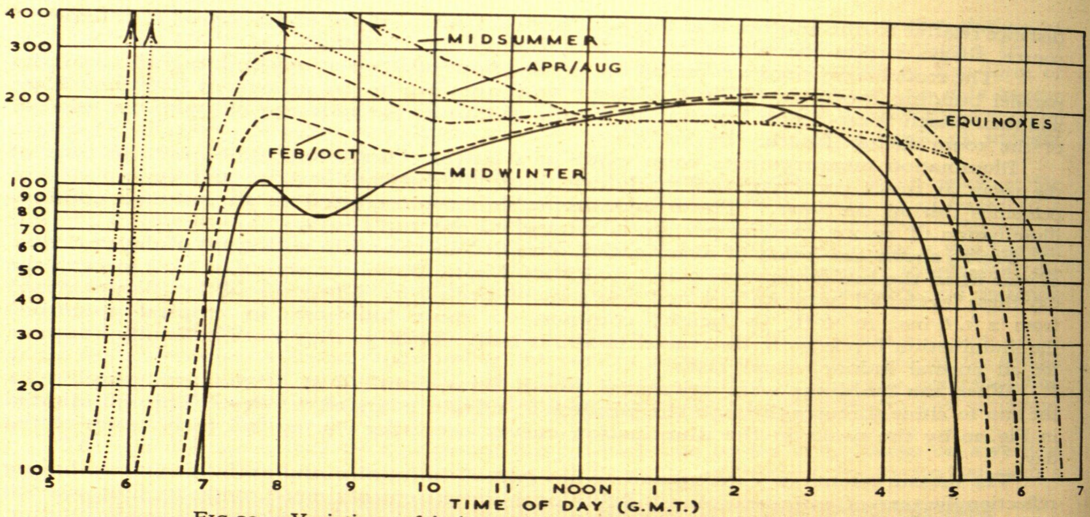

FIG. 20 — Variations of indoor illumination due to reflected sunlight when buildings are orientated North West — South East (HOPKINSON and PETHERBRIDGE)

This is because the sun shines more normally to these surfaces at these particular times of year. The effect of the reflection factor of the room interior on the illumination was found to be independent of the time of year.

It is of interest to note that DRESLER (30) has subsequently calculated the levels of indoor illumination for the same conditions as were studied with the model, using his inter-reflection formula to determine the resultant luminances of the various reflecting surfaces. The agreement between the measured and calculated values was found to be very good, particularly if allowances are made for the approximations adopted with the two techniques.

A refinement in the accuracy of this work would be to relate the illumination levels measured in the model to actually observed levels of solar illumination, in which atmospheric transmission losses have been properly accounted for, rather than to an assumed constant level of 10 000 lumens per sq. ft. normal to the sun's rays at all hours of the day.

CONCLUSIONS

It will be seen from the foregoing that for a complete understanding of the daylighting of a building interior, frequent reference has to be made to meteorological data, even though, as with the reflected sunlight study, that data may only comprise sun positions for different times of the day and year.

During recent years there has been an increasing tendency to change from the assumption of uniform sky luminance to an empirical expression based on an analysis of existing meteorological observations. An example of this has been the daylight-illumination of a building. This was originally expressed in terms of a uniform sky, even though it was appreciated that such a sky rarely if ever existed. Now daylighting is becoming increasingly expressed in terms of naturally-occurring skies, of which the Moon and Spencer luminance distribution is an example.

It is to be expected that as more photometric data become available then there will be an increasing trend towards this approach to daylight problems. One of the matters which will shortly be considered is whether the time is yet ripe to define the luminance distribution of an overcast sky internationally, and if so whether the Moon and Spencer or some other empirical distribution is the best one to adopt.

The evidence so far is that the Moon and Spencer distribution applies adequately to temperate zones in the Northern hemisphere. Further data are required from other parts of the world, either to determine its applicability there or to establish some other more suitable luminance distribution for building design purposes.

Towards this end the School of Cosmic Physics in Dublin has initiated a study of the luminance distribution of different types of sky using a specially-designed photo-electric photometer. A similar study using a continuously-recording instrument has been initiated at the National Building Research Institute in Pretoria.

Such studies as these are likely to yield data of great value to architects and others concerned with the daylighting of buildings and may lead to even more precise techniques for the assessment and measurement of interior daylighting.

Acknowledgements

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