A Lumen Method of Daylighting Design

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THIS PAPER presents the basis of a new method of daylighting design and daylight prediction for interiors. It has been prompted by the fact that the existing methods of daylight prediction, such as the rectangular surface source methods of Higbie,[1, 2] and Moon and Spencer,[3, 4] the daylight factor or sky factor methods of Waldram[5] and others, and the Fenestra method of Randall and Martin,[6] have been limited in their application by the assumptions made in their development. In general, these methods have been applicable to large spaces such as industrial plants, in which interior reflections and ground reflections have had little significance.

During the past two years, therefore, the major objective of the Daylight Study Project at Southern Methodist University, sponsored by the Detroit Steel Products Company and the Libbey-Owens-Ford Glass Company, has been to develop a prediction method which would be applicable to a different range of conditions, to smaller spaces such as classrooms, offices, hospital rooms, small industrial spaces, and the like, in which interior reflections and ground reflections do have significance.

The method outlined in this discussion is based on the premise that it is unnecessary to know the exact illumination at every point in the room, if a determination can be made of the average illumination, the minimum illumination, and the maximum illumination, since these three values would be considered sufficient by the practicing architect and illuminating engineer.

Even so, the problem has been quite complex, because of the large number of independent variables which affect the amount and distribution of daylight reaching the work surfaces of a daylighted room. The variables can be divided into several categories as follows:

A. Variables affecting the amount of light reaching the windows from above the horizontal.

1. The brightness and brightness pattern of the clear or overcast sky. (A partially cloudy sky is even more variable.)
2. The angular position of the sun with respect to the window, and the sun intensity.

B. Variables affecting the amount of light reaching the windows from below the horizontal.

1. The horizontal illumination of the ground (determined by the brightness and brightness pattern of the sky, plus the angular position of the sun with respect to the ground and the intensity of the sun.)
2. The reflection factor of the ground or ground cover.

C. Variables affecting the amount of light leaving the inner surface of the window or fenestration for a given amount of light incident on the outside of the window.

1. The window area.
2. The ratio of actual transmitting area to nominal fenestration area.
3. The actual transmission factor of the clean transmitting media for the incident light conditions.
4. The effect of dirt collection on the transmission factor of the transmitting medium, in service.

D. Variables affecting the utilization and distribution of light on the work plane after leaving the inner face of the window.

1. The distribution pattern of the light leaving the window.
2. Geometric factors as follows:
   a. The length and height of the window.
   b. The height of the window above the work plane.
   c. The height of the ceiling.
   d. The ratio of ceiling or window height to room width and room length.
3. Reflection characteristics of the ceiling, walls and floor of the room.

The list is impressive, and made a point-by-point method appear impractical. Consequently, it was deemed advisable to investigate a possible lumen method of daylighting design. This was to be patterned after the basic Harrison-Anderson lumen method for interior lighting design,[7, 8] since it appeared to afford the best possibility of allowing for all the variables. In particular, it was to employ

A paper presented at the National Technical Conference of the Illuminating Engineering Society, Sept. 8-12, 1952, Chicago, Ill.
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a similar computation technique, since most illuminating engineers and architects are familiar with the Harrison-Anderson method. This attack has proved quite fruitful, even though the number of variables to be encompassed has been greater for the daylighting problem than for artificial lighting.

Basic Considerations

The Harrison-Anderson method is essentially a technique for rapid determination of the average horizontal illumination to be expected on the work plane in the interior being studied. Its basic feature is the concept of a "Coefficient of Utilization," which can be expressed as follows:

$$\text{Coefficient of Utilization} = \frac{\text{lumens reaching the work plane}}{\text{generated lamp lumens}}$$

In the case of daylight, a similar coefficient of utilization can be postulated. To avoid confusion with the Harrison-Anderson term, however, it will be referred to as the "Average Illumination Coefficient," which can be expressed as follows:

$$\text{Average Illumination Coefficient} = \frac{\text{lumens reaching the work plane}}{\text{lumens incident on the nominal window area}} = K_{avg}$$

This average illumination coefficient depends on similar factors to those which determine Harrison's coefficient of utilization, such as the amount and distribution of light flux leaving the windows, the room geometry, and the room finishes. There are, however, certain essential differences.

First, the amount of daylight flux varies depending on a number of external factors which have been listed previously, whereas the generated lamp lumens of a given electric lighting installation can be considered constant.

Second, whereas the Harrison-Anderson method assumes and even restricts the placement of luminaires in a symmetrical arrangement such that the illumination at any point will not differ greatly from the average illumination, the very asymmetry of the more common daylighting designs precludes this possibility. The daylighting designer must be concerned therefore with the minimum illumination which will be produced on the work plane, and will at times be concerned with the maximum as well. Consequently, two additional coefficients are postulated, which are defined as follows:

$$\text{Minimum Illumination Coefficient} = \frac{\text{Minimum work plane illumination} \times \text{work plane area}}{\text{Lumens incident on the nominal window area}} = K_{min}$$

$$\text{Maximum Illumination Coefficient} = \frac{\text{Maximum work plane illumination} \times \text{work plane area}}{\text{lumens incident on the nominal window area}} = K_{max}$$

As a result, when the designer is concerned with the minimum and maximum illumination, in addition to the average, it is necessary for him to determine the additional coefficients, and to repeat his calculations to establish the minimum and maximum illumination values.

A second basic feature of the Harrison-Anderson method is the use of a "Room Index" to account for the effect of room geometry. It has proved advantageous in the development of this daylight computation method to adopt a similar index to account for room geometry. Again, to avoid confusion with the Harrison-Anderson term, this index will be referred to as the "Window Index," with the symbol "W.I."

Experimental Technique

The method presented here is an empirical one, based on an extensive series of tests. The tests were conducted in a one-quarter size model, Fig. 1, lighted by what is believed to be the largest artificial sky in active use at present for daylighting experimentation. The model and artificial sky were employed for several reasons, most important of which were that any desired sky brightness pattern

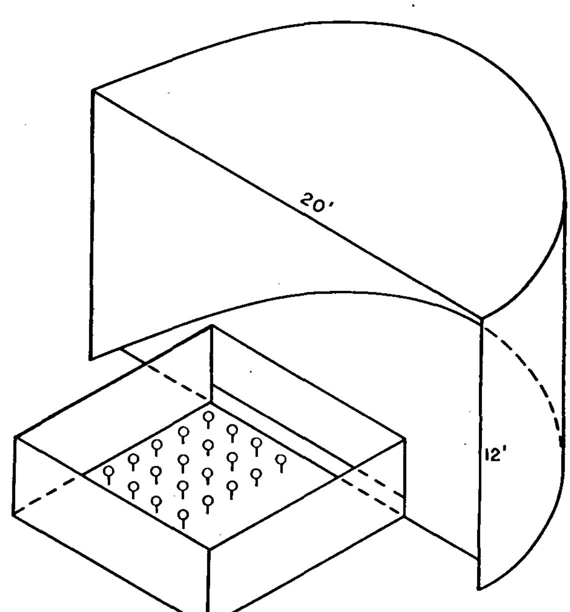

Figure 1. Sketch showing artificial sky, right, with one-quarter scale model, left, with photocells in position for test. Sky illuminated by light sources above and at sides of model.

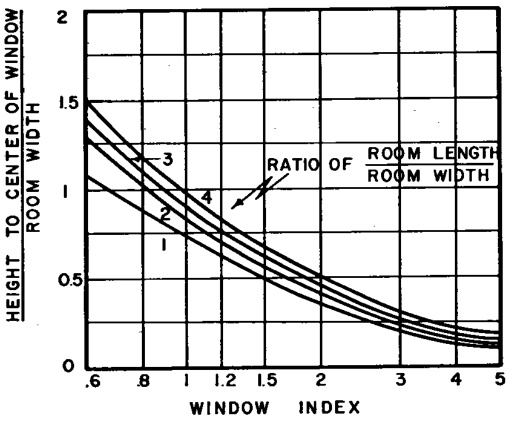

Figure 2. Curves for determination of Window Index for light from sky alone.

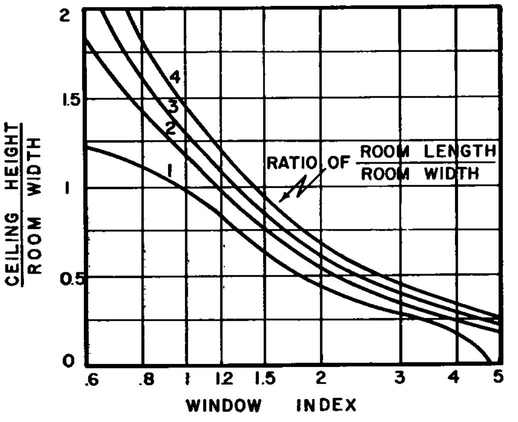

Figure 3. Curves for determination of Window Index for light from ground alone.

could be held constant, and reproduced consistently for successive tests.

The test program has included a study of the following variables:

1. Room sizes from 10 feet by 10 feet to 40 feet by 40 feet, including square and rectangular rooms, with ceiling heights from 8 feet to 14 feet.
2. Reflection factors of 85 per cent, 70 per cent, and 4 per cent on ceiling; 70 per cent, 50 per cent, 30 per cent and 4 per cent on walls; and 30 per cent and 4 per cent on floor.
3. Sky brightness patterns representing clear, overcast, and uniformly bright skies, all without ground reflections.
4. Independent studies of light from below horizontal representing ground reflections, with no sky light.

Tests covered by the data of this paper include only those applying to clear glass windows set vertically in one wall, extending without major breaks the full length of the wall. and extending from a normal sill of 30 to 42 inches to a window head not more than 12 inches below the ceiling.

Instrumentation has proved to be a major problem, as in all daylighting research. Color and cosine corrected photocells have been employed for the measurements. The cells have been mounted on clear plastic stands to a height representing a conventional 30-inch work surface. Stands were arranged to permit precise levelling with a bubble level each time the cell was moved. The artificial sky and model were located in an air-conditioned space to eliminate any drift due to temperature and humidity variations. Cells and galvanometer have been calibrated on the optical bench against photometric standards each day of testing.

Each cell was used consistently in the same position during the test program. Test stations were at five-foot intervals, in terms of full scale, in each direction, beginning five feet in from the window and from the end walls. Cell readings were taken with a high-sensitivity, low-resistance laboratory galvanometer to assure linearity, and considerable precautions were taken to eliminate thermal and other stray measurement circuit effects. Cells were connected to the galvanometer for reading by means of a switching arrangment which connected a resistance equal to that of the galvanometer across the photocell terminals at all times except when actually taking a reading. In order to eliminate fatigue effects, the sky was left lighted at all times, so that cells were continually illuminated at levels in the range of those which the cells were reading during the actual tests.

The lighting system for the sky was arranged to permit switching readily from one sky pattern to another. This lighting system was supplied from carefully regulated constant-voltage supplies. Sky patterns for clear and overcast skies approximate closely those shown on the right-hand portions of Figures C-4 and C-7, page 25, of the Recommended Practice of Daylighting.[9] The ground brightness pattern was uniform, as was the uniform sky pattern.

Daylighting Performance Data

The data obtained were voluminous. Approximately four hundred tests have been included in the data evaluated for this paper, and a nearly equal number of preliminary tests were run while perfecting techniques and in studying the effects of individual parameters.

The six curves, Figs. 2 through 7, present the essence of the data. Figs. 2 and 3 give Window Index values for light from sky alone and light

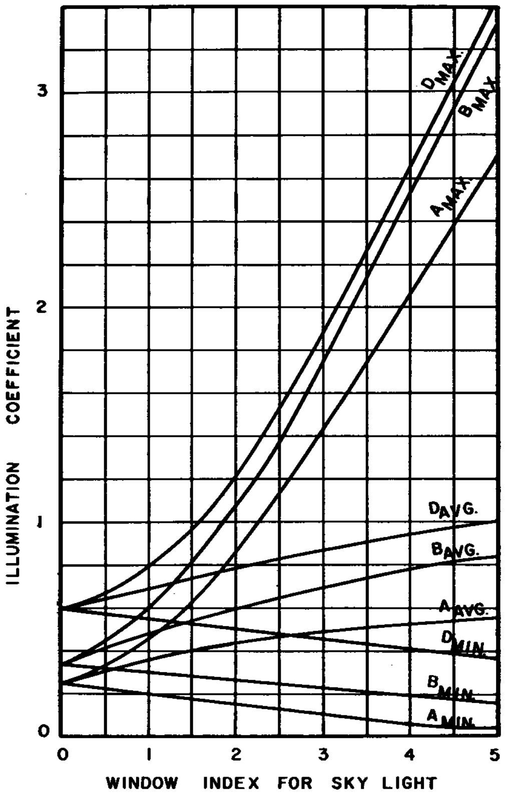

Figure 4. Illumination Coefficient - Window Index curves for light from clear sky only. Reflection factors: A—Ceiling 4 per cent, walls 4 per cent, floor 4 per cent. B—Ceiling 85 per cent, walls 30 per cent, floor 30 per cent. D—Ceiling 85 per cent, walls 70 per cent, floor 30 per cent.

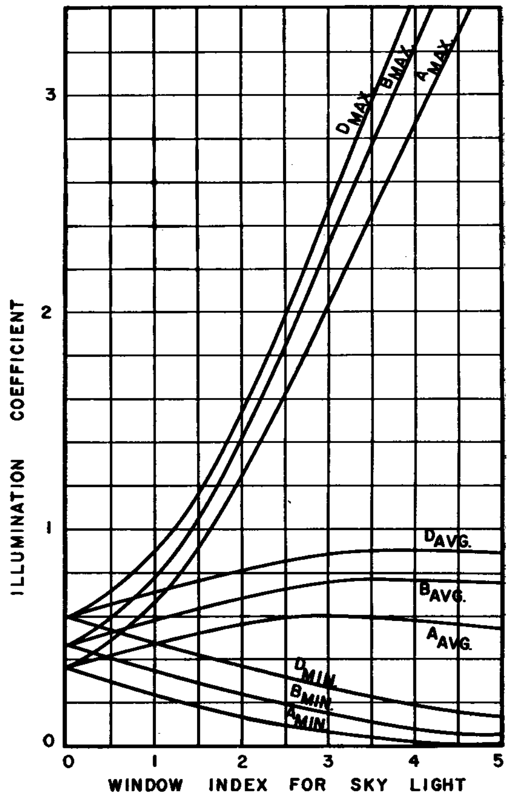

Figure 5. Illumination Coefficient - Window Index curves for light from overcast sky only. Reflection factors: A—Ceiling 4 per cent, walls 4 per cent, floor 4 per cent. B—Ceiling 85 per cent, walls 30 per cent, floor 30 per cent. D—Ceiling 85 per cent, walls 70 per cent, floor 30 per cent.

from ground alone, respectively. They are quite similar to the corresponding "Room Index" curves for the Harrison-Anderson technique, as published in the Westinghouse Lighting Handbook, 1943.[10] The curves as shown give a good empirical fit for the data analyzed in detail at the time of writing. Further analysis may indicate the desirability of some modifications, however, which would in turn affect the curves of Figs. 4 through 7.

The curves of Figs. 4 through 7 give the Average, Minimum, and Maximum Illumination Coefficients for Clear, Overcast, and Uniform Sky Brightness Patterns, and for Ground Brightness, respectively, The first three are for light entering the room in a predominantly downward direction and represent what can be considered as very broad spread direct lighting distribution. The fourth is for light entering the room in an upward direction, and represents an indirect lighting distribution.

Although the curves were obtained for clear glass for various incident lighting conditions, it is anticipated that the distribution of light inward from the various commonly used glazing and control media, such as clear and patterned glass, diffusing shades, or draperies, louvers, blinds, or refracting media, will be found to be of such a nature that each can be closely approximated by some combination of these basic distributions. The curves as shown reflect the directional effect of two air to glass faces, but the coefficients obtained from them must be adjusted in use for the transmission factor of the glazing and control media for the incident light condition, as well as for the obstruction due to window elements such as mullions, muntin bars, or mortar joints, which reduce the net transmitting area below that of the gross area of the masonry opening.

The curves as given here do not include all combinations of reflection factors which were tested. This omission has been intentional, as a greater number of curves per figure would have introduced confusion, and space limitations have precluded additional figures at this time. It is believed, however, that the curves presented will by interpolation permit work of sufficient accuracy for most practical problems.

In addition, no data have been presented here for conditions of sun on the windows. The data are

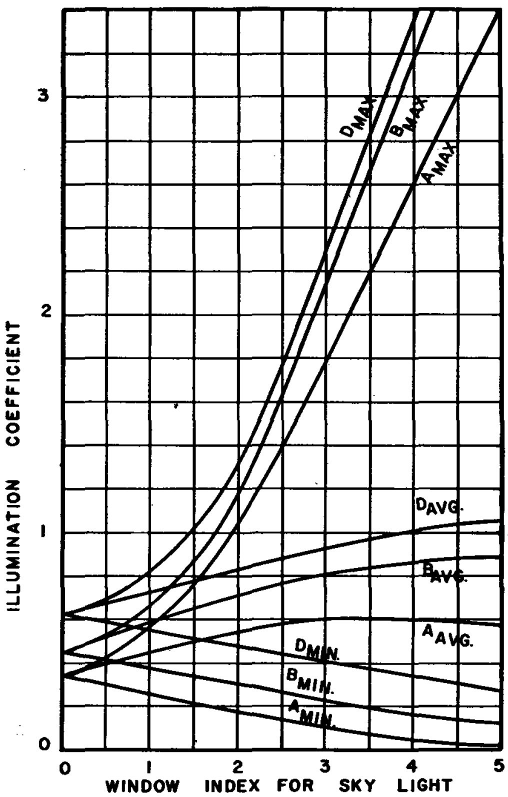

Figure 6. Illumination Coefficient - Window Index curves for light from uniform brightness sky only. Reflection factors: A— Ceiling 4 per cent, walls 4 per cent, floor 4 per cent. B—Ceiling 85 per cent, walls 30 per cent, floor 30 per cent. D—Ceiling 85 per cent, walls 70 per cent, floor 30 per cent.

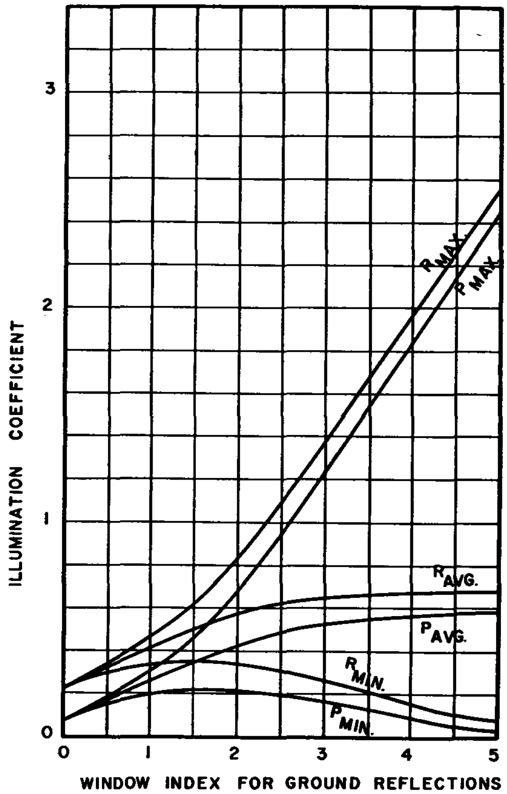

Figure 7. Illumination Coefficient - Window Index curves for light from ground only. Reflection factors: P—Ceiling 85 per cent, walls 30 per cent, floor 30 per cent. R—Ceiling 85 per cent, walls 70 per cent, floor 30 per cent.

confined for the present to windows glazed with clear flat glass, with light from sky and ground.

Example

Compute the average, minimum, and maximum illumination produced in a 30x24x12-foot classroom, with reflection factors of 85 per cent ceiling, 60 per cent walls, and 30 per cent floor, with windows extending the full length of one 30-foot wall, and from a 42-inch sill to the ceiling, with clear flat glass, and with no controls in the windows. Assume a clear sky having a brightness pattern as shown on the right side of Figure C-4, page 25, "Recommended Practice of Daylighting," which produces 287 lumens per square foot incident on the vertical windows. Assume a sun position and ground reflectance such that light from ground reflections produces 213 lumens per square foot incident on the vertical windows, for a total of 500 footcandles total incident light.

Step 1. Determine the Window Index for Sky Light from Figure 2.

(a) Height to Center of Window $= H_{cw} = 7.75$ feet
(b) Room Width $= W = 24$ feet
(c) Room Length $= L = 30$ feet
(d) $H_{cw}/W = 7.75/24 = .323$
(e) $L/W = 30/24 = 1.25$
(f) Window Index for Sky Light (from curve) $=$ W.I.$_s$ $= 2.20$

Step 2. Determine the Illumination Coefficients for Clear Sky Light from Figure 4.

(a) Aver. Illumination Coefficient $= K_{savg} = 0.76$
(b) Min. Illumination Coefficient $= K_{smin} = 0.45$
(c) Max. Illumination Coefficient $= K_{smax} = 1.29$

Step 3. Determine the Average, Minimum, and Maximum Work Plane Illumination from the Clear Sky Light Only.

(a) $$E_{savg} = \frac{E_{is} \times A_w \times K_{savg} \times T_g \times T_w \times M.F.}{A_f}$$

where

E_{savg} = Average Work Plane Illumination from Sky Light, footcandles

E_{is} = Illumination Incident on Vertical Windows from Sky Alone, footcandles

A_w = Area ot masonry opening for window, square feet

K_{savg} = Average Illumination Coefficient for Sky Light

T_g = Transmittance of glazing medium for diffuse incident light (0.8 for clear flat glass)

T_w = Ratio of clear window opening to masonry opening (0.8 for typical metal window construction)

$M.F.$ = Maintenance Factor (Assumed 1.0 — representing initial conditions — for this example)

A_f = Area of floor, or work plane, square feet

$$E_{savg} = \frac{287 \times 8.5 \times 30 \times .76 \times .8 \times .8 \times 1.0}{30 \times 24}$$

$= 49.5$ Ft-c

Similarly,

(b) $$E_{smin} = \frac{287 \times 8.5 \times 30 \times .45 \times .8 \times .8 \times 1.0}{30 \times 24}$$

$= 29.3$ Ft-c

(c) $$E_{smax} = \frac{287 \times 8.5 \times 30 \times 1.3 \times .8 \times .8 \times 1.0}{30 \times 24}$$

$= 84.7$ Ft-c

Step 4. Determine the Window Index for Ground Light from Figure 3.

(a) Ceiling Height $= H_c = 12$ feet
(b) $H_c/W = 12/24 = 0.5$
(c) $L/W = 1.25$
(d) Window Index for Ground Light (from Curve) $= 1.9$

Step 5. Determine the Illumination Coefficients for Ground Light from Figure 7.

(a) Aver. Illumination Coefficient $= K_{gavg} = 0.52$
(b) Min. Illumination Coefficient $= K_{gmin} = 0.32$
(c) Max. Illumination Coefficient $= K_{gmax} = 0.75$

Step 6. Determine the Average, Minimum, and Maximum work plane illumination from Ground Light only.

(a) $$E_{gavg} = \frac{E_{ig} \times A_w \times K_{gavg} \times T_g \times T_w \times M.F.}{A_f}$$

where

E_{gavg} = Average work plane illumination from ground light, footcandles

E_{ig} = Illumination incident on vertical windows from ground alone, footcandles

K_{gavg} = Average illumination coefficient for ground light

$$E_{gavg} = \frac{213 \times 8.5 \times 30 \times .52 \times .8 \times .8 \times 1.0}{30 \times 24}$$

$= 25.1$ Ft-c

(b) $$E_{gmin} = \frac{213 \times 8.5 \times 30 \times .32 \times .8 \times .8 \times 1.0}{30 \times 24}$$

$= 15.5$ Ft-c

(c) $$E_{gmax} = \frac{213 \times 8.5 \times 30 \times .75 \times .8 \times .8 \times 1.0}{30 \times 24}$$

$= 36.2$ Ft-c

Step 7. Determine the Average, Minimum, and Maximum work plane Illumination from Sky Light and Ground Light

(a) $E_{avg} = E_{savg} + E_{gavg} = 49.5 + 25.1 = 74.6$ Ft-c
(b) $E_{min} = E_{smin} + E_{gmin} = 29.3 + 15.5 = 44.8$ Ft-c
(c) $E_{max} = E_{smax} + E_{smin} = 84.7 + 36.2 = 120.9$ Ft-c

The daylighting prediction method presented in this paper has a number of features to commend it, as follows:

1. It is relatively simple. It employs a computation technique with which many architects and all illuminating engineers are already familiar, and which many of them use regularly in artificial lighting design.

2. It may prove possible with further study to develop tables of illumination coefficients for almost any desired types of fenestration and controls, for any desired sky and ground brightness patterns, as well as for direct sun conditions. Such tables would initially involve fairly extensive experiment for their empirical development. With experience, it may be possible to devise methods of developing the tables from the distribution curves of light leaving the inner surfaces of fenestration and controls. Such tables would simplify the method further.

3. The method, by interpolation and extrapolation, is applicable to an almost infinite number of room sizes and shapes, and window arrangements, and hence should be widely useful in daylighting design.

4. The method can assume any desired initial sky or sun conditions, thus permitting computations for any time of day or year, in any locality, for any orientation, and for any special or unusual conditions under consideration.

5. The method takes into account the exact behavior of interreflections and ground reflections, in spaces such as classrooms, offices, hospitals, small industrial spaces, and similar areas where such reflected light is important.

In short, it is a general method of daylighting design and prediction, which should prove widely useful in the architectural and engineering design of daylighted buildings.

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DISCUSSION

RUSSELL C. PUTNAM*: For the illuminating engineers who deal almost entirely with electric lighting, the complexity and uncertainty of daylighting computations seem rather baffling. A paper such as this is welcomed as a much-needed step toward a simpler approach that might parallel electric lighting computations. It should be read with great interest.

Unfortunately, curves for Fig. 4 and Fig. 5 were interchanged in the paper as preprinted, which made it impossible to check the example given to illustrate the method. This has been corrected in the paper as printed here, but as many engineers prefer to use the convenient preprint form, this error should be noted and the preprint changed.

The advantages of this lumen method of daylighting design as summed up at the end of the paper evidently include future work that may be planned, or information that may be published in later papers. This paper is concerned only with conditions of clear sky, overcast sky or sky of uniform brightness, and gives no data involving the addition of a component from the sun.

As a first paper the possibilities of the lumen method of daylighting design are indicated, and this discussor will look forward with interest to future developments.

DOMINA EBERLE SPENCER**: In many ways this is a good paper. Certainly, daylight calculations that include interflections are needed. The principal fault of the paper is that it is pitched at the level of the Harrison-Anderson lumen method of 1916. In the last 35 years there has been considerable development in the treatment of interflections of light. We have progressed from the expensive, laborious, empirical determination of coefficients of utilization to the comparatively simple theoretical treatment of the interflection method which gives not only quantity of light but also enables us to predict the distribution of light on walls, ceilings, and floors. If Biesele, Arner, and Conover had been working a quarter of a century earlier their strictly empirical approach would be justified. Today we have adequate theoretical means to obtain much more general results than are likely to ever be worked out on an empirical basis.

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The interflection method has been applied with considerable success to artificial lighting[1] and also to some special cases in daylighting.[2] What is needed, is to complete the application of the interflection method to daylighting. For this application the only experimental data needed are a specification of the amount of light incident on wall, ceiling, and floor (without interflections) for typical types of fenestration lighted by overcast and clear skies. Then, by the methods[2] developed already, or a slight generalization thereof, both quantity and quality can be handled in a form similar to the lumen method for all types of daylighting.

There is one detail of the Biesele, Arner, Conover paper that I should especially like to question. Is there any justification for introducing still another room index: the empirically defined window index "W. I."? The specification of room shape, k_r, employed in the interflection method under the name "domance" has already been shown to have both a theoretical and an experimental basis in artificial lighting. And the integral equation formulation of the daylighting problem for very long rooms[2] is also expressed in terms of k_r. Although we do not yet have a proof that the general daylighting problem for rooms of finite length can be expressed in terms of k_r, this appears probable. Would it not be desirable to investigate this question with great care before burdening the illuminating engineer with still another kind of room index?

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WARD HARRISON*: The authors have given us a most ingenious new concept of daylight illumination calculations — so new in fact that it took considerable mental discipline for me to hold clearly in my mind the meaning of "window index" and "illumination coefficient" both at the same time. On the third reading, however, my mental fog seemed to disappear and I want to congratulate Professor Biesele and his associates upon the constructive work that they have carried out. The fact that they have closely paralleled the widely used interior lighting computations should, as they have suggested, make the computations much easier for the illuminating engineer and the architect to follow. Inasmuch as their curves were obtained from some 400 tests covering different room proportions, reflection factors and sky brightness patterns, computations based upon them ought to be sufficiently accurate for all practical purposes.

I think they were wise in deciding to deviate somewhat from the familiar terms — room ratio and coefficient of utilization — possibly, however, the term "window ratio" would show a parallelism more clearly than "window index." Also I would like to ask whether window index is based upon the height above the plane or the height above the floor. Some of those present may recall that the Harrison-Anderson method started out with height above plane as the basis of room ratio but had to revise the figures to use height above the floor because their first and more scientific choice was so widely misapplied in the industry. Again, I think the term "room width" should be clearly defined, as rooms particularly offices in some instances have a greater dimension perpendicular to the windows than with them.

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I have just one question in regard to maximum and minimum illumination. Do the minima for skylight and ground reflections always come at just the same point in the room so that it is necessary to add the low points, or is the actual minimum higher than this total?

H. B. VINCENT*: The need for simplification of calculation procedures is shown very effectively by the dozen or so factors mentioned as influencing daylighting results. As indicated, the problem is complex. However, the authors have been very successful in packing this complexity into a small number of reference charts. Instructions for use are simple and straightforward and it appears that anyone should be able to use them to make daylighting predictions.

I am unable to agree with the authors on the example which they work out. It appears to me that E avg., E min. and E max. should be 77.2, 36.3 and 143.7 footcandles, respectively. I have, however, checked the calculation method against several sets of illumination data for similar rooms and found that in all cases differences between calculated and measured lighting were within ten per cent.

It is noted that in the example cited the ratio of sky brightness to the brightness of a task of 70 per cent reflectance may be as high as about 30 to 1, pointing to the need for extension of the authors' methods to include calculation procedures for light-controlling devices which may be used effectively in the control of brightness contrast. It is hoped that they will favor us in the near future with a paper along these lines.

R. W. MCKINLEY**: These authors have really taken a cut at the ball and will, I suspect, be pursuing it around the park for several innings. I like particularly their idea of presenting daylighting design techniques in forms familiar to electric lighting engineers. Too often, the lighting engineer concerned primarily with electrical systems has acted as if there were an iron curtain over the fenestration wall beyond which his engineering interests did not extend.

When its development is complete, a system of this type should help interest the lighting engineers in evaluating the daylight contribution in an architectural design. Once they have made a daylighting evaluation, I believe the daylighting and electrical systems will be better coordinated and that the visual environments will be improved at no additional cost to any parties involved.

Since this is obviously the first step in a long program, I would like to make several suggestions for the authors' consideration. Perhaps they already have some of these thoughts in mind.

(1) Before publishing a "finished" procedure, I would suggest that they spot check their charts and tables by means of careful survey measurements in full scale rooms with natural terrain, shrubbery, furniture, etc., included to be sure that the "model factor" involved is not of large consequence.

Some of the model tests conducted under the direction of W. W. Caudill at Texas A & M indicated that variations between model and full scale data as large as 50 to 100 per cent were not uncommon. The full scale work on various fenestration systems conducted by Pittsburgh Corning in 1938 included tests of clear glazed windows both unshaded and shaded by blinds and roller shades as well as of various types of glass blocks. These data which were very carefully collected and which are quite familiar to Mr. Conover are immediately available for cross-checking. I refer of course to the paper presented to this Society by Baker and Rapp[1] at the 1941 National Technical Conference. Extensions of their work by the staff of the PC Daylighting Research Center have been published in the form of the PC Daylighting Nomograph in progressively improved arrangements which first appeared in a booklet on daylighting in 1950 and which more recently has been presented in *Engineering News Record,* May 3, 1951.

For example, the data for steel sash reported in Fig. 7 of the Baker-Rapp paper shows that at points 5 and 20 feet from the fenestration wall in a 28 x 28-foot room with ceiling, wall and floor reflectance of 78, 60 and 26 per cent, we would expect to measure 40 footcandles "maximum" and 14 footcandles "minimum" for an average sky brightness of about 532 footlamberts. I believe this average sky brightness would represent conditions comparable to those assumed in the example. In a longer, shallower room with more fenestration as assumed in the example, the Baker-Rapp data indicate that actual measurements would show a 55-footcandle maximum and a 19-footcandle minimum. If we stepped the data up another 10 per cent in line with the high reflectance of ceiling and floor assumed in the example, the values should be about 61 and 21 footcandles. These values based on full scale field measurements have been demonstrated to be reliable yet they do not approach even half the values predicted on the basis of the data collected in models. It is for this reason that I feel that field checks are necessary. If it is essential that the majority of the data for such a system be based on model measurements, though I doubt this need be true, it seems to me it should lean on the side of conservatism as did the original Harrison and Anderson system.

(2) I would like to suggest that the authors extend this approach to include a practical means of brightness prediction. Perhaps they would find the form developed for the *I.E.S. Lighting Handbook* based on the Helios Method of Moon and Spencer a good basis for reference. As reported in our Conference paper in 1951, the model theory correlation for daylighting has already been established by a cooperative research project undertaken by the PC Daylighting Research Center and Brown University.[2]

That this is quite possible at this stage of the game will be evident when you examine the brightness prediction charts which we have included in our PC Daylighting Nomograph. These brightness prediction charts are based on full scale field measurements.

(3) There is a real need in the field for a standard system of daylight analysis, evaluation and design and I would like to propose that the Society assign the chore of evaluating the various suggestions to the appropriate Committee so that as soon as a reliable technique applicable to all types of fenestration is available it can be published and thus be made available for general usage.

1. Rapp, George M., and Baker, A. H.: "Daylight Illumination on Interiors Fenestrated with Glass Blocks," ILLUMINATING ENGINEERING, Vol. XLI, p. 1129 (1946).
2. Spencer, D. E., Stakutis, V. J., Kingsbury, H. F., and McKinley, R. W.: "Glass Block Fenestration and the Interflection Method," (in abstract), ILLUMINATING ENGINEERING, Vol. XLVI, No. 9, p. 445 (September 1951).

H. S. BULL*: The authors are to be commended for this important contribution to the techniques of designing for

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daylighting. From my own work with model rooms I have a keen appreciation of the immense amount of effort that was involved in securing and correlating the data upon which the paper is based.

One question I would raise involves the validity of test data taken at five-foot intervals if the room dimensions approach the lower limit of 10 x 10 mentioned in the paper. I assume the authors have checked this point carefully in their preliminary tests.

The likelihood of large variations in ground reflectance in the critical area near the window wall, along with the relatively short distance from this area to the window plane raises the question as to whether some sort of weighted average reflectance might not be necessary in predicting ground contributions. If so, how would the weighting be accomplished?

I hope that the authors will expand the scope of their studies to include the determination of empirical values of maximum and minimum brightness on the wall as functions of window index and illumination coefficient, so that certain critical brightness ratios might be computed from the design data.

BERNARD F. GREENE*: It is gratifying to note the increased interest and associated research in the field of daylighting. The large number of variables described by the authors no doubt has been responsible for some of this delay.

Everyone concerned with the design of lighting installations has looked forward to a method which can be readily used to obtain values of maximum, minimum and average illumination from daylight.

There are two questions we would like to raise:

(1) Will the method be applicable to multilateral fenestration and to prismatic control materials such as glass block?

(2) Where are the points of maximum and minimum illumination located? It is thought that the maximum illumination within a room would be at the window and equal to the illumination at the window multiplied by the losses due to the window. The value for maximum illumination in the authors' example differs considerably from what we have assumed would be the maximum value.

It would be interesting to see the authors' data checked against actual installations and against values obtained using the interflection tables of Moon and Spencer.

Some time ago, this writer made some preliminary studies to determine a method of daylight calculation. Checks were made against experimental figures based upon the proposition that the illumination varied as a function of the ratio of the window to floor area times the ratio of window height to room depth. We would be interested in learning if this approach checks against the experimental data obtained by the authors.

R. L. BIESELE, JR., W. J. ARNER, and E. W. C*&*158**: The interest in our paper shown by the various discussors has been quite pleasing to us as authors. At the same time, we have been all but staggered by the additional work suggested as desirable extensions of our investigations.

There appear to be no reasons why the method cannot be applied to all types of control devices, and to conditions of sunshine on the windows, as suggested by Professor Putnam and others, provided controls are employed whose interior distribution of light is relatively diffuse when subject to sunlight. This would include designs using prismatic controls, as well as those using louver controls or diffusing devices. It is also probable that a modification of the method could be developed for brightness prediction. That these things can be done, however, does not obviate the fact that they will take considerable doing, both in time and expense.

Dr. Spencer's suggestion that a mathematical approach could be made through the interflection method is welcome. Tentative attempts were made in the early stages of our work to apply the interflection method, but the asymmetry of the daylighting arrangements being considered introduced rather formidable complications. Consequently, we felt we could arrive at a useful technique more rapidly through our empirical approach, leaving the mathematical approach to those whose inclinations ran more in that direction.

This has resulted, as has been indicated in the discussion, in the use of a "Window Index" which may be an unnecessary addition to our list of indices. Our data, however, indicate that the asymmetry of the daylighting design will prevent the adoption of the usual room index or "domance." It can possibly be employed for rooms which are square, or whose long dimension is parallel with the window wall. At present, it does not appear applicable when the longer room dimension is perpendicular to the window wall. In this connection, we have used the term "width" to be that dimension perpendicular to the window wall. It might better have been referred to as the room depth, as has been done by several of the discussors. We have used also the height to the center of the window *as measured from the floor,* to correspond with interior lighting design practice, since we were aware of the confusion to which Dr. Harrison refers in his comments.

Assuming that our data are accurate, and every attempt has been made to make them so, the empirical and mathematical approaches should corroborate each other, unless the assumptions of the mathematical approach differ from the conditions of the empirical one.

The important point about the method, regardless of the procedure used in its development, is whether it checks with tests at full scale. The example in the paper was intentionally chosen to correspond with the test G2-6 of our earlier work, data for which was published in a previous paper by R. L. Biesele, Jr.,** and which is here compared with the example of the paper on a basis of equal total illumination incident on the window.

	Illumination, Ft-c		
	Average	**Maximum**	**Minimum**
Computed Example	74.6	120.9	44.8
Test G2-6 (Full size)	91	124	57

It is seen that the correlation is good, and that the method is on the conservative side. Dr. Vincent's difficulty in following our example is the result of the interchange of Figs. 4 and 5 in the preprint. The discrepancy between our data and the Rapp and Baker data which Mr. McKinley has mentioned is, we believe, the result of the addition of a considerable component of ground light in addition to the light from the sky in our example, which could possibly have caused a discrepancy of this order. We have been unable to check through this completely, however, since the Rapp and

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**"Daylight in Classrooms," ILLUMINATING ENGINEERING, July 1950.

Baker paper does not give a clear relation between the reading of the sphere and photocell, which they use as the basis of their data as presented, and the actual illumination incident on the vertical window.

An arbitrary choice had to be made on location of test points, and intervals representing five-foot intervals at full scale appeared reasonable, for all except 10-foot room dimensions. For these, additional readings were taken at points representing 2½ feet from end or inside walls, and were included in the development of the curves of the paper. No data were taken closer than a point representing 5 feet from the window wall. There might be occasion to quibble over this decision, but this is the basis on which the data are presented, and we believe it to be reasonable.

The maximum value of illumination, in all cases including ground reflections, occurred at the point nearest the center of the window. The minimum value of illumination in all but a few cases involving high wall reflectances occurred at the test point nearest the front or rear of the inside wall. It is believed, however, that the method can be applied to multilateral designs by the addition of the data computed for the individual windows, provided the small error occasioned by adding a maximum occurring near the center of a window to a minimum occuring near its end, from a second window, is recognized. With normal reflection factors, it is believed that this error will be small, possibly under 10 per cent.

Professor Bull indicates one of the difficulties in dealing with the ground reflections, namely the shading of the ground area near the building by the building itself. This condition will have to be weighted judiciously by the designer.

Mr. Greene asks a question which emphasizes a point of considerable interest in our data, whether the daylight illumination varies "as a function of the ratio of window area to floor area times the ratio of window height to room depth." Our data indicate, however, and Rapp and Baker mention that theirs does also, that for the higher room surface reflectances coming into common use in schools and offices, the room illumination is directly proportional to window area, and independent of height of window above the floor, for most normal room configurations.

Lighting a Large Area Drafting Office

High-level illumination for a very large area with unusually high ceilings (18 feet) has been achieved by the continuous row technique shown, at the Airesearch Inc. drafting offices, Los Angeles, Calif. The engineering drafting office measures 125 x 220 ft. Four-lamp louvered luminaires, containing 96T12 lamps operating on 430 ma, provide 100 footcandles average maintained illumination. The luminaires are arranged in 13 rows of 27 units and 3 rows of 25 units making a total of 426. The rows are 8 ft on centers. Photo and data submitted by Illuminating Engineering Unit, Department of Water and Power, Los Angeles, Calif.