Glare Ratings

By WARD HARRISON

UP TO the present time, most discussions of glare have, of necessity, taken the form of general statements. It has often been emphasized by the writer that what we need in illuminating engineering is something much more specific, in fact, some simple way of arriving at a discomfort glare evaluation or "glare factor", for any lighting installation; preferably a method as simple as our ordinary methods of lighting calculation. You can visualize how fortunate we would be if, in submitting a design for office lighting, we could state that the installation would be "capable of supplying a maintained illumination of 40 footcandles and that its glare factor would not exceed 10, a figure safely below the accepted limit for office areas." Such a method of rating the discomfort factor in direct glare is about to be proposed to you; whether this proposal, or some modification of it, will stand all the tests to which it may be properly subjected, time alone will tell. Should such a method prove reliable, it does have the advantage of making it simple to compute and to compare on a common rating basis two or more dissimilar systems of lighting.

This proposal, like others, must be based upon certain assumptions; the first is that the user of a lighting system will, in practice, judge its comfort largely by his impression of glare or the lack of glare when his line of sight is substantially horizontal; he will not be satisfied with a system which is free from discomfort only when he keeps his head bent over his work. Also, the adoption of a unit of discomfort glare is assumed, and the unit which is proposed is the glare resulting from a source of:

1 square inch of surface, of
1000 footlamberts brightness, at
10 feet from the eye, and at an angle of
10° above the line of vision, with a
10 footlambert surrounding brightness.

It is well known that the sensation of glare increases with the area of source and in this proposal *all of the principal factors in glare are evaluated in terms of equivalent size of source.* The glare source described above is arbitrarily given a glare rating of one. All other light sources will have a glare rating greater or less than one depending upon whether their area is larger or whether they are brighter, or nearer to the observer, or at a lesser angle

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to his line of vision or whether the environment in which they are seen is darker or lighter. The glare factor for a complete lighting installation will be the sum of the glare factors of the light sources of which it is comprised. For example, a glare rating of 125 for a lighting installation would indicate simply that the installation, *taken as a whole*, is equivalent from the glare standpoint to a source of

125 square inches of surface of
1000 footlamberts brightness, at
10 feet from the eye and at an angle of
10° above the line of vision with a
10 footlambert surrounding brightness.

The various factors which affect the glare rating will now be considered separately.

The Five Factors

1. *Area*—If the area of our standard light source is increased from unity to two square inches, other factors being held constant, the glare rating will be stated as two. If the dimensions are increased to 4 inches on a side (sixteen square inches), its glare rating becomes 16. If the four-inch square is tipped away from the observer so that it is foreshortened to half its height, the apparent area becomes only eight square inches and consequently its glare rating will be eight.

2. *Brightness*—It is well known that, other things being equal, an increase in light source brightness results in increased glare. If we were interested only in the veiling effect of glare, that is, in the increased difficulty of distinguishing objects when a glaring source is placed in the field of vision, we would have ample data to support the conclusion that increasing the average brightness of a source in the ratio of two to one is no worse than increasing its area in the same ratio; in other words, total candlepower toward the eye is all that is important. However, when it is discomfort with which we are concerned, this relation no longer holds; we all know from experience that doubling the average brightness of a source is, from the discomfort standpoint, more serious than doubling its area. How much more serious? Unfortunately, there is not too much definite information on this point. Limited investigations have been reported[1,2] and they do not check too closely between themselves, due perhaps to the different criteria employed. Also, since observers are human beings, it is possible that glare affects them so differently and that there will never be complete agree-

[1] Harrison, Ward—*I. E. S. Transactions*, 1920: page 34.
[2] Holladay, L. L.—*Journal of the Optical Society of America*, 1926, page 271.

ment on such evaluations. However, for the purpose of this discussion, some quantitative relationship between the effect of brightness and area must be assumed, and the writer is simply going to offer what appears to him to be a reasonably probable relationship, namely, that doubling the brightness of a source is as serious from the discomfort standpoint as increasing its area four times. Or to state it another way, a glare rating in the proposed system will be increased as the square of the average brightness of the light source. For example, if we increase the brightness of our one-square inch source to 3000 footlamberts—the glare rating will then become

$$\left(\frac{3000}{1000}\right)^2 = \left(\frac{3}{1}\right)^2 = 9$$

We mean by this that it is just as glaring as a source of 9 square inches having the standard 1000 footlamberts brightness.

3. *Distance*—Of course when we talk about area of the light source, we really refer to the solid angle which it subtends at the eye rather than its actual size, independent of its distance from the eye. For example, when viewed with one eye only, a 16-inch globe at 20 feet cannot be differentiated from an eight-inch globe at ten feet. It follows therefore that if the size of the glare source is held constant, its glare rating will decrease inversely as the square of its distance from the eye. If the source of 3000 footlamberts which received a glare rating of nine had been 20 feet from the eye instead of ten, its rating would become

$$9 \times \left(\frac{10}{20}\right)^2 = 2.25$$

We mean by this that it would be just as glaring as a source of 2.25 square inches at the standard 1000 footlamberts brightness at the standard distance of ten feet.

4. *Angle*—It has been shown by the work of Holladay[2] that the veiling effect of glare from a source decreases rapidly as it is removed farther and farther from the line of vision; his data show that the veiling effect varies inversely as the square of the angle between the source and line of vision. It seems probable that the effect on comfort is at least as severe and for the time being we shall assume that it is just equally severe.

In our example, therefore, if the 3000 footlamberts one-square inch source, placed at a distance of 20 feet had been removed only five degrees from the line of vision, its rating would then have become

$$2.25 \times \left(\frac{10^\circ}{5^\circ}\right)^2 = 9$$

If you sketch this out, you will see that this is about what occurs when a light source is moved farther away from the eye without changing the height of the eye or the height of the glare source. In other words, the figures indicate that a source of this type is equally glaring whether it is at ten feet or 20 feet from the observer so long as heights remain fixed. The effect of increased distance is almost exactly balanced by the narrower angle to the line of vision. We know that this is true in the case of veiling glare.

It will be observed that in any equation which involves a simple function of angle whether it be the square, the first power or the square root, the glare factor becomes infinity whenever the angle to the line of sight becomes zero. From a strict mathematical standpoint, therefore, our formula should be modified by the introduction of a constant so that, under no ordinary circumstances, can an infinite glare rating be obtained. On the other hand, for overhead lighting installations, at a fixed height above eye level, the angle becomes zero only when the distance to the lighting unit becomes infinity, a situation which takes care of itself.

5. *Surroundings*—There is one more factor to be evaluated and that is the brightness level of the surroundings; this includes not only the brightness of one's visual task but also the brightness of the general background, including the walls and ceiling against which the light sources are seen. We well know from experience that when the general brightness level goes up we can tolerate brighter and/or larger areas of light source. The work of Nutting[3] and of Holladay[2] has shown that increasing the brightness of surroundings ten times permits doubling the brightness of the glare source, and we assumed in Item 2 that doubling the brightness of the source is equal from the glare standpoint to increasing the source size four times. If this is true, it follows that increasing the general brightness level ten times permits increasing the source size four times without increasing its glare rating. In other words, if, by supplying more light, we increase the level of brightness from ten footlamberts, our base, to 100 footlamberts, the glare rating of any one light source in the new environment will be decreased to one-quarter of its previous rating. This may be stated mathematically, by saying that, other things being equal, the glare varies inversely as the relative brightness of surroundings raised to the 0.6 power. (In many cases, it should be sufficiently accurate to call it the 0.5 power, especially as square roots are much easier to calculate on a slide rule.) A table of the most-likely-to-be-used values based on 0.6 is included at this point. The second column in the table is headed *Footlambert Factor*, meaning the effect on the glare rating of changes in the footlambert level of the surroundings.

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[3] Nutting, J. Gordon—*I. E. S. Transactions*, 1916, pp. 939–46.

TABLE I

Weighted Brightness of Visual Task and Surroundings	Footlambert Factor
1 Footlambert	0.25
2 "	0.40
3 "	0.50
5 "	0.66
10 " (base)	1.00
20 "	1.5
30 "	2.0
50 "	2.6
75 "	3.3
100 "	4.0

It will be noted that the change in glare rating is less rapid than the change in footlamberts. For example, if we have a source whose glare rating in a ten-footlambert surrounding is nine, in a 30-footlambert surrounding it becomes

$$9 \times \frac{1}{2.0} = 4.5$$

and in a two-footlambert surrounding, it would be 22.5.

We are now ready for a formula which will bring together all these five factors, we may say that:

$$\text{Discomfort Glare Varies as } \frac{\text{Area} \times \text{Brightness}^2}{\text{Distance}^2 \times \text{Angle}^2 \times \text{Surrounding Brightness}^{0.6}}$$

(*Formula No. 1*)

or stating it mathematically if

A is the apparent area of the source in square inches
B is the brightness of the source in footlamberts divided by 1000
D is distance in feet from the source to the eye divided by 10
$\angle$ is the angle in degrees above the horizontal divided by 10
S is the surrounding brightness in footlamberts divided by 10
F is the footlambert factor
Cp is the candlepower in the direction of the eye

$$\text{The Numerical Glare Factor} = \frac{A \times B^2}{D^2 \times \angle^2 \times S^{0.6}} \quad \text{(Formula No. 2)}$$

$$= \frac{A \times B^2}{D^2 \times \angle^2 \times F} \quad \text{(Formula No. 3)}$$

It will be noted that the terms in the numerator have to do with the light source and the terms in the denominator with its environment. It often saves time to handle them separately when comparing different sources or the same sources in different locations.[4]

Instead of expressing the brightness of a light source in footlamberts, it is also possible to express it in terms of candlepower divided by area (and multiplied by 452 for footlamberts). If this is done, after simplification, the same formula may be rewritten in a form which is more convenient when the candlepower of a source is known but not its brightness.

$$\text{Glare Factor} = \frac{(Cp)^2}{5A \times D^2 \times \angle^2 \times F} \qquad \textit{(Formula No. 4)}$$

In using these formulae, it must be kept in mind that the exponents proposed are tentative only, and very much subject to revision, because they contain certain assumptions as to the relation between source brightness and source area and also between source area and surrounding brightness, which may need considerable modification with more complete knowledge. It follows that great precision should not be attributed to numerical ratings thus derived.

Examples

Example 1—Take a 16-inch spherical globe containing a 500-watt incandescent lamp, globe absorption 20 per cent; let us place this globe $5\frac{1}{2}$ feet above the eye level and 15 feet ahead of it (diagonal distance to eye 16 feet) with eight to ten footcandles horizontal illumination which, in a room with light finish, may result in a brightness level of approximately five footlamberts.

Solution—A 500-watt lamp emits 10,000 lumens so that the lamp in a globe with 20 per cent absorption will emit 8000 lumens, or 635 spherical candlepower. The globe center is at an angle of approximately 20 degrees above the line of vision.

$$\frac{635^2}{5 \times 64\pi \times \left(\frac{16}{10}\right)^2 \times \left(\frac{20}{10}\right)^2 \times 0.66} = \frac{635 \times 635}{5 \times 64\pi \times 2.56 \times 4 \times 0.66} = 59$$

If the calculation is repeated for the same source at the same height but removed to a point 35 feet ahead of the eye, none of the figures are changed except the square of the distance (35 feet) and the square of the angle (9°). In other words, for $\left(\frac{16}{10}\right)^2 \times \left(\frac{20}{10}\right)^2 = \left(\frac{3.2}{1}\right)^2$ in the denominator we substitute $\left(\frac{35.2}{10}\right)^2 \times \left(\frac{9}{10}\right)^2 = \left(\frac{3.18}{1}\right)^2$ or almost the same thing. In other words, the glare factor is practically unchanged whether the unit is 35 feet ahead of the eye or only 15 feet ahead of it.

Now suppose we have an area 20 x 40 with an 11-foot ceiling (Fig. 1) which we wish to light with these enclosing globes placed on 10-foot centers and $1\frac{1}{2}$ feet from the ceiling ($5\frac{1}{2}$ feet above a four-foot eye level).

[4] For $D^2 \times \angle^2$ in the above equation, it is possible with reasonable accuracy to substitute the expression $(0.6H)^2$ where H is the height in feet of the light source above the eye level. This change shortens calculations but will not be used in this paper because the author desires to show separately the effect of each of the five factors in glare.

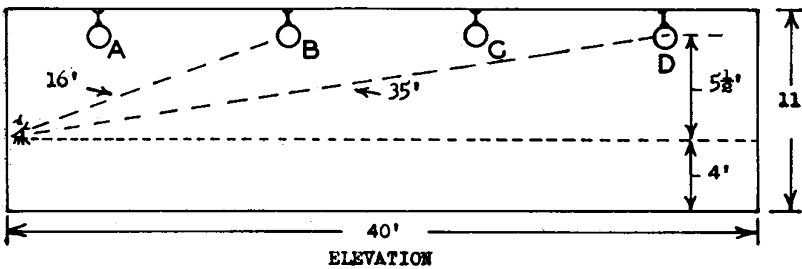

FIG. 1

If we assume that the observer is at the extreme end of the room, the units at *A* are substantially outside his field of vision but the pairs of units at *B* and at *C* and at *D* are all clearly visible. We have already made a calculation for units as at *B* and *D* arriving at practically the same rating for each and it will be about the same for *B* also. The glare factor for this room might therefore seem to be

$$59 \times 6 = 354.$$

But wait, the eight lighting units in this room will produce nearly twice as much light as the eight to ten footcandles for the condition initially assumed, and the footlambert factor which there appeared as .66 becomes 1.0, so that the glare rating of each unit is now 39 instead of 59, and the rating for the complete system as viewed from one end of the room

$$39 \times 6 = 234.$$

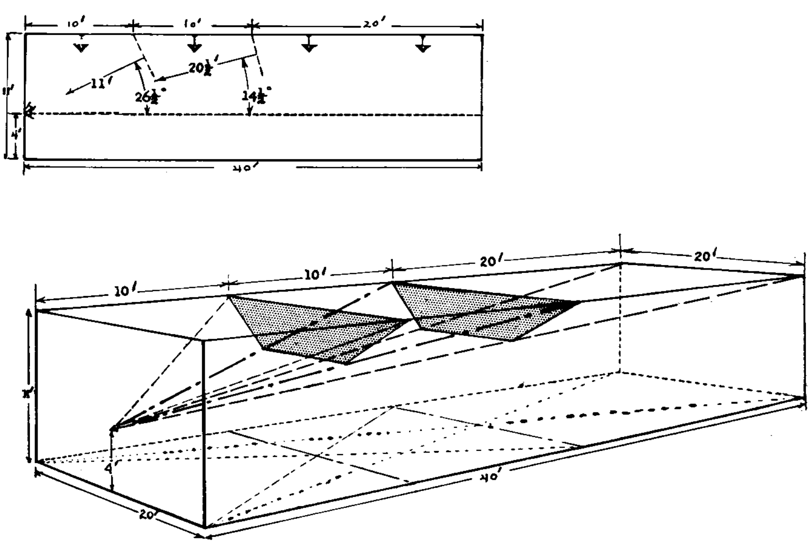

FIG. 2

This means that the installation is equivalent from the glare standpoint to a source 234 times the size of our standard unit of glare, that is, it is equivalent to a source of 234 square inches, having a brightness of 1000 footlamberts, placed ten feet from the eye and 10 degrees above the line of vision when the surroundings are at a ten-footlambert level. A "glare factor" of 234 means just this and nothing more.

Suppose that instead of being 40 feet long, the room under discussion were 80 feet long. In this case, there would be seven pairs of light sources in view instead of three. The "glare factor" would be 39 × 14 or 546.

Example 2—The glare rating calculations for an indirect lighting system (Fig. 2) in the same room may appear more formidable but are really quite easy. First, we find by calculation that we must put an average of about 70 lumens per square foot on the ceiling initially to obtain 20 footcandles in the room (maintained value). It is assumed that this will result in a general brightness level of ten footlamberts.

$$70 \times 0.75 \text{ reflection factor} = 55 \text{ footlamberts (ceiling brightness).}$$

Suppose we consider the distant half of the ceiling first. It is foreshortened so that it takes the apparent form of a trapezoid very nearly $3\frac{1}{2}$ feet high; top 20 feet, and base 10 feet. It is seen at a distance of 21 feet and an angle to the center of $14\frac{1}{2}°$. Hence, using Formula No. 3

$$\frac{3\frac{1}{2} \times 15 \times 144 \times \left(\frac{55}{1000}\right)^2}{\left(\frac{21}{10}\right)^2 \quad \left(\frac{14\frac{1}{2}}{10}\right)^2} = 2.4.$$

Also for the section between ten and 20 feet, we find a trapezoid of the same size and the same height above eye level only at a different distance and angle so that the figures are again substantially the same and the glare rating for the whole 40 foot room becomes

$$2.4 + 2.4 = 4.8 \text{ (glare factor)}$$

Again, if the room were 80 feet long, the glare figure for the area between 40 and 80 feet would be almost exactly 2.4 and likewise for the whole installation

$$2.4 + 2.4 + 2.4 = 7.2 \text{ (glare factor).}$$

If we go one step further and plan on a 100 footcandle indirect lighting installation for this room, then the ceiling will have a brightness of 275 footlamberts or 5 times greater than before. The effect of this change will be to increase the glare rating by 5^2 or 25 times. But simultaneously, the surroundings will have their brightness increased five times which will require the glare rating to be divided by 2.6 so that the rating for the 40-foot room illuminated to 100 footcandles becomes

$$\frac{4.8 \times 5^2}{2.6} = 46. \text{ (glare factor)}$$

or nearly ten times that of the first system. This is in line with what we well know of the vast difference in comfort between 20 and 100 footcandle installations of indirect lighting.

Example 3—Interest has been expressed in the glare rating of an installation of bare fluorescent lamps. Let us assume that 27 or 28 lamps of the 40-watt size are required to produce 20 footcandles (ten footlamberts) in the room previously considered. If the lamps are placed crosswise, seven rows of four lamps each would be used (Fig. 3). When placed lengthwise, there would be three rows of 9 lamps each as in Fig. 4. It is assumed that these lamps will be placed about six inches from the ceiling, that is, $6\frac{1}{2}$ feet above eye level.

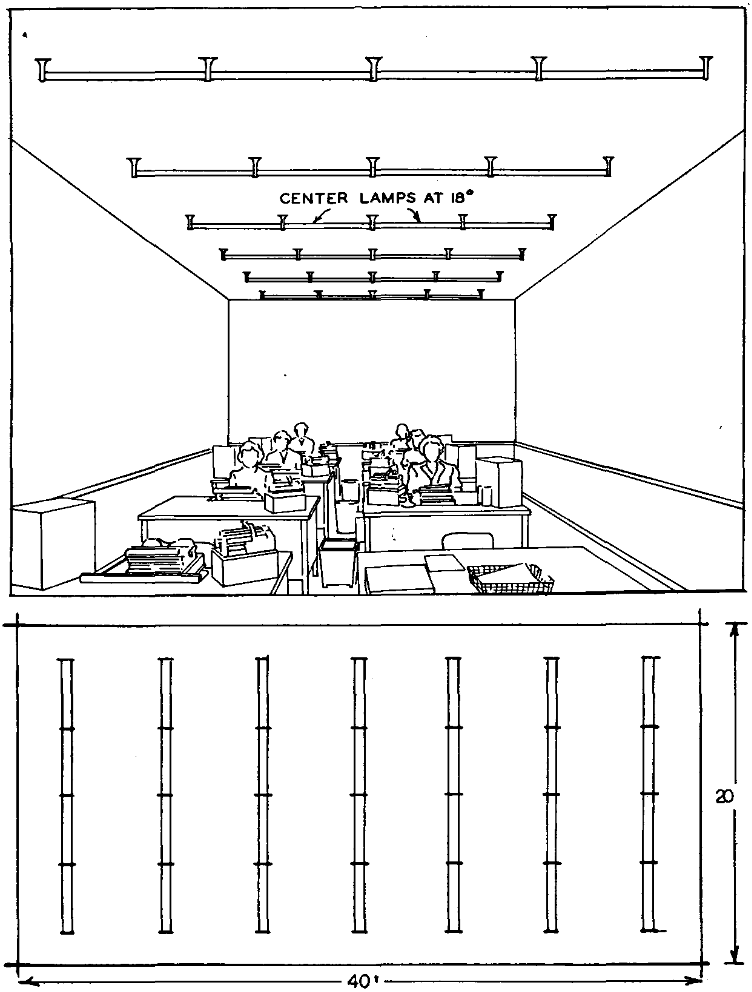

FIG. 3

A. For a lamp located at the center of the room and placed crosswise, using formula No. 4, the glare factor will depend upon (a) the candlepower of the lamp (230 cp) and (b) its luminous area $1\frac{1}{2} \times 46 = 69$ square inches, and (c) the distance to the eye, 21 feet and (d) the angle above the line of vision 18 degrees.

$$\frac{230 \times 230}{5 \times 69 \times \left(\frac{21}{10}\right)^2 \times \left(\frac{18}{10}\right)^2} = 10.6$$

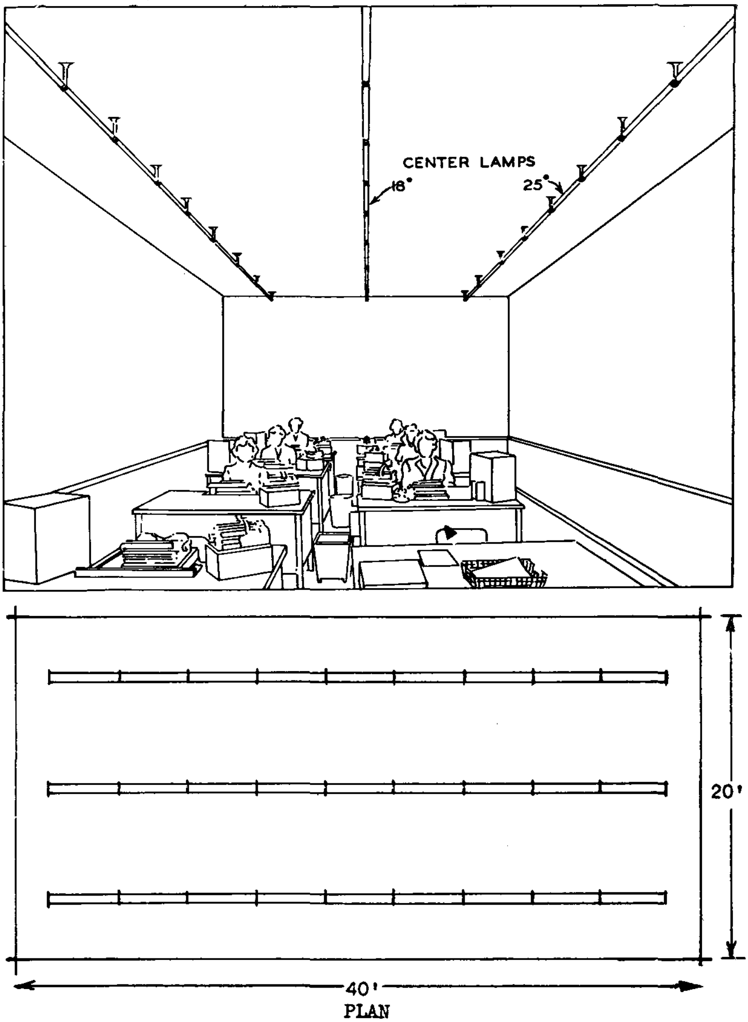

FIG. 4

Since from the end of the room 24 of the lamps will probably be within the field of vision, the glare factor for the entire area becomes

$$10.6 \times 24 = 254 \text{ (glare factor)}$$

which is a figure a little higher than for the opal globes in the same room.

RELATIVE CANDLEPOWER OF A FLUORESCENT LAMP AT VARIOUS ANGLES

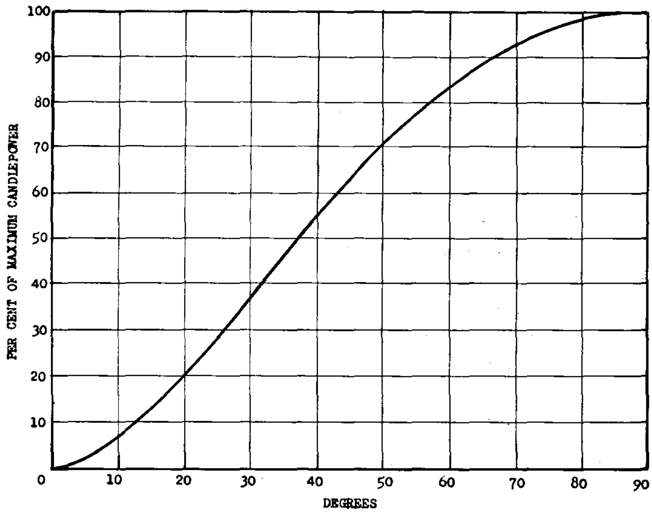

FIG. 5

If the room were 20 feet long (and we assume that only two rows of lamps are in the field of view) the answer would be approximately:

$$10.6 \times 8 = 85 \text{ (glare factor)}$$

or if they were 80 feet long with 14 rows:

$$10.6 \times 52 = 550 \text{ (glare factor)}$$

B. If the lamps were run lengthwise of the room, the result would be quite different. From Fig. 5 which is a distribution curve, typical of all fluorescent lamps, it is seen that the candlepower of the lamps at 18 degrees is 17 per cent of the candlepower at 90 degrees. Also at $6\frac{1}{2}$ feet above the eye and 20 feet beyond it, the apparent area[5] is $\frac{6\frac{1}{2} \times 69}{20} = 22.4$ square inches. The equation for the center lamp therefore becomes:

$$\frac{(0.17 \times 230)^2}{5 \times 22.4 \times (2.1)^2 \times (1.8)^2} = 0.93$$

Caution: This value applies not to all the lamps in the room but only to the lamp at 20 feet because all of the others have different cnadlepower values in the direction of the eye and also they are foreshortened by different amounts. The glare values for lamps in other positions in the center row must each be calculated and are shown in Column A of Table II.

The total of 6.70 for Column A gives the glare rating for the middle row of lamps directly ahead of the observer. In the case of either of the outside rows, the angle between the axis of a lamp

[5] In calculating approximate foreshortening, the diagonal distance to the lamp has been assumed to be the same as the horizontal distance.

TABLE II

Lamp Position		Column A	Column B
36 ft—$10\frac{1}{4}°$	$\frac{(0.07 \times 230)^2}{5 \times 12.5} \times \frac{1}{(2.1)^2 \times (1.8)^2} =$	0.28	0.73
32 ft—$11\frac{1}{2}°$	$\frac{(0.08 \times 230)^2}{5 \times 14} \times \frac{1}{14.4} =$	0.34	0.83
28 ft—13°	$\frac{(0.10 \times 230)^2}{5 \times 16} \times \frac{1}{14.4} =$	0.45	1.02
24 ft—15°	$\frac{(0.13 \times 230)^2}{5 \times 18.8} \times \frac{1}{14.4} =$	0.65	1.40
20 ft—18°	$\frac{(0.17 \times 230)^2}{5 \times 22.4} \times \frac{1}{14.4} =$	0.93	1.90
16 ft—22°	$\frac{(0.24 \times 230)^2}{5 \times 28} \times \frac{1}{14.4} =$	1.50	2.47
12 ft—$28\frac{1}{2}°$	$\frac{(0.35 \times 230)^2}{5 \times 35} \times \frac{1}{14.4} =$	2.55	3.17
Total...		6.70	11.50

located at 20 feet, and a line from the lamp center to the eye is 25 degrees instead of 18 degrees, hence the candlepower toward the eye is 0.29 of 90° and the foreshortening is also reduced. Hence

$$\frac{(0.29 \times 230)}{5 \times 32} \times \frac{1}{14.4} = 1.9$$

It will be observed that the fraction $\frac{1}{14.4}$ is again used in this calculation. That is because the eye seems to rove very easily, in fact, involuntarily through a considerable angle in the horizontal plane and ocular discomfort is not very greatly reduced by sideways displacement of the glare source. This conclusion is borne out by the findings of several groups of engineers who have, by observation, verified the fact that in an actual installation of bare fluorescent lamps, each of the rows to the right and left of the observer are the cause of more discomfort than is the row directly ahead.

The values for lamps in other positions in the outside rows have been calculated similarly and are given in Column B of Table II. It will be noted that the glare rating for the sum of the lamps in each outside row is nearly double that for the center row. The rating for the entire room viewed lengthwise becomes

$$6.7 + 11.5 + 11.5 = 29.7 \text{ (glare factor)}$$

This figure would not increase very much if the room were 80 feet long or even 160 feet long, the reason being that both the candlepower and brightness of fluorescent lamps fall off very rapidly at angles near the horizontal.

If the same room were viewed crosswise from a central point along the side, two rows of units would be in the field of vision but perhaps only five lamps in the far row and three in the middle

TABLE III

	20 Footcandles			100 Footcandles		
Room Length	20 ft	40 ft	80 ft	20 ft	40 ft	80 ft
16″ Globes (Ex. 1)	78	234	546	148	444	1040
Indirect (Ex. 2)	2.4	4.8	7.2	23	46	69
Crosswise F (Ex. 3-A)	85	254	550	162	480	1050
Endwise F (Ex. 3-B)*	20	30	35	38	57	66
Endwise F (Ex. 3-B)*	80	85	85	152	150	160

*Line 5—Occupants facing in any direction.
Line 4—Occupants facing lengthwise of room only.

row would be central enough to be objectionable. On this assumption, the glare rating would be

$$10.6 \times (5 + 3) = 85 \text{ (glare factor)}$$

This is probably a truer appraisal for a 20 x 40 room with the lamps lengthwise than the rating of 29.7 unless it is certain that no one will be seated crosswise of the room.

Where enclosing globes or bare fluorescent lamps are used, the simplest way to increase the footcandle level is to add more units of the same brightness; example, for 100 footcandles, using 40-watt lamps, 140 would be required instead of 28. The glare rating would be multiplied by five on this account but would then be divided by 2.6 of this value because of the higher brightness level attained. In other words, it would be $5 \times \frac{1}{2.6} = 1.9$ times the rating at 20 footcandles. The rise in glare rating is less rapid than with indirect lighting. On the other hand, this example illustrates very clearly the well known fact that adding more sources in the field of vision very definitely increases the glare in spite of the fact that contrasts are decreased.

Summary

One may obtain the impression that this method of glare rating involves a considerable amount of laborious calculation such, for example, as that followed to evaluate the system of fluorescent lamps viewed endwise (Example 3B). It is the author's opinion, however, that if the rating plan fulfills a real need, much of the calculation will be done, at the time the distribution curves are made for a luminaire, just as flux values are customarily furnished for the various zones included in the distribution curve; also when the data are available for one lighting installation using a given luminaire, the values for other installations can usually be derived quite readily.

Table III summarizes the calculations for various luminaires, room lengths and footcandle levels, as worked out in Examples 1 to 3.

Fig. 6 shows that the glare factor for enclosing globes and also for bare fluorescent lamps crosswise increases directly with the length of the room whereas, the glare factor for indirect installations increases more slowly and

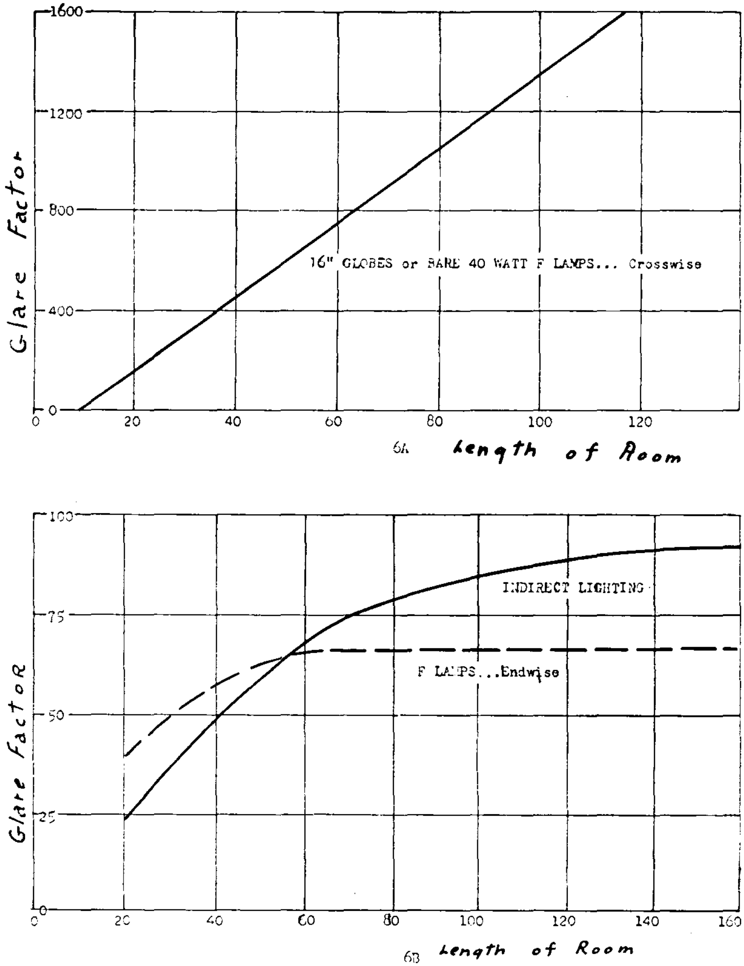

FIG. 6—Effect of room length on Glare Factor (at 100 footcandles).

for fluorescent lamps lengthwise there is practically no increase with room lengths beyond 60 feet.

The writer's experience would indicate that glare factors below 15 or thereabouts are probably satisfactory for complete installations in offices, drafting rooms and schools, that is, in locations where people are seated facing in one direction for long periods of time. For the majority of stores and similar establishments, very much higher values would, of course, be permissible.

It should be stressed again that a light source with a glare factor of 100 is not 100 times as glaring as one with a glare factor of one. It is simply equivalent to the latter source, increased 100 times in area; however, any source with a glare rating of 100 should be found more discomforting than any source with a lower rating such as 70. It would perhaps give a better picture of the relative discomfort caused by two sources if both their ratings were plotted to a logarithmic scale rather than to express them arithmetically. On the other hand, it would be easy to arrange these refinements later on if desired, and the present situation is really no different from that we are entirely accustomed to in the case of footcandles. Everyone knows that we do not see 100 times as well at 1000 footcandles as we do at ten footcandles. Perhaps high numerical ratings will cause people to avoid glaring light sources.

There are several other general criticisms and questions which may be raised regarding the glare rating proposals in this paper, in addition to those relating to proper values of exponents as already discussed. For example, it may be asked, what provision there is for penalizing a lighting system which employs glassware of uneven brightness or an indirect system in which the ceiling is not uniformly illuminated. So far, no simple method seems available for properly evaluating such brightness differences. On the other hand, it is also true that unless the departure from uniformity is extreme, it is questionable whether it has much effect comfortwise; a globe which is somewhat brighter at the center has the merit that it is less bright at the periphery and therefore makes a less severe contrast there with its background.

Another question which might be raised is with regard to the footlambert factor to be used in cases where the lower part of a room is well illuminated but the light sources themselves are viewed against a practically black ceiling, a situation not infrequently encountered in factories. Again, no definite answer can be made now, but it does seem probable that experience will in time indicate whether under such conditions the average overall surrounding brightness should be considered as three-quarters or half or a quarter of working plane value to compensate for the bad contrasts.

Finally, it should be repeated that the exponents used in the formulae in this paper are tentative and very much subject to revision although the results they yield do check quite well with the author's experience. In his opinion, the important point to be established is whether the entire idea of a mathematical glare rating is sound; criticism of the particular method outlined here is also solicited. Most of all, it would be of value if additional quantitative measurements of glare were undertaken in the laboratory to establish the proper exponents, and also if individual members of the Society would record their carefully considered visual appraisals of a number of different lighting installations now in actual use and then determine whether or not glare factors arrived at by calculation would rate these installations in the same order of merit.

DISCUSSION

J. F. Parsons:* The author's concept of a discomfort glare rating for lighting installations, based on a glare unit which is readily visualized and easily reproduced, is a useful one which should find wide acceptance in the fields of design and application, once the numerical values of the various exponents have been authoritatively determined.

It is interesting to note that a similar glare rating system using, with one exception, the same factors is implicit though perhaps not readily apparent in Holladay's formula as restated by Crouch and Fowler.

The original statement[1] of the formula is

$$K = \log B + .25 \log Q - .3 \log F$$

The restatement[2] is $B = \dfrac{C F^{.3}}{Q^{.25}}$, with B and F in footlamberts, Q in steradians and C the numerical glare rating factor defining the degree of comfort or discomfort.

This may be further transformed so that Q is replaced by $\dfrac{A}{D^2}$ (a very close approximation for small angles) and A appears in the first power to conform with the author's glare unit as follows:

Substituting $\dfrac{A^{.25}}{D^{.5}}$ for $Q^{.25}$ and transposing,

$$\frac{BA^{.25}}{D^{.5} F^{.3}} = C$$

bringing A to the first power,

$$\frac{B^4 A}{D^2 F^{1.2}} = \text{a measure of glare for any condition.}$$

It now becomes apparent that the author has assigned exponents to the various factors which are in two cases at marked variance with Holladay's formula and a question naturally arises concerning the propriety of making such changes without further qualitative (1) refutation of Holladay's exponents, (2) justification of the author's. The differences between the two formulae are brought out by the following table:

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	Origin of Formula	
	Holladay	Harrison
Doubling the brightness increases the glare factor	16 times	4 times
Doubling the area increases the glare factor	2 times	2 times
Doubling the distance reduces the glare factor to	$\frac{1}{4}$	$\frac{1}{4}$
Increasing the surround brightness 10 times reduces the glare factor to	$\frac{1}{16}$	$\frac{1}{4}$
Doubling the angle between the glare source and the line of sight reduces the (discomfort) glare factor to	No relation established	$\frac{1}{4}$

The choice of a glare unit at an angle of 10 degrees with the line of sight and the variation of the glare factor with the inverse square of the angle causes the glare rating to increase at a tremendous rate as the angle approaches 0 and results in the anomoly that almost any brightness of any area in any surround becomes intolerable when approaching the line of sight, a statement which has little relation to reality. Holladay's researches did not cover the effect on discomfort glare of the angle of the glare source with the line of sight. The inverse square relation as stated by the author is not in agreement with the findings of the Society's Committee on Standards of Quality and Quantity for Interior Illumination which states[3] that the effect of the angle on discomfort glare is inversely as the .49 power. This disagreement requires justification.

The author's suggestion that research should be instigated to authoritatively determine the proper exponents for the various factors should be followed if the glare rating formula is to gain acceptance or be of practical use.

References

1. Holladay, L. L., *Journal of the Optical Society of America*, 1926, p. 271.
2. Crouch, C. L. and Fowler, E. W., ILLUMINATING ENGINEERING, XXXVI–9, p. 897.
3. Report No. 1 of Committee on Standards of Quality and Quantity for Interior Illumination, ILLUMINATING ENGINEERING, XXXIX–10, p. 713.

PARRY MOON:* Holladay's empirical equation for "discomfort glare," with its inexplicable exponents, seems to have a peculiar fascination for illuminating engineers. In the *I. E. S. Transactions* and in ILLUMINATING ENGINEERING one finds again and again attempts to manipulate this equation and to apply it to regions in which it cannot possibly be valid.

* Massachusetts Institute of Technology, Cambridge, Mass.

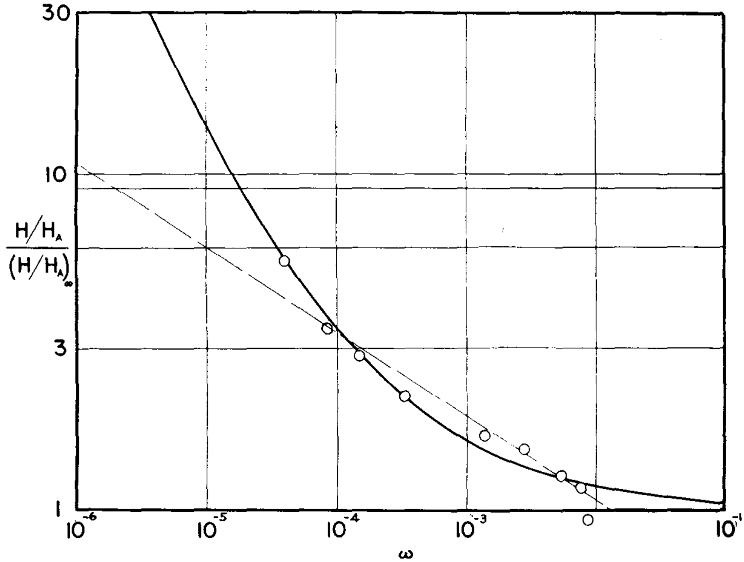

Fig. 1—Effect of size of glare source. The scale along the bottom represents the solid angle (steradian) subtended by the source. The scale on the left gives the allowable helios ratio (H/H_A) expressed as a fraction of the helios ratio for a very large source. ○, experimental points of Holladay; – –, calculated by Holladay formula; —, calculated by photochemical theory.

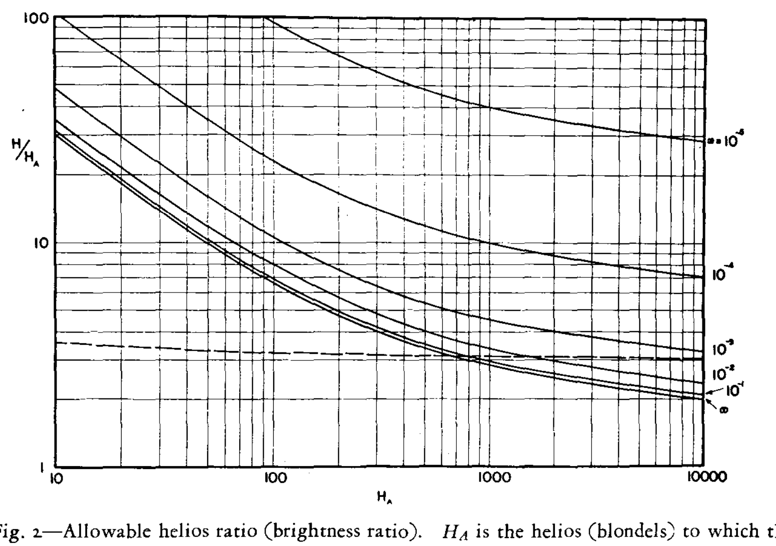

Fig. 2—Allowable helios ratio (brightness ratio). H_A is the helios (blondels) to which the eye is adapted. To convert to brightness in "footlamberts", divide the values on the scale by 10.76. H is the helios of the glare source subtending an angle of ω steradians. —, based on "discomfort glare", – –, based on "disability glare".

The latest application of Holladay's formula is made by Ward Harrison. I agree heartily with the aim of his paper and realize that the intangible nature of glare makes high precision impossible. Nevertheless, I wonder if a better formulation is not possible, even without additional experimental data.

The Holladay formula, considered as a general equation, is an absurdity, as anyone can convince himself after a few moments thought. As pointed out previously[1], the formula applies only over a small range of the variables and does not even fit the experimental data very well in this limited range. Extrapolated with respect to either adapting helios (brightness) or size of glare source, the formula gives results that everyday experience shows to be false.

With respect to helios, the Holladay formula predicts (for boundary between "pleasant and unpleasant") that even when the entire visual field is perfectly uniform, no tolerable condition exists above a helios of 14,000 blondels (B = 1400 ml). But everyone adapts himself to this helios outdoors on an overcast day and is quite comfortable.

With respect to the size of glare source, the experimental results extend to a maximum of only 0.01 steradian, corresponding to a luminous disk of radius 6.7 inches at a distance of 10 feet. Thus the experimental results have little bearing on modern lighting with large luminous areas. It is well known that for very small sources, the allowable brightness for a given visual effect varies inversely as the *first* power of the solid angle, not as the 0.25 power as given by Holladay. Also, common sense indicates that an increase in the size of a large glare source, say from 10 degrees to 20 degrees, has very little effect on glare. In fact, the experiments of Steinhardt[2] and others have shown that (for foveal fixation, which is the only condition employed in the Holladay "discomfort glare" tests) any increase beyond the foveal angle (1.5 degrees) has little effect. Therefore, the Holladay formula cannot be even an approximation for very small or for very large sources. A better equation, which satisfies both conditions at limiting areas and which fits Holladay's data is[1]

$$\frac{H}{H_A} = \frac{(H/H_A)_\infty}{\omega}\left[0.00874 + \sqrt{\omega}\right]^2,$$

where

H = allowable helios[3] of glare source,
H_A = helios to which the eye is adapted,
$(H/H_A)_\infty$ = allowable helios ratio for very large source,
ω = solid angle subtended by glare source (steradian).

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1 Moon and Spencer, "The visual effect of non-uniform surrounds," *Journal of the Optical Society of America*, 35, 1945, p. 233.

2 J. Steinhardt, "Intensity discrimination in the human eye," *Journal of General Physiology*, 20, 1936, p. 185.

3 Moon and Spencer, "Brightness and Helios," ILLUMINATING ENGINEERING, 39, 1944, p. 507.

Note that H and H_A occur only in ratios so that any brightness units may be used provided the same unit is employed for H and for H_A.

This equation is compared with the Holladay data and equation in Fig. 1.

I have directed attention to the danger of extrapolating the Holladay data. It may seem that my comments are more a discussion of the Holladay formula than they are of the Harrison paper, inasmuch as Harrison's equation is based on a strange mixture of experiments and guesses. More specifically applicable to the paper in question are the following:

(1) The paper states that "the exponents are tentative only and very much subject to review." As noted above, *the trouble is not in the exponents but in the whole form of equation.*

(2) The scale of "glare" is set up on the basis of *area*. But no one could possibly feel that the increase of a large luminous area to say five times its previous size would give five times the glare. If a glare rating is to be developed, the scale should not vary directly with area but should have some relation to vision.

(3) The results seem to apply only to sources subtending small solid angles. What possible meaning can one attach, for instance, to the "area", "distance", or "angle" of an overcast sky or of a very large indirectly-lighted room?

(4) According to Harrison's formula, the glare factor increases as the 1.4 power of brightness, even when the whole visual field approaches uniformity. An attempt to approximate the glare factor for uniform outdoor conditions by use of Harrison's equation gave the high value of 140. This is not in accordance with experience.

(5) The formula ignores *reflected glare,* which is probably one of the most troublesome factors in modern fluorescent lighting.

(6) It is doubtful if a "glare rating" of this kind is advisable. It cannot be measured directly; and its calculation, taking into account every luminaire and every position in the room, is inherently arduous. From a practical standpoint, therefore, would it not be better to recommend *maximum helios* (brightness) *ratios* rather than to attempt the calculation of glare ratings?

A graph showing such maximum allowable ratios is given in Fig. 2. It is based on the photochemical theory of vision[4] and agrees with all the experimental data that I have seen. A statement that "the office lighting system will maintain 40 'footcandles' and its helios ratio will be below the recommended values" (Fig. 2) should be at least as valuable as the statement that Ward Harrison proposed in his first paragraph.

DOMINA EBERLE SPENCER:* All illuminating engineers will sympathize with the aim of Mr. Harrison's paper and realize the vast amount of practical experience behind it. Certainly it would be of great practical value if the illuminating engineer could specify an adequate glare criterion for any lighting installation. But if such a rating is to be developed it should be based on quantitative visual research. Qualitative experience in lighting is valuable but it does not provide an adequate basis for an equation.

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[4] Moon and Spencer, "A modified photochemical theory of vision," *Journal of the Optical Society of America,* 35, 1945, p. 43.

* Tuft's College, Medford, Mass.

The first criticism of Harrison's glare rating is that it has no definite meaning in terms of visual performance. There are five factors in Harrison's scheme. These five factors are evaluated as follows:

(1) *Area*, qualitative experience,
(2) *Brightness*, qualitative experience,
(3) *Distance*, incorrect statement concerning solid angle,
(4) *Angle*, Holladay's disability glare experiments,
(5) *Surrounding*, Holladay's and Nutting's discomfort glare experiments.

Each of the factors has meaning, if at all, only under a particular set of circumstances. The effect of distance in changing the solid angle subtended by the glare source at the eye, varies inversely as the square of the distance only if the solid angle is very small. Yet Harrison applies this formula to the large solid angle subtended in indirectly lighted rooms. The Holladay experiments on disability glare and discomfort glare happened to be reported in the same paper. But this does not mean that they were performed under the same conditions, or will have meaning if they are rashly combined. It is impossible to predict what will be the meaning of a rating system based on such broad assumptions.

If there were no definite experiments on which a glare rating could be based, such assumptions might have slight justification. But this is not the case. Two methods of attack have been proposed and discussed at considerable length.

The criterion of comfort has been suggested in the first report[1] of the Committee of Standards of Quality and Quantity for Interior Illumination. This method assumes that the observer has become adapted to the helios of a uniform screen and is then suddenly exposed to a single glare source. He evaluates his initial sense of comfort or discomfort. This method of evaluating glare can be criticized in several ways.

(1) It is based on one set of experiments with verification at a few points by Nutting.
(2) The linear equation used by the committee does not fit the published Holladay data. Many extrapolated results are given.
(3) Holladay's experiments were with a single glare source. The committee has made assumptions as to the effect of several glare sources.
(4) The comfort method is exceedingly cumbersome.
(5) It is a question as to whether lighting should be designed merely to produce comfort at the first glance. People want rather to be able to work for long periods without annoyance from the lighting.

An alternative method is to base the evaluation on the ability of the eye to discriminate fine detail. It seems quite reasonable to assume that if the

[1] Brightness and Brightness Ratios. Report No. 1 of the Committee on Standards of Quality and Quantity for Interior Illumination of the Illuminating Engineering Society. ILLUMINATING ENGINEERING, 39, 1944, p. 713.

eye is able to see small detail at all times, then the lighting system will no produce undue annoyance. For the range of helios found in interior lighting a very simple relation[2] holds between minimum perceptible size of detai and the adaptation helios. Assume that the observer is just able to see a detail of unit size after having looked at the work for a long time. If h then looks at a glare source until his adaptation helios increases to thre times its previous value, then when he looks back at the work he will b able to see no detail smaller than three times unit size. This variation i adaptation helios can be limited to a maximum ratio of three and thus provides a simple criterion.

These results can be expressed most simply in terms of the *adaptation helio* and a new concept called *delos*. If the observer looks at a light source o large area and uniform helios for a long time, his eyes become adapted to th helios of the light source. In this case the adaptation helios is equal to th helios of the light source. If the helios in the field of view is non-uniform then the equivalent adaptation helios can be calculated[2] or measured wit an adaptation meter. Let H_{A1} be the helios when the eyes are directed t the work and α_1 the minimum perceptible visual angle corresponding to thi adaptation helios. Let H_{A2} be the adaptation helios when the eyes ar directed toward any glare source. The minimum perceptible visual angl when the eyes look back at the work, after becoming adapted to H_{A2} is α_2 The relative visibility or delos, for this case, is defined as

$$\Upsilon = \alpha_1/\alpha_2.$$

With a perfectly uniform surround, the delos is equal to one. If the surroun contains glare sources, then the delos will be less than one. On the usua range of interior lighting design, it is shown[2] that

$$\Upsilon = H_{A1}/H_{A2}.$$

It has been suggested that the *delos* should never be permitted to drop below one third. This means that

$$H_{A2} \leq 3H_{A1},$$

or the adaptation helios of any part of the field of view should never b permitted to become more than three times the adaptation helios of the work The second criterion of the S. Q. Q. report[1] can be interpreted as coincidin with this result. This criterion was not stated in precise terms and does no therefore cover all possible cases. A study of the meaning of adaptatio

[2] The Visual Effect of Non-Uniform Surrounds, Parry Moon and D. E. Spencer, *Journal of the Optical Society of America*, 35, 194 p. 233.

helios will show that a three to one ratio of adaptation helios does not preclude small areas of high helios.

The advantages of this method may be summarized as follows:

(1) The method is based on the experiments of many different observers in both England and America.
(2) If variation in adaptation helios is limited to a ratio of three, comfort is also insured (according to the Holladay formula).
(3) It has a specific meaning in terms of what the eye is able to see.
(4) Adaptation helios can be calculated simply in all cases.
(5) Adaptation helios can be measured by a photoelectric device.

In other words, since we already have two methods of evaluating glare which are based on quantitative experiment, why should we set up a rating system based on qualitative experience?

JOHN O. KRAEHENBUEHL:* I have been asked to discuss the paper on the subject of glare ratings by Mr. Ward Harrison. In the light of the fact that Mr. Harrison has so thoroughly covered this material for many years, there would be a definite danger in disagreeing with him. In his Society Presidential Address, in 1923, we find "In my opinion our greatest technical need today is for a better working knowledge of *brightness* and *glare* from both a quantitative and qualitative standpoint". This paper, 22 years later, is a definite approach to the quantitative analysis of glare. Turn again to the author's work reported in the *Transactions of the A. I. E. E.*, in 1922, and we find "in a word, 'flux entering the eye' rather than the brightness or contrast are the dominant factors in glare".

The paper in presenting a process for determining a *glare factor* suggests the coordination of work which has been leading toward a progressive clarification of what is commonly called "direct glare". An analysis of the expression, formula No. 4, yields the footcandles at the eye normal to the line of sight to the luminaire, times a modifying factor.

Mr. H. L. Logan, in papers of 1939 and 1941, makes an analysis of the flux entering the eye from various regions of the field of vision and compares his results with the natural distribution found under the open sky. Again a consideration of the "flux entering the eye" emphasizes the solid angle instead of the plane angle as has been done in the past.

Mr. C. L. Crouch, in the July (1945) issue of ILLUMINATING ENGINEERING, in his latest contribution to glare analysis (previous papers and discussions as co-author) turns to methods for solid angle treatment in the enclosure problem as applied to the lighting installation. In that same issue, Mr. Frank Benford contributes another of his ingenious devices for answering a

* Professor, Electrical Engineering, University of Illinois, Urbana, Illinois.

difficult problem without complicated mathematics, an idea which Mr. Logan has been using in finding the flux distribution in the various regions of the field of vision.

The subject is being studied, answers are being determined, devices for speedier computation of data and suggested proper lighting distribution and brightness ratios are appearing; now coordination is necessary. Since the treatment must be checked by subjective means there should be a coordination between the methods suggested, actual installations and the grading given the installations after proper use over a reasonable period of time.

This seems to be a problem for a committee which is not being rushed to produce results, and which, if it does not have those who have been doing the actual studies as a part of its membership, should have them as consultants. The committee on "quality and quantity" brought in a report last year recommending a practice much better than those found in general use, based on assumptions only partly meeting the conditions presented, results which are obtainable only by more difficult computations than the glare factor analysis.

The problem of footcandles has been the complication factor in our "comfortable lighting" specifications. When we enclosed the bright light source in semi-indirect and luminous indirect equipment, the desirable brightness of luminaire was recommended at 0.25 and not to exceed 0.5 candles per square inch for office lighting. Attempting to increase the footcandles caused uncomfortable ceiling brightness, which in the larger room, became a source of annoyance. With the fluorescent lamp came the idea that we could increase the luminaire brightness beyond the bounds definitely set down in papers presented before the Society and reported in other countries. We are in need of a single factor that will indicate the failing point of an installation, from the comfort point of view. The "glare factor" considers the essentials that have been investigated and establishes a single coefficient. It seems to be safe, and time should prove its soundness or show the necessary corrections.

The determination of the direct glare factor leaves one more condition that should be reduced to a coefficient and that is *reflected glare*. This is probably the source of much of the present complaint concerning the higher footcandle installations of fluorescent lighting. Experience has demanded that luminaire brightness, or direct glare, be eliminated or reduced to a comfortable level, but the brightness of the source exposed to the work surface causes discomfort. Consider the use of the new circular fluorescent lamp in portable lamps for a light source, without complete protection from the 4.5 candles per square inch for the bare lamp. A reader could place himself in such a position as to be unaffected by the reflected glare; however, if a table were placed in the usual position for study purposes, the worker would be exposed to serious and uncomfortable glare. Is this the correct equipment design by which we should obtain higher footcandles and are footcandles so obtained actually useful footcandles? A rating factor for reflected glare would be very useful.

To test for "glare factor" a standard classroom 20 x 30 feet with a 12-foot ceiling and the equipment mounted 30 inches from the ceiling (H = 5.5 feet above line of horizontal vision) was arranged so that independent control could be exercised on the work surface illumination, the equipment brightness and the surround. The lighting was tested over one to three-hour periods with the following arrangements:

Condition*	Work Brightness	Equipment Brightness	Surround Brightness	Room Glare Factor
A	20 ft-L	226 ft-L 0.5 c/sq in	22.6 ft-L	2.4
B	20 ft-L	678 ft-L 1.5 c/sq in	67.8 ft-L	10.8 or 16**

* Four pieces of equipment in field of vision.

** Depending on whether the footlambert factor is based on 67.8 footlamberts or on an average between 20 and 67.8.

Condition *A* proved comfortable. Condition *B* could be tolerated but was not comfortable and at the end of three hours was very unpleasant. The glare factors were obtained by the simplified form suggested in the paper:

$$\text{Room Glare Factor} = \text{No. luminaires in field of vision}$$

$$\times \frac{\text{Apparent Equip. Area sq in} \times (\text{Equip. ft-L} \times 10^{-3})^2}{\left(\begin{array}{c}0.6 \times \text{equip. height}\\ \text{(feet above eye level)}\end{array}\right)^2 \times \left(\dfrac{\text{Surround Brightness ft-L}}{10}\right)^{0.6}}$$

It will be noted that the "room glare factor" for "*B*" falls close to the 15 limit recommended by the author, as satisfactory.

Although I do not know any lighting equipment which will reproduce the controlled effects listed, the illuminating engineer should be able to approach some reasonable arrangement to secure these results. We should not be guided in our recommendations by what is available but by what is correct. What is the highest "room glare factor" we should recommend? Frequently the surround and the object viewed are not at the same brightness. Should the factor *F* not cover this situation?

T. W. Rolph and H. L. Logan:* The writers agree heartily with Mr. Harrison's statement of the advantages which would accrue if some simple method of computing a glare rating could be devised. He is to be congratulated for attacking such a difficult problem.

Unfortunately, the state of our knowledge on discomfort glare is not sufficient to provide any hope of success at this time. Consequently the rating system which Mr. Harrison proposes is based largely on assumptions. These cannot be justified in many cases, and the resulting system is so misleading that we cannot seriously consider applying it to practice. Indeed there is an insidious danger in the mere proposal of such a system at the present time when it must be based on guess work. We regret that we find so much to criticize in Mr. Harrison's treatment of the subject, but we feel that this danger justifies rigorous criticism.

In the first place, it should be clearly recognized that Mr. Harrison's proposal applies only to "discomfort glare". It has nothing to do with "disability glare", which is the important glare effect which reduces the ability of the eye to see clearly. Mr. Harrison mentions discomfort in the text, but only casually. The paper purports to treat of a method of rating glare, yet the method ignores completely that very large and important effect of glare which relates to the efficiency of vision, and considers solely the effect on comfort. It ignores also the effect of reflected glare, considering only direct glare. Therefore, the comprehensive title "Glare Ratings" is misleading.

As stated above, there are in the paper many assumptions which cannot be justified. For example, with the area of the glare source entering into his glare rating directly, he assumes that brightness will enter the rating as the square of its value. One of the few investigations we have on the subjective effect of discomfort glare is that of Holladay, as referred to by Mr. Harrison, and Holladay found the exponent of area to be one-fourth of the exponent of brightness. In other words, in any scale in which area enters directly, brightness would have to enter as the fourth power. We do not believe that Holladay's research determination is final, but it is probably better than Mr. Harrison's guess.

Another unjustified assumption is made by Mr. Harrison when he comes to figuring the effect of angle. There is actually very little information available on the discomfort effect of a glare source when it is removed from the line of vision. There is no justification for assuming that the angular relationship expressed in the well-known formula for disability glare applies also to discomfort glare. Consequently, no confidence can be placed in this factor in Mr. Harrison's proposed equation.

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* Holophane Company, Inc., Newark, Ohio, and New York, N. Y., respectively.

Finally and of very great importance, is the fact that the scale obtained by Mr. Harrison does not mean anything after he gets it. It is deceptive in its effect on the possible user. For example, 50 on the scale is not five times as much as ten, and in fact, has no known relation to the value ten except that it is larger. Mr. Harrison expresses the thought that values in his rating system might be closer to their true relationship if plotted to a logarithmic scale rather than arithmetically. This again is only a guess and the mere fact that such a guess is made shows how little confidence can be placed in the relationship between different values obtained through his formula.

Mr. Harrison has recognized the existence of some of these objections in the concluding paragraphs of his paper. He hopes that research and experience will in time correct his incorrect figures and fill out the unknown values in his proposed formula. We recognize that he has suggested the framework of a possible discomfort glare rating system and has made an ingenious proposal for a unit of discomfort glare. The point we wish to emphasize particularly is that it would be unfortunate if any serious attempt were made to utilize this structure or to promote its use while its foundations are as shaky and inadequate as they are at present.

G. P. Wakefield:* Ward Harrison's paper "Glare Ratings" represents an answer to the problem of how to evaluate the footcandle, footlambert, area, distance, and the angle, when they are aimed at the eye.

Not wishing to dispute Mr. Harrison's method in arriving at a glare factor I believe it probable an attempt could be made to consider among the assumptions of the second paragraph, another consideration, namely: That the user of the lighting system will judge its comfort on the quality of reflected glare emitted from the seeing task.

While it seems reasonable to judge a lighting system on direct glare, reflected glare from luminaires overhead may be at work taking their comfort toll. You may say reflected glare is dependent on the surface—whether it is matt or glossy. If our seeing tasks were as dull a finish as typewriter paper or newsprint, our problems of providing good illumination would be relatively an easy one. Common seeing tasks in the home, school, or office are on glossy paper, suitable to reproduce photographs. Drafting paper or cloth requires a smooth surface. Many desk tops and machines are of a specular finish. Where the light source is primarily from one point, as from a lamp at home, adjustment of the seeing surface can be altered to change the angle of reflected glare and send it away from the eyes. When luminaires are fixed on the ceiling and used continuously on five or six-foot centers, it is difficult to loose the glare.

* F. W. Wakefield Brass Company, Vermilion, Ohio.

To justly rate comfort of a lighting system, the seeing task should be a factor to further produce a working formula.

The writer would like to see under Table III factors for 50 footcandles as well as ratings for the conventional troffer system of illumination.

When papers of the sort make their appearance, it is indeed gratifying to know that scientific efforts are being expended in the direction of conservation of eyesight.

R. G. Slauer:* In his final paragraph, Mr. Harrison indicates that the important point to be established is whether the idea of a numerical rating is sound. I would like to express an affirmative opinion, despite some obvious pitfalls.

Numerical ratings have always been of assistance in interpreting trends, values, etc. The most common example is the schoolroom rating which indicates that a student may have "an average of ninety per cent". This does not mean that he is 90 per cent of Superman or some other perfectionist being, but that in comparison with certain arbitrary standards and in relation to his fellow students, he has a relative evaluation. Even the proponents of progressive education don't eliminate such ratings—in fact, the I.Q. system frequently used by them is certainly a numerical approach to assessed valuation.

With only ten days to review Mr. Harrison's paper, it is impossible for me to comment adequately or properly on the basic assumptions on which the formula is built. As an impression, however, there seems to me to be an over-simplification of ideas to arrive at the numerical answers. It may be that the five points which are given consideration are sufficient to stabilize calculations, and indicate a relative standing; however, even if this is satisfactory, the mathematical approach to each may have to be very largely arbitrary rather than presumptively based on very circumscribed test work.

Ward Harrison:** I am pleased at the evident interest of the discussors in the primary aim of this paper which is to establish some generally acceptable form of glare rating; and also in their desire to get all of the facts out in the open. They are all helpful. I find no denial that the five factors mentioned in the paper are the ones which affect glare. In general, the discussions have centered on the relative weightings assignable to these factors and also upon whether some of them are worth evaluating at all.

Mr. Parsons has pointed out wherein the proposals in this paper agree

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* Manager, Applications Laboratory, Sylvania Electric Products, Inc., Salem, Mass.

** Author.

with the Holladay exponents and wherein they do not. His table bringing out the similarities and differences is, I believe, quite correct. The differences are, of course, not accidental. The Holladay formula indicates that if you have a large blank surface in the direct line of vision and a bright light is superimposed on that surface, the observer's appraisement of glare will be in accord with his formula. This is a far cry from establishing a glare rating system for a complete lighting installation and I believe that assumptions which have been found necessary to extend it to cover such a rating system are not warranted by his data, and that is not within the scope of Holladay's original investigation.

The truth is that our scientific data on glare are pitifully meagre but experience with glaring installations is extensive. It is my belief that when we have to choose between long-time experience on the one hand and insufficient data on the other hand, we are wise not to accept conclusions which flatly contradict experience. For many years, it has been my practice to study every type of lighting installation that has come within my purview and to try to answer to my own satisfaction the question, "Why is this particular installation comfortable or uncomfortable?" Over this period, I have become convinced of five propositions.

1. In a room of ordinary size, it is not necessary to look up at the lighting units or at any one lighting unit in order to experience an oppressive feeling of glare. I am sure that in most cases, dissatisfaction with lighting units comes, not from looking up at some one of them, but from an appraisement reached when the line of vision is substantially horizontal or even below horizontal. The Q & Q formula is based on looking directly upward toward one unit; I am not interested in foveal fixation of the light source.
2. Based on experience I have, with many others, come to the conclusion that the total flux reaching the plane of the eye is a very important consideration in glare. In my opinion, there is no question but that a room of large floor area, illuminated by a multiplicity of light sources, is definitely less comfortable than a small room employing a few of the same type of units at the same height. In other words, the effect of larger and larger areas of glare source are cumulative.
3. I am convinced that increasing the mounting heights of units in a room results in a very rapid decrease in glare factor. $(\text{Angle})^2$ is the value which seems well established where reduction in visibility is concerned. As a matter of fact, I am of the opinion that there is a considerable element of "reduction in visibility" in one's ordinary consciousness of and appraisement of glare, and that disability glare and discomfort glare are often not far different. When we look up from our work to

rest our eyes by changing their focus, or just sit talking to someone across the table, our retina is not entirely a blank—it is approximately focused to the general scene before us. If veiling glare interferes with that picture, we are likely to register discomfort.

4. I am convinced that, based on substantially horizontal vision, the area of light source is a most important consideration in glare than is the level of illumination. In other words, in a room with a considerable number of light sources which are overly bright, a more comfortable condition is often attained by turning out half the units. This conclusion is directly contrary to the Holladay formula which gives more weight to brightness level than light source area; his formula is no doubt correct for the special case around which it was developed.
5. Time is, in my opinion, an important factor in glare. Sources which seem almost pleasantly bright at first, often become definitely annoying if within the field of vision for a considerable period. A person with a desk facing a battery of windows affords a good illustration of this phenomenon.

It is true, as Mr. Parsons points out, that in any formula in which the glare rating is a single function of the angle, glare rating becomes infinite when the angle is zero. This is true whether $(\text{angle})^2$ is used or $(\text{angle})^{.49}$. Apparently it has not worried us very much in the case of veiling or disability glare where we have used the function $(\text{angle})^2$ for a good many years. I must agree, however, that a constant is needed in any equation which is applied to light sources which are located at or very near the horizontal, as in the case of an overcast sky with the horizon unobstructed. I do feel however that in most cases the effect of the constant would be inconsequential and that its inclusion would greatly extend the routine of glare factor calculations.

The Q & Q Committee's conclusion that glare diminishes as the $(\text{angle})^{.49}$ is necessarily based on the same kind of assumptions as those which I questioned in an early paragraph of this discussion. I do not think that this $(\text{angle})^{.49}$ is any relation whatever to the $(\text{angle})^2$ to which I have referred. Again $(\text{angle})^{.49}$ suggests a degree of precision which I have always thought unavoidably absent in glare measurements.

Professor Moon and Dr. Spencer both differ with the Q & Q Committee's application of the Holladay formula; this is a bit surprising since Dr. Spencer's name appears on the Q & Q report. They also differ with the method offered by the writer. Professor Moon and also Messrs. Rolph and Logan point out specifically that, by using area as the basis of evaluation, the effect of glare is exaggerated; that 50 square feet of glare source is not five times as glaring as 10 square feet. Quite true; but it is nevertheless very definitely more glaring, especially to the man who experiences it for a considerable period of time. Furthermore, as I pointed out in my paper, we have a close parallel in illumination; 50 footcandles is not five times as revealing as 10 footcandles. Area was used deliberately as a basis so that the difference in numerical ratings for lighting installations of varying degrees of freedom from glare would be large and therefore arrest attention. All previous forms of numerical evaluation seem to have minimized differences between the good installations and the poor ones and would lead the layman to believe these differences unimportant.

Professor Moon is concerned with the relatively poor rating of 140 which the formula in my paper will attribute to an outdoor condition with a uniformly overcast sky.* I want to point out that to be out of doors under a wide expanse of overcast sky, especially without one's hat, is not as ideal and comfortable a lighting condition as many assume it to be. This is particularly true where the eye is required to focus on near objects. For example, I hope some of you will try reading a book in the middle of an open field on such a day. I would never give an overcast sky as good a rating as the formula yields for a 20-foot room illuminated with four 500-watt lamps in 16-inch globes (Table III). People much prefer sunshiny days and on such days the brightness of the sky in the field of view generally goes down by two-thirds and the brightness of the work goes up perhaps five to one. A glare rating for 140 which applies to a cloudy day would, accordingly, be reduced to a rating of about six for a clear day.

Professor Moon and others also bring up the point that the glare rating plan proposed fails to evaluate reflected glare. I realize this and perhaps the title of my paper should have been limited to "Direct Discomfort Glare." I agree most heartily that reflected glare is a factor that ought not to be neglected, nevertheless, it is very difficult to see how the two different phenomena can be evaluated fairly in a single formula. For example, one might have a lighting installation where powerful incandescent lamps in clear bulbs were all entirely hidden by deep beams spaced at close intervals. This would be entitled to an excellent rating as to direct glare by any means of appraisal, yet if the work surfaces beneath the units were polished steel or aluminum, reflected glare might be almost intolerable. I would like very much to see a separate formula developed for reflected glare and possibly this can be accomplished.

Dr. Spencer has very properly pointed out that a solid angle does not vary inversely as the square of the distance unless the angle is small. On the other hand, my belief is that for the degree of accuracy that we can hope to

* Where trees or buildings obstruct sky exposure for the first few degrees above the horizontal, a value of 140 would, no doubt, be appreciably reduced.

attain in glare ratings, the error due to this cause will usually be inconsequential. For example, if the solid angle is equivalent to a cone of 40 degrees spread, the error is but seven per cent and the inaccuracy is greatly reduced at 30 degrees. The 40-degree equivalent would seldom be exceeded even in an indirect lighting installation.

I am interested in Dr. Spencer's comment as to looking at a glare source and then back at the work at which time the subject's ability to discriminate fine detail is measured. It seems to me that in this test if instead of gazing at one source, the observer simply raised his eyes to the horizontal and allowed them to remain there in a natural manner for, say, 30 seconds, and then back to the work, and if this were repeated for, say, one hour before the final measurements were taken, some very interesting data might be secured. From the standpoint of comparative results between different installations they might not be in too severe disagreement with the method of evaluation outlined in my paper. At any rate, it would be interesting to see such a comparison.

Professor Kraehenbuehl's discussion reached me after my answer to the others had been written and some of the points he has raised, particularly as to reflected glare, are already commented upon. His statement that with fluorescent lamps, many seem to think that the old brightness limitations can be allowed "to go by the boards" is significant. What is more, *poor* fluorescent lighting installations usually transgress also all the old maxims regarding limits on total flux in the direction of the eye. It seems that with every new illuminant, we have to be re-educated all over again—the hard way, by experience. I recall that lighting practice stepped backward very definitely during the time the gas filled incandescent lamp was succeeding the vacuum type and it did not fully recover for four or five years.

Professor Kraehenbuehl's contribution is particularly helpful because he has constructed two lighting installations on a strictly comparable basis and calculated their glare factors. He also recorded his own judgment as to how satisfactory these installations were from the standpoint of glare. He was likewise thoughtful enough to send on a copy of his detailed computations to see if they checked with the author's idea of how such calculations should be carried out, and they do. Professor Kraehenbuehl thinks that his installation "B" is pretty bad and yet its glare factor is not more than 16. In view of this, perhaps, the suggested figure of 15 will prove to be too high a limit to be acceptable for offices and school rooms and it will have to be revised downward, say to 10, in the light of subsequent data.

Many of the points raised by Rolph and Logan have also been cited by others. I disagree flatly with their implication that lighting can claim to be good even though somewhat uncomfortable. I do not claim precision for the exponents in the formula, however, I would not be guilty of suggesting something based simply on wild guesses, and before the proposal is characterized too strongly as "misleading" "dangerous" and "deceptive", I would suggest that the commentators take time to make some actual appraisals with it and then decide how reasonable or unreasonable it is. The fact is that we have muddled along for about thirty years, needing but doing without any yardstick for the measurement of discomfort glare, and with not more than the vaguest conception of what the other fellow meant by such terms as "pretty comfortable" or a "bit glaring".

I believe that it was Lord Kelvin who said that one does not know much about a thing until he can measure it. The first human instruments for measuring—the "hand" and the "foot"—were far from precise but they were much better than no measure at all. I have but one brief suggestion for the formula. It is that if the people who have taken the trouble to contribute to this discussion were first, each to appraise half a dozen lighting installations, second, also rate these installations by the formula, and, third, meet together to discuss the results, I am sure that the revision in exponents made by their mutual agreement would form a very good basis for a glare rating. Give it then one year of wide use and a second review and revision and the problem should be solved for all practical purposes. Wouldn't this be better than just waiting around for another thirty years?

The foregoing comes pretty close to Professor Kraehenbuehl's suggestion of an I. E. S. committee to study and coordinate the various methods that have been proposed for evaluating glare. I think his suggestion is an excellent one.