IES Transaction

New Concepts in Direct Glare Control

Ian Lewin

IN KEEPING with the general mood of the country, the trend in illuminating engineering is towards greater esthetic appeal, with emphasis on the pleasantness of the lighting environment rather than considering only the performance aspects of the system. Discomfort glare control is vital if luminaires are to be an unobtrusive and attractive element of building design.

Glare and Luminaire Efficiency

The IES recommended method for the evaluation of discomfort glare takes the form of Visual Comfort Probability, VCP, where the probability of an observer experiencing comfortable visual conditons is tabulated for a range of room geometries, for a system of a given type of luminaires.[1] The important word is "system," for the VCP method does not simply rate a luminaire as a laboratory object; it provides a rating for that luminaire when used in conjunction with other luminaires of the same type, in a complete lighting installation.

As is usual in any branch of engineering, designing to fulfill more than a single criterion usually results in compromise. Luminaire design is no exception. If we consider fluorescent troffer lighting fixtures, which normally are designed for two major criteria, control of discomfort glare and high efficiency, we will find that there is a tradeoff in the degree to which the two criteria can be achieved. Fig. 1 shows a plot of VCP *vs.* coefficient of utilization, for a random sampling of 30 types of fluorescent troffer luminaires, under given room conditions. The values are shown for a typical large room, 60 ft × 60 ft × 10 ft, (18 m × 18 m × 3 m), with ceiling wall and floor cavity reflectances of .80, .50, and .20 respectively.

As can be seen from Fig. 1, the points fall within a definite band, indicating the general reduction in visual comfort as the luminaire efficiency is increased. Although a plot such as this should not be used to draw precise conclusions, in general those luminaires giving an advantageous combination of the two features will be situated towards the upper boundary of the band. Only luminaires having relatively low efficiency are able to meet the IES recommended minimum VCP of 70 for the stated conditions.

The normal reaction to the curve is to assume that high efficiency and high VCP are inherently incompatible. This is not an unnatural assumption, for control of discomfort glare requires reduction of that portion of the luminaire output which causes glare, and luminaire efficiency would seem therefore to have to be reduced. If these problems could be overcome, then high efficiency and low glare could be achieved together, and the VCP/CU point would fall above the normal band shown in Fig. 1, in the upper right-hand corner of the graph.

Let us consider the relationship between the luminous flux emitted by a luminaire and resulting coefficients of utilization. Fig. 2-A illustrates an imaginary luminaire which emits 50 per cent of its total lamp lumens in the 0° to 10° zone, with no emission in the 10° to 180° zone. A table of coefficients of utilization was computed for this imaginary symmetric luminaire for a 60 ft × 60 ft × 10 ft, (18 m × 18 m × 3 m), room with .80, .50, and .20 ceiling, wall and floor cavity reflectances respectively.

C.U.'s then were calculated for another similar imaginary luminaire, with identical output emitted in the 10 to

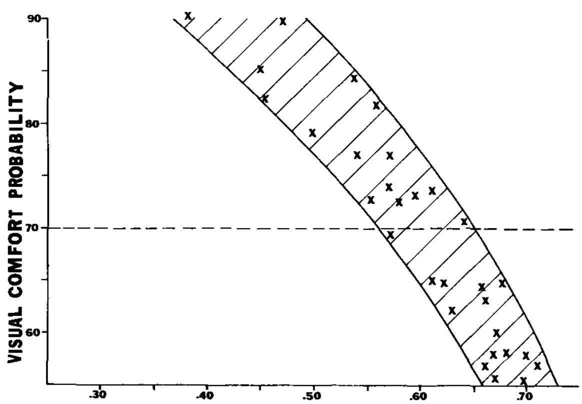

Figure 1. Plot of VCP C.U., for typical fluorescent troffer systems.

A paper presented at the Annual IES Conference, July 24–27, 1972, Tulsa, Okla. AUTHOR: Holophane Company Inc., Newark, Ohio. Dr. Lewin is now associated with Environmental Laboratories, Scottsdale, Ariz.

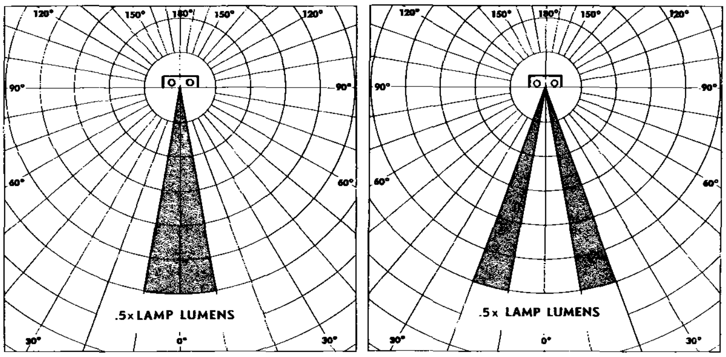

Figure 2. Illustration of theoretical candlepower distributions.

20-degree zone only, as illustrated by Fig. 2-B. This process was repeated for outputs confined to 10-degree zones, in steps to emission in the 80 to 90-degree zone only.

Fig. 3 shows a graph of mid-zone angle of the emitted flux *vs.* the corresponding C.U., for the stated room conditions. It can be seen that the C.U. reduces sharply as the emitted flux approaches the horizontal. We may draw the conclusion from Fig. 3, for a practical luminaire which emits flux in all zones, that while flux emitted in any zone will produce useful illumination on the work plane, the contribution to such illumination from light emitted close to the horizontal is substantially less than that emitted in the lower zones. This point will be used later in the paper.

A Simplified VCP Technique

Recently, a simplified technique for visual comfort assessment has become available, the "Equal Area Equal Glare System," EAEGS, which is compatible with the VCP method.[2]

The basic premise of the EAEGS is that in a given room a certain number of fixtures will be viewed at an angle of, for instance, 65 degrees. These fixtures will have a certain luminance at 65 degrees which will contribute to the overall glare effect. Other fixtures will be viewed at other angles, each angle having associated with it a luminaire luminance which forms part of the total glare sensation. The EAEGS takes the luminance values at the various angles in the glare zone, and weights these luminances according to the amount of glare produced by fixtures viewed at the particular angles. The products of luminance and weighting factor are then added, to give a sum which is a measure of the total glare effect.

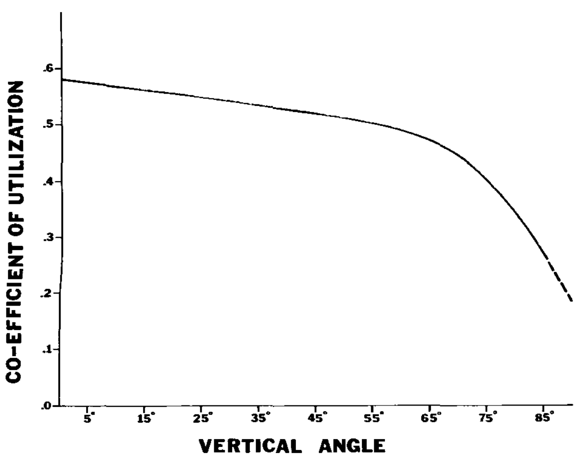

Figure 3. Effect of vertical angle of emission upon C.U., for fixed lumen output.

Table I illustrates the procedure used for the calculations. The weighting multipliers are called "T-factors." The summation of $\bar{L} \times T$ is designated $\bar{L}$, the weighted luminance.

When the $\bar{L}$ value is large, the discomfort glare is also large. Conversely, a comfortable lighting system will have a low $\bar{L}$. Lighting systems with an $\bar{L}$ of greater than 320 will have a VCP of less than 70.[2]

The EAEGS allows simple assessment of the glare controlling capabilities of a luminaire. However, rather than apply the technique in this way, we can use the method in reverse. We may determine what photometric distribution is required by a luminaire to produce high visual comfort. The method then becomes a design tool, rather than simply a rating system.

Table I—EAEGS for Discomfort Glare

Plane	Vertical Angle	L, Average Luminance	T-Factor	L × T
Parallel to Mounting Direction	85	L_{85}	.0375	L_{85} × .0375
	80	L_{80}	.1080	L_{80} × .1080
	75	L_{75}	.0884	L_{75} × .0884
	70	L_{70}	.0703	L_{70} × .0703
	65	L_{65}	.0543	L_{65} × .0543
	60	L_{60}	.0406	L_{60} × .0406
	55	L_{55}	.0312	L_{55} × .0312
	50	L_{50}	.0229	L_{50} × .0229
	45	L_{45}	.0159	L_{45} × .0159
	40	L_{40}	.0102	L_{40} × .0102
Diagonal	85	L_{85}	.0203	L_{85} × .0203
	80	L_{80}	.1065	L_{80} × .1065
	75	L_{75}	.1022	L_{75} × .1022
	70	L_{70}	.0841	L_{70} × .0841
	65	L_{65}	.0681	L_{65} × .0681
	60	L_{60}	.0507	L_{60} × .0507
	55	L_{55}	.0333	L_{55} × .0333
	50	L_{50}	.0214	L_{50} × .0214
	45	L_{45}	.0109	L_{45} × .0109
	40	L_{40}	.0021	L_{40} × .0021
90° to Mounting Direction	80	L_{80}	.0046	L_{80} × .0046
	75	L_{75}	.0096	L_{75} × .0096
	70	L_{70}	.0052	L_{70} × .0052
	65	L_{65}	.0017	L_{65} × .0017
				Total = $\Sigma LT = \bar{L}$

Fig. 4 shows the variation in T-factor plotted against vertical angle, (for fixtures viewed along-axis). It is immediately apparent that a given luminance will produce a much greater degree of glare if it occurs at a high angle rather than at a low angle. If we suppose that a luminaire has a luminance of 1000 fL, (3420 cd./sq.m.), at 40 degrees, then $L \times T$, the contribution to the glare sensation, is 10.2. If, however, the same luminance occurs at 80 degrees, the $L \times T$ value is 108. A given luminance therefore contributes more than ten times the discomfort glare at 80 degrees than at 40 degrees.

Why should this be so? Fig. 5 illustrates an observer seated at the rear of a 60 ft × 60 ft × 10 ft (18 m × 18 m × 3 m) room, the room being equipped with continuous rows of 4-foot (1.2 m) luminaires on 6-foot (1.8 m) centers. In the entire zone from 40 to 70 degrees he views only 10 fixtures, while between 70 degrees and 90 degrees he views 94 fixtures. Obviously the luminance of the fixtures viewed at the higher angles must be of dominant importance. Furthermore, although the solid angles projected by the more distant luminaires are smaller, the fixtures are closer to the observer's line of sight and therefore can create a large glare sensation.

In view of such considerations, the curve shape shown in Fig. 4 is not unexpected. What is new is our ability to put precise numbers on the effect.

Luminaire design, however, is not carried out on the basis of luminance, as optical engineers design in terms of the candlepower distribution they wish to create.

$$\text{Glare Measure} = L \times T$$

For a flat-bottomed luminaire:

$$\text{Glare Measure} = \frac{I_\alpha \times T}{A_\alpha}$$

where I_α = candlepower at a vertical angle, α, and A_α = projected area at vertical angle, α.

$$A_\alpha = A_o \cos \alpha$$

$$\therefore \text{Glare Measure} = I_\alpha \times \frac{T}{A_o \cos \alpha}$$

The amount of glare for a given candlepower occuring at a vertical angle, α, therefore is dependent on $T/A_o \cos \alpha$. If we plot $T/A_o \cos \alpha$ against vertical angle, we will obtain a curve equivalent to the curve shown in Fig. 4, excepting that it will indicate the effect of glare zone candlepower distribution upon discomfort glare, rather than luminance distribution. Different fixture orientations may be taken into account, by using diagonal and perpendicular viewing T-factors, but the difference will be negligible in the case of luminaires having approximately symmetric distribution.

Fig. 6 gives the curve obtained for a flat-bottomed luminaire, indicating how the amount of discomfort glare changes for a fixed candlepower occurring at varying vertical angles. The curve illustrates the dominant effect of candlepower emitted in the zone from 70 degrees to approaching 90 degrees. The overwhelming glare sensation from a system of luminaires having uniform candlepower would be from those luminaires viewed between these very high angles, while a comparatively negligible sensation would be caused by luminaires viewed at angles below 70 degrees.

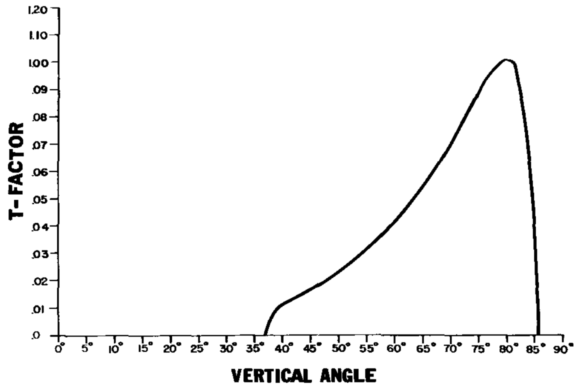

Figure 4. Vertical angle vs T-factor.

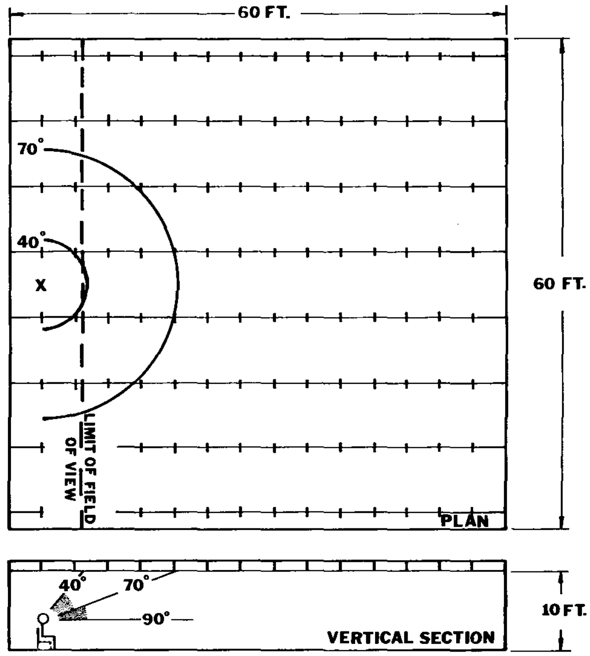

Figure 5. Observer in 60 ft × 60 ft × 10 ft (18 m × 18 m × 3 m) room.

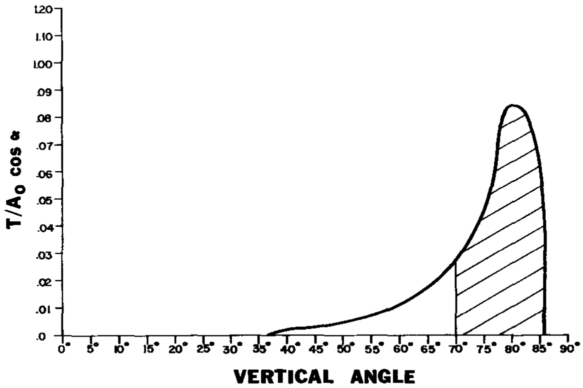

Figure 6. Measure of resultant glare sensation vs vertical angle, for uniform candlepower distributions.

Designing for High VCP and High Efficiency

Using the conclusions derived from Figs. 3 and 6, fundamental principles can be derived.

In order to achieve high C.U.'s, light should be emitted in all zones, but to produce the highest possible VCP's, no light should be emitted in the zone between 37 and 90 degrees. A vertical angle of 37 degrees corresponds to the limit of the field of view as used in the VCP calculations.[1,3] These requirements are incompatible. However, we do not require the highest possible VCP, which is 100, but rather we seek to meet the criterion of a VCP of 70 or greater, which is recommended in RQQ Report No. 2.[1] The design problem therefore reduces to the following question: What candlepower distribution in the 37° to 90° zone will produce the highest possible C.U.'s, while giving a VCP of 70 or above for all room configurations?

Detailed examination of the data used to produce Figs. 3 and 6 revealed a particular design principle, illustrated by Fig. 7. C.U.'s are affected less by a reduction of output in the 70 to 90-degree zone than in any other similar zone, and therefore candlepower values in the 70 to 90-degree zone may be extremely small without seriously reducing the C.U.'s. The light giving the major contribution to discomfort glare therefore will have been removed. A high output between 37 degrees and 70 degrees then becomes acceptable, as this light has much less effect upon visual comfort and will be in itself insufficient to create an overall glare sensation. The overall visual comfort therefore will be high. Additionally, the high output between 37 degrees and 70 degrees, when added to a large output between 0 and 37 degrees, will produce the required high C.U.'s.

Using this "zonal design principle," the data upon which Figs. 3 and 6 are based were examined in detail. While keeping in mind the feasibility aspects of design, a candlepower distribution was determined which appeared desirable in view of the foregoing. This distribution is shown by Fig. 8, alongside the distribution curves for a typical high efficiency lens and a low brightness lens, for a 2 ft × 4 ft (.6 m × 1.2 m) four-lamp fluorescent troffer.

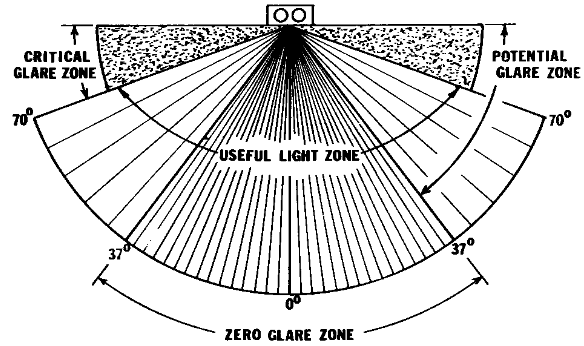

Figure 7. Illustration of zonal design principle.

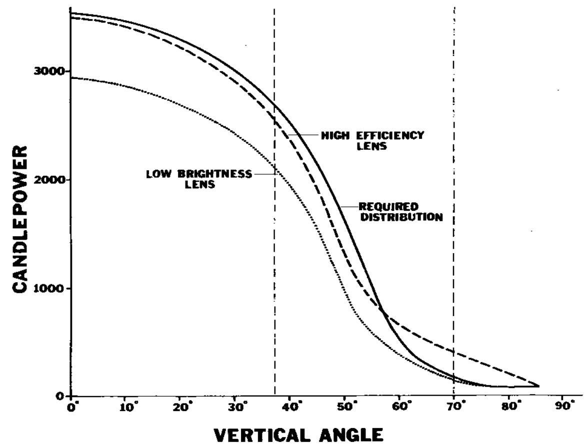

Figure 8. Required candlepower distribution, with curves for conventional equipment.

Optical Design and Results

An extensive program of research was carried out in an attempt to design an optical system which would produce the candlepower distribution shown in Fig. 8. A lens system was developed which operated on a completely new system of geometric optics, consisting of a grid of uniform refractive elements, Fig. 9, which allows passage of light in the 0 to 70-degree zone. The grid lens was tested in a standard 2 ft × 4 ft four-lamp fluorescent troffer, and produced the candlepower characteristics as shown in Fig. 10. Close coordination with the theoretical curve suggested that the design criteria had been achieved. The table of VCP's, Table II, indicates that the minimum value of 70 was reached, while the C.U. values, Table III, are approximately 30 per cent higher than other luminaires having VCP's of 70 or over.

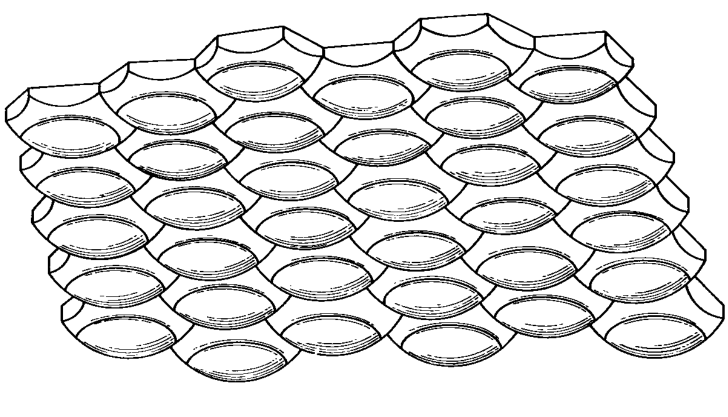

Figure 9. Grid lens.

Table II—IES Visual Comfort Probability—Grid Lens in 2 ft by 4 ft Four-Lamp Troffer

$\rho cc = .8$, $\rho w = .5$, $\rho fc = .2$
Work plane illumination = 100 footcandles
Work plane height = 2.5 feet

Room W	Room L	Luminaires Lengthwise 8.5	10.0	13.0	16.0	Luminaires Crosswise 8.5	10.0	13.0	16.0
20	20	81	77	76	78	79	75	72	74
20	30	81	78	76	74	79	76	72	70
20	40	82	79	77	74	79	77	74	71
20	60	81	80	78	76	79	77	75	72
30	20	84	80	77	76	82	78	74	74
30	30	83	80	77	73	82	79	74	70
30	40	83	81	78	73	81	79	75	70
30	60	82	80	78	74	80	78	76	72
30	80	82	80	79	76	80	78	76	73
40	20	86	83	80	77	85	81	77	75
40	30	85	83	79	74	84	81	76	71
40	40	84	82	79	74	83	81	77	72
40	60	83	82	79	75	82	80	77	73
40	80	83	81	79	76	81	80	77	73
40	100	82	81	80	76	80	79	77	74
60	30	86	84	81	76	85	83	79	74
60	40	85	83	81	76	84	82	79	74
60	60	84	82	80	76	82	81	79	74
60	80	83	82	80	77	81	80	78	75
60	100	82	81	80	77	81	80	78	75
100	40	87	86	83	79	86	85	82	78
100	60	85	84	82	79	84	83	81	78
100	80	84	83	82	79	83	82	80	77
100	100	83	82	81	79	82	81	79	77

Table III—Coefficients of Utilization—Zonal Cavity Method. Grid Lens in 2 ft by 4 ft Four-Lamp Troffer

Effective Floor Cavity Reflectance (ρfc) = 20 Per Cent

ρcc	80	70	50	30	10	0
ρw	70 50 30 10	70 50 30 10	50 30 10	50 30 10	50 30 10	0
1	0.73.71.69.67	0.72.70.68.66	0.67.65.64	0.64.63.62	0.62.61.60	0.59
2	0.68.65.61.58	0.67.63.60.58	0.61.59.56	0.59.57.55	0.57.56.54	0.53
3	0.64.58.54.51	0.62.57.54.51	0.56.52.50	0.54.51.49	0.52.50.48	0.47
4	0.59.53.48.45	0.58.52.48.44	0.50.47.44	0.49.46.43	0.48.45.43	0.41
5	0.55.48.43.39	0.53.47.42.39	0.46.41.38	0.44.41.38	0.43.40.38	0.36
6	0.51.43.38.34	0.50.43.38.34	0.41.37.34	0.40.37.34	0.39.36.33	0.32
7	0.47.39.34.30	0.46.38.34.30	0.37.33.30	0.36.33.30	0.36.32.29	0.28
8	0.43.35.30.26	0.42.34.30.26	0.34.29.26	0.33.29.26	0.32.29.26	0.25
9	0.40.32.26.23	0.39.31.26.23	0.30.26.23	0.30.25.23	0.29.25.22	0.21
10	0.37.29.24.20	0.36.28.24.20	0.28.23.20	0.27.23.20	0.26.23.20	0.19

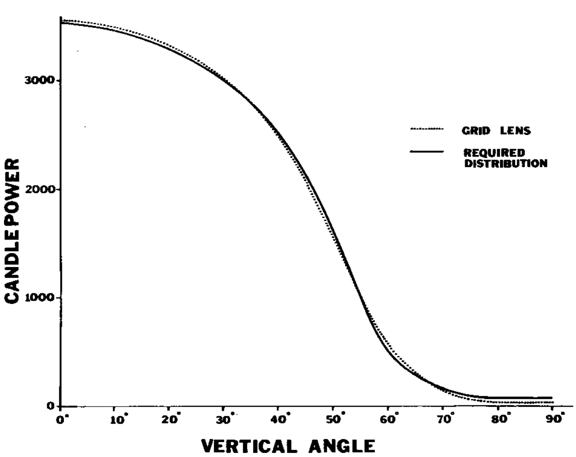

Figure 10. Grid lens candlepower distribution and required distribution.

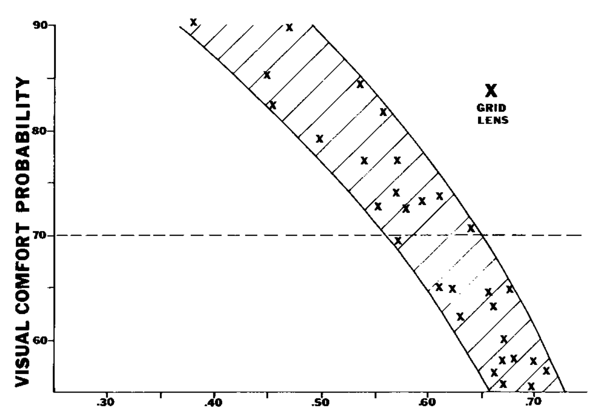

Figure 11. Plot of VCP vs C.U., with grid lens point.

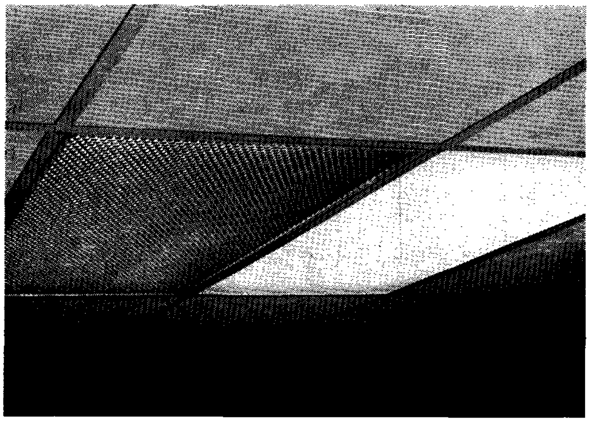

Figure 12. Side-by-side comparison in similar troffer luminaires. Left: Grid lens. Right: Conventional lens.

Plotting the C.U. and VCP values for the standard 60 ft × 60 ft × 10 ft room, Fig. 11, indicates a superior positioning in comparison with the band of points for other designs in similar fluorescent troffers.

The newly developed optical system is shown in Fig. 12 alongside a unit of conventional high efficiency design. While the C.U. values of the new device are greater, the average luminances in the critical 70 to 90-degree zone are approximately 70 per cent lower, giving an average improvement in VCP of 17 points over the conventional design.

Conclusion

A principle of design has been developed which differs from the conventional approach. As coefficients of utilization are less sensitive to a reduction in output above 70° than in any other zone, we may greatly reduce the candlepower in the 70° to 90° zone without causing a large drop in C.U.'s. VCP, however is affected most strongly by emission in the 70° to 90° zone, a high VCP therefore will be produced. By having high output in the 37° to 70° zone, high C.U.'s are achieved while maintaining high VCP's.

The results obtained with the new lens design appear to verify the above principles.

References

1. Report No. 2 of the Committee on Recommendations of Quantity and Quality of Illumination (RQQ), "Outline of a Standard Procedure for Computing Visual Comfort Ratings for Interior Lighting," ILLUMINATING ENGINEERING, Vol. 61, October 1966, p. 643.
2. Report No. 3 of the Committee on Recommendations of Quantity and Quality of Illumination (RQQ), "An Alternative Simplified Method for Determining the Acceptability of a Luminaire From the VCP Standpoint for Use in Large Rooms," JOURNAL OF THE ILLUMINATING ENGINEERING SOCIETY, Vol. 1, No. 3, April 1972, p. 256.
3. Fry, G. A., "Limits of the Field of View," ILLUMINATING ENGINEERING, Vol. 64, May 1969, p. 403.

DISCUSSION

CHARLES L. AMICK:* This paper presents an interesting mathematical approach, by determining optimum candlepower distributions, and then designing an ingenious refractive panel that appears to defy previous relationships of visual comfort and utilization. The influence of candlepower distribution on luminaire utilization has interested me for many years,[1] and that portion of Dr. Lewin's paper brought back memories.

Based on the information in this paper, the author (and his associates that did the optical design of the refractive panel described) are certainly to be congratulated for their technical achievement. I am concerned about extensive use of the "Equal Area Equal Glare System" of evaluating direct glare. Because of failure to comprehend room size and actual mounting heights, it becomes a "Go–No Go" gauge like the Scissors Curve, and certainly cannot be as accurate as the VCP method for predetermination of direct glare under specific installation conditions.

1. Weitz, C. E. and Amick, C. L., "Luminaire Utilization as Specified by Candlepower Distribution," ILLUMINATING ENGINEERING, Vol. XLIII, January 1948, p. 65.

T. L. BALLMAN:* The author's approach of using the EAEG system for design of an optical system is intriguing and the progression is logical and well thought out.

The reduction in VCP for increasing ceiling heights in a given room size does indeed show the success of the approach. The reason seems to be that the lower ceiling height VCP are higher rather than the higher ceiling VCP values being lower indicating a definite reduction in candlepower at the critical glare angles.

The only question: is the development of such a technique worth the effort? With a much greater importance being placed on the veiling reflections and resulting contrast loss caused by lighting systems, it seems that concern only with direct glare just goes half way. What has been seen in many studies so far, is that the concentration of candlepower in the 0 to 37- degree zone is actually reducing the effect of the device from an overall visibility and comfort standpoint.

It would be interesting to know if the author had visibility data on this device and how it compared in performance with the three lighting systems described in his paper on "Application of ESI Predetermination Techniques."

W. M. WALDBAUER:* Dr. Lewin and his associates are to be commended on the development efforts which led to their presentation of this paper. While the zonal lumen design approach to an "ideal" distribution is not new or unusual, the combination of this methodology with techniques to predict and achieve high VCP is new and provides interesting potential for future designs.

The resultant lens system represents, in the writer's opinion,

* Day-Brite Lighting Division of Emerson Electric Co., St. Louis, Mo.

* Westinghouse Electric Corp., Interior Lighting Division, Vicksburg, Miss.

one of the most unique new prismatic concepts for repetitive optical design to be developed in recent years. Our own testing has confirmed most of the results reported by the writer.

It should be noted, however, that since this paper was written, the author's company has deemed it necessary to provide a diffuse overlay sheet to improve the esthetic characteristics of the lens with a significant reduction in efficiency. When this is factored into the results, much, if not all, of the gain shown in Fig. 11 is lost.

One last question for the author: has the performance of this lens been compared to a conventional cone prism lens in terms of the ESI predetermination techniques he reported on earlier in this conference?

IAN LEWIN:* The author is grateful to the discussers, particularly in view of their comments regarding their own testing which has confirmed the findings published in this paper.

Mr. Amick queries the extensive use of the "Equal Area Equal Glare System" for evaluating visual comfort. This is with some justification as the applicability of this technique is limited to the conditions as specified in RQQ Report No. 3. However, its use as a guideline to the design of luminaries with high visual comfort is evidenced by the VCP table presented in the paper, where the minimum VCP is exceeded for all room sizes, and not simply the room size specified in the EAEGS report.

Mr. Waldbauer mentions the use of an optical interface, in the form of a diffuse overlay sheet, to improve the esthetic characteristics of the grid lens. It should be pointed out that for all normal viewing angles the grid lens form of optics produces an excellent appearance; it is only at angles between 0 and 30 degrees from the vertical that lamp images may be detected. These are abnormal viewing conditions, and for this reason we have found practically no interest in the use of the overlay. Further, it is important to note that Mr. Waldbauer is erroneous in stating that the gain shown in Fig. 11 of the paper is lost when the interface is used. Rather, the grid lens point shifts upwards and to the left and maintains a large separation from the general band of points. This is due to the moderate nature of the efficiency drop, coupled with a substantial further reduction in high angle brightness. The advantages are not lost, but rather shifted to a different balance between efficiency and VCP, while producing the further advantage of total lamp obscuration.

Regarding the ESI production from the grid lens, this optical design is not intended for the purpose of producing ESI footcandles. It provides a conventional form of candlepower distribution. Let us remember that while the IES is now recommending ESI footcandles, this only applies to a small proportion of the working areas in the tables of IES recommended levels. There will always be a large application for luminaires designed for conventional footcandle production, for areas such as corridors, lobbies, eating areas, etc. where the logical design criteria is not ESI.

* Author