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DESIGN CONSIDERATIONS INFLUENCING THE SIZE AND COST OF OPTICAL COMPONENTS IN AUTO-INSTRUCTIONAL DEVICES

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FOREWORD

This study was initiated by the Behavioral Sciences Laboratory of the Aerospace Medical Research Laboratories, Aerospace Medical Division, Wright-Patterson Air Force Base, Ohio. The research was conducted in part by Graflex, Inc., Rochester, New York 14603, under Contract No. AF33 (657)-11339. Mr. William H. Trow, Project Engineer, was the principal investigator for Graflex, Inc. Dr. Edgar A. Smith of the Technical Training Branch, Training Research Division was the technical monitor. The research reported herein was begun in May, 1963 and was completed in March, 1964. The work was in support of Project 1710, "Training, Personnel and Psychological Stress Aspects of Bioastronautics," Task 171007 "Automated Training and Programed Instruction." Dr. Gordon A. Eckstrand was the Project Scientist, and Dr. Ross L. Morgan was the Task Scientist.

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This technical report has been reviewed and is approved.

WALTER F. GRETHER, PhD
Technical Director
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ABSTRACT

The increasing demand for low-priced projectors for self-instructional purposes has prompted investigation of design factors which contribute to the manufacturing costs in this class of product. Because cost and intended use are prime factors, design must be based upon the optimum combination of optical components which satisfies these design objectives. The problems of the projector design itself are considered, primarily the design considerations for optical components that might be used. Recent developments in lens and reflector fabrication methods do not yet permit a reduction of cost below that of conventional methods and designs. Some principles and practices for rear projection are presented, and the interdependence of major factors involved in maximizing screen performance is expressed in mathematical terms. The environmental factors of room illumination level, audience size and the contrast of the filmed material are found to be highly influential in the design of a rear-projection device.

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LIST OF SYMBOLS

A	Area of screen
C	Contrast ratio
℄	Centerline
F	Luminance fall-off factor
FL	Focal length
G	Screen gain
I_a	Ambient illumination (footcandles)
K	Projector illumination fall-off factor
L	Clear-film luminance
R	Reflectance factor
W	Width of screen
α	Half screen width angle (at projection lens)
β	Bend angle
γ	Viewing angle
Φ	Projector lumen output (flux)

SECTION I

INTRODUCTION

The purpose of this study is to investigate the optical factors inherent in rear-projection auto-instructional equipment and present these factors in a logical manner which will provide a basis for design considerations.

Studies made over many years in psychology laboratories, in schools, and in factories have established the value of properly applied audio-visual media in the learning process. Audio-visual equipment designed to present individualized instruction has been available for some time and has been used successfully, provided the instructional programs were well prepared, the equipment controls and viewing screen were suitable for the man-machine system, and the instruction site offered the proper level of illumination.

Today, needs exist for such devices in many applications involving requirements far from ideal from the point of view of the designer. Specifications for equipment suitable for various applications might include one or more of the following requirements:

(a) it must be self contained;
(b) it must allow interchangeable film sizes;
(c) it must be compact;
(d) it must be portable;
(e) it must be able to project without external power supply;
(f) it must present a good projected image in an undarkened area;
(g) it must offer the widest viewing angle possible;
(h) it must be able to withstand rough handling;
(i) it must be designed to minimize maintenance.

These are but a few of the considerations. But whatever the considerations, it must be produced at reasonable cost.

The primary basis for design in the auto-instructional field is intended use under a given set of conditions. A design for a specific purpose will in most cases never become a high production item of manufacture. The burden rests heavily upon the designer, particularly if a reasonable unit cost is to be attained. Therefore, exploration of the areas of design consideration in the auto-instructional field can be a valuable tool in development of future designs and improvement of existing designs.

The aspects of audio-visual equipment dealt with in this report relate to the optical projection system. The two major areas are the projector itself and the rear-projection screen. The various factors affecting the projector design are discussed in Section II in terms of an evaluation of alternative designs and methods of fabrication and their influence on performance and cost. The properties of rear-projection screens and the external factors affecting their performance are discussed in Section III in order to provide perspective in evaluating screens or specifying screen requirements.

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SECTION II

THE PROJECTOR AS A MANUFACTURED PRODUCT

In the design of equipment such as this, which is to be manufactured in limited quantities, yet be acceptably priced, there are bound to be certain parameters which must be compromised. That is, they must be balanced off against other parameters in a way which depends upon the relative importance placed on their individual effect. As an example, a compact package is often one of the foremost design features. One way to accomplish this is to use a very short focal length projection lens to shorten the lens-to-screen distance. However, unless a relatively expensive four or five element lens design is used, the shorter focal length will cause the screen brightness to fall off noticeably at the corners, even to the point of vignetting. Another method of developing a compact unit is to place a mirror as close as possible to the screen. In this position, a larger and hence more costly mirror is required.

There are many such examples of ways that special design requirements can be accomplished, but usually at the expense of quality of performance, or of increased cost of another component required to counteract the undesirable effects of the first, or both. Design should not suffer to realize small savings. Far greater savings may be made in the following ways:

(1) Design a more versatile product to reach a broader market, thereby establishing larger production quantities, in order to (a) secure greater discounts on purchased parts, and (b) provide the better tooling that high quantity production permits to reduce labor costs.

(2) Design for standard purchased parts to take advantage of competitive prices.

(3) Design for cost-saving finishes, simpler fabrication methods and materials.

(4) Design for module interchangeability and inventory at the module level, rather than at the final end product level.

DEVELOPMENT OF NEW CONDENSING OPTICS

One conceivable major advance in the optics of low-cost slide projector design would be the replacement of the condensing lens system with a high-quality converging reflector. (See Figs. 1 and 2.) This type of reflector is presently in common use in 8mm and 16mm projection systems, and is contained inside the lamp envelope. Rather than being spherical, the reflector is ellipsoidal, with the lamp filament at one focus of the ellipse and the projection lens at the other. An example of this type of lamp is the "Tru-Flector," manufactured by Sylvania Electric Products, New York, N. Y. It should not be confused with the "proximity reflector" lamp which contains a small low-quality metal reflector. This redirects the rearward radiation back through the filament in the same manner as the usual spherical external reflector and at a comparable cost.

The advantage of the converging reflector system is the elimination of not only the condensing lenses but also the usual heat filter by the use of a "dichroic" coating on the reflector. This coating is fabricated by multilayer vacuum evaporation of magnesium fluoride on a ground and polished glass substrate. The dichroic reflector transmits infra-red and reflects visible light, whereas heat absorbing glass transmits the visible and absorbs the infra-red.

If this type of reflector were to be designed for the much larger 35mm frame and a short focal length projection lens, this would require an ellipsoidal reflector having a minimum diameter of four inches and a depth of one inch. Such a reflector, if ground and polished, would be prohibitively expensive. Many reflectors, both larger and smaller, have been "sag molded" for some time by many companies, including Lancaster Glass Corporation, Lancaster, Ohio. In the sag molding

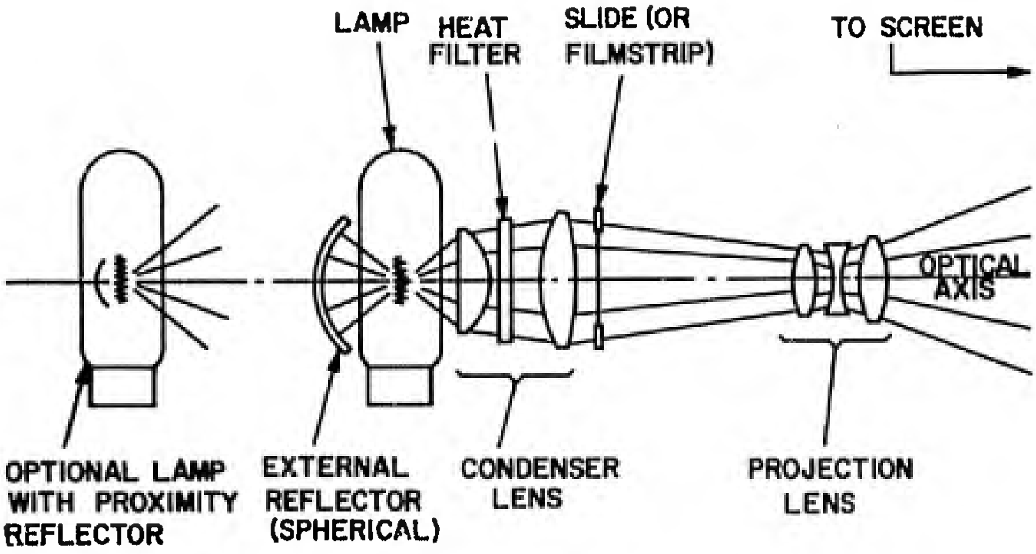

Figure 1. Components in a Typical 35mm Projector Optical System.

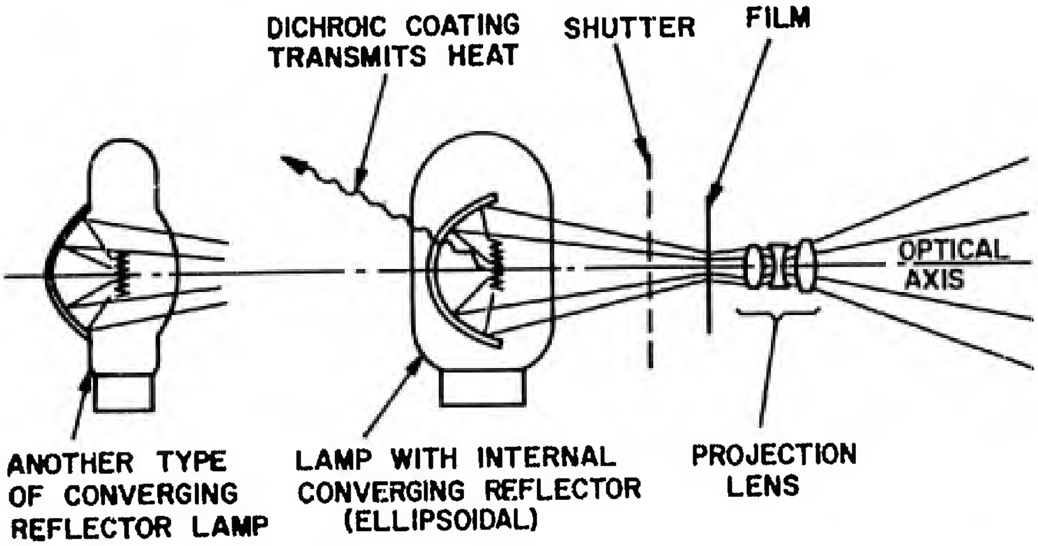

Figure 2. Components in a Typical 16mm Projector Optical System.

process, a glass plate is placed on a concave cast iron or ceramic mold and heated in a furnace until the glass sags into conformity with the mold. This process demands considerable skill, and for this reason, results are not entirely predictable. Rejection rates as high as 50% are not uncommon. Sylvania is currently developing a production quantity sag molding process for their dichroic reflectors.

Another method of fabricating high-quality reflectors is the plastic replica process which has been in limited use for a few years. Bausch and Lomb, Inc., Rochester, New York and Perkin-Elmer Corporation, Norwalk, Conn., are among those attempting to expand the applicability of the process. The process has inherent problems requiring careful selection of a substrate whose coefficient of expansion very closely matches that of the replica material. Results are good, but skill, again, plays an important part in the yield that can be obtained. Emphasis in both the sag molding and the replica processes has been placed on reducing the skill factor, thereby improving process reliability.

The surface uniformity of both the converging reflector and the lamp envelope must be such that objectionable shadows are not projected. This becomes a difficult problem in a 35mm design, in that the reflector is too large to be built into the lamp envelope, yet not large enough to render the lamp an insignificant obstruction. Even the small quartz-iodine lamp would obstruct a considerable portion of the reflector area. One solution to this problem is to use only a portion of the ellipsoid to one side of the focus, so that the lamp is out of the projected light path. This arrangement has been used in the Transpaque, an overhead projector manufactured by Projection Optics, East Orange, New Jersey. The geometry of an off-axis ellipsodidal system, unless corrected, produces a distinct fall-off in the intensity of illumination towards the far edge of the reflector. Some methods of overcoming this deficiency have been studied in detail by Lessman for Bell and Howell, Chicago, Illinois (U. S. Patent 3, 038, 372), but no manufactured examples of this type of system smaller than the 14-inch Transpaque application have been seen.

In order to illustrate the effect of surface irregularities on the uniformity of screen illumination, a quartz-iodine lamp was substituted for the large conventional lamp in a Transpaque projector. The illumination became rather splotchy due to imperfections in the thick quartz tube that were not present in the blown glass envelope. A specially prepared 4-inch reflector with almost imperceptible ripples was also tried with a quartz lamp. The resulting shadowy areas on the screen indicated that a much greater degree of surface uniformity would be required for 35mm applications.

Thus, a major break-through in optical fabricating methods is necessary before an ellipsoid of the size and depth required and having acceptable surface uniformity can be produced economically. At present the commonly used condensing lens system remains the most economic approach in the auto-instructional field.

DEVELOPMENT OF NEW PROJECTION OPTICS

A similar advance in the projection system might be made by using reflection optics. The Micro-Aid, a Microfilm Teaching Unit manufactured by Graflex, Inc. uses a rectangular section of a spherical reflector for viewing and depends upon surrounding light for illumination in the viewing field. This system produces a virtual image which cannot be used for projection onto a screen. The principle can be employed because of the ability of the eye to accommodate to the curvature of the virtual image plane. A wide field, short focal length, off-axis, real image system would have serious aberrations which would have to be corrected by an aspheric surface and/or a correcting lens in order to focus on a flat screen. This has been done on a small scale in 16mm projection by Linke for Bell and Howell (U. S. Patent 3, 044, 357). Projection of a 35mm frame would require a large lens and mirror system and would be much more costly than a standard triplet projection lens system.

A few scattered examples of lens performance versus cost would not give a reliable generalized relationship. Aside from the rule of thumb that, for large lenses, the cost increases with the cube of the diameter, for present purposes any variation in cost would depend on the "off-the shelf" availability as against the cost of optical design and tooling of a special lens.

ALTERNATIVE OPTICAL MATERIALS AND PROCESSES

The optical industry long ago realized that to obtain an optical surface conforming to the theoretical surface within one wave length of light or less, there was no material that served as well as glass. This is true today. Glass responds to grinding and polishing and retains its shape and its optical properties better than other materials. Nevertheless, many attempts have been made to reduce the manufacturing cost at the expense of quality where lower quality can be tolerated, and with some success.

One technique is the molded glass lens sometimes used for condensers in low-priced projectors. With special polishing and maintenance, a mold can be made to produce a minimal "orange-peel" surface that can be almost completely removed by fire polishing. This process has not found widespread acceptance. However, it is the only method economically feasible for aspheric condenser lenses. The difficulty here is the high cost of making and maintaining the mold compared to standard spherical grinding and polishing tools, and the resultant impracticality of modifying the curvature. Only high production can justify the tooling costs. Although this technique is frequently initiated, manufacturers later abandon it after serious production difficulties, many of which should have been anticipated prior to using the process for fabrication of the lens.

The other major optical fabrication method is that of molded plastics, generally crystal-clear acrylics. The index of refraction of plastics requires a completely new optical design. A simple adaptation of a glass design is not satisfactory. More important, production process development must be very extensive. As an example, the molding machines must be integrated with the production line to minimize handling, or eliminate it completely. (The lenses are often held by the sprue and cut off as they are dropped into the cell.) Also, the mold generally must be designed and made to deviate from the exact spherical curve required to allow for shrinkage of the acrylic during the molding process. As the amount of shrinkage is a function of thickness, each application becomes a separate design consideration, which means costly computations in the design of the mold. For these reasons, molded plastic lenses are not economically feasible in quantities less than 100,000. As a matter of fact, vendors generally will not quote on quantities under 50,000. If production quantities are not high, the only justifiable applications of plastic lenses are for large diameters (over six inches) where weight can be a problem. However, it is generally recommended by manufacturers that large molded lenses be finished by grinding and polishing.

A considerable amount of credence can be placed on the current practices of the many projector manufacturers. Bausch and Lomb's "Balmite 50", a simple slide projector, was designed to reach a very low cost market. The Balmite uses a single condenser lens and a single projection lens, but both are glass. However, quality in performance characteristics had to be sacrificed to meet a price. The uncorrected chromatic and spherical aberrations of the single lens used here produce a noticeable deterioration of image quality when compared with fully corrected optical systems found in more expensive projectors.

A general knowledge of lens-making practices can lead to lens designs which allow small, though worthwhile cost savings. For example, more plano or long radius lenses can be inlaid in a grinding or polishing block than short radius lenses, permitting a higher production rate per spindle. Thus, three relatively flat condenser lenses may be more economical than two thick ones, provided the mounting is simple. Another example is the possible elimination of centering, wherein the geometrical axis is made to coincide with the optical axis of the lens and the edge is ground concentric to both axes. This can be accomplished by locating the mount off the curve of the lens, ignoring the edge of the lens as an alignment surface. In the area of lower quality optics, however, high speed surfacing and centering techniques often result in lower costs.

As for the raw glass itself, the only way cost of material is held to a minimum is through competitive bidding among the manufacturers for their commercial "pot" glass which will meet specifications for such characteristics as bubbles, inclusions and striae. Special formula glass is always much more expensive.

EFFECTS OF COST REDUCTION ON PERFORMANCE

Table I has been compiled to show the effects on performance of a projection system that could be expected to result from a reduction in quality of the various parameters of each component in an effort to reduce its cost. This tabulation is not intended as a quantitative evaluation of these effects. It is presented only as an illustration of the variety of design considerations involved in arriving at acceptable performance. A more thorough discussion of the properties of rear-projection screens is presented in the next section.

TABLE I

EFFECTS OF PROJECTOR COMPONENT QUALITY REDUCTION ON PERFORMANCE

Component	Quality Reduction	Effects on Performance
Lamp	Lower wattage; Non-prefocused base	Dimmer picture, greater illumination fall-off, smaller viewing angle
Reflector	Smaller diameter; improper alignment	Lost light
	Wavy surface	Shadow spots
Heat filter	Improper heat treatment; used as thick condenser lens	Susceptible to shattering
Condensers	Smaller diameter; longer focal length	Lost light
	Molded plastic	Thermal distortion and discoloration
Filmstrip track	No flattening device	Poor focus
	Minimum clearance guide channels	Will not pass splices
Projection lens	Smaller aperture (higher f/no.)	Lost light
	Smaller field coverage	More vignetting
	Coarser mounting; more wedge	Poorer resolution and contrast
	Less correction	More distortion, color, astigmatism, etc.
	Molded plastic	Less correction possible; easily abraded
Mirrors	Farther from screen (smaller)	Deeper case required
	Second surface	Double image
Screen	No non-reflective coating	Less contrast; lower ambient required
	Thin diffusing layer	Hot spot

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SECTION III

THE REAR-PROJECTION SCREEN

The principal advantage of rear projection over front projection onto a small screen is the freedom from obstruction by the viewer. Of nearly equal importance is the fact that rear-projection screens can provide adequate contrast between blackness and brightness under normal indoor illumination. The following explanation shows why darkened room conditions are not necessary.

Typical matte screens used for front projection are about 85% reflective. That is, 85% of all light impinging upon the surface of the screen, from both the projector and the room lights, is reflected back to the viewer. By reducing the screen reflectance, one cannot reduce the reflected room light without reducing the brightness of the projected picture as well. However, when the picture is projected onto the rear of a translucent screen, the reflectance of the front surface may then be advantageously reduced. The fact that the screen is translucent requires that the area behind it be darkened, preferably by an enclosure. The better quality rear-projection screens are only about 5 to 10% reflective (ref 1). This permits the room illumination to be 10 to 15 times higher with rear projection while maintaining the same ratio of picture brightness to "dark" screen brightness.

In addition to the desirability of being able to write or perform tasks while viewing a screen in a lighted room, visual acuity increases as the ambient light level is raised. Therefore, greater viewing distance can be accommodated effectively. In practical terms this means that where the recommended maximum audience distance from a front projection screen of width W is usually given as 5W to 6W, this may be increased (ref 2) to around 10W for rear projection in a normally lighted room.

VIEWING ANGLE AND BEND ANGLE

The recommended maximum viewing angle for a non-beaded front projection screen is generally given as 30° off-axis. This is represented by the angle γ in Fig. 3. Beyond 30°, the fall-off of illumination becomes very noticeable, as does the foreshortening of the picture. For a beaded screen, which concentrates more light along the axis, the recommended maximum viewing angle is reduced to 20°. For rear projection, we shall specify an almost identical limiting angle, but specify it in terms of screen width. As shown in Fig. 3, γ is the angle obtained when the viewer is located at the commonly recommended minimum distance of 2W from the screen and off-center, or off-axis, a distance of 3/4W.

The viewing angles γ at three principal points across the screen are then:

Near side	7.1°
Center	20.6°
Far side	32.0°

At this location the direct beam from the projector (peak brightness) will fall just inside the near edge. This can be verified by tabulating the half screen width angles α of various projector systems that are applicable to this study and noting that they are all greater than 7.1°. (See Table II.) Adding the far side viewing angle (32.0°) to α gives the maximum bend angle β_{max} through which the light must be diffused by the screen to reach the viewer. It is seen that β_{max} will generally fall between 40° and 50°. (In actual practice, the extreme edges of the picture will be unused; therefore the values of β_{max} can be applied to points within the corners of the screen a distance of 1/2W from the center.)

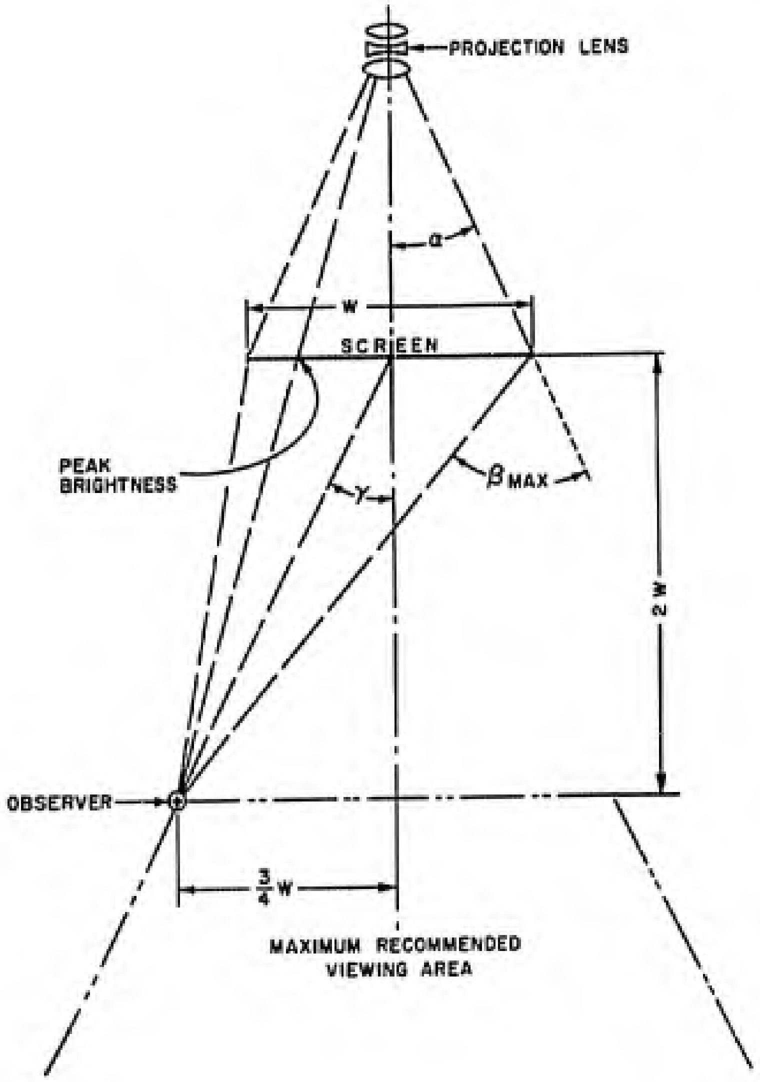

Fig. 3. Viewing Angle γ and Bend Angle β for a Rear-Projection Screen

UNIFORMITY OF SCREEN BRIGHTNESS

The permissible range of brightness across the screen, as viewed from any point within a recommended area, should be in accordance with the demands of the situation. For example, a projected backdrop for television or moving pictures must be much more uniformly bright than a classroom screen needs to be. Conversely, an auto-instructional device, where the viewer is generally on-axis, may be considerably less uniform, that is, it can have a wider range of screen brightness. (In this last case, in the uncommon event that detail in a dark corner of the picture is not sufficiently illuminated to carry out the intended purpose of the picture, the viewer's head can be moved slightly to bring the zone of maximum brightness into the dark corner area of the picture.)

The term "brightness" will be used in this study to refer specifically to the viewer's sensation of luminance. This is the response of the viewer to the stimulus of light. This response, rather than being linear, is nearly logarithmic, according to Fechner's Law (ref 3). The observable effect of this is that an apparent brightness difference will decrease as the surrounding illumination increases, even though the luminance ratio remains constant. For example, if the luminance falls off from 20 to 5 foot-Lamberts (ratio = 4:1), the brightness falls off 46%. However, if the luminance range is 80 to 20 foot-Lamberts (ratio = 4:1), the brightness drops only 32%.

TABLE II

BEND ANGLES FOR TYPICAL PROJECTION SYSTEMS AT 20° OFF AXIS

16mm movie			35mm filmstrip		35mm slide	
F. L.	α	β max.	α	β max.	α	β max.
0.625	16.9°	48.9°	----	----	----	----
1.0	10.8	42.8	----	----	----	----
1.5	7.2	39.2	16.8°	48.8°	----	----
2.0	----	----	12.7	44.7	18.6°	50.6°
3.0	----	----	8.6	40.6	12.6	44.6
4.0	----	----	----	----	9.5	41.5

NOTE: Of the three examples given in each category, the two longer focal length systems are standard with most manufacturers, while the shortest focal lengths are used in certain rear-projection products.

The diffusing property of a rear-projection screen is best described by the fall-off of luminance from the maximum at an on-axis position to that at any given bend angle. This factor can be determined from measurements or from reference data and may be expressed in terms representative of one of the following three methods:

(A) Relative luminance, as measured by a directional light meter, or goniophotometer, in uncalibrated readings.

(B) Luminance, as measured by an illuminometer, with reference to a standard diffusing surface, such as magnesium carbonate.

(C) Gain, or the ratio of luminance in foot-Lamberts to illumination in foot-candles.

In all cases, for standardization, the illumination should be a parallel beam of light impinging normally on the rear of the screen. Thus, the fall-off factor F_{β} at any bend angle β is the ratio of the reading at β to the maximum (on-axis) reading. At the far edge of the screen, these quantities become $F_{\beta\,max}$ at β_{max}. (Refer to Fig. 3.) In practice, readings should be taken at various bend angles. Sufficient points should be plotted to produce a smooth curve, thereby eliminating random errors.

Measurements were made on several commercially available untinted screen samples using Method (A) above, which is described in more detail in Appendix I. The test screens were obtained from the following major sources:

Polacoat, Inc., 9750 Conklin Rd., Blue Ash, Ohio	10 varieties
Trans-Lux Corp., 30-12 41st Ave., Long Island City 1, N. Y.	6 varieties

For comparison, some other diffusing materials were measured, including:

2x and 4x (Marks Polarized Corp., 153-16 Tenth Ave., Whitestone, N. Y.)
Kronoflex drafting mylar (Chas. Bruning Co., Inc., 1800 Central Rd., Mount Prospect, Ill.)
Ground Lucite or Plexiglas
Ground glass
Opal glass

The readings for eight representative screens selected from the complete tabulation in Appendix I have been plotted on a logarithmic scale in Fig. 4. (The bracketed scale graduations indicate the degree of logarithmic attenuation in the low-level readings.)

The ground glass, which diffuses the least, exhibits the narrowest peak, appearing as the objectionable "hot spot." The peak can be broadened by increasing the thickness of the diffusing layer to a few thousandths of an inch. This may be accomplished in different ways:

(a) by using a coarser grind, as in the ground Lucite sample

(b) by using a thin material that has diffusing (matte) surfaces on both sides, as in the Kronoflex

(c) by applying a specially formulated coating to a transparent base material.

The "ideal" screen would have a distribution curve approaching a horizontal line at a high level extending out to 50° or more, at which bend angle the luminance would drop rapidly to a low level. Such a screen would appear equally bright from all points in the audience area. However, the directional scattering of light by orienting microscopic reflecting surfaces is far from 100% efficient. Therefore, as the central peak is broadened by increasing the amount of diffusion, it is also lowered, as is illustrated dramatically in Fig. 6. Since the projected image will then appear dimmer, the best compromise will depend on the brightness of the area where the screen is used and other circumstances. Thus both Polacoat and Trans-Lux provide a variety of types suited to various situations. Most audiovisual applications, however, are well served by the general purpose types, Polacoat LS60 or Luxchrome 70. Full information on the characteristics and applications of special types can be obtained from the manufacturers.

Briefly, the special types include highly diffusing white screens for such applications as wide angle viewing in darkened rooms or simultaneous front and rear projection. Examples are Polacoat Type OC50, Trans-Lux Types S-50-R and Process, and Marks Polarized "Spredlite" screens. Most other types of coating are blackened to improve contrast by reducing diffuse front reflection. (This problem will be discussed in the next subsection.) Examples of especially dark screens are Polacoat Type LS40 and Trans-Lux Black. Looking again at Fig. 4, the considerable difference in diffusing power between these last two screens is clearly evident. Yet the fairly consistent rate of fall-off of the other types shown, as well as their improvement over ground glass, is equally evident.

From the curves shown in Figs. 4, 5 and 6, values of $F_{\beta\ \max}$ were found for the two limiting values of $\beta_{\max}$ determined earlier, namely 40° and 50°. These values are given in Table III in decreasing order, which corresponds to a decreasing order of diffusing power. Although the data given for three of the samples were arrived at by different researchers using different methods and different numerical values, it can be seen that the resulting fall-off factors for each of these samples are in fairly close agreement.

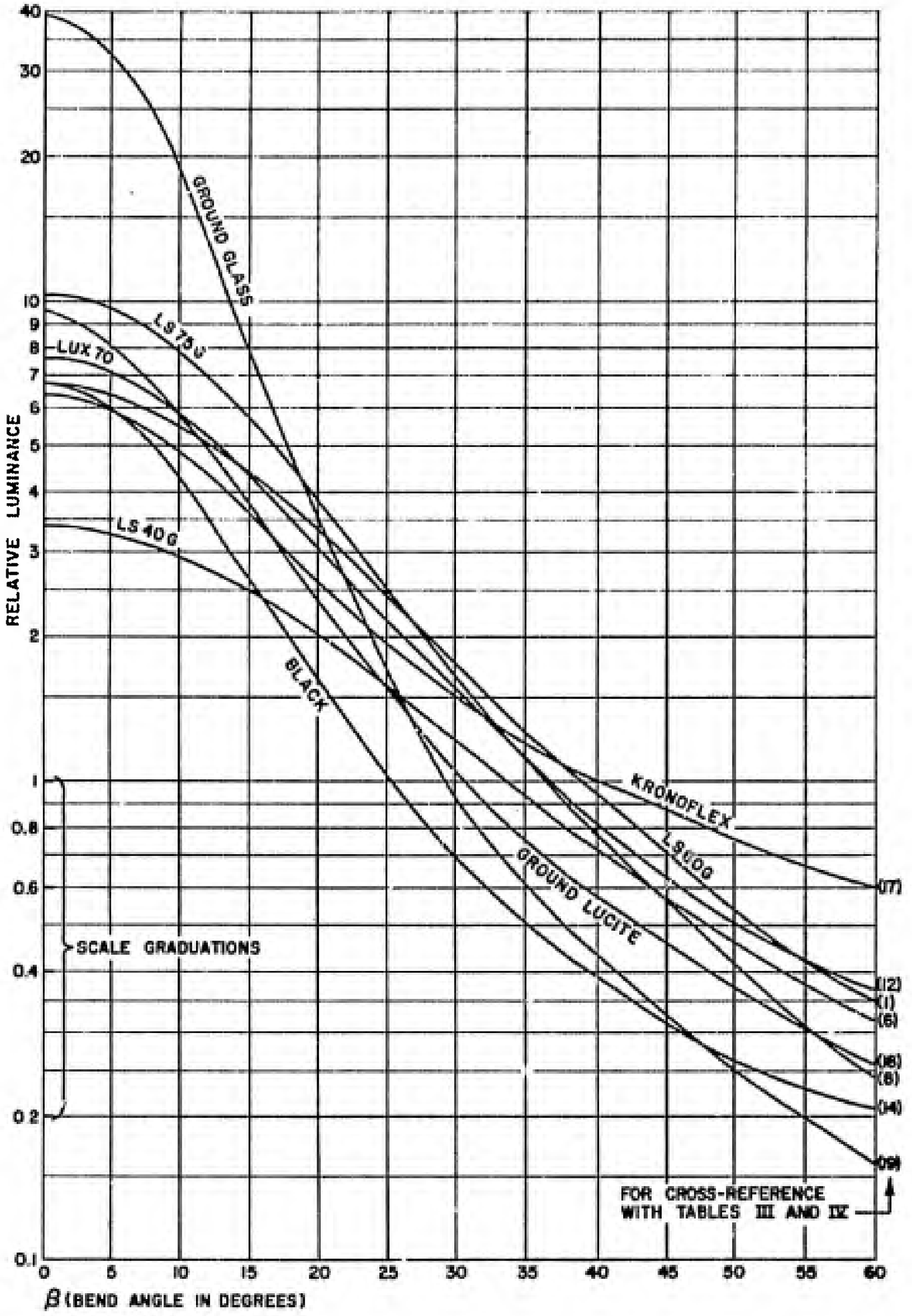

Fig. 4. Distribution Curves for Several Typical Screens

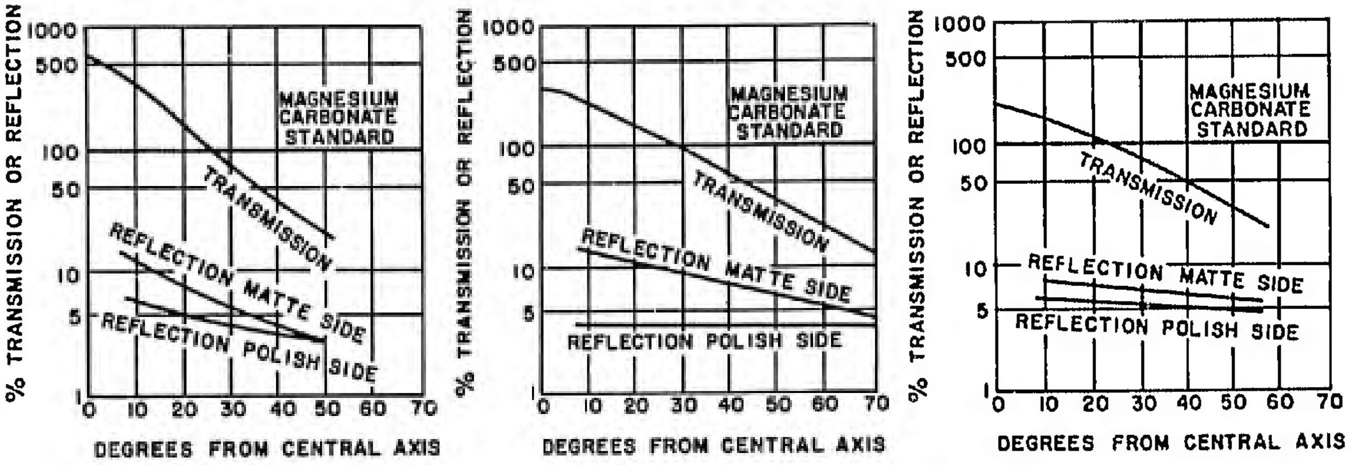

Fig. 5. Distribution Curves for Three Polacoat Screens, l. to r., LS75G (500% Gain), LS60G (250% Gain), and LS60F (Flexible, 200% Gain). Reproduced from Dryer (Ref 1).

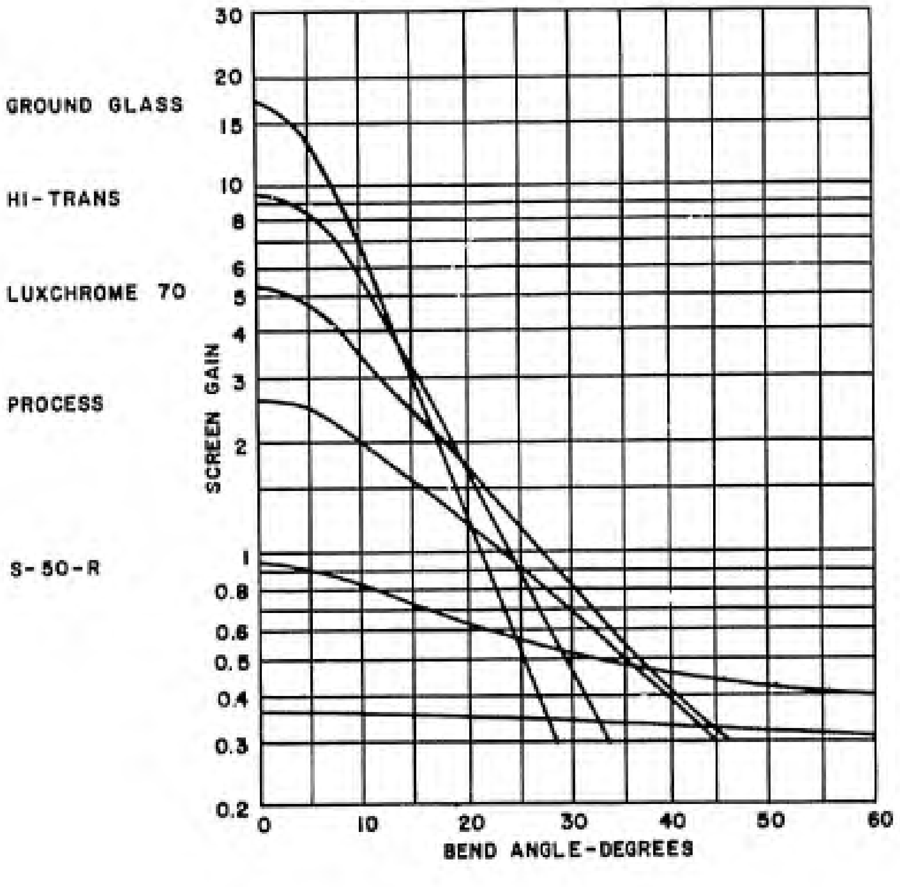

Fig. 6. Distribution Curves for Several Typical Screens, Identifiable as the Trans-Lux Products Shown. Reproduced from Vlahos (ref 4).

TABLE III

FALL-OFF FACTORS AT MAXIMUM BEND ANGLES FOR VARIOUS SCREENS

Material	Method (see notes)	Readings at β =			F_β at β =	
		0°	40°	50°	40°	50°
LS40G (6)	A	3.40	.71	.46	.21	.14
Kronoflex (17)	A	6.40	1.01	.75	.16	.12
LS60G (1)	A	6.75	.93	.54	.14	.08
	A'	1.00	.18	.10	.18	.10
	B	3.00	.62	.38	.21	.13
Luschrome 70 (12)	A	7.60	.81	.54	.11	.07
	C	5.30	.42	.24	.08	.05
LS75G (8)	A	10.20	.77	.41	.08	.04
	B	5.80	.39	.22	.07	.04
Trans-Lux Black (14)	A	6.70	.39	.26	.06	.04
Ground Lucite (18)	A	9.50	.57	.37	.06	.04
Ground glass (19)	A	39.30	.43	.25	.01	.006

NOTES:

1. Method A data are from the author's measurements, using a goniophotometer. (Method A' refers to the Audio-Graphic measurements described in Appendix II.)

2. Method B data are from Fig. 5 (redrawn from Dreyer, ref 1) and are relative to a $MgCO_3$ standard.

3. Method C data are from Fig. 6 (redrawn from Vlahos, ref 4) and are in terms of gain.

4. The readings (relative luminance), being derived from different methods, are based on different arbitrary scales. The fall-off factors F_β, however, are normalized and may be compared.

As a further illustration of the effect of viewing angle on the distribution of screen luminance, an analysis of a specific audiovisual product, the Graflex Audio-Graphic, is presented in Appendix II. From these data, the apparent brightness B was calculated for each of several points on the screen viewed from each of several positions in the audience area. The actual fall-off of incident illumination was combined with the screen fall-off as a function of bend angle, using the published LS60 gain of 2.5 (250%). These curves, plotted in Fig. 7, show the variation in brightness across the screen from each of several viewing angles.

AMBIENT ILLUMINATION REFLECTANCE AND CONTRAST

At the beginning of this section it was stated that an important advantage of rear projection is that reflection of surrounding, or ambient, light by the front of the screen can be reduced to improve contrast in the picture. As a frame of reference, a logarithmic scale of ambient light levels (in footcandles) which occur in typical situations pertinent to this study is given below. The values at work stations were measured in the final assembly area of Graflex, Inc. The others are adapted from the IES Lighting Handbook (ref. 5).

0.1	Theaters during performance.
0.3	Minimum for areas of uncertain footing.
1	Work station well shielded from all extraneous light sources for optical image evaluation.
3	Radar room; darkened classroom.
10	Between work stations, well away from bench lights and windows.
30	Minimum for classroom or office.
100	Work station for medium assembly work.

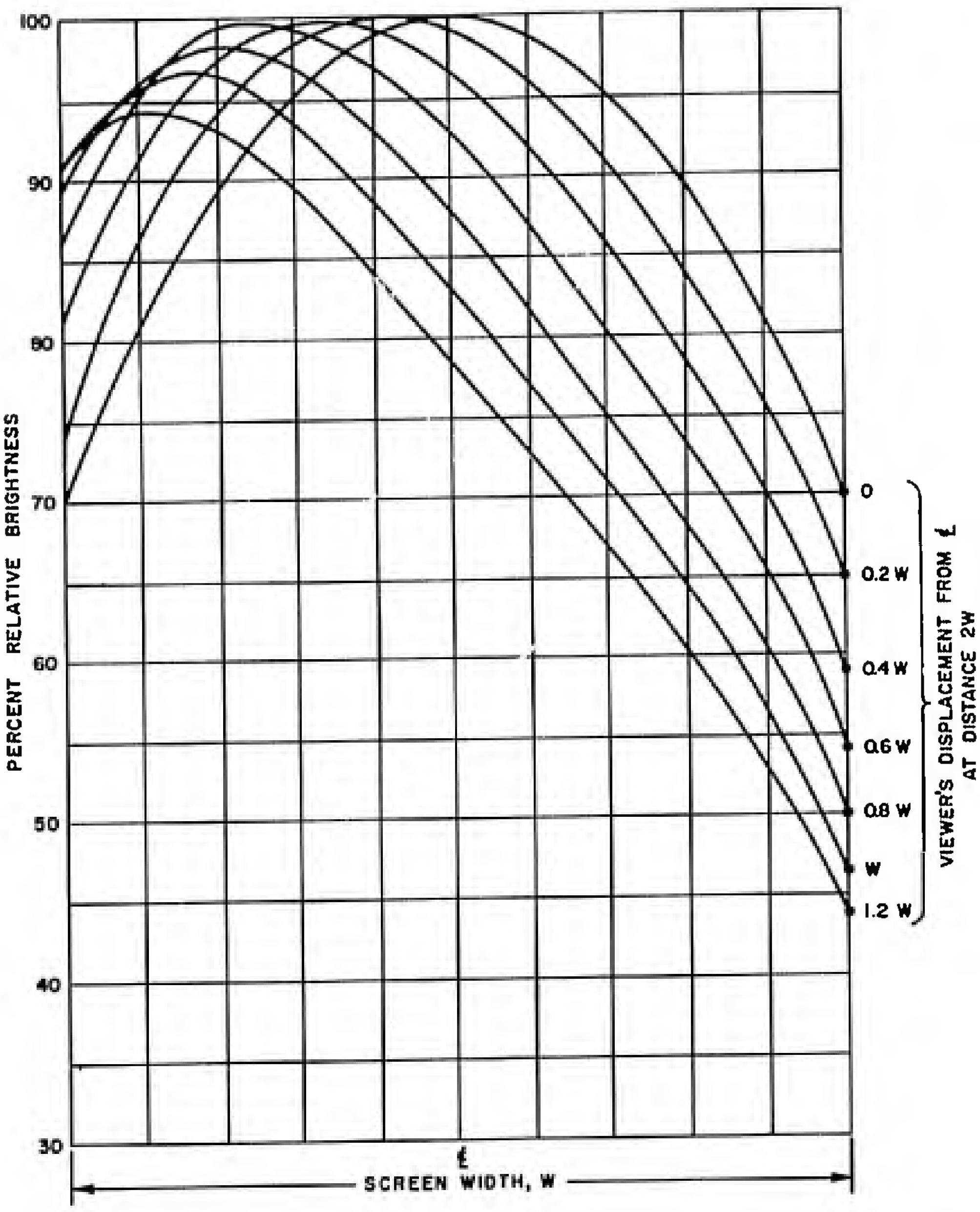

Fig. 7. Brightness Distribution of the Audio-Graphic Screen

For most instructional applications, the lighting can be controlled sufficiently to consider the limits to be 3 to 30 foot-candles. If the room is strongly lighted by overhead fixtures, a hood is effective in shading the screen. If the light is well diffused by light-colored walls, as is often the case, a hood adds little to the performance of the screen, especially the low reflection type of screen discussed in the following paragraphs. But regardless of conditions, direct illumination from windows or light fixtures behind the viewer is to be avoided.

The greater part of ambient illumination in a typical classroom or work area is diffuse and can be measured as I_a footcandles. When I_a is diffusely reflected toward the viewer by a screen, the "dark screen" luminance of the screen from ambient light alone can be expressed by I_aR_γ, where R_γ is the reflectance factor at the viewing angle γ. Reflectance factor measurements were made on all the screen samples which had been measured previously for luminance. Although the screen brightness is actually derived from diffused ambient light scattered in one direction toward the observer, a more convenient arrangement, which avoids the difficulty of standardizing the diffuseness of the ambient light yet is a close approximation of reality, is to reverse the situation, as described below.

Illumination was provided by a projector at close range throwing a parallel beam at an angle of 45° to the sample. The resulting elliptical spot was held constant. Readings were taken with a foot-candle meter mounted parallel to, and 2-1/2 inches away from the sample, so as to accept a wide angle of diffused light yet avoid any specular reflection. Calibration of readings was attained by measuring several white paper samples and correlating the readings with book-value reflectances (ref 6).

It can be seen from Table IV that there is a distinct difference between one group of screens, whose reflectances range from 3 to 13%, and the remainder, which range from 23 to 42%. In general, the low reflectance screens, the Polacoat LS (Lenscreen) series and the Trans-Lux Luxchromes and Black, have a black pigment added to the formula which absorbs a certain percentage of the incident light instead of reflecting it. This also reduces the transmittance or gain. The net result of blackening is a picture with better contrast (deeper blacks). The use of the darkest screens should be restricted to applications where ambient light behind the screen cannot be controlled by an enclosure. In this situation, the output of the projector must also be greater to compensate for the light loss. Further information on the proper selection of screens can be found in the technical literature available from the above-named companies.

The cost per square foot of these screens generally varies with the base material (glass, Plexiglas or vinyl), the processing cost being reasonably stable. Recently, "No-Glare" picture glass and Plexiglas screens have been made available, though at additional cost.

TABLE IV

REFLECTANCE AND TRANSMITTANCE OF SCREEN MATERIALS

NOTE: R indicates that the coated side is to the rear, ie, the light is reflected off the uncoated side. F indicates the reverse.

		Reading		Reflectance		Transmittance
		R	F	R	F	
(1)	LS60G-1/8	2.8	5.0	5.4%	9.7%	59%
(2)	LS60PL-1/16	2.7	4.9	5.2	9.5	52
(3)	LS60VSR-015	5.7	5.1	11.0	9.9	54
(4)	LS60VR-025	2.9	4.4	5.6	8.5	50
(5)	LS60FM	4.9	6.5	9.5	12.5	54
(6)	LS40G-1/8	1.6	4.0	3.1	7.7	39
(7)	LS40BFM	2.9	4.5	5.6	8.7	45
(8)	LS75G-1/8	2.7	4.9	5.2	9.5	68
(9)	OC50FW	12.5	12.5	24.0	24.0	67
(10)	OC50G-1/8	12.5	13.5	24.0	26.0	54
(11)	Luxchrome 50	4.5	4.3	8.7	8.3	49
(12)	Luxchrome 70	6.6	6.4	12.8	12.4	57
(13)	S-50-R	18.0	17.0	35.0	33.0	45
(14)	Translux Black	3.0	2.9	5.8	5.6	33
(15)	Translux Process	13.0	13.5	25.0	26.0	61
(16)	Hi-Trans	12.0	12.5	23.0	24.0	68
(17)	Kronoflex	16.5	16.5	32.0	32.0	59
(19)	Ground glass	4.0	4.7	7.7	9.1	87
(20)	Opal glass	16.0	17.5	31.0	34.0	51
(21)	Marks 2X	7.0	7.3	13.5	14.1	79
(22)	Marks 4X	19.5	21.5	38.0	42.0	46

Calibration of Reflectance Scale.

Type of paper	IES reflectance	Reading	Calibrated reflectance*
White bond	73 - 80	42.0	81
Adding machine	73 - 80	37.0	72
Matte photo	83	43.5	84
Glossy photo	83	42.0	81
Newsprint	68	33.5	65

* Conversion factor = 1.93

It should be noted that the low reflectance of ground glass is due, not to absorption, but to its low diffusion and corresponding high straight-through transmittance, which causes the ground glass to appear dark when viewed against a dark background. If adequate projection illumination is available, the most desirable characteristics for rear projection screens will be found in the moderately blackened screens which combine two otherwise mutually exclusive properties: the low reflectance (but low diffusion) of ground glass and the high diffusion (but high reflectance) of thicker or double diffusing layers such as the matte mylar.

Table IV also gives the percent transmittance of these materials. Measurements were made by placing the footcandle meter cell directly behind the sample. Reference direct readings were taken at the same position with the sample removed. It can be seen that the reduction in transmittance due to the blackening agent is generally considerably less than the corresponding reduction in reflectance. For example, let us compare two diffusers with very similar luminance distributions (especially in the range $\beta = 10°$ to $45°$), unblackened Kronoflex and moderately blackened Polacoat

LS60PL-1/16. The reflectance (coated side to the rear) is reduced from 32% to 5%, while the transmittance is reduced only from 59% to 52%. This illustrates the disadvantage of using a Kronoflex screen in a well-lighted room, even though its distribution is remarkably good. The importance of reducing reflectance is in the improvement of contrast.

Values of the contrast ratio C (highlight to dark screen, or clear film to maximum density) for various classes of filmed presentation have been recommended as follows (ref 7):

100:1	Full color rendition
25:1	Color diagrams and continuous tone black and white
5:1	Line drawings and text

Continuing our mathematical analysis, the product $I_a R_\gamma C$ thus gives the lowest clear-film luminance L_{min} allowable for a given combination of viewing location, screen and film. It is generally recommended that L_{min} not be allowed to fall below 5 to 10 footlamberts.

LUMEN OUTPUT REQUIREMENTS

From the discussion of the parameters of the system and its environment, a formula can be derived to give the minimum projector lumen output, or flux, Φ required for adequate screen illumination. The parameters, as have been shown, are subject to practical limitations. The flux formula is as follows:

$$\Phi \min = \frac{L_{min} A}{K G_{\beta_{max}}}$$

where L_{min} = lowest allowable clear-film luminance (footlamberts)

A = area (square feet)

K = projector illumination fall-off factor (0.5 to 0.75)

$G_{\beta_{max}}$ = screen gain at maximum bend angle

For the substitution of known values we shall use the form:

$$\Phi \min = \frac{I_a R_{\gamma_{max}} C A}{K F_{\beta_{max}} G_{max}}$$

where I_a = ambient illumination (footcandles)

$R_{\gamma_{max}}$ = reflectance factor at maximum viewing angle

C = recommended contrast ratio

$F_{\beta_{max}}$ = luminance fall-off factor at maximum bend angle

G_{max} = peak screen gain (on axis).

To illustrate the extreme range of lumen output required to satisfy all combinations of the parameters, even though they are held within quite reasonable limitations, two examples will be evaluated.

Example A

The Grailex Shadow Box, a mirrorless rear-projection enclosure, designed for group use in remote areas, has a 17 x 22-1/2 inch Kronoflex screen. For this example, it is being used to show ordinary color filmstrips (i. e., full color rendition not required) by means of a projector of average classroom quality under normal classroom lighting conditions.

Example B

A unit having a 6 x 8 inch Polacoat screen (LS-40) is being used to show line drawings and text projected by a well-designed projector intended for individual instruction (βmax = 35°) in a darkened classroom.

The substituted values representative of Examples A and B and the computed results are as follows:

	I_a	$R_{\gamma_{max}}$	C	A	K	$F_{\beta_{max}}$	G_{max}	Φ_{min}
(A)	30	.32	25	2.66	.60	.12	3.5	2500
(B)	3	.03	5	.33	.70	.28	1.7	5

use 5 (min.)

This range of 500 to 1 is far beyond the roughly proportional range of lamp wattages encountered in units designed for individual or group instruction. These generally run from 30 to 750 watts, a range of only 25 to 1. Obviously, limitations must be placed on the use of large screens in undarkened rooms. In any case, no sure statement can be made concerning the required lamp wattage until the actual optical system has been modeled, in conformance with the target cost and the performance parameters of the application.

SECTION IV

CONCLUSIONS

The dominant parameter in the lumen output requirement is ambient illumination, which we have already restricted to a range of 3 to 30. Even with such a restriction, this is a variation factor of 10. Reflectance is another variable which can reach a factor of 10 for an unblackened screen, as compared with a blackened screen, whose variation factor will not exceed 3. The range of acceptable contrast ratio, excluding the amount required for full color rendition, contributes a factor of 5. In addition, the screen area affects the power requirements of the optical projection system in direct proportion. The diffusing characteristics of the screen vary in a more limited range by comparison, inasmuch as the gain for maximum bend angles most often encountered (between 40° and 50°) does not exceed a factor of 4 for all screens.

It can be concluded that the desirable lumen output of a projector is very strongly dependent upon three factors relating to intended use: room lighting, audience size and picture content. If the requirements of the application are of a minimal nature, opportunity exists for substantial reduction in component cost at the design stage by specification of such units as a low wattage convection-cooled lamp, an uncoated diffusing screen, a lens system of lower quality, or combinations thereof.

The specification of lower level performance units will contribute significantly to a reduction in the quality of the viewing image. Such lowered quality would find little acceptance, given the current standards in schools and industry, even though cost is made attractive. However, there are vast areas in which present standards do not apply. Instruction in underdeveloped countries, where a sense of great urgency in attainment of skills and knowledge exists, presents a broad field for design of low-cost equipment to meet specific needs. As an example, it is entirely conceivable that remoteness of the area in which instruction is to be given would place much greater emphasis upon weight and portability of an instruction unit at the expense of image quality. This is an area of specific needs, and audiovisual designers must design to satisfy the specific requirements of the situation.

Defining the specific requirements, especially the minimal performance, that can be tolerated in relation to anticipated lighting, audience and picture content, is a separate consideration. It is here that the training specialist must be able to communicate his requirements to the audiovisual designer in measurable terms, so that the resulting product is adequate in both performance and reliability yet not burdened by excessive costs resulting from providing characteristics above and beyond those that will be actually utilized.

GLOSSARY

ACCOMMODATION	- The elastic ability of the eye and its support muscles which permits it to respond physically to changes in focal distance and light intensity.
AMBIENT	- Environmental, i.e., the immediate surrounding conditions.
ASPHERIC	- Lens surface which deviates from spherical to improve the optical performance.
BRIGHTNESS	- Quantitative sensation of light intensity. Specifically, the logarithm of luminance.
CELL	- A short tube which holds a lens or lens system.
FALL-OFF-FACTOR	- The quotient of a specified off-center value divided by the central maximum value.
FIRE POLISH	- A commercial process used to produce a low quality surface finish on optical elements.
FLUX (LUMINOUS)	- The flow of radiant energy emitted by a point source. (Unit: 1 lumen = 1 candle per steradian)
FOCAL LENGTH	- The distance from the node of a lens system to the point at which parallel rays will converge after refraction by the lens system.
FOOT-CANDLE	- See illumination.
FOOT-LAMBERT	- See luminance.
GAIN	- The ratio of on-axis luminance in foot-Lamberts to incident illumination in foot-candles.
ILLUMINATION	- Luminous flux per unit area (Unit: 1 foot-candle = 1 lumen per square foot).
IMAGE PLANE	- The plane in space where the image of an object is formed after refraction by a lens system.
LUMINANCE	- The luminous intensity of a diffusing surface per unit area as viewed from any specified direction (Unit: 1 footlambert = 1 lumen per square foot).
LUMEN	- See flux.
"ORANGE PEEL"	- A term used to describe a finished surface which appears smooth, but when viewed at an acute angle, will exhibit minute regular depressions resembling the outer skin of an orange.
SPRUE	- The stem on an injection molded part formed by the channel through which the molten plastic is forced into the mold.
VIRTUAL IMAGE	- A theoretical point from which light rays appear to diverge after refraction or reflection. In a lens system, a virtual image becomes the object for the next lens in the system.
VIGNETTING	- Darkening at the edges of a picture. In illumination, a reduction in brightness as the distance from the optical axis increases.

APPENDIX I

GONIOPHOTOMETRIC MEASUREMENTS

EQUIPMENT

The projector used was a 750-watt Graflex School Master with a 2-inch f/3.5 projection lens from a Graflex Compact projector specially mounted in the lens tube. It was operated at 118 volts, regulated to within ± 0.2 volts.

The goniophotometer consisted of a baffled, light-tight enclosure 12 inches long with a 1-1/2 inch diameter aperture at the front end and a slot to accept the foot-candle meter paddle at the back end. An upright stage to support the screen samples was mounted 1 inch in front of the front aperture. A pivot directly under the stage allowed the enclosure to be swung horizontally through an angle of 45° with the photocell at a constant distance from the vertical centerline through the sample. The foot-candle meter was a Weston Model 603. (For measurements in foot-candles, all readings must be doubled, since only one of the two photocells in the paddle was used.) The angular response distribution (beam width) of the goniophotometer was computed as that portion of the photocell area illuminated by a parallel beam entering the front aperture as a function of the off-axis angle. From Fig. 8 it can be seen that the acceptance angle at half the measured illumination is about 6°, which is quite acceptable for the smooth rate of fall-off encountered here.

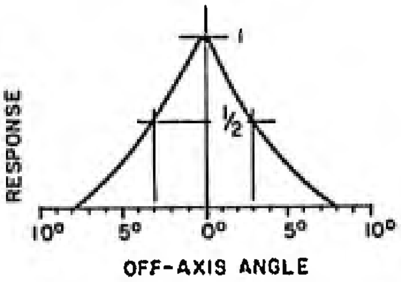

Fig. 8. Angular Response Distribution

PROCEDURE

The single-frame projector aperture (18 x 24mm) was projected in focus on the stage, enlarged to 8 x 6 inches, in two positions. Position A - projector axis in line with 0° photometer axis; Position B - projector rotated 15° horizontally on pivot axis for measurement at bend angles up to 60°. (See Fig. 9.)

NOTE: The screen-to-photocell distance (one foot) and the 750-watt lamp were chosen so that all readings would fall within the range of the foot-candle meter. The 2-inch lens and 20-inch lens-to-screen distance were chosen to simulate a small rear-projection device.

Readings were taken every 5° up to 45° in position A and from 20° to 45° in position B. The overlapping readings were averaged. A constant check was maintained on progressive errors by taking readings with sample removed periodically throughout the series. The materials and readings are listed in Tables V and VI, respectively.

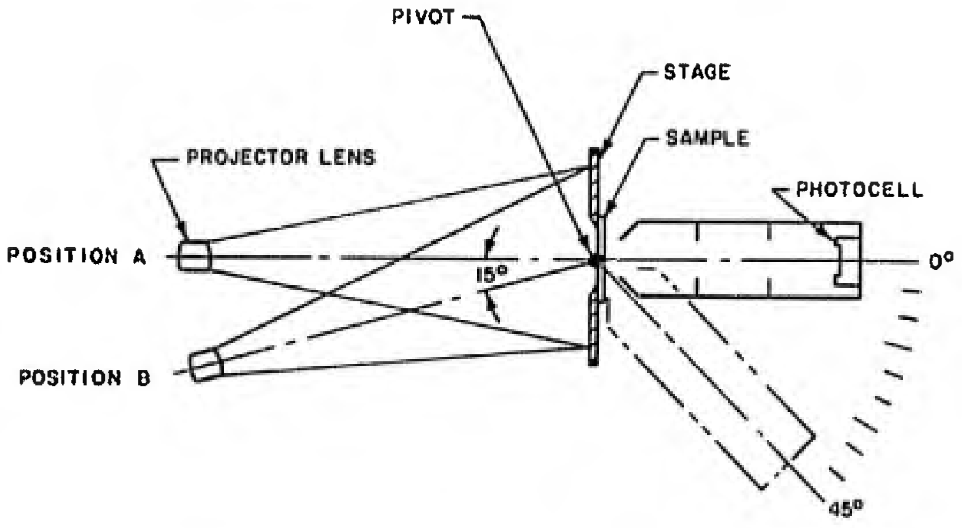

Fig. 9. Top View of Goniophotometer

TABLE V

SAMPLE SCREEN MATERIALS

POLACOAT, INC., Blue Ash, Ohio

*(1) LS60G 1/8
(2) LS60PL 1/16
(3) LS60VSR 015
(4) LS60VR 025
(5) LS60FM
* (6) LS40G 1/8
(7) LS40BFM
* (8) LS75G 1/8
(9) OC50FW
(10) OC50G 1/8

TRANS-LUX CORP., Long Island City, N. Y.

(11) Luxchrome 50
*(12) Luxchrome 70
(13) Type 9-50-R
*(14) Type Black
(15) Type Process
(16) Type Hi-Trans

MISCELLANEOUS MATERIALS

*(17) Drafting Mylar (Kronoflex)
*(18) Fine ground Lucite
*(19) Fine ground glass
(20) Opal glass

MARKS POLARIZED CORP., Whitestone, N. Y.

(21) 2X
(22) 4X

*Plotted in Fig. 4.

TABLE VI

GONIOPHOTOMETRIC READINGS ON SAMPLE SCREEN MATERIALS

β	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
0°	6.75	4.75	5.60	4.45	4.60	3.40	4.50	10.20	4.70	2.80
5	6.40	4.60	5.40	4.40	4.40	3.25	4.30	9.75	4.45	2.75
10	5.55	4.15	4.80	4.00	3.90	2.95	3.70	7.90	3.85	2.60
15	4.40	3.45	4.00	3.40	3.25	2.45	3.00	5.60	3.20	2.45
20	3.25	2.75	3.15	2.75	2.65	2.00	2.45	3.80	2.65	2.25
25	2.40	2.10	2.40	2.20	2.20	1.60	1.90	2.50	2.20	2.00
30	1.75	1.60	1.80	1.70	1.80	1.20	1.55	1.65	1.80	1.80
35	1.25	1.20	1.30	1.25	1.45	0.90	1.20	1.05	1.55	1.65
40	0.95	0.90	0.95	0.95	1.20	0.75	0.95	0.80	1.35	1.45
45	0.70	0.75	0.70	0.75	0.95	0.60	0.80	0.60	1.15	1.30
50	0.55	0.60	0.55	0.60	0.80	0.45	0.70	0.40	0.95	1.20
55	0.40	0.45	0.45	0.50	0.65	0.40	0.60	0.30	0.85	1.00
60	0.35	0.40	0.35	0.40	0.60	0.30	0.50	0.25	0.75	0.90

β	(11)	(12)	(13)	(14)	(15)	(16)
0°	7.70	7.60	2.50	6.70	6.00	14.8
5	7.00	7.00	2.45	6.00	5.65	12.7
10	5.45	5.80	2.20	4.20	4.70	8.15
15	3.80	4.30	1.45	2.60	3.65	4.60
20	2.50	3.00	1.70	1.65	2.75	2.75
25	1.70	2.20	1.50	1.00	2.10	1.80
30	1.10	1.55	1.30	0.70	1.70	1.30
35	0.80	1.10	1.15	0.50	1.35	1.00
40	0.60	0.80	1.05	0.40	1.10	0.85
45	0.50	0.65	0.95	0.30	0.95	0.75
50	0.40	0.50	0.85	0.25	0.75	0.60
55	0.35	0.45	0.80	0.25	0.65	0.55
60	0.25	0.35	0.75	0.20	0.55	0.50

β	(17)	(18)	(19)	(20)	(21)	(22)
0°	6.40	9.50	39.3	1.80	10.9	1.70
5	6.00	8.00	33.3	1.80	10.15	1.70
10	4.85	5.70	18.3	1.75	8.50	1.70
15	3.60	3.70	7.75	1.70	6.25	1.60
20	2.60	2.35	3.45	1.65	4.45	1.50
25	1.95	1.55	1.70	1.60	3.10	1.45
30	1.50	1.00	0.90	1.55	2.20	1.35
35	1.20	0.75	0.60	1.45	1.60	1.30
40	1.00	0.60	0.40	1.40	1.15	1.25
45	0.90	0.50	0.35	1.30	0.85	1.15
50	0.75	0.35	0.25	1.25	0.70	1.05
55	0.65	0.30	0.20	1.25	0.55	1.00
60	0.60	0.25	0.15	1.20	0.40	0.95

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APPENDIX II

MEASUREMENTS ON AUDIO-GRAPHIC INSTRUCTOR

INCIDENT ILLUMINATION

The screen was removed from an Audio Graphic Instructor and, with the filament operating at very low voltage, the lamp and its spherical reflector were adjusted to present a full and uniform filament image to all parts of the screen area. A foot-candle meter cell was held at one inch intervals across the screen aperture vertically and horizontally thru the center, and at the corners. The cell was tilted to intercept the incident light normally to give a maximum reading. (Later measurements involving bend angle used normal incidence). The voltage was held constant to ±0.2 volt at 118 volts. Since readings could be taken no closer than an inch from the edges of the 8" x 10" screen aperture, the corner readings, being taken at a distance of 5" from the center, were substituted for readings at the extreme edges. The averages of the readings were plotted. A shadow and adjacent bright spot near the center caused some uncertainty as to the peak illumination. However, a smooth curve could be drawn (Fig. 10). The distribution of incident illumination, I, which appears to be typical of a well designed but low cost projection system, is as follows:

Distance from center (inches)	I (Foot-candles)	I (Relative)
0	106	1.00
1	105	.99
2	103	.97
3	98	.92
4	86	.81
5	64	.60

Using a short-cut method of calculating average screen illumination, namely, the mean of one center reading and two readings taken at a distance of 4.5" from center (5% of screen width measured from edge), the incident luminous flux was found to be:

$$L = \frac{8 \times 10}{144} \times \frac{106 + 76 + 76}{3} = 48 \text{ lumens}$$

SCREEN LUMINANCE

An Audio-Graphic screen (Polacoat type LS60PL-1/16) was selected at random and measured for relative luminance at various bend angles by the method described in Appendix I, with the following changes: (a) The projector was focused at infinity to give a parallel incident beam, (b) the screen was brought close enough to the projector to give a full scale reading (1.00) on axis, and (c) readings were extended to 65° by using a 20° off-axis incident beam. The plotted readings produced a smooth curve as shown in Fig. 11.

The angles of incidence α at one-inch intervals S across the screen were calculated, using a node-to-screen distance of 16.88". (See Table VII.) Then the viewing angles γ_{PS} for observers at 7 positions P 20" (2W) from the screen and at 2" intervals from the centerline out to 1.2W, were tabulated for each of the 11 points S across the screen at which the illumination was measured. The bend angles were found from $\beta = \alpha + \gamma_{PS}$, with due regard for sign. From Fig. 11 the relative luminance from uniform illumination, L_o, was read off for every β. The relative luminance due to the non-uniform illumination for every point and observer location was found from $L_i = I \times L_o$. (This completes the calculations in Table VII). A family of curves was plotted (Fig. 12) to demonstrate the variation in luminance across the screen for the several positions checked.

Lastly, the percent brightness for each P and S was calculated by normalizing to 100 each value of log 250 L_i, as in Table VIII. (The factor of 250 results from a gain of 2.5 times 100 foot-candles.) The plot of these values appears in Fig. 7 in the text.

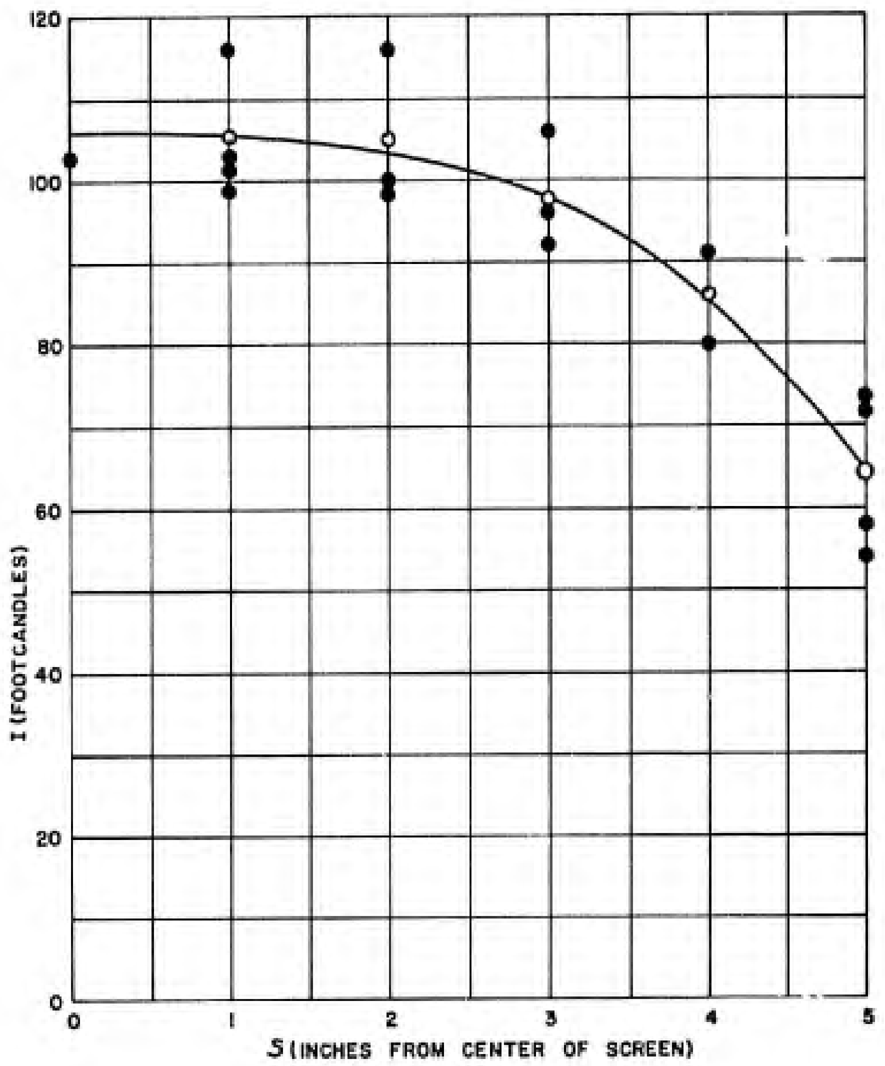

Fig. 10. Incident Illumination Distribution (Open Circles are Average Readings)

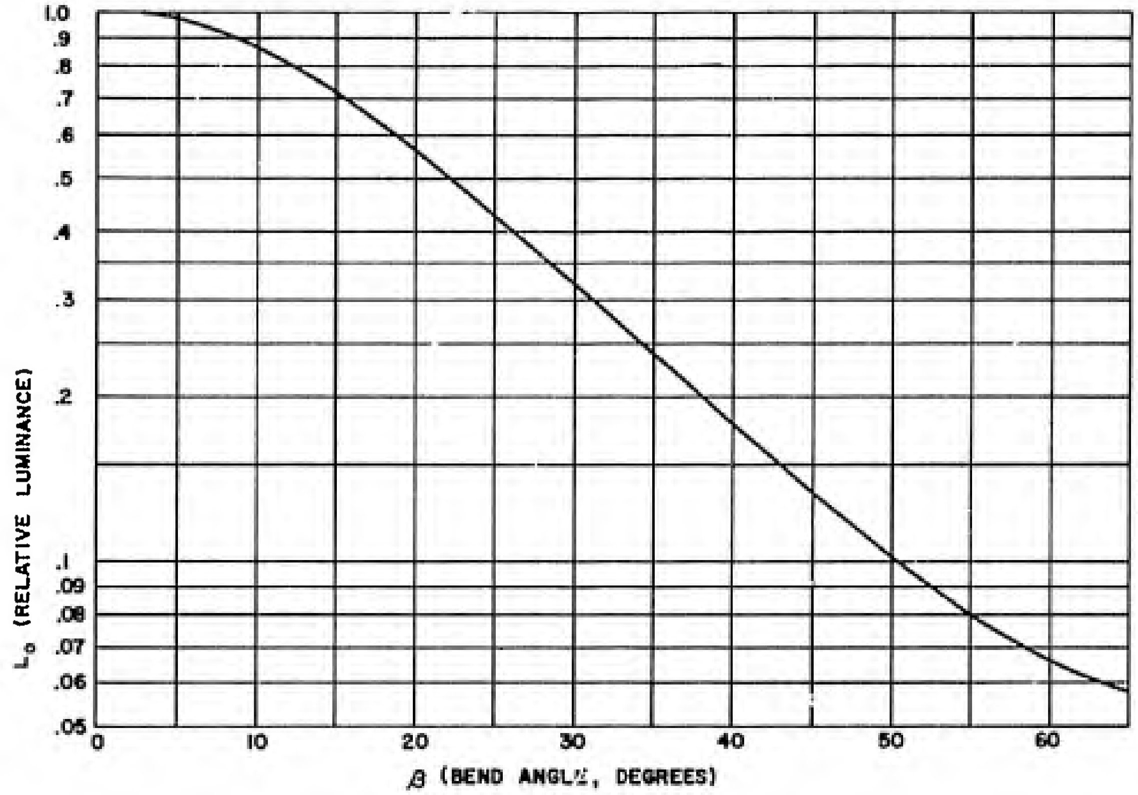

Fig. 11. Relative Luminance Distribution from Uniform Illumination

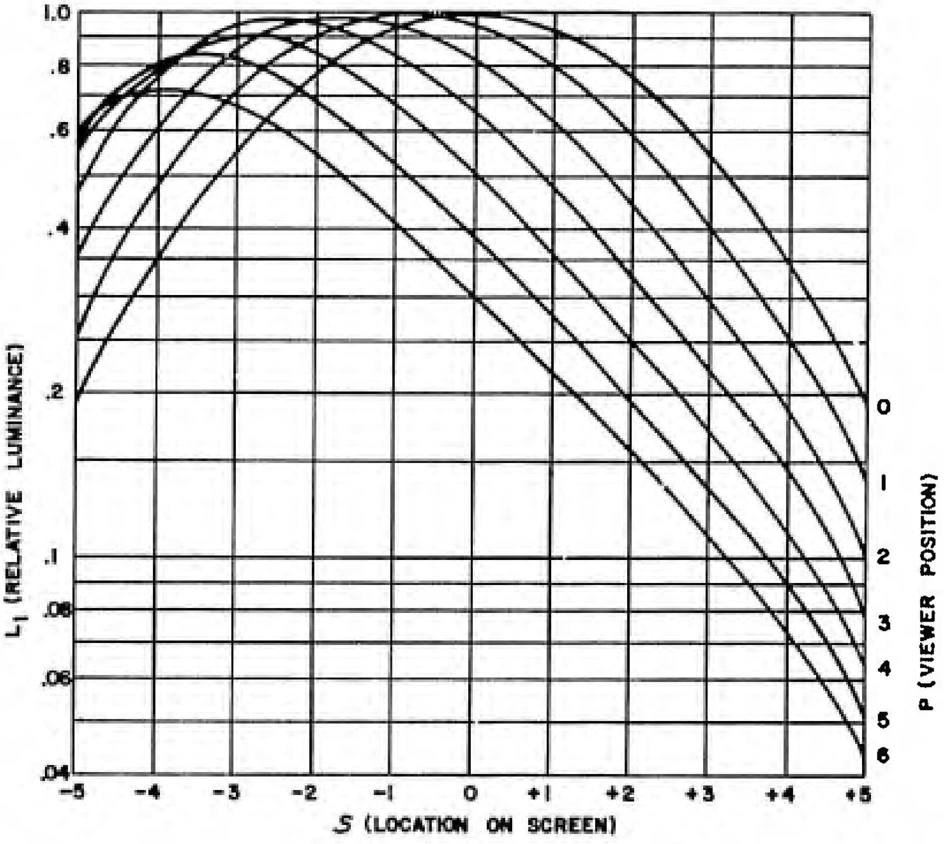

Fig. 12. Luminance Distribution of the Audio-Graphic Screen

TABLE VII

RELATIVE LUMINANCE CALCULATIONS

		P =	0	1	2	3	4	5	6
		γ =	0.0°	5.7	11.3°	16.7°	21.8°	26.6°	31.0°
S = +5	α = 16.5°	γ_{PS} =	14.0	19.3	24.2	28.8	33.0	36.9	40.0
		β =	30.5	35.8	40.7	45.3	49.5	53.4	56.9
	I = .60	L_o =	.31	.23	.17	.13	.105	.085	.073
		L_i =	.19	.14	.102	.078	.063	.051	.044
+4	13.3°		11.3	16.7	21.8	26.6	31.0	35.0	38.7
			24.6	30.0	35.1	39.9	44.3	48.3	52.0
	.81		.43	.32	.24	.18	.14	.11	.090
			.35	.26	.19	.15	.113	.089	.073
+3	10.1°		8.5	14.0	19.3	24.2	28.8	33.0	36.9
			18.6	24.1	29.4	34.3	38.9	43.1	47.0
	.92		.60	.44	.33	.25	.19	.15	.12
			.55	.40	.30	.23	.17	.14	.11
+2	6.8°		5.7	11.3	16.7	21.8	26.6	31.0	35.0
			12.5	18.1	23.5	28.6	33.4	37.8	41.8
	.97		.79	.62	.46	.34	.26	.20	.16
			.77	.60	.45	.33	.25	.19	.16
+1	3.4°		2.9	8.5	14.0	19.3	24.2	28.8	33.0
			6.3	11.9	17.4	22.7	27.6	32.2	36.4
	.99		.94	.81	.64	.48	.36	.28	.22
			.93	.80	.63	.48	.36	.28	.22
0	0.0°		0.0	5.7	11.3	16.7	21.8	26.6	31.0
			0.0	5.7	11.3	16.7	21.8	26.6	31.0
	1.00		1.00	.95	.83	.66	.51	.39	.30
			1.00	.95	.83	.66	.51	.39	.30
-1	-3.4		-2.9	+2.9	8.5	14.0	19.3	24.2	28.8
			6.3	0.5	5.1	10.6	15.9	20.8	25.4
	.99		.94	1.00	.96	.85	.68	.53	.41
			.93	.99	.95	.84	.67	.52	.41
-2	-6.8		-5.7	0.0	5.7	11.3	16.7	21.8	26.6
			12.5	6.8	1.1	4.5	9.9	15.0	19.8
	.97		.79	.94	1.00	.97	.87	.71	.57
			.77	.91	.97	.94	.84	.69	.55
-3	-10.1		-8.5	-2.9	+2.9	8.5	14.0	19.3	24.2
			18.6	13.0	7.2	1.6	3.9	9.2	14.1
	.92		.60	.78	.93	.99	.98	.89	.74
			.55	.72	.86	.97	.90	.82	.68
-4	-13.3		-11.3	-5.7	0.0	5.7	11.3	16.7	21.8
			24.6	19.0	13.3	7.6	2.0	3.4	8.5
	.81		.43	.59	.77	.92	.99	.98	.90
			.35	.48	.62	.75	.80	.79	.73

TABLE VII, CONTINUED

	P =	0	1	2	3	4	5	6
S = -5	-16.5	-14.0	-8.5	-2.9	+2.9	8.5	14.0	19.3
		30.5	25.0	19.4	13.6	8.0	2.5	2.8
	.60	.31	.42	.58	.76	.91	.99	.99
		.19	.25	.35	.46	.55	.59	.59

TABLE VIII

PERCENT BRIGHTNESS CALCULATIONS

	P =	0	1	2	3	4	5	6
S = +5	L_i =	.19	.14	.102	.078	.063	.051	.044
	250 L_i =	47.5	35.0	25.50	19.5	15.75	12.75	11.0
	log 250 L_i =	1.677	1.544	1.406	1.290	1.197	1.106	1.041
	B (%) =	69.9	64.4	58.6	53.8	49.9	46.1	43.4
+4		.35	.26	.19	.15	.113	.089	.073
		87.5	65.0	47.5	37.5	28.25	22.25	18.25
		1.942	1.813	1.677	1.574	1.451	1.347	1.261
		81.0	75.6	69.9	65.6	60.5	56.2	52.6
+3		.55	.40	.30	.23	.17	.14	.11
		137.5	100.0	75.0	57.5	42.5	35.0	27.5
		2.138	2.000	1.875	1.760	1.628	1.544	1.439
		89.2	83.4	78.2	73.4	67.9	64.4	60.0
+2		.77	.60	.45	.33	.25	.19	.16
		192.5	150.0	112.5	82.5	62.5	47.5	40.0
		2.284	2.176	2.051	1.916	1.796	1.677	1.602
		95.2	90.7	85.5	79.9	74.9	69.9	66.8
+1		.93	.80	.63	.48	.36	.28	.22
		232.5	200.0	157.5	120.0	90.0	70.0	55.0
		2.366	2.301	2.197	2.079	1.954	1.845	1.740
		98.7	96.0	91.6	86.7	81.5	76.9	72.6
0		1.00	.95	.83	.66	.51	.39	.30
		250.0	237.5	207.5	165.0	127.5	97.5	75.0
		2.398	2.376	2.317	2.217	2.106	1.989	1.875
		100.0	99.1	96.6	92.5	87.8	82.9	78.2
-1		.93	.99	.95	.84	.67	.52	.41
		232.5	247.5	237.5	210.0	167.5	127.5	102.5
		2.366	2.394	2.376	2.322	2.224	2.106	2.011
		98.7	99.8	99.1	96.8	92.7	87.8	83.9
-2		.77	.91	.97	.94	.84	.69	.55
		192.5	227.5	242.5	235.0	210.0	172.5	137.5
		2.284	2.357	2.385	2.371	2.322	2.237	2.138
		95.2	98.3	99.5	98.9	96.8	93.3	89.2

TABLE VII, CONTINUED

P =	0	1	2	3	4	5	6
-3	.55	.72	.86	.97	.90	.82	.68
	137.5	180.0	215.0	242.5	225.0	205.0	170.0
	2.138	2.255	2.332	2.385	2.352	2.312	2.230
	89.2	94.0	97.2	99.5	98.0	96.4	93.0
-4	.35	.48	.62	.75	.80	.79	.73
	87.5	120.0	155.0	187.5	200.0	197.5	182.5
	1.942	2.079	2.190	2.273	2.301	2.296	2.261
	81.0	86.7	91.3	94.8	96.0	95.7	94.3
-5	.19	.25	.35	.46	.55	.59	.59
	47.5	62.5	87.5	115.0	137.5	147.5	147.5
	1.677	1.769	1.942	2.061	2.138	2.169	2.169
	69.9	73.8	81.0	85.9	89.2	90.5	90.5

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