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PHOTOMETER FOR LUMINESCENT MATERIALS

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ABSTRACT

In evaluating the usefulness of luminescent materials it is necessary to take into account the behavior of the human eye at low values of luminance. A photometer that provides for the determination of low luminances, with due regard for the characteristic behavior of the eye at such values, is described. It is interesting to note that both the luminescent materials and some of the phenomena of vision for the nearly dark-adapted eye have been known for many years, although the use of modern lamps to produce higher and higher illuminations has made it generally unnecessary to consider these phenomena. However, the use of the airplane for bombing with the countermeasure of blacking out as a means of passive defense and the need for markers in the interiors of blacked-out ships have shown many of the luminscent materials to be practical instead of merely novel, and has led to the development of methods for measuring the luminances they yield.

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I. INTRODUCTION

Some of the luminescent materials have been known for hundreds of years but were considered more or less as novelties until recently, when their practical usefulness became apparent. Luminescence not outlasting the excitation (fluorescence) was, in all probability, not observed until after the invention of irradiating sources and devices especially designed for the purpose of detecting such luminescence. Luminescence, such as that of glowworms and rotting wood, and that which outlasts the excitation (phosphorescence), must have been noticed by man in his early existence. Aristotle's pupil, Theophrastus, says that a carbuncle exposed to sunlight glows like a live coal,[1] and Aristotle himself (about 350 BC) mentions the luminescence of rotting wood. Benvenuto Cellini tells of seeing a white sapphire that illuminated a perfectly dark room.[2] As early as 1625 Peter Poterius made little toy animals from phosphorescent material (see footnote 1). An alchemist, Vincenzo Cascariolo, in Bologna, Italy, about 1600 found a stone which seemed heavier than one of its size should be, and upon heating it, in the hope of finding gold, he dis-

[1] P. Pringsheim and M. Vogel, Luminescence of Liquids and Solids and its Practical Applications (Interscience Publishers, Inc., New York, N. Y., 1943).
[2] S. H. Ball Sci. Monthly, p 497 (1938).

covered that it would glow in the dark, "sometimes for as long as an hour" and also found how to make it glow at will.[3]

The luminance [4] of the luminescent light from phosphorescent materials ranges downward from that of a white surface viewed in full moonlight. In measuring such luminances it is necessary to consider the behavior of the weakly illuminated eye. In 1826 J. Purkinje [5] showed that after a red surface and a blue surface have been illuminated so as to have the same brightness, a reduction of the illumination of both surfaces in the same proportion will cause the red surface to appear darker than the blue after a certain limit of reduction has been passed. The dependence of the observed values also upon the size of the field of view for the nearly dark-adapted eye was determined by P. Reeves [6] in 1917. The trend to higher and higher illumination for lighting purposes had made it unnecessary for the photometrist to remember these effects in the measurements customarily made in the laboratory. However, when the use of luminescent materials was shown to be practical it became necessary to take account of both of these phenomena in constructing a photometer for the measurement of their luminance.

II. PHOTOPIC, MESOPIC, AND SCOTOPIC VISION

The human eye has the ability to adapt for light conditions over a wide range. The approximate upper limit is represented by the condition of viewing fresh snow in full sunlight, which is uncomfortable and, if long continued, results in a temporary blindness, "snow blindness," or if viewed for prolonged periods, may result in permanent injury to the eye. The lower limit is considerably below the condition of viewing a white surface on a clear, moonless night. The change in size of the pupil of the eye is easily observed, and, as everyone knows, the pupil is small if strongly illuminated, and as the illumination weakens the pupil becomes larger. There are other less obvious changes, such as the change in the luminosity curve, which explains the Purkinje effect and the loss of the ability to detect detail (acuity) and of the ability to detect chromaticity differences, all associated with the transition from cone to rod vision.

When we view a surface of high brightness with photopic vision, that is, when the eye may be said to be light-adapted, we find that the eye has a nearly constant luminosity curve, independent of the luminance range under consideration. All definitions of units of luminance (photometric brightness) imply that comparisons between differently colored surfaces be made at values of luminance sufficiently high to insure that the observer's eye is in a state of light adaptation. This is to insure that luminance values obey the additive law, by which a luminance of y units superimposed upon one of x units will provide a luminance of $(x+y)$ units. If this law is not obeyed, the ordinary inverse square law, the ratio of areas of openings in diaphragms, and the ratio of the areas of the open and opaque sectors of a rotating disk (Talbot's law) may not be applied to the luminance values under consideration. If differently colored surfaces are viewed, obedience to the above-mentioned laws occurs only if the luminosity curve of

[3] G. T. Schmidling, Protective and Decorative Coatings, **III**, 657 (John Wiley & Sons, New York, N. Y., 1943); also reference 1.

[4] Psychophysics of color, OSA Committee on Colorimetry, J. Opt. Soc. Am. **34**, 245 (1944).

[5] J. Purkinje, Magazin gesammte Heilkunde (Berlin) **20**, 199 (1826).

[6] P. Reeves, J. Opt. Soc. Am. **1**, 148 (1917); P. G. Nutting, Trans. Illum. Eng. Soc. **XI**, 939 (1916).

the eye is constant and independent of the adaptive state of the eye throughout the range of luminance under consideration. Fortunately the eye in observing luminances greater than 1,000 microlamberts does possess a nearly constant luminosity curve, and for this condition (when the eye is said to be light-adapted) we have photopic vision and the values of luminance (photometric brightness) for differently colored surfaces not only obey the additive law but also correlate well with brightness, subjectively evaluated. We may speak of such values as photopic luminance.

Unfortunately the luminosity curve of the eye does not remain constant when the luminance of an extended surface is reduced below 1,000 microlamberts; in fact, the eye becomes progressively more

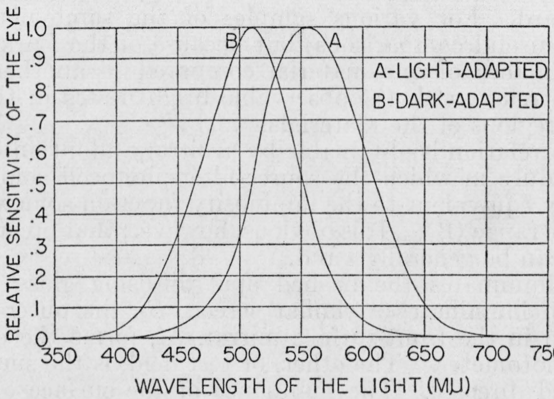

FIGURE 1.—*Comparison of the luminosity curves for the light-adapted* (*A*) *and for the dark-adapted* (*B*) *eye.*

sensitive to short-wave (blue) and less sensitive to long-wave (red) light as the luminance to which it is adapted is reduced from 1,000 to about 0.5 microlambert, the rate of change being most pronounced between 200 and 1 microlambert. This shift of the luminosity curve toward shorter wavelengths explains the Purkinje effect. For adaptation to luminances below 0.5 microlambert, the eye again reaches a steady state, with a constant luminosity curve characteristic of scotopic vision, and the eye may be regarded as dark-adapted. We may speak of these luminances as scotopic luminances. In figure 1 the adopted luminosity curve of the light-adapted [7] eye and an average curve for the dark-adapted [8] eye are shown. As the luminance of the observed surface is diminished, we pass through the region of mesopic vision, and the luminosity curve moves progressively from that of the light-adapted eye toward that of the dark-adapted.

The following are four of several ways to assign numerical values to a scale of luminance below the photopic region to include mesopic and scotopic luminance.

A. Arbitrary application of the photopic luminosity function to all luminances by making visual comparison of fluorescent and phosphor-

[7] A résumé of the data on which the standard ICI luminosity factors are based and of the present status of these factors is given in a paper by Kasson S. Gibson, *Spectral luminosity factors*, J. Opt. Soc. Am. **30**, 51 (1940).

[8] "Summary of American Opinion on BS/ARP 18, British Standard Specification for Fluorescent and Phosphorescent Paint," prepared for the American Standards Association by L. A. Jones under date of June 15, 1942, gives an average of the luminosity data for low luminances determined by Hecht and Williams and by Weaver.

escent materials only with a standard of similar spectral composition, the standard to be evaluated by way of the photopic luminosity function.

B. Adoption of an arbitrary photoelectric procedure for evaluating the radiant energy from fluorescent and phosphorescent materials.

C. Definition of the unit and scale of mesopic and scotopic luminance in terms of the hypothetical equal-energy source.

D. Definition of the unit and scale of mesopic and scotopic luminance in terms of an incandescent lamp operating at 2,360° K color temperature.

There have been attempts to make the standard photopic luminosity function (A) do. Each material characterized by radiant energy of a new spectral composition requires the setting up and evaluation of a new standard. For various samples of the same material, the method gives useful comparisons; but because of the Purkinje effect, photopic luminance of one material compared to another does not necessarily correlate with the observable brightnesses in the mesopic and scotopic regions of the materials.

A better correlation is obtainable by arbitrary adoption of a photoelectric procedure in which the source-filter-photocell combination is approximately equivalent to the luminosity function somewhere within the mesopic range (B). It is obvious, however, that no one luminosity function can be generally valid.

The lamp illuminates the flashed opal diffusing glass screen, S_1, which in turn illuminates a similar screen, S_2, the outer surface of which, viewed in the front-surface mirror, *M*, forms the comparison field of the photometer. The other, or test field, is the surface of the sample viewed directly. The luminance of the surface of S_2 facing the mirror depends upon the light reaching the surface toward S_1, which is closely proportional to the product of the area of the opening in the diaphragm *D* and the luminance of the surface of S_1 exposed to S_2, since the distance between S_1 and S_2 is constant. The luminance of the surface of S_1 away from the lamp is proportional to the illuminance of the surface toward the lamp which, of course, depends upon the distance between S_1 and the lamp.

Procedures C and D are similar and give values of mesopic and scotopic luminance that correlate well with brightness. The use (C) of the hypothetical equal-energy source would bring a unique, logical simplicity to the general concept of luminance, but the predominant opinion (see footnote 8) is that an incandescent-lamp source at 2,360° K is more convenient in practice and, on that account, preferable for tentative standardization and use at the present time. By this choice the comparison source is assigned mesopic and scotopic luminances by the same methods (inverse-square law, sector-disk relations, aperture relations) used for photopic luminance.

III. DESCRIPTION OF THE PHOTOMETER

1. PHOTOMETRIC DETAILS

The photometer is shown in figure 2. The views depart from conventional drawing practice by showing the openings in the baffles and diaphragms as in a section taken through the axis of the beam. Otherwise, figure 2 shows conventional plan and elevation views.

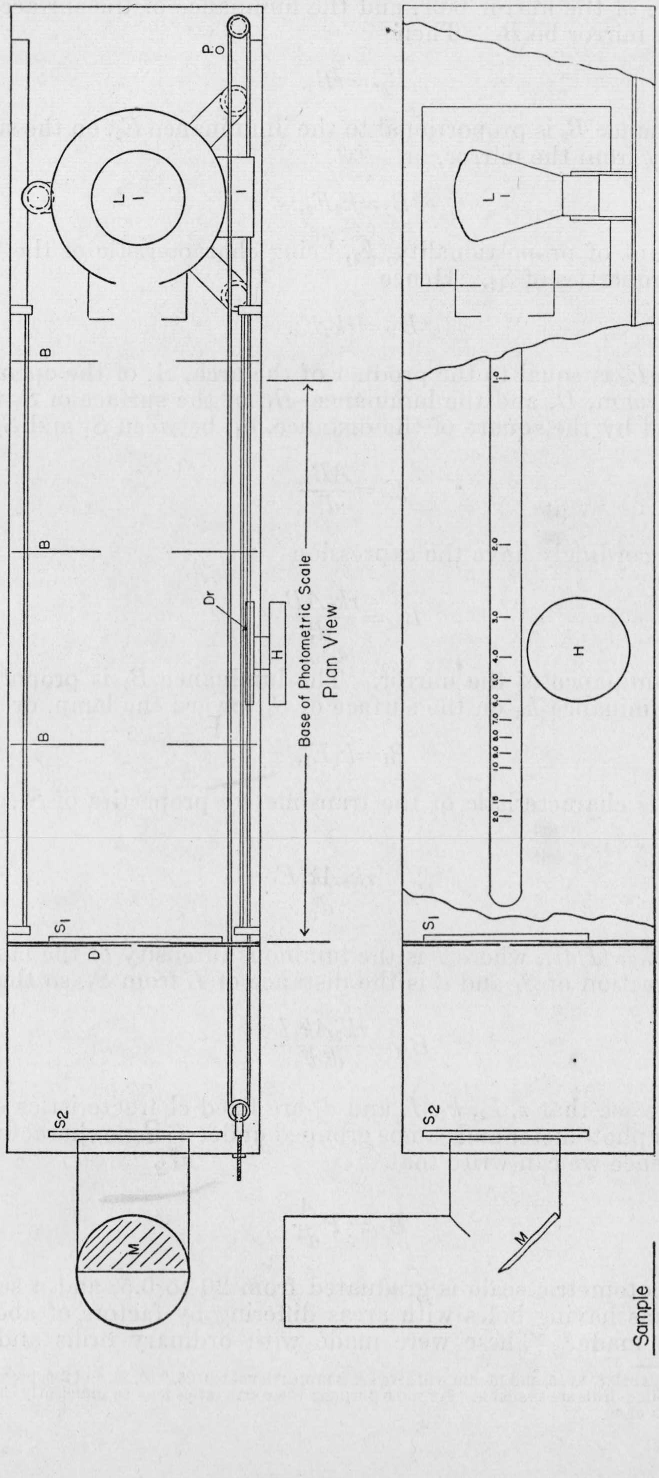

FIGURE 2.—*Photometer for luminescent materials*

Let the luminance of M, as viewed from the sight tube, be B_M, the reflectance of the mirror be r, and the luminance of the surface of S_2 facing the mirror be B_2. Then

$$B_M = rB_2.$$

The luminance B_2 is proportional to the illuminance E_2, on the surface of S_2 away from the mirror, or

$$B_2 = k_2E_2,$$

the constant of proportionality, k_2, being characteristic of the transmissive properties of S_2. Hence

$$B_M = rk_2E_2.$$

However, E_2 is equal to the product of the area, A, of the opening in the diaphragm, D, and the luminance, B_1, of the surface of S_1 facing S_2, divided by the square of the distance, d_1, between S_1 and S_2,

$$E_2 = \frac{AB_1}{d_1^2},$$

and we accordingly have the expression

$$B_M = \frac{rk_2AB_1}{d_1^2}$$

for the luminance of the mirror. The luminance B_1 is proportional to the illuminance E_1 on the surface of S_1 toward the lamp, or

$$B_1 = k_1E_1,$$

where k_1 is characteristic of the transmissive properties of S_1, which gives us

$$B_M = \frac{rk_2Ak_1E_1}{d_1^2}.$$

Finally, $E_1 = (I/d^2)$, where I is the luminous intensity of the lamp, L, in the direction of S_1 and d is the distance of L from S_1, so that

$$B_M = \frac{rk_2Ak_1I}{d_1^2d^2}.$$

In this we see that r, k_2, k_1, I, and d_1 are fixed characteristics of any particular photometer and can be grouped under a single characteristic, P, and hence we can write that

$$B_M = P\frac{A}{d^2}.$$

The photometric scale is graduated from 20 to 0.5, and a set of 4 diaphragms having holes with areas differing by factors of about 10 has been made.[9] These were made with ordinary drills and then

[9] Metric drills of 0.5, 1.6, 5, and 16-mm will give areas proportional to 0.25, 2.56, 25, and 256, provided new accurately ground drills are available. For some purposes these area ratios may be sufficiently close to the desired factors of 10.

calibrated. The photometric scale and the ratios of the areas of the openings in the diaphragms overlap and values near the ends of the scale can be measured by means of either of two diaphragms. The use of these mechanical means to control the luminance of the comparison field gives a long range with no change in spectral composition. When the photometer is used without any of the removable diaphragms, the maximum reading is more than 150,000 times the minimum reading with the smallest-aperture diaphragm. The opening in the metal plate holding S_1 is a limiting diaphragm when none of the removable diaphragms are used.

The field is a plain elliptical field (diametrically divided circle viewed at 45°), the major axis being 1½ inches long. The major axis coincides with the dividing line of the field, which usually is viewed so that the two halves are seen side by side. Since the end of the sight tube is 4 inches from the mirror, the angles subtended at the eye by the field are 15 and 20 degrees for the minor and major axes, respectively. The mirror when placed as shown in figure 2 serves as a baffle to prevent any light from screen S_2 falling on the test surface.

2. MECHANICAL DETAILS

The mechanical details may, of course, be varied to suit the maker's materials and choice. The photometer used at the Bureau employs the box, track, lamp housing, and scale of a Sharp-Millar [10] photometer. The photometric cube and eyepiece were removed and the diaphragm-diffusing-screen arrangement described in the previous section installed. Since this type of photometer is no longer commercially available a description of the mechanical details will serve as a guide for anyone wishing to construct one.

The box (fig. 2) is about 4 by 4 by 22 inches. The lamp, *L*, is moved by means of an endless cord which passes over a drum, *Dr*, which is turned by the handwheel, *H*. The sight tube may be turned in its collar to view the test surface at various angles. In order to avoid errors due to light reflected from the interior of the box a series of baffles, *B*, made of fiber is placed between the lamp and the screen S_1, and the interior is painted with a flat (mat) black paint. These baffles are carried on two light rods and are attached to each other and the lamp housing by cords. When the lamp moves toward S_1 the housing pushes the baffles successively in front of it and when it moves away from S_1 the cords pull the baffles one after another into their original position. The lamp housing carries an index, *I*, the shadow of which falls upon the translucent scale in the side of the box and thus there is no parallax. The scale is covered by red plastic to preserve the dark adaptation of the photometric observer. This arrangement also makes it unnecessary to provide a light for reading the scale, which is a great convenience, and avoids the usual scale marked on a space-wasting rod protruding from the box. Since readings are taken in a dark room, no stray light will enter the photometer through the translucent scale. It would be necessary to provide a shutter to cover the translucent scale if readings were taken in a lighted room, the shutter being opened only to read the scale after a setting had been taken.

[10] Elec. World **51**, 181 (1908); Elec. Rev. (New York) **52**, 141 (1908); Electrician (London) **60**, 562 (1907–08).

The lamp housing has a second index on the side opposite the scale index to facilitate the accurate positioning of the filament of the lamp at the unity mark of the photometric scale. The housing runs on a track made of angle brass fastened to the sides of the box. The single wheel has a spring to force it against the track to prevent sidewise motion.

IV. SUMMARY

A photometer, such as described in this paper, makes possible the determination of scotopic and mesopic luminance, such as that of fluorescent and phosphorescent materials. The use of a comparison field of color temperature 2,360° K and the mechanical control of the luminance of the comparison field are in accord with current American opinion on the datum and method of evaluating luminances in the mesopic and scotopic regions. Luminance so evaluated takes the Purkinje effect into account and correlates perfectly with brightness, subjectively evaluated.

The photometer has been used for nearly 3 years in routine measurements of the luminance-time (brightness decay) curve of phosphorescent materials, as well as to determine both the luminance and chromaticity of the fluorescent light from papers impregnated or coated with fluorescent chemicals. In measuring the luminance of phosphorescent materials, different observers agree within about 5 percent in the region near 10 effective microlamberts, but the spread between observers increases to about 25 percent when the luminance is in the region of 0.005 effective microlambert. The measurement of fluorescent materials has not been extensive. However, some measure of the effect of color is given by tests of blue fluorescence at about 100 effective microlamberts where 4 observers made observations within a little less than 25 percent and tests of yellow fluorescence where with the same observers the results did not spread by as much as 10 percent at about 200 effective microlamberts. The use for determining chromaticity (where the spectral composition of the comparison source must remain constant while the luminance is varied) has been so satisfactory at low luminances that a photometer has been designed with a much wider range of luminance than the present photometer possesses. This increased range will be adequate for measuring the chromaticity of nonluminescent materials in the photopic range of luminance.

WASHINGTON, January 27, 1945.