NBS

Technical Note 198

PHOTOMETRY OF PROJECTORS AT THE NATIONAL BUREAU OF STANDARDS

L. CHERNOFF

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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Photometry of Projectors at the National Bureau of Standards

L. Chernoff

A projector consists of a light source and optical system which produces a beam of light. In the photometry of projectors, the intensity of the projector as a function of angle of viewing is measured. For many years the National Bureau of Standards has conducted photometric tests on various types of projectors, and a variety of techniques and equipment has correspondingly been developed.

Photometric testing is carried out on a photometric range of which there are two at NBS: a short range on which the test distance may be varied up to a maximum of 30 meters and a longer range with a fixed test distance of 279 meters. Photometric measurements are made by comparison with a standard lamp of known luminous intensity in a specified direction. These comparisons are made with photosensors which are color-corrected by filters so that the spectral response is similar to the CIE luminous efficiency function. While precision requirements are not severe, considerable care is required to keep the experimental errors within the desired limits.

1. INTRODUCTION

One of the most complicated problems encountered in practical photometry is the measurement of the luminous intensity of a light projector at various angles of view. A projector consists of a light source and an optical system which produces a beam of light. A common example of a projector is the PAR-type lamp which is a sealed-reflector lamp consisting of a filament placed at the focus of a parabolic reflector with a glass cover. Another example is a light source placed at the focus of a Fresnel lens.

For measuring the luminous intensity of a projector, a photometer employing an electrical photosensor is used. The response of the photosensor is read or recorded on an electrical measuring device such as a self-balancing recording potentiometer. This response is a function of the illuminance on the face of the photosensor; the illuminance is expressed by the inverse-square law as follows:

$$E = \frac{I}{d^2}$$

where *E* is the illuminance at the photosensor,
I is the luminous intensity of the light source, and
d is the distance between the light source and the photosensor.

The photometer is calibrated by using a standard lamp of known luminous intensity in a specified direction oriented in that direction at a known distance from the photosensor.

Projectors are mounted at one end of a photometric range. There are two ranges for the photometric measurement of projectors at the National Bureau of Standards. On the shorter range, the distance between the projector and the photosensor can be varied to a maximum of 30 meters. On the longer range, this distance is a fixed 279 meters.

For many years the National Bureau of Standards has made photometric measurements of various kinds of projectors, particularly those units used in airfield and aircraft lighting. Since these projectors have been of many sizes, shapes, beam characteristics, and intensities, a variety of procedures, techniques, and equipment have been correspondingly developed for their measurement.

When photometric measurements are to be made, each projector must be considered individually, and it is not possible to put forth any one general method for testing them. The organization of this paper, therefore, is first to describe the photometric equipment most commonly used, with emphasis on its application to particular types of projectors. Next, the theory and practical considerations of the various calibration procedures are discussed. Finally, there is a general description of the procedures used in these measurements.

The information and data contained herein have been obtained from many photometric tests of projectors by the Photometry and Colorimetry Section of the Metrology Division, NBS, and have specific reference to the work of this section*. Some of the material has been presented in papers listed in References but has been reviewed briefly in this paper in the interest of completeness. While this paper deals specifically with photometry of projectors, the techniques and equipment mentioned are adaptable to the photometry of other kinds of light units.

2. EQUIPMENT

2.1 Ranges

There are two ranges for the photometry of projectors at the National Bureau of Standards. The choice of range and the actual photometric set-up are determined by the intensity, size, shape, and type of the unit to be tested.

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*There are many publications which treat projection photometry in general. Among these are:

IES Lighting Handbook, 3d ed., Sec. 4 (Illuminating Engineering Society, New York, N.Y., 1959).

Waldram, J.M., The Photometry of Projected Light, Ill. Eng. 47, 397 (1952).

Walsh, J.W.T., Photometry, Chap. XIV (Constable and Company Ltd., London, England, 1953).

a. 30-Meter Range

Smaller units are usually tested on the 30-meter range, which is located in the attic of the East Building of the National Bureau of Standards. The photosensor and standard lamp for calibrating it are mounted on a movable "photometer bar", shown in figures 1A and 1B. By moving the photometer bar, a maximum distance of 30 meters can be obtained between the unit under test and the photosensor. The standard lamp can be moved in and out of the calibration position by remote control.

Test units are mounted on a goniometer, a device which can rotate the unit through known angles about a horizontal and a vertical axis. The test unit can then be set at a given angle with respect to one axis, and when photometric measurements are made, a traverse can be taken at this angle by rotating the goniometer about the other axis, thus obtaining an intensity distribution.

The goniometer which is located at one end of the 30-meter range is shown in figure 2. Units mounted on it can be rotated about a horizontal axis through two pivot points on the U-shaped inner frame. There are two rotary tables for horizontal traverses which permit the goniometer to be used as either a class A or class B goniometer as described by Projector.[1] The inner table on which the test unit is mounted is used almost exclusively, however. This table provides rotations about a secondary axis corresponding to the vertical, perpendicular to the horizontal axis which in this case is fixed. When the goniometer is operated in this manner, it is a class A goniometer.

Horizontal traverses obtained by rotating the larger table on which the outer frame is mounted result in rotations about a fixed vertical axis. When the goniometer is operated in this manner, it is a class B goniometer.

The goniometer is gear-driven in the horizontal and vertical directions and is usually turned by means of synchronous motors. When a self-balancing recording potentiometer is used to record the output of the photosensor, the recorder chart of the potentiometer is driven by another synchronous motor which is powered from the same source as is the goniometer motor. Gear ratios for the recorder and the goniometer can be varied to make available several choices of speed of rotation and chart speed, and hence provide a range of angular scales (degrees per division) on the chart.

One source of error in goniometry is the backlash of the driving gears. For horizontal traverses, the errors caused by backlash are minimized by running traverses in only one direction. In the vertical direction, backlash can result from inconstant torque and from the goniometer cradle passing through a balance position in the course of the traverse. To minimize these effects, with the test unit mounted on the goniometer the pinion gear on the vertical drive is disengaged, and the inner frame

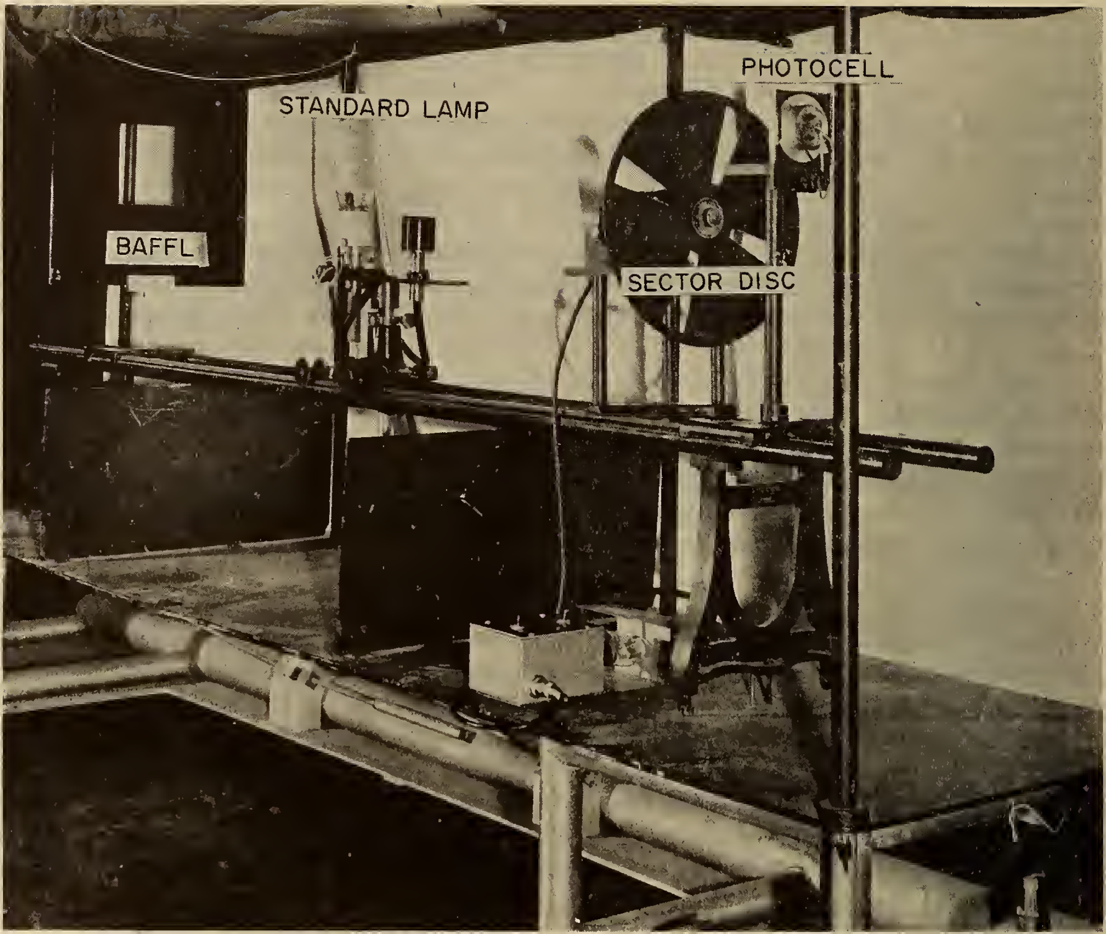

Figure 1A THE PHOTOMETER BAR OF THE 30-METER RANGE- Mounted on the bar is the equipment used in calibrating, however the shielding for stray light between the standard lamp and the photocell has been removed, and a white background has been substituted for the normally black one.

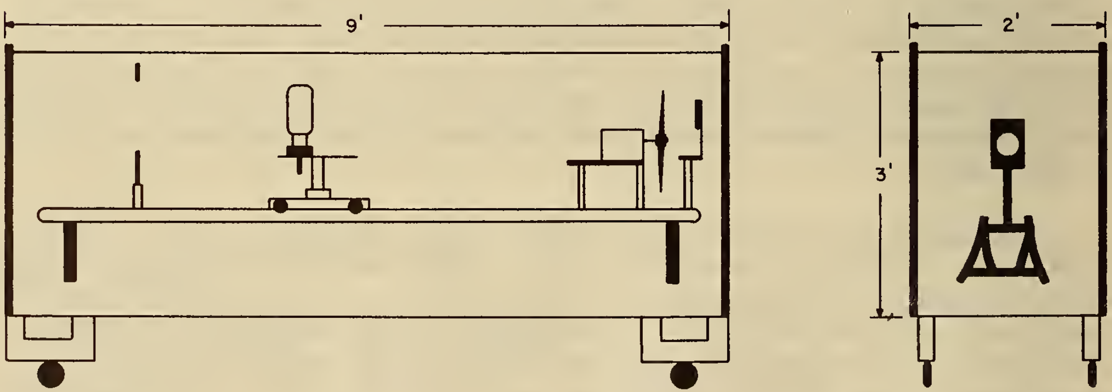

Figure 1B DIMENSIONAL DIAGRAM OF THE PHOTOMETER BAR

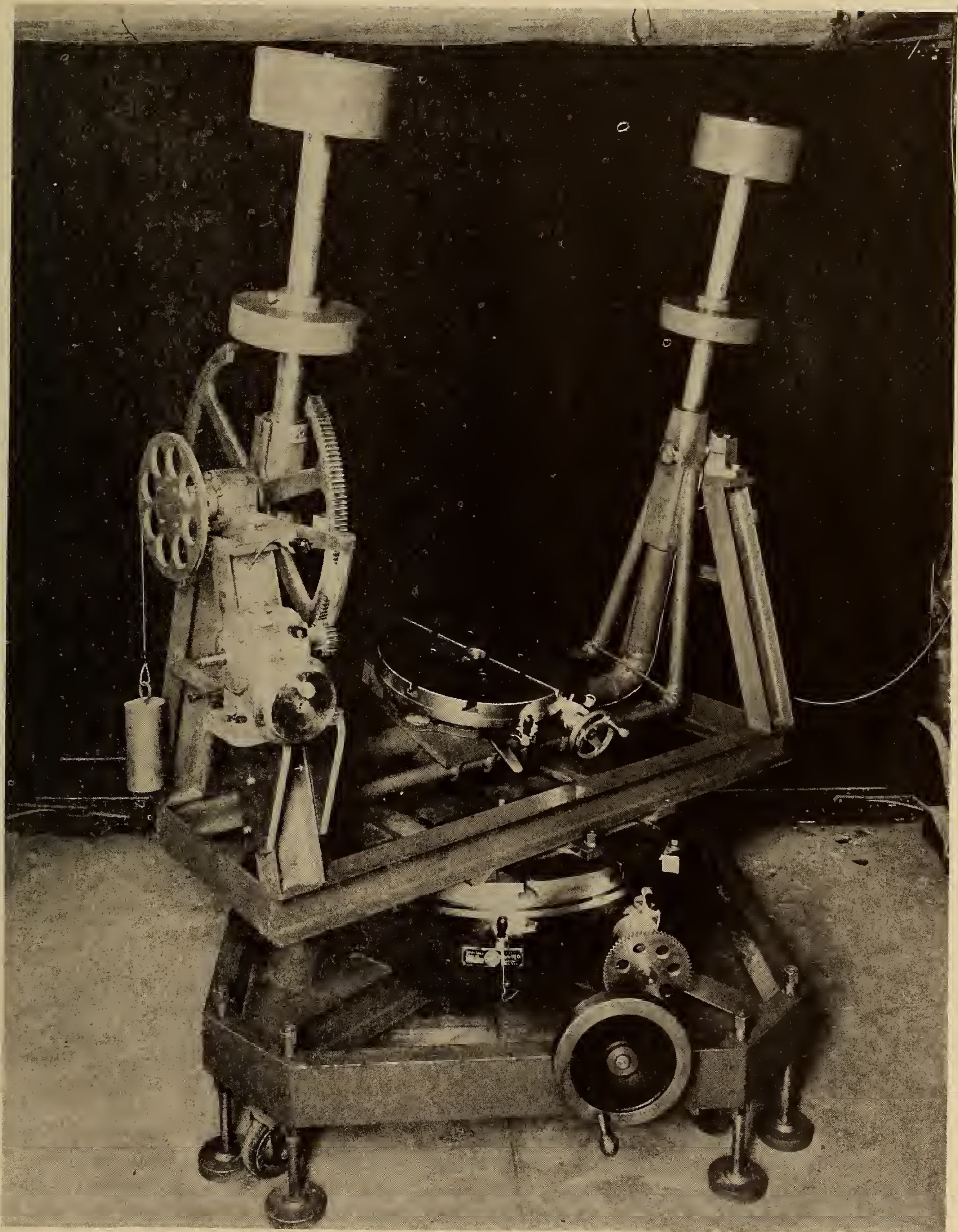

Figure 2 THE GONIOMETER OF THE 30-METER RANGE

is balanced by means of the counterweights at the top of the goniometer. After this balancing, a constant torque is applied by means of a small weight at the end of a cable, which passes over a pulley connected to the vertical drive shaft.[1] The pulley and weight are seen to the left of the goniometer (figure 2).

In order to minimize the errors caused by stray light from spurious reflections, the photometer bar is provided with a series of baffles. One of these baffles is seen in figure 1. In addition, there are adjustable baffles situated along the range between the goniometer and the photometer bar. The walls behind and around the goniometer and the background of the photometer bar are black.

The minimum test distance used in photometry of projectors is called the "minimum inverse-square distance".[2] The illumination from the light unit, measured at distances greater than this minimum, obeys the inverse-square law which is a necessary criterion for the determination of luminous intensity. The photometric distance is made greater than this minimum distance. The minimum inverse-square distance is determined by the type and size of the light source, lens, reflector, etc., and must be considered individually for each unit. If this distance is more than 30 meters (100 feet), the 30-meter range can not be used.

The case of the photometry of a searchlight with a finite sized light source and emitting a collimated beam is shown in figure 3. For this case, the angle subtended by the optic (reflector) of the searchlight at the photosensor must be less than the angle subtended at the point on the reflector farthest from the light source by the smallest projected dimension of the light source. If the reflector is viewed through a telescope at the position of the photosensor, the reflector will then appear bright over all the aperture.

From these considerations, the minimum inverse-square distance, $\underline{L_o}$ is given by

$$L_o = \frac{ad}{6s} \quad *$$

where

$\underline{L_o}$ is the minimum inverse-square distance (in feet),
$\underline{a}$ is the distance from the point on the reflector that is farthest from the light source to the axis of the searchlight(in inches),
$\underline{d}$ is the distance from the light source to point "$\underline{a}$" (in inches),
and $\underline{s}$ is the smallest projected dimension of the light source as viewed from point "$\underline{a}$" (in inches).

To illustrate, these considerations may be applied to the photometry of two different sealed-reflector lamps of the PAR-64 type, one with a 300-watt, 6.6-ampere filament, and the other with a 120-watt, 6-volt(20-ampere) filament. These lamps have the same overall dimensions and differ

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* The number 6 appears in this equation as a result of the mixture of length units.

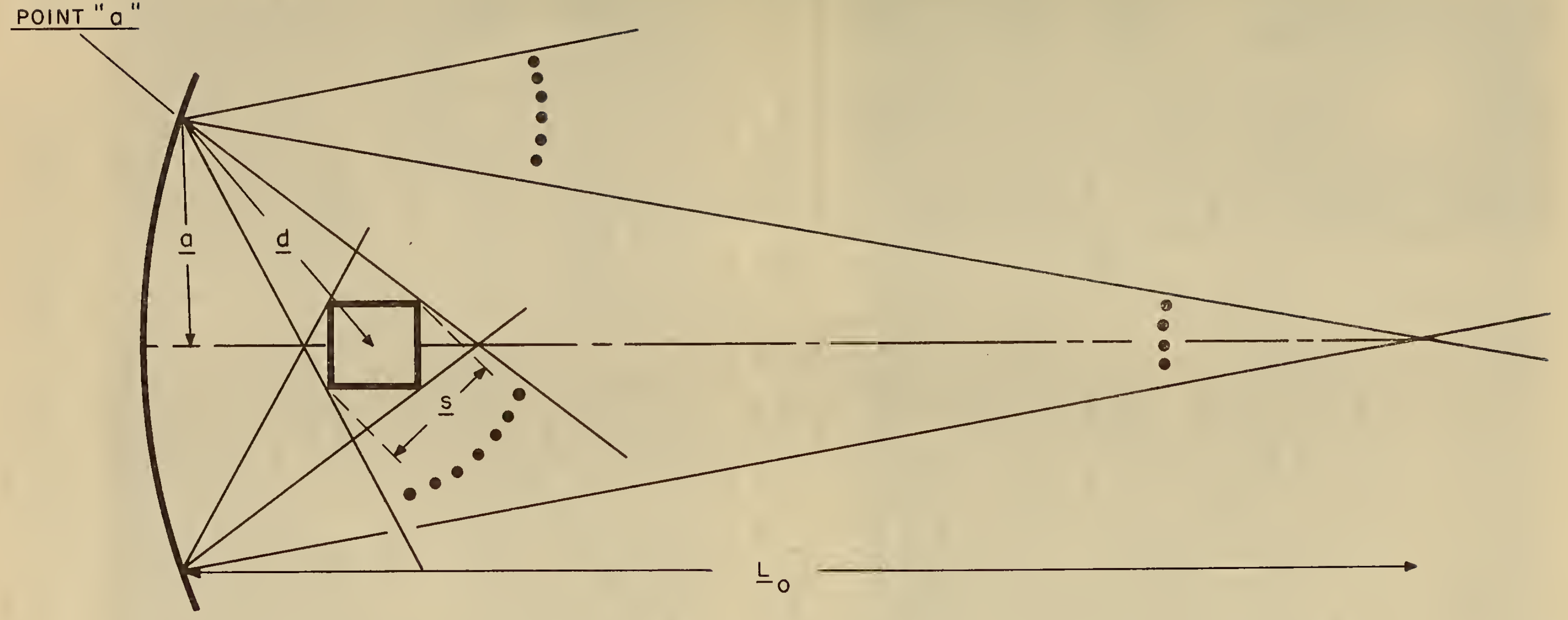

Figure 3 DIAGRAM FOR THE DETERMINATION OF THE "MINIMUM INVERSE SQUARE DISTANCE"- The dotted lines subtend equal angles.

only in the size and construction of the filaments. Both lamps have clear covers and parabolic reflectors, and both emit collimated beams of light. For both lamps, the dimension $\underline{a}$ is 3.7 inches and the dimension $\underline{d}$ is 3.8 inches.

The filament of the 300-watt lamp is of the CC-6 type; that is, the filament wire is wound in a helix, and the helix is again wound into a larger helix. The axis of the larger helix is perpendicular to the axis of the reflector. The smaller helix is wound so tightly that its diameter can be considered the smallest dimension of the light source, and its projected dimension, dimension $\underline{s}$, is this diameter, 0.033 inch. $\underline{L}_o$ is therefore 70 feet, which permits the lamp to be photometrically measured on the 30-meter range.

The filament of the 120-watt lamp is of the C-6 type. The filament wire is wound into a single helix. This helix is wound so loosely that the single turns of the coil can be discerned. Therefore, the diameter of the filament wire itself, 0.020 inch, is considered its smallest projected dimension. $\underline{L}_o$ is 120 feet, and on this basis this lamp should be photometered on the 279-meter range described below. However, the separate turns of the helix cannot be discerned from the extreme regions of the reflector. For the region of the reflector where the separate turns of the helix can just be discerned, both $\underline{a}$ and $\underline{d}$ are about 2.2 inches, and $\underline{L}_o$ computed for this region is 40 feet. At the extreme regions of the reflector, the diameter of the helix, 0.083 inch, is the smallest projected dimension of the light source, and $\underline{L}_o$ is 28 feet. This lamp could also, therefore, be photometrically measured on the 30-meter range.

The above discussion for the determination of the minimum inverse-square distance is exact only for axial measurements. For measurements off the axis, test distances of two or three times these computed minimum inverse-square distances are sometimes required but are often impractical. Measurements near the axis are usually the most important in the testing of projectors; therefore, test distances only slightly greater than the computed minimum inverse-square distances are necessary for most practical purposes.[3]

b. 279-Meter Range

Larger lights are usually tested on the 279-meter range. The photosensor and the standard lamp are located in an enclosure on the roof of the Industrial Building at the National Bureau of Standards. The range has been designed with the photosensor facing south so that during the day the photosensor views the shaded side of the building in which the goniometer is located and the shaded sides of the intervening stray-light baffles. A baffling tube and two additional stray-light baffles are situated on the same roof. This arrangement can be seen in figures 4A and 4B.

Figure 4A THE BAFFLING TUBE OF THE 279-METER RANGE- Seen are the baffling tube and one of the two other baffles.

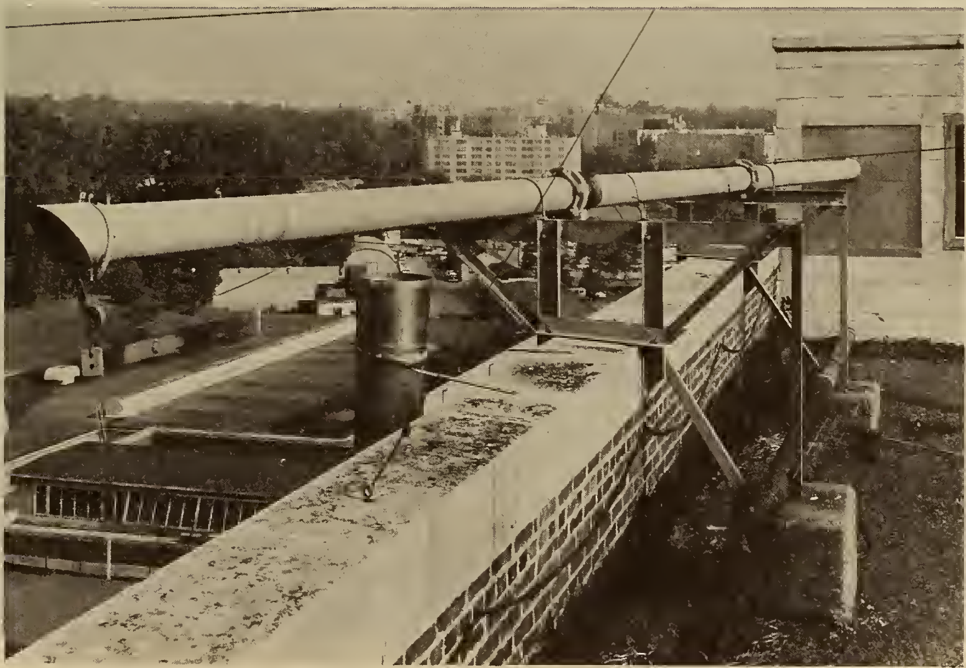

Figure 4B A CLOSE-UP VIEW OF THE BAFFLING TUBE- The front of the tube is covered with a removable protective shield.

The goniometer, recording potentiometer, and all electrical controls are located in a room on the top floor of the Computer Laboratory. The distance between the photocell and the goniometer is fixed at 279 meters.

This goniometer was constructed from an available 60-inch coast-defense searchlight and is shown in figure 5. To obtain greater precision in the angle settings, the old gearing, which had a great deal of play and friction, was removed, and more precise gearing was installed. Angles are measured through the gears because they can thereby be more conveniently read than if they were measured directly on the goniometer table. The accuracy achieved by this procedure is sufficient for the purpose. Tests have shown that the angles for small traverses can be set with an error of less than 0.03° in both horizontal and vertical settings.[4]

Units mounted on this goniometer can be rotated about a fixed vertical axis and about a secondary axis perpendicular to it. Errors resulting from inaccurate vertical centerings of the test unit are generally negligible; e.g., if a unit is mounted 2 feet below or above the center of rotation of the goniometer, for a vertical rotation of 30° there will be an error of 0.2 percent in the candlepower reading due to the change in photometric distance, and a corresponding error in the vertical angle readings of 0.015°. The goniometer is so sturdy that there is very little flexure resulting from inconstant torque. It was found that under an extremely asymmetrical loading of a test unit the angular error resulting from flexure was within 0.04°.[4]

This goniometer is usually driven by hand although motor drives are installed. An "x-y" recorder is used to trace the goniophotometric distribution. The chart drive of the recorder, a servo-motor, is controlled by a self-balancing potentiometer. A voltage signal from a potential divider attached to the drive mechanism of the goniometer is connected to the input of the y-axis amplifier, thus making the chart position a function of the goniometer angle.

The baffling tube and some of the other stray-light baffling seen in figures 4A and 4B block out all but a 6-foot diameter area of view at the goniometer. This baffling is effective enough to permit much of the photometry on the 279-meter range to be conducted during the day. The illumination from the background is measured at the time of each test and has been found to be equivalent to or less than that of a light with an intensity of about 1 kilocandle. Correction is made for background illumination in making photometric measurements. During the course of a traverse, the background illumination will usually not vary by more than 10 percent. Therefore, as a general rule, any light having a peak intensity over 100 kilocandles can be photometrically measured during daylight.

A barrier-layer photocell is usually used as the photosensor on the 279-meter range. A barrier-layer photocell is mounted in a fixed position in the enclosure at the receiving end of the range.

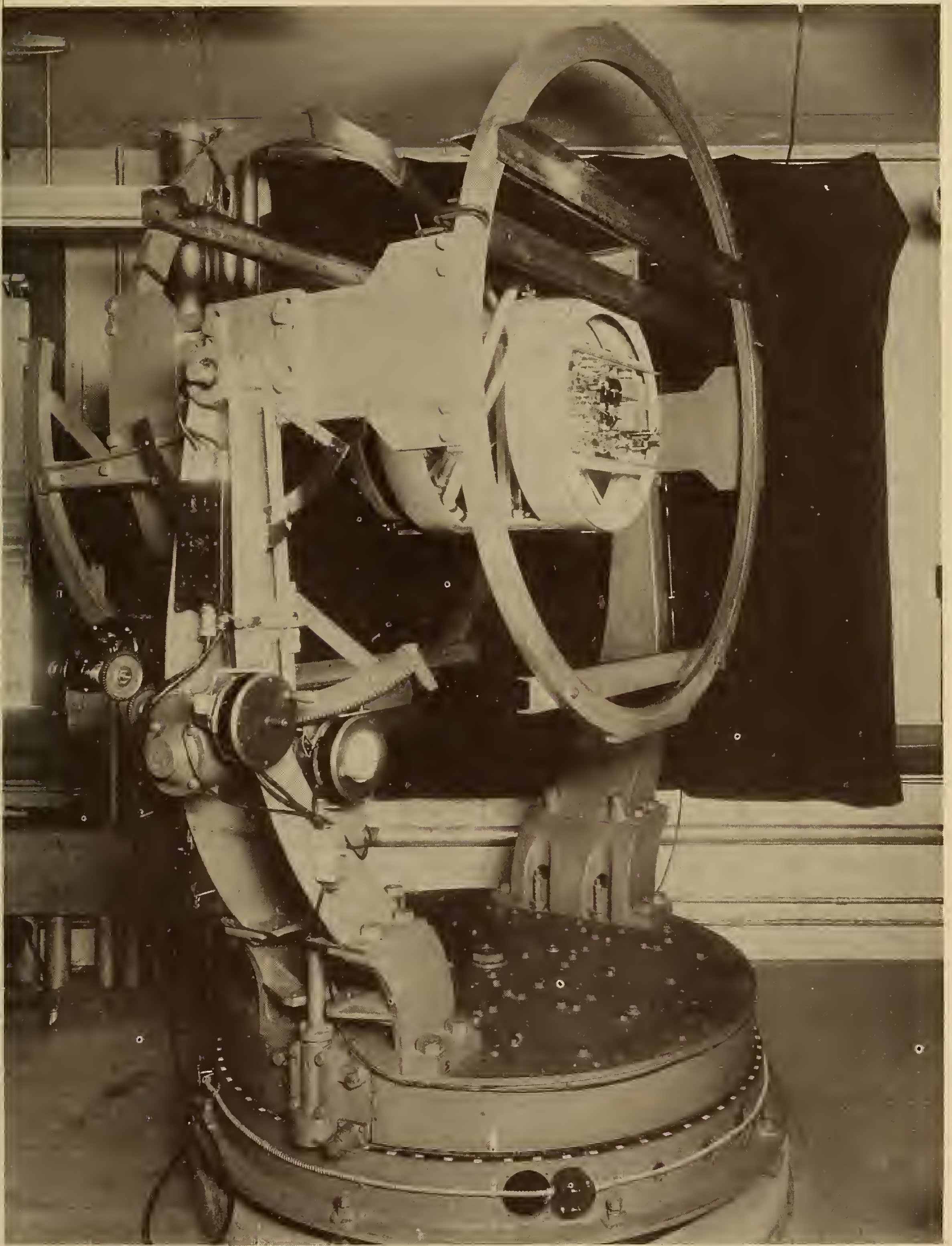

Figure 5 THE GONIOMETER OF THE 279-METER RANGE- An aircraft search-light is mounted on the goniometer

As shown in figure 6 the standard lamp and photocell are so arranged that they do not have to be moved for calibration or test measurements. The photometric axes from the standard lamp and from the test unit are respectively 5° left and right of an axis perpendicular to the face of the photocell. The response of the photocell used in the 279-meter range was tested for symmetry and was found to be symmetric with respect to these angles of incidence of the light illuminating it. Therefore, such an arrangement introduces negligible experimental errors.

A correction for the transmittance of the 279-meter air path must be made. The transmittance at the time of photometry is measured by means of the transmissometer described by Douglas[5] and is used as a correction in the calibration of the photometer.

2.2 PAR Lampholder

A special holder for PAR-type lamps is used to facilitate the mounting of lamps of this type. Since PAR-type lamps are usually tested on the 30-meter range, the holder for PAR-type lamps has been designed to be mounted easily on the goniometer of this range. It is shown in figure 7. A set of removable mounting rings makes it possible to mount any of the several sizes of PAR lamps on the holder.

The holder contains a telescope which is used to align the holder with a mark at the other end of the range so that the axis of the PAR lamp reflector will coincide with the photometric axis. It is therefore possible to remove the holder from the goniometer and to replace it at some future time, aligned as before.

2.3 Photosensors

The photosensors used in the photometric measurements are constant-current devices which produce currents proportional to the illuminance on their faces. All photosensors used are color-corrected by means of optical filters in order to make their spectral response similar to the CIE spectral luminous efficiency function. Two different types of photosensors are in general use, the barrier-layer photocell and the vacuum phototube. Although photomultiplier tubes are available, there has been no occasion to use them for the photometry of projectors at the National Bureau of Standards laboratories in the last few years.

a. Barrier-Layer Photocell

The barrier-layer photocell, a solid-state photoelectric device, is used in most of the photometric measurements. In the selection of a photocell for photometric testing, several cells which have been color-corrected by means of color-correcting filters are checked for linearity and similarity of spectral response to the CIE luminous efficiecy function. In order to check the adequacy of the color-correction, the luminous transmittance of several colored filters for light of a specified

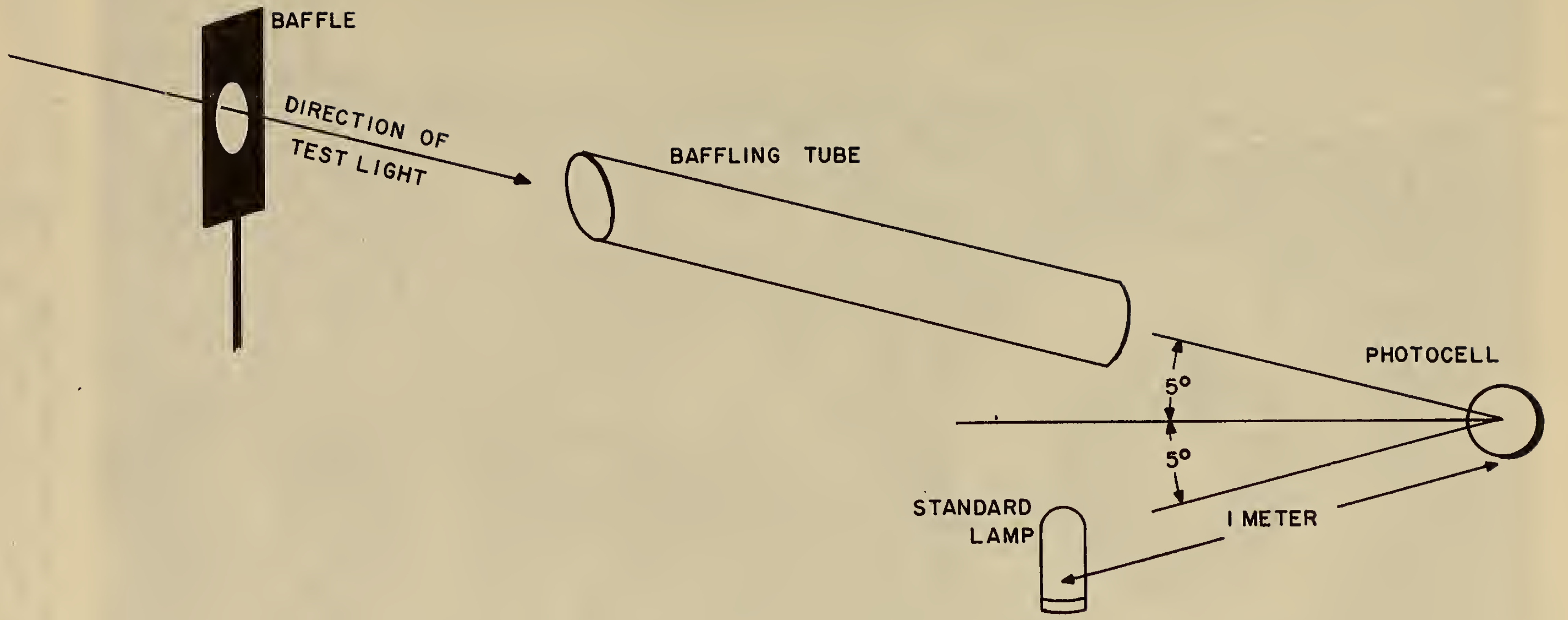

Figure 6 THE ARRANGEMENT OF THE PHOTOMETRIC EQUIPMENT ON THE 279-METER RANGE

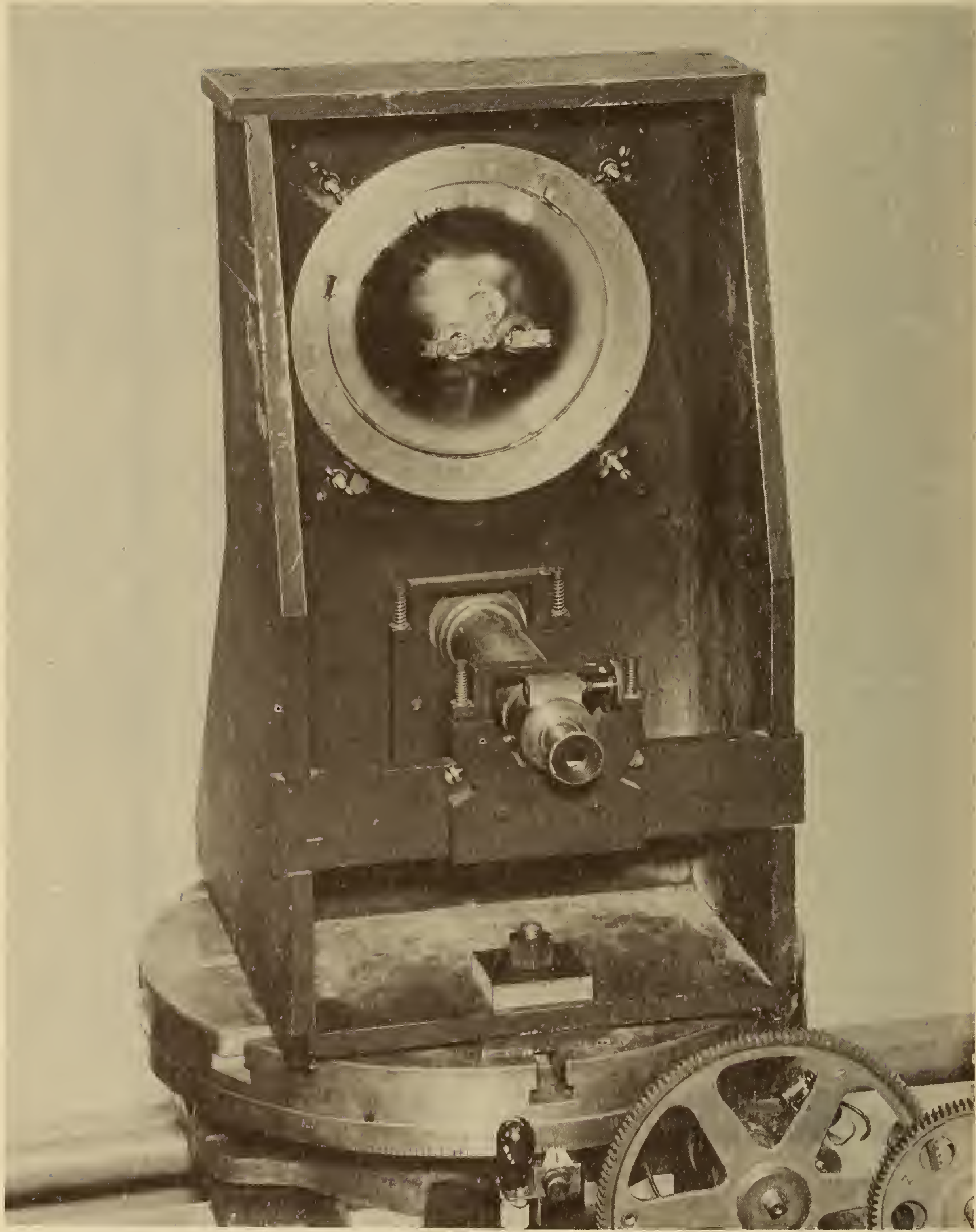

Figure 7 A REAR VIEW OF THE PAR LAMP HOLDER- Seen are the telescope for aligning, the mounting ring, and the back of a PAR-56 lamp which has been mounted on the holder.

color temperature is measured with these photocells. These measurements are compared with transmittances determined from spectrophotometric measurements. The results of one such series of measurements, using a lamp operating at Source A (color temperature 2854°K) are given in table I.

The photocells with good color response are then tested for linearity; the one most nearly linear in its response is selected for use. The response of the photocell being used at present, cell number 3 of table I, was found to be linear to better than 0.1% in the most useful range, which is sufficiently linear for photometric testing. Here, linearity was tested using several standard lamps of known horizontal intensity in turn at distances from 1 to 30 meters from the photocell. The results of the linearity measurements of this photocell are shown in figure 8.

The barrier-layer photocell is used with two different circuits. For most photometric work with this type photocell, an external shunt is used. The voltage drop across the shunt is amplified by means of a linear amplifier, and the output of the amplifier is recorded on the recorder chart of a self-balancing potentiometer. This circuit is shown in figure 9. However, when greater precision is required in the measurements, or when the illumination of the face of the photocell is either very large or very small, a "zero-resistance" circuit is employed, and intensity measurements are made by using a Kohlrausch potentiometer.[6,7]

b. Vacuum Phototube

For flashing lights of short flash duration such as condenser-discharge lights, and for lights of very low intensity, a G.E. type PJ-14B vacuum phototube is used.[8] The phototube with its power supply is housed in a metal box as shown in figure 10. The phototube is color-corrected by means of a specially designed filter; the accuracy of this color correction is indicated in figures 11A and 11B.

A d-c electrometer-amplifier is used to amplify the output of the phototube. The electrometer has been modified so that it may also be used as a null-detector for a self-contained potentiometer when greater accuracy is necessary.[9]

In the photometry of flashing lights, it is desirable to compute the effective intensity* of the flash, which is determined from a measurement of the average intensity of the flash.[8] In order to read the average intensity, a resistance-capacitance network is placed across the phototube so that the photometer circuit will have a suitable time constant. A diagram of the photometer circuit employing the PJ-14B phototube, together with such a resistance-capacitance network, is shown in figure 12. The combination of d-c amplifier and phototube is useful in measuring steady illuminations as low as 0.00001 footcandle.

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* The effective intensity of a flashing light is equal to the intensity of a steady-burning light of the same color which will produce the same visual effect under identical conditions of observation.

Table I. Color Response of a Group of Barrier-Layer Photocells with Filters

Color	Filter Characteristics for Source A			Transmittance Ratio #					
	x*	y**	T***	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6
Red	.725	.275	.0410	1.17	1.04	1.00	1.20	1.13	.98
"	.687	.313	.222	1.07	1.00	1.00	1.07	1.05	1.03
"	.648	.351	.324	.97	.95	.94	.94	.96	.94
Yellow	.630	.370	.427	1.02	1.00	.99	1.02	1.01	1.00
"	.578	.421	.612	1.02	1.01	1.01	1.02	1.01	1.01
"	.554	.444	.725	.97	.97	.97	.97	.96	.95
Green	.233	.679	.0370	.98	.98	1.01	.96	.94	.96
"	.310	.573	.201	.97	.97	1.00	.96	.94	.96
"	.350	.450	.409	1.00	1.01	1.02	1.00	.99	1.00
Blue	.160	.080	.020	1.01	.98	.99	.95	.96	1.00
"	.162	.293	.140	.90	.90	.92	.87	.88	.97
"	.320	.329	.250	.87	.88	.88	.88	.87	.87

Ratio of transmittance measured by photocell to transmittance determined from spectrophotometric measurements

* x-coordinate on the CIE chromaticity diagram

** y-coordinate on the CIE chromaticity diagram

*** Luminous transmittance of the filter as determined by spectrophotometric measurements

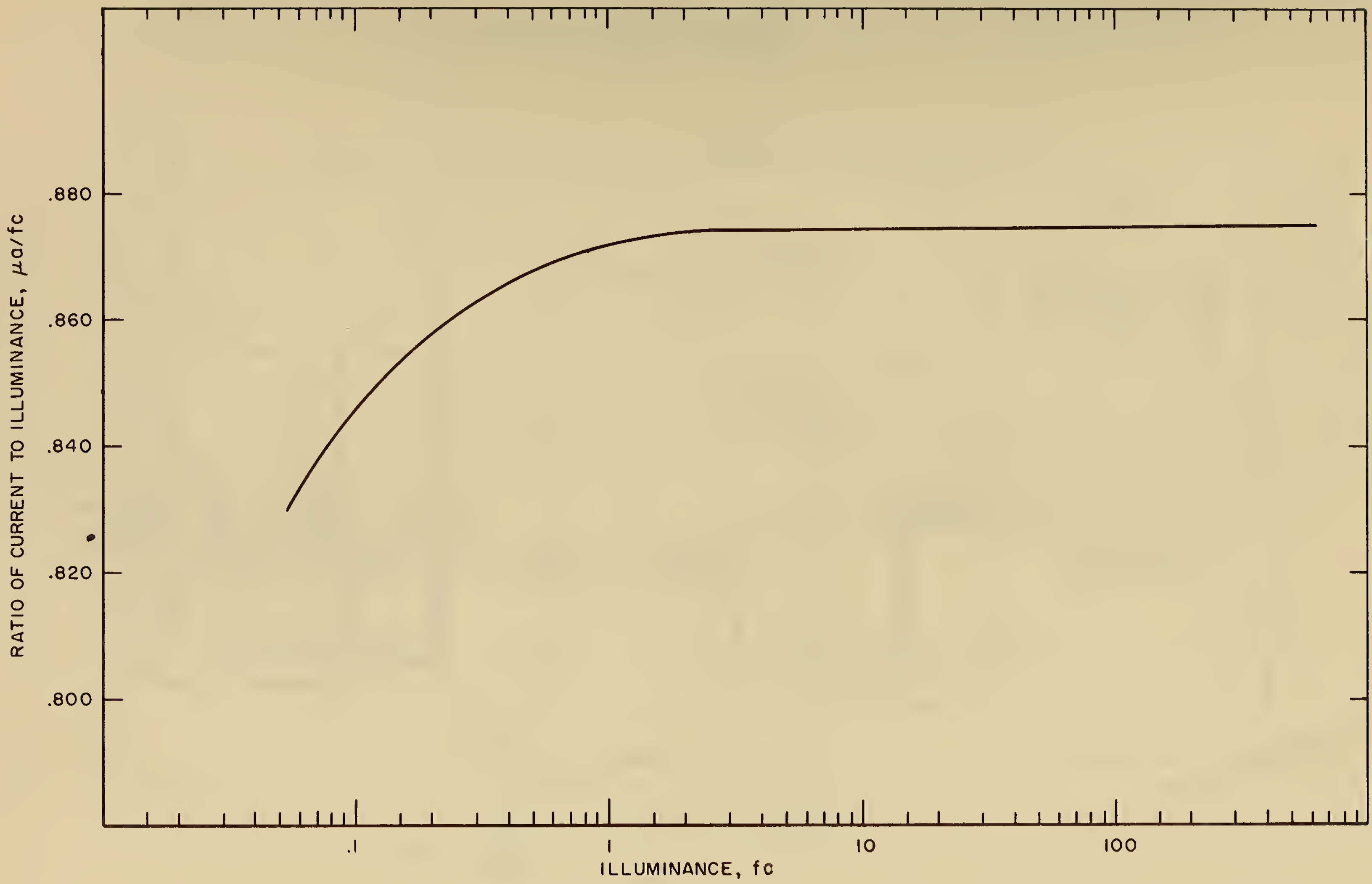


Figure 8 LINEARITY OF RESPONSE FOR SELECTED BARRIER-LAYER PHOTOCELL
Note-Voltage drop across photocell did not exceed 1 millivolt.

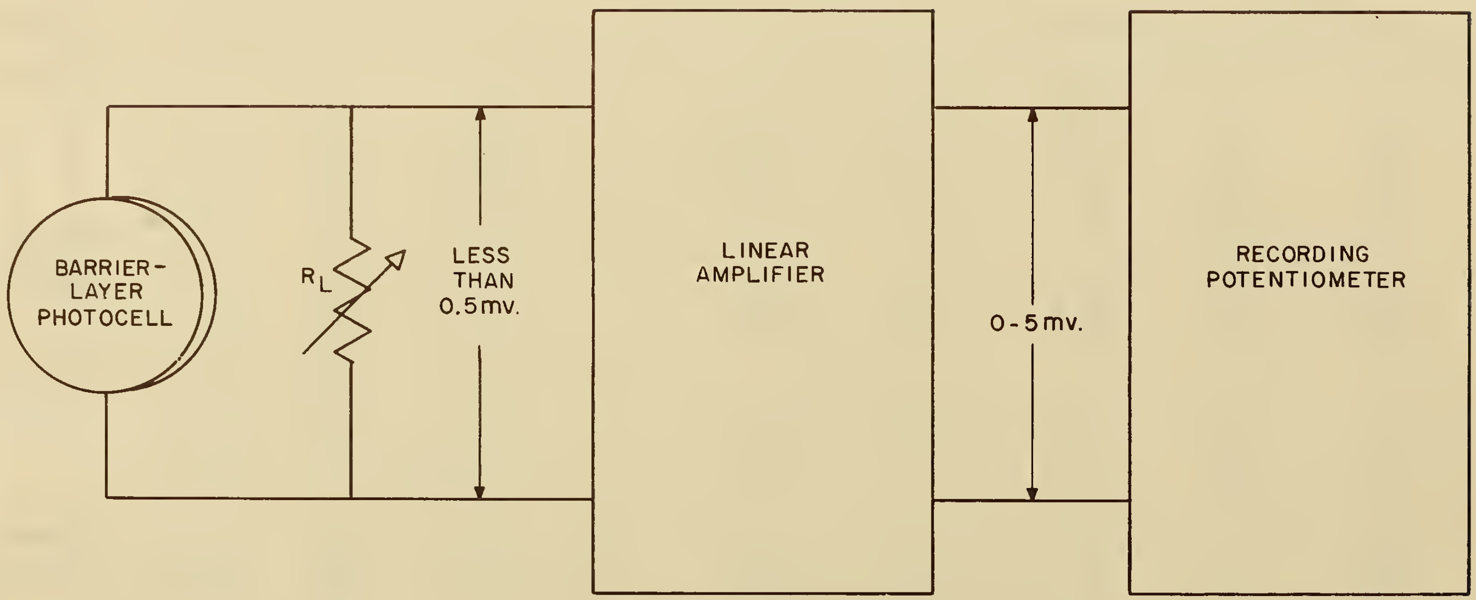


Figure 9 BLOCK DIAGRAM OF A BARRIER-LAYER PHOTOMETER

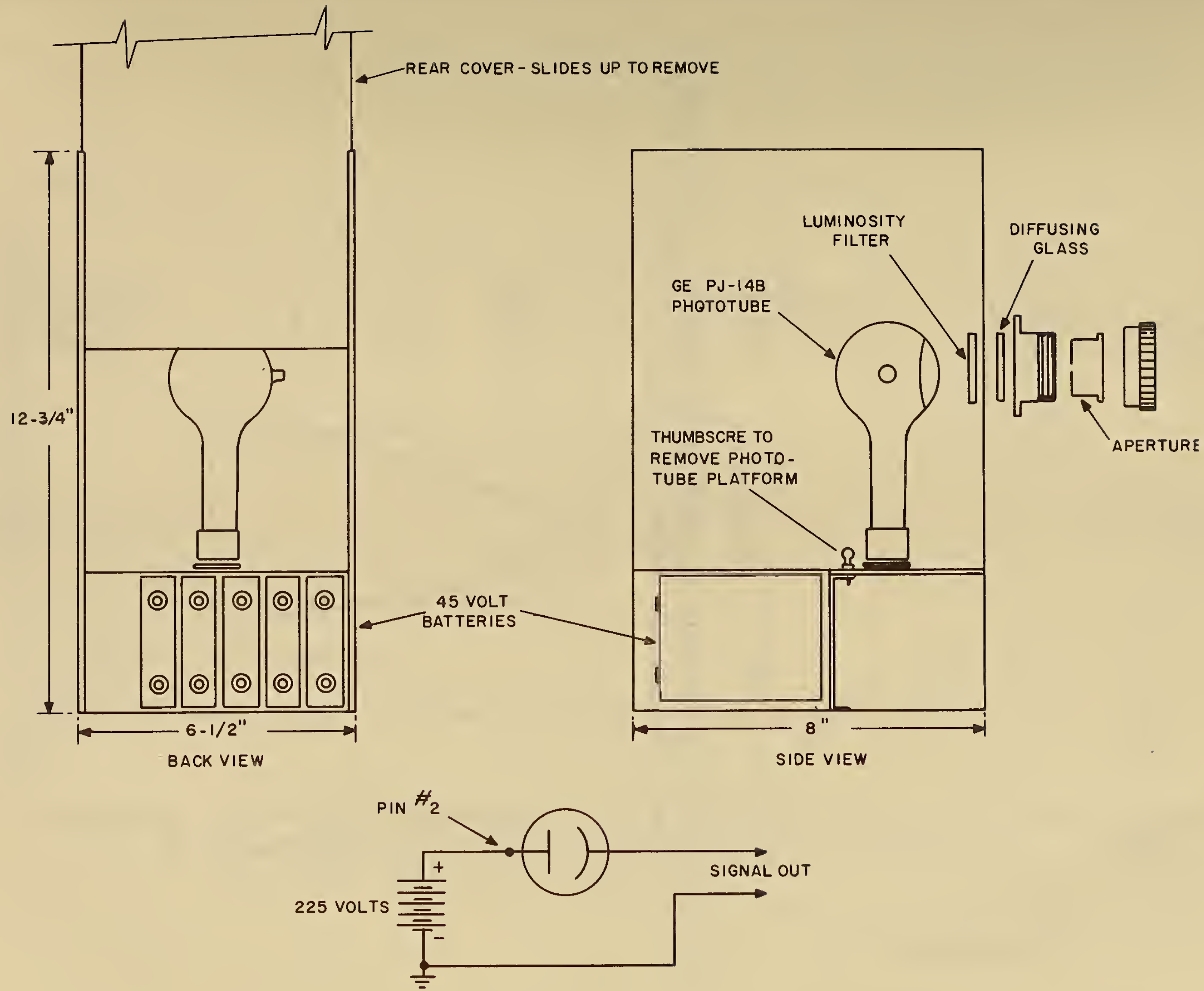


Figure 10 PJ-14B PHOTOTUBE PHOTOMETER HEAD

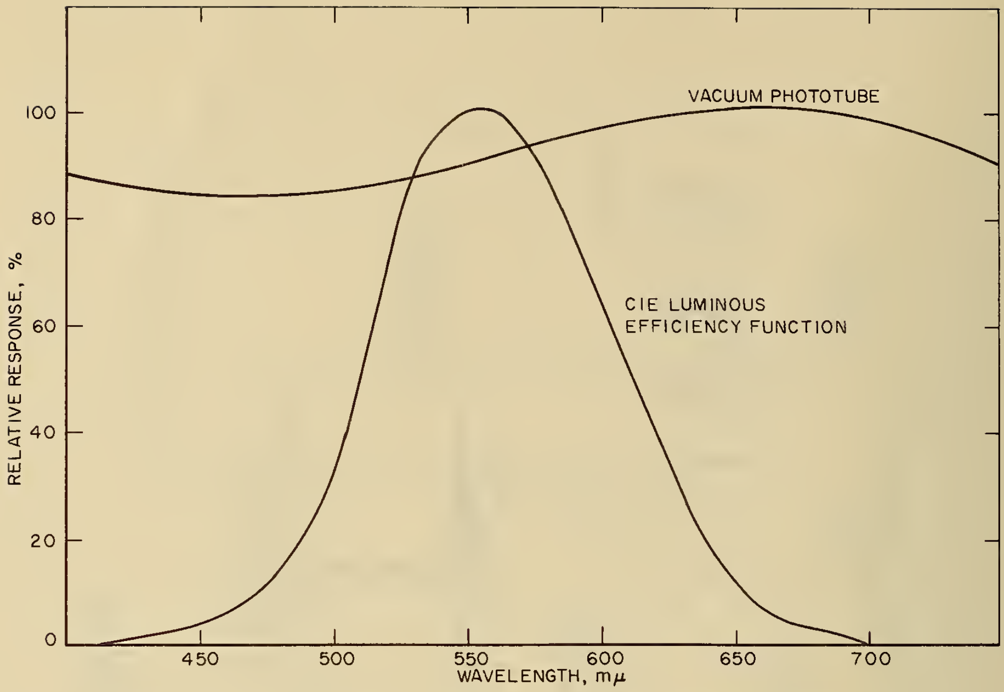


Figure 11A RELATIVE SPECTRAL RESPONSE OF UNCORRECTED PJ-14B VACUUM PHOTOTUBE AND CIE LUMINOUS EFFICIENCY FUNCTION

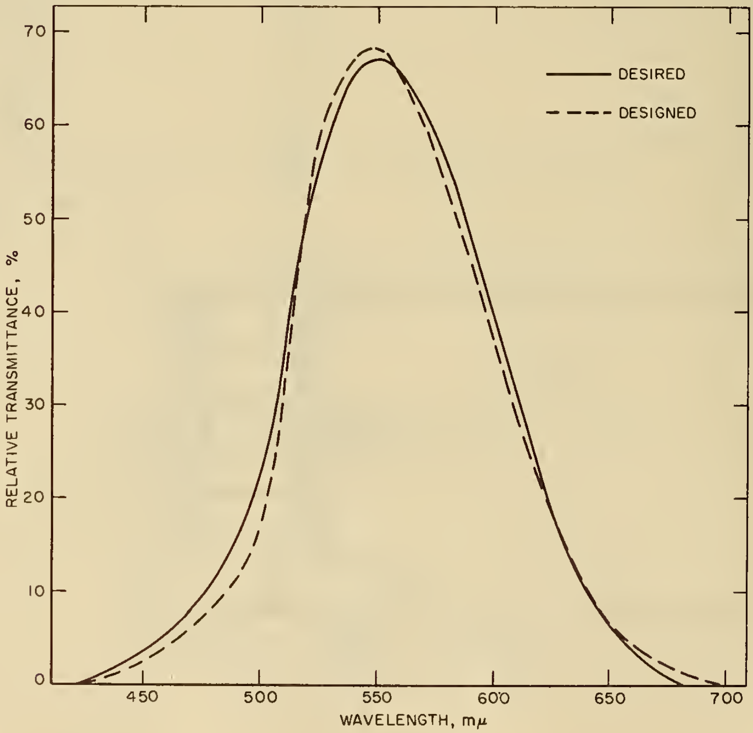
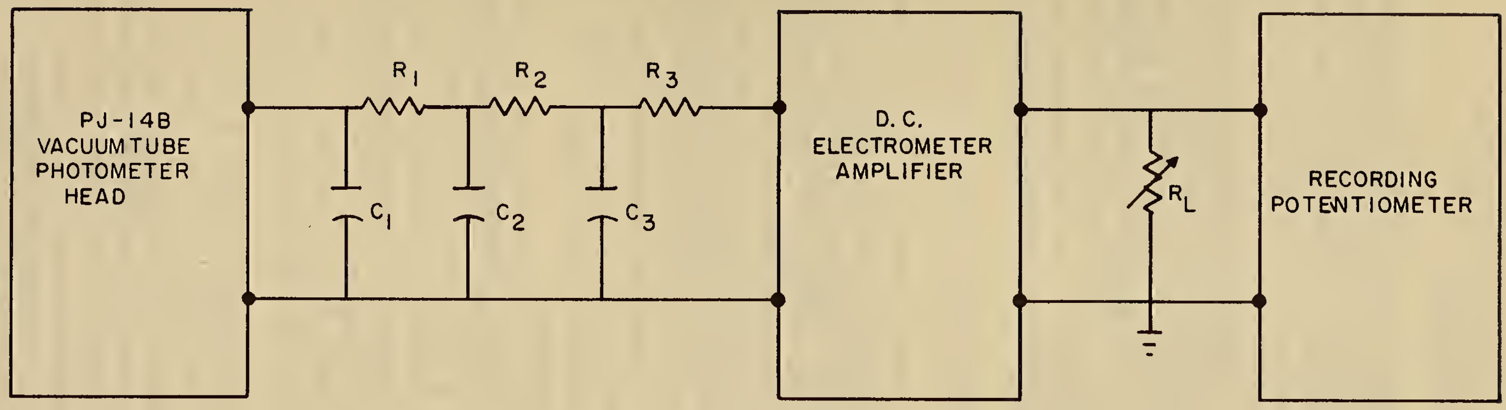


Figure 11B SPECTRAL TRANSMITTANCE OF DESIRED AND DESIGNED COLOR-CORRECTING FILTER



C_1, C_2, C_3: 0.05 mfd., 1200 volt Mica

R_1, R_2, R_3: 2.2 megohms

R_L: Calibration Adjusting Resistor, Decade Box 9X (10+1+0.1+0.01)

Figure 12 PJ-14B PHOTOTUBE PHOTOMETER- The resistance-capacitance network between the photometer head and the amplifier is used in the photometry of flashing lights and is otherwise removed.

3. CALIBRATION OF THE PHOTOMETRIC SYSTEM

3.1 Introduction

Lamp standards of luminous intensity are used for calibrating the photometric testing equipment; a separate calibration is made before each test, and a record is kept of the photometer sensitivity in order to detect any irregularities. The illumination on the photosensor produced by the standard lamp is adjusted to some typical value of the illumination produced by the test light, usually in the range of 75% to 100% of the peak illumination produced by the test light. This procedure minimizes errors resulting from nonlinearity of the response of the photosensor. The adjustment of the illumination of the standard lamp on the photosensor is accomplished by varying the distance of the standard lamp from the photocell and by using optical attenuators. The photometer is usually calibrated so that it is direct reading in luminous intensity.

3.2 Standard Lamps

The standard lamps used are "working standards" whose luminous intensity in a given direction has been determined at a given voltage.[10] Standard lamps are available ranging in intensity from about 8 to 900 candles. When a colored light is being tested, a filter is placed between the standard lamp and the photosensor, which results in a standard lamp-filter combination having approximately the same spectral characteristics as those of the light to be tested. This procedure minimizes errors resulting from inadequate spectral correction of the photosensor. In this procedure, a standard lamp of known color temperature as well as of known luminous intensity is needed.

3.3 Attenuators

Sector disks are almost always used for light attenuation, although neutral filters are also available. A sector disk is usually placed between the standard lamp and the photosensor to calibrate the photometer for the proper range of illumination. However, when the intensity of the light being photometrically measured is unusually high, the sector disk may be used to attenuate the illumination from the test light. The range of sector disks available is from 1% to 80% transmittance.

When a sector disk is used, it is placed within a few inches of the photocell in order to reduce error from stray light. The disk is rotated at a few hundred revolutions per minute, which is fast enough to minimize error from apparent flicker. When a high illumination is attenuated by a sector disk of low transmittance, there is an error which results from only one part of the photocell being illuminated at a time; this error is successfully eliminated by placing a condenser of about 4 mfd. across the output of the photocell. (In utilizing this technique, one must be careful to obtain a capacitor which does not itself generate an emf.)

3.4 Calibration Procedure

The calibration involves illuminating the photosensor with light from a standard lamp placed at a given distance from the photosensor, and then adjusting the sensitivity of the photometric system to some desired value.

If $\underline{i}$ is the photosensor current,
$\underline{I}$ is the intensity of the light illuminating the photosensor,
and $\underline{D}$ is the distance from the test unit to the photosensor,
then, since the photosensor produces a current proportional to the illuminance on its face,

$$i = kI/D^2 \tag{1}$$

where $\underline{k}$ is the sensitivity of the photosensor.

It is usually convenient to calibrate the photometer to be direct reading, so that

$$I = N\delta \tag{2}$$

where $\underline{\delta}$ is the reading of the potentiometer of the measuring circuit, and where $\underline{N}$ is an integral power of 10 or the product of an integer, usually 2 or 5, and an integral power of 10.

The photometer is then calibrated by using a standard lamp of known horizontal luminous intensity. If

$\underline{I_s}$ is the luminous intensity of the standard lamp,
$\underline{D_s}$ is the distance of the standard lamp from the photosensor,
$\underline{\delta_s}$ is the potentiometer reading and $\underline{i_s}$ is the photosensor

current when the photosensor is illuminated by light from the standard lamp placed at the distance $\underline{D_s}$ from the photosensor, then

$$i_s = k\, I_s/D_s^{\,2} \tag{3}$$

and since the potentiometer reading is proportional to the photosensor current,

$$i_s/\delta_s = 1/\delta \tag{4}$$

Combining (1), (2), (3), and (4),

$$\delta_s = I_s D^2/ND_s^{\,2} \tag{5}$$

Calibration is accomplished by the following procedure: $\underline{I_s}$ and $\underline{D_s}$ are chosen so that I_s/D_s^2 will be approximately equal to I/D^2, where $\underline{I}$ is some typical value of the intensity of the light to be tested. A suitable value of $\underline{N}$ is then selected. Calibration to make the photometer direct reading is completed by one of the three following procedures, depending on the photometer circuit used.

a. External Shunt Circuit

A diagram of this circuit is shown in figure 9. In this circuit

$$\delta_s = \frac{R_L S k I_s}{D_s^2} \qquad (6)$$

where S is the sensitivity of the photometer circuit and R_L is the resistance of the shunt.

Calibration, therefore, requires that, with the photocell illuminated by light from the standard lamp, the external shunt resistance is set so that the potentiometer indicates the value δ_s given in equation (5). The other parameters of the calibration are usually chosen so that the shunt resistance will be of the order of a few ohms. This order of resistance is used as it is large enough to be set accurately, and small enough so that the voltage developed across the photocell will not cause the photocell to respond nonlinearly. The practice is to maintain the sensitivity of the recorder at a fixed value of 5 millivolts for full-scale deflection. The sensitivity of the preamplifier is therefore set so that this recorder sensitivity and desired range of resistance may be used.

b. Phototube with Electrometer Amplifier Circuit

The procedure for calibration is the same as that for procedure a. (See figure 12.) The load resistor on the phototube and the controls of the amplifier are adjusted for the optimum performance range of the amplifier. Also, the output of the amplifier should not exceed 5 milliamperes. Hence, other parameters are adjusted so that R_L is greater than 1 ohm and is less than 5 ohms.

c. Zero-Resistance Circuit

A diagram of this circuit is shown in figure 13. In this circuit, if the photometer is balanced so that no current flows through the galvanometer, then

$$i = i_a a/r_x \qquad (7)^*$$

where

i is the photocell current,

i_a is the current through the slidewire between 0 and A(figure 13),

a is the resistance of the slidewire between 0 and A (figure 13),

and r_x is the resistance of the resistor, r_x.

Assuming the slidewire is graduated from 0 to 100, the reading of the indicator of the slidewire is

$$\delta = a/a_o \qquad (8)$$

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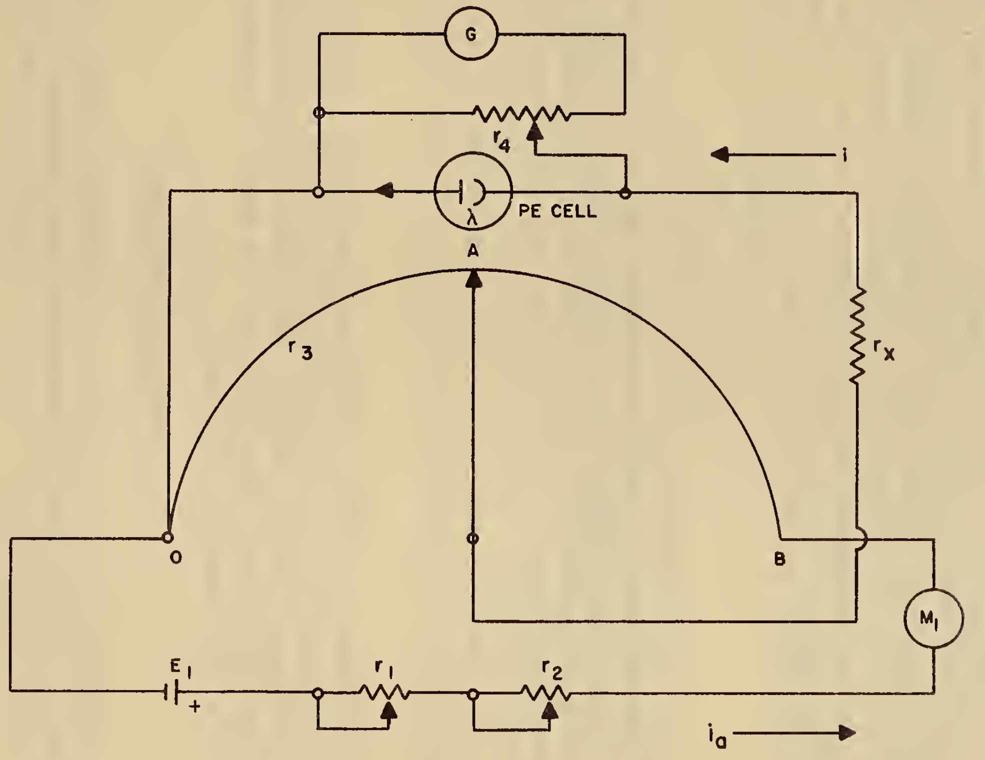
*This equation is an approximation which depends on i_a being much greater than i. In practice, i_a is kept at about 10 milliamperes, and the range of i is from 1 to 20 microamperes. If i is 20 microamperes, the error resulting from the use of this approximation will be 0.3%. For larger values of i, a correction in the calibration can be made.[6]



r_1	100-ohm rheostat
r_2	5-ohm rheostat
r_3 (OAB)	10-ohm precision potentiometer or slidewire
r_4	galvanometer sensitivity control, resistance equal to critical damping resistance of galvanometer
r_x	4-decade resistance box 0-100,000 ohms
E	1 1/2-volt dry battery
M_1	milliammeter, 10ma full scale, 30 ohms resistance.
G	galvanometer, sensitivity about 0.004 μamp/mm

Figure 13 "ZERO-RESISTANCE" PHOTOMETER CIRCUIT where a_o is the total resistance of the slidewire (the resistance between 0 and B in figure 13).

Then, combining (1), (7), and (8),

$$\delta = \frac{r_x kI}{i_a a_o D^2} \qquad (9)$$

In the calibration of the zero-resistance circuit, i_a is usually kept constant and r_x is varied.

When the photocell is illuminated by light from the standard lamp, r_x is adjusted to obtain a zero reading of the galvanometer when the slidewire is set at the value δ_s of equation (5) for a given test distance, D. With the photometer thus calibrated, the intensity of the test light is given by equation (2).

d. Special Procedures

While photometric data are usually presented for a test light operating under the design condition, photometry of the test light under operating conditions other than the design condition is often desirable. Equation (5) can be generalized, taking into account this condition as well as the transmittance of any filters or sector disks used in calibrating, so that

$$\delta_s = \gamma_c \gamma_s FI_s \frac{D^2}{ND_s^2} \qquad (5a)$$

where γ_c is the transmittance of the color filter at the color temperature of the standard lamp, γ_s is the transmittance of the sector disk, and F is the ratio of the output of the light under test when it is operated under the design conditions to the output of the light when it is operated under test conditions. This ratio may be, for example, the ratio of the rated lumen output of the test lamp to the output of the lamp at the test voltage. It also may be the ratio of the intensity in a given direction at the operating voltage to the intensity in this direction at the test voltage.

In the case of lights which are flashed in service but on which photometric measurements are made with the light burning steadily at a selected voltage, the factor F is the ratio of the effective intensity of the flash in a given direction to the steady intensity at the selected voltage in this direction of view.

4. TESTING PROCEDURE

The photometer is calibrated as described under "Calibration Procedure" (Section 3.4) to an illuminance range determined by the intensity of the light being tested, the test distance, and the information desired.

The test unit is mounted on the goniometer and is aligned. The angular settings of the goniometer are adjusted so that the origin of the goniometer settings will correspond to the desired axis. This axis usually is chosen with respect to either the seating plane of the unit or some characteristic of the beam such as its peak.

The baffling for stray light is put into place. The eye is placed in the position normally occupied by the photosensor. Examination can then be made to insure that the baffling is properly placed so that no obstructions exist between the light and the photosensor and so that reflections from the walls, floor, and ceiling of the range are intercepted before they reach the photosensor. When the 279-meter range is used, the baffling tube is periodically checked to insure that it is not being obstructed by birds.

If a sealed-reflector lamp is being photometrically measured, the lamp is usually operated at either rated voltage or rated current. Other lamps, such as those used in combination with an optical system, are usually operated at or corrected to rated lumen output. Power for the test and standard lamps is usually obtained from storage batteries, which are periodically recharged. Voltage and current are measured on a potentiometer, and photometric measurements are not made until the lamp has reached stability.

If the goniometer is to be motor driven, the gear ratios are chosen so that the traverse will be slow enough to insure the accurate recording of the characteristics of the light.

5. ACKNOWLEDGMENT

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