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A PHYSICAL PHOTOMETER

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ABSTRACT

The unreliable and differing characteristics of observers' eyes have prevented photometry from being an exact science. A physical photometer has been constructed, consisting of a thermopile, a potentiometer, and a filter which has at each wavelength a transmission proportional to the ICI luminosity factor for that wavelength. This photometer gives results which are consistent with the ICI luminosity factors and which are more accurate than those obtained by visual observers when the photometric fields are not color-matched.

CONTENTS

I. INTRODUCTION

Photometry has been carried on for many years by means of visual observations, not because the eye is an accurate measuring instrument but because there has been no physical apparatus which would respond to radiant energy in the same manner as the human eye with an accuracy comparable with that of visual observations made under the best conditions.

Vision is a combined physiological and psychological process. In the visual photometry of colored lights, otherwise normal observers may obtain markedly differing positions of photometric balance because of their differing brightness evaluations of different parts of the spectrum.

Experience shows not only that the results obtained in heterochromatic photometry are influenced by the characteristics of the eye of the observer, but also that nearly all observers using the equality-of-brightness method will change their decision as to a photometric balance over a period of a month or more. Some observers even exhibit a variation in this decision during a single day.

Even in homochromatic photometry the results obtained are influenced by the attitude of the observer and by his ocular and bodily fatigue or discomfort, and the immediate prior use of an observer's eye must be controlled before observations are made; for example, an observer entering a photometric laboratory from a brightly lighted room requires a period of time to become properly adapted to the light conditions of the photometer room. All of these variations make it desirable to devise a physical instrument to evaluate light.

Various experimenters have worked on the problem. It is sufficient here to note the experiments of Ives and Kingsbury, and of Ives,[1] in 1915, in which a luminosity filter and a thermopile were employed. The luminosity "filter" in one case was a template which was placed in the path of the radiant energy dispersed by a prism. The optical system required and the mechanical difficulties encountered in constructing, mounting, and alining a template has made this method impractical. In the other case the luminosity filter consisted of a liquid solution. In both cases a Thomson galvanometer was used. The susceptibility of this galvanometer to mechanical disturbances and drift of zero, and the lack of exact proportionality between current and deflection in the circuit, imposed serious limitations on their measurements. In order to avoid the difficulties which Ives and Kingsbury encountered, which are present even with the best of modern galvanometers, it was decided in the present work to measure the emf developed, instead of drawing and measuring current from the thermopile. Since this emf is small, it was necessary to develop a special potentiometer and procedure in order to make the measurements to the required accuracy, and these have been described in a previous paper.[2] The present paper gives a more complete description of the physical photometer which was constructed and describes the method of operation and the results of tests which were made to determine its performance.

II. THE PHYSICAL PHOTOMETER

The most fundamental concept in photometry is that of luminous flux. Luminous flux is the rate of passage of radiant energy evaluated by reference to the luminous sensation produced by it. If we have a source emitting equal amounts of radiant energy per unit wavelength throughout the visible spectrum (called an equal-energy spectrum) and have observers evaluate the brightness of this energy at each wavelength, we find that the human eye is not equally responsive to radiant energy throughout the visible spectrum. We find two things: (1) all normal observers find the region of greatest luminosity to be in the yellow-green part of the spectrum, the luminosity gradually decreasing in either direction; but (2) there are important differences in the spectral luminosity curves for different normal observers, which result in their different evaluations of the brightnesses of colored lights. The average spectral luminosity curve of the eye at different wavelengths has been determined for a large number of observers, and an average set of relative values has been accepted by the International Commis-

[1] H. E. Ives and E. F. Kingsbury, Phys. Rev. **6**, 319 (1915).
H. E. Ives, Phys. Rev. **6**, 334 (1915).
[2] R. P. Teele and S. Schuhmann, J. Research NBS **22**, 4 (1939) RP1195.

sion on Illumination as a definition of a "standard" photometric observer.[3] The luminosity curve showing the response of this ideal standard observer for energy received at different wavelengths is given as a solid line in figure 1.

No physical detector has been constructed which has the same relative response curve as the average human eye for radiant energy of different wavelengths. It is possible, however, to make a nonselective receiver, which indicates the amount of received energy per unit time independent of its wavelength. In order to have this nonselective receiver give the same luminous response as the eye of the "standard" observer, it is necessary to interpose between the source and receiver a filter which has at each wavelength a transmission proportional to the luminosity factor for that wavelength. Such a luminosity filter, together with a nonselective receiver and an indicator or measuring device attached to the receiver, constitutes a physical photometer which will measure the rate of passage of radiant energy evaluated by reference to the luminous sensation produced by it, that is, will "see" radiant energy in the same manner as the eye of the standard ICI observer.

1. LUMINOSITY FILTER

The luminosity filter first realized[4] for use as part of the physical photometer was found to lack satisfactory reproducibility, and a second filter,[5] which tests indicate is sufficiently reproducible, was devised. The extent to which the relative transmission of the second luminosity filter duplicates the accepted ICI luminosity curve in the wavelength interval from 380 to 770 mμ is shown in figure 1. The solid line is the ICI luminosity curve, and the plotted points are the transmissions obtained from spectrophotometric data for the luminosity filter. A slight amount of radiant energy is also transmitted by this filter in the infrared region from 800 to 1,320 mμ. The method of correcting for this unwanted band of transmitted energy is discussed in section III.

The filter consists of a piece of glass used in conjunction with a liquid solution. The glass used is a Corning uranium (canary) glass of such a thickness as will give a transmission at 486 mμ of 0.40 $\pm$0.01. The solution has the following composition:

Copper sulfate, $CuSO_4.5H_2O$	20. 00	grams
Cobalt ammonium sulfate, $CoSO_4(NH_4)_2SO_4.6H_2O$	2. 05	grams
Potassium dichromate, $K_2Cr_2O_7$	0. 150	grams
Sulfuric acid, H_2SO_4 (1.835 sp gr)	10	ml
Distilled water to make 1 liter of solution.		

The solution must be used in a cell of 5.00-cm length, which should be placed between the illuminant and the uranium glass (to reduce fluorescence of the latter). Further details regarding the luminosity filter will be published separately.

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[3] 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).

[4] K. S. Gibson, R. P. Teele, and H. J. Keegan, J. Opt. Soc. Am. **28**, 178 (1938).

[5] K. S. Gibson, R. P. Teele, and H. J. Keegan, *An improved luminosity filter*, J. Opt. Soc. Am. **29**, 144 (1939).

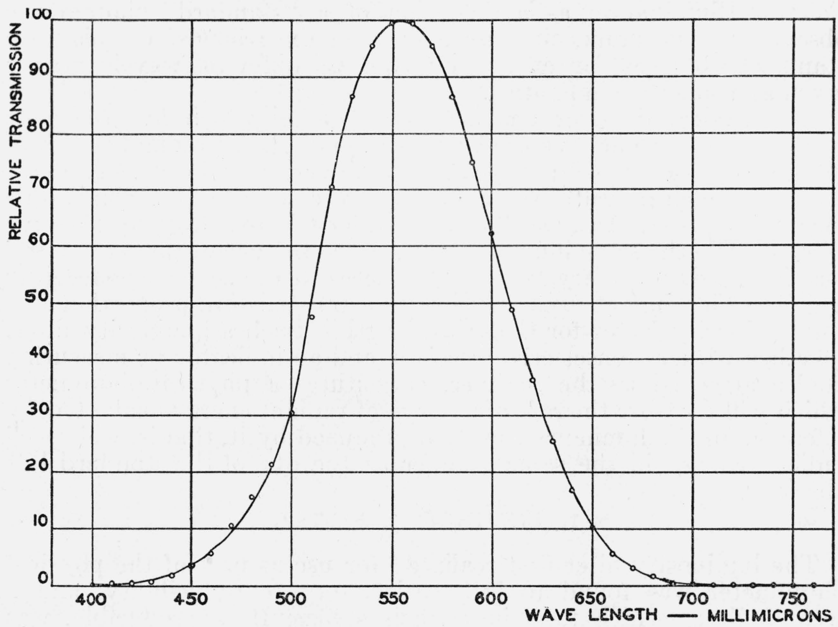

FIGURE 1.—*Relative spectral transmission for the luminosity filter (circles) compared with the standard ICI luminosity curve (continuous line).*

2. RECEIVER

The choice of receiver is dependent upon the reproducibility of its indication, the selectivity, the sensitivity, and the linearity of response with respect to the rate of reception of radiant energy. There are a number of types of receivers whose response to radiant energy is reproducible; hence this requirement does not limit to any considerable extent the choice of receiver. Their selectivity to radiant energy rules out from consideration in the present case receivers such as phototubes and barrier-layer photocells. Although it might be possible to find a combination of a particular selective receiver and filter which together would respond to radiant energy in agreement with the luminosity factors, such a solution to the problem is not yet generally satisfactory because selective receivers even of the same type have differing spectral characteristics. A combination of a filter and a barrier-layer cell which approximates the desired results has been worked out by one manufacturer. This combination is very useful for many purposes which do not require a high accuracy, and refinements in its use have recently been described.[6] In the case of nonselective receivers—such as thermopiles, bolometers, and certain radiometers—the sensitivity and the range over which the response is linear need to be considered together. However, the most sensitive radiometers are either susceptible to various disturbing influences or their range of linearity is too limited. At present there seems to be little choice between bolometers and thermopiles. A thermopile was chosen as the receiver for the present work.

[6] L. E. Barbrow, *A photometric procedure using barrier-layer photocells*, J. Research NBS **25**, 703 (1940) RP1348.

The thermopile used is of the Moll surface type and consists of 80 thermojunctions of constantan-manganin arranged in a circle of 2-cm diameter. The thermopile is designed for use in air and its resistance is approximately 60 ohms.

3. POTENTIOMETER

In preliminary experiments it was found that the voltages were of the order of magnitude of 10 μv (microvolts), and a special potentiometer was accordingly designed to measure such electromotive forces. In work with the completed physical photometer it was found that measurements covering a range from a few tenths of a microvolt to over 100 μv would be necessary in practical photometric work. The potentiometer is capable of covering this range without modification of the original design.

In the measurement of small electromotive forces the most serious difficulty lies in the presence of extraneous thermal electromotive forces in the various parts of the measurement circuit. The major part of the apparatus, comprising the potentiometer, was designed to prevent or eliminate the effects of such electromotive forces.

The galvanometer was selected to work with the combination of thermopile and potentiometer. The potentiometer circuit is such that its resistance is of secondary importance, and a galvanometer was specially built to be critically damped by the thermopile—that is,the critical damping resistance of the galvanometer is approximately equal to the resistance of the thermopile. The galvanometer has, of course, a circuit which is all of copper. The sensitivity is 12 mm/μv for a scale distance of 1 m. The galvanometer is used with a scale distance of 10 m, and the circuit is always reversed to obtain an indication of balance of the potentiometer, which in effect doubles the sensitivity. These two expedients give an effective sensitivity of 240 mm/μv in actual use, and a change of 0.24 mm upon reversal corresponds to 0.001 μv.

4. PRECAUTIONS TO BE OBSERVED

Obviously it is desirable to locate the galvanometer on a vibrationless support. An A-frame support fastened to a heavy masonry wall was found to be adequate for a reasonable percentage of the time.

The thermopile-galvanometer circuit is subject to such disturbances as would be caused by neighboring electric devices, electrostatic and electromagnetic influences, etc. The thermopile should be electrostatically shielded and located as far as possible from all electric equipment. The electrostatic shielding must include the galvanometer circuit. The wires of the thermopile-galvanometer circuit must be fastened down at closely spaced intervals to prevent swinging or movement that would change the magnetic field included by them. Festoons or loops of wire are to be avoided, and the use of twisted pairs of wires is desirable.

III. METHOD OF TAKING OBSERVATIONS

As already stated, the filter transmits radiant energy slightly in the region from 800 to 1,320 mμ in addition to its principal transmission in the visible region. This unwanted energy will also be measured by the receiver. The entire response of the receiver is, therefore, proportional to the radiant energy transmitted in the visible region plus that transmitted in the infrared. By inserting a filter which does not transmit any visible energy but has a high transmission in the infrared region, the band of energy in the infrared may be evaluated. An infrared (Corning No. 255, sextant red glass) filter will separate the two regions adequately. The measurement must be made in two parts: (1) a measurement of the total energy transmitted by the luminosity filter, and (2) a measurement of the energy transmitted by the luminosity filter and the infrared filter used together.

If we designate the response of the thermopile for the respective measurements outlined above by P_{LT} and P_{LI}, we have

$$P_{LT}=k(E_{LV}+E_{LI}) \tag{1}$$

and

$$P_{LI}=kE_{LI}F_{I}, \tag{2}$$

in which k is a proportionality constant, E_{LV} is the energy from the source transmitted by the luminosity filter in the visible region only, E_{LI} is the energy from the source transmitted by the luminosity filter in the infrared region only, and F_I is the infrared transmission factor for the infrared filter. From eq 1 and 2 it is seen that the response, P_{LV}, in the visible region alone is

$$P_{LV}=kE_{LV}=P_{LT}-kE_{LI}=P_{LT}-\frac{P_{LI}}{F_I}. \tag{3}$$

As a preliminary to the use of the physical photometer, it is therefore necessary to determine the infrared transmission, F_I of eq 2 and 3, of the infrared filter to be used. This may be done by using the physical photometer to measure the transmission of the infrared filter for energy from an incandescent source passing through a similar infrared filter. This determination has been carried out for incandescent sources over the color-temperature range 2,046° to 2,842° K, and F_I was found to be constant at 0.70 within ± 0.01. For such sources this uncertainty in F_I introduces at most an error of 0.2 percent of the luminous flux. Therefore the determination of F_I for the usual incandescent source can be made at an intermediate color temperature once for all.

The total response of the thermopile-galvanometer circuit is caused both by the radiant flux from the source being measured and by stray or extraneous flux from the surroundings. By the surroundings are meant the laboratory room and its contents, including the persons who are operating the equipment.

The electromotive force caused by the radiant flux from the source is distinguished from the rest by the use of a shutter to allow the flux being measured to reach the receiver at desired times. The shutter used should be designed and placed so that its operation will not change the conditions of the surroundings or cause air currents around the thermopile. In the present work a rotary shutter made from a disk of plywood with an opening to let the energy pass through to the receiver proved to be satisfactory. By placing this shutter between the source and the luminosity filter, the latter can be used as a window for the thermopile housing and thus reduce materially the trouble from air currents which would be encountered in using an uncovered thermopile.

The surroundings are, in general, not at the same temperature as the thermopile, and thus there is an exchange of radiant energy between the thermopile and the surroundings. The thermoelectromotive force of each of the junctions is about 40 μv/°C, and hence the total for the 80 junctions is more than 3,000 μv/°C. Since it is sometimes desired to make measurements imprecise by less than 0.001 μv, the receiver surface and the dark junction cannot be considered to be at the same temperature unless their temperatures differ by less than about 3×10^{-7} of a degree centigrade. It is not practical to maintain these temperatures within such small limits, and it is, therefore, neces-

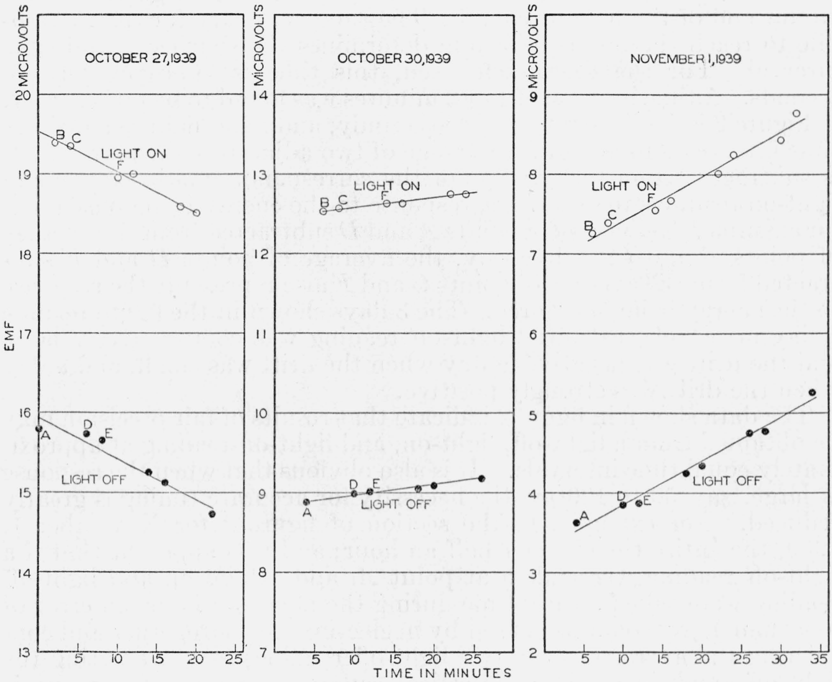

Figure 2.—*Response for a 300-watt lamp at a distance of 1.56 meters at constant voltage.*

Observations were taken at 2-minute intervals.

sary to eliminate the effect of the stray energy by an accurate timing of the measurements of the response when the receiver is screened from and when it is open to the energy from the source. Gradual warming or cooling of the surroundings causes a first-order drift in response due to stray energy, and second-order changes are avoided by taking precautions to prevent sudden changes in conditions of the surroundings—that is by keeping doors and windows closed, by having the operators located at a distance from the thermopile housing, and by keeping equipment located in one position during a series of measurements.

Figure 2 shows readings taken with a 300-watt lamp at a distance of 1.56 meters on different occasions. These readings are taken in the following manner. The light source is turned on and the potentiometer approximately balanced with the shutter closed. Temperature equilibrium is reached in the course of 2 or 3 minutes. An accurate balance is then obtained and the shutter opened. After a definite time interval, say 2 minutes, another reading is taken. The shutter is kept open for the chosen time interval and another reading taken and the shutter closed. After 2 minutes a reading is taken. The shutter is kept closed for an additional 2 minutes and a reading taken. This cycle is continued for a group of three or four pairs of readings. The time interval will depend to some extent upon the ability of the potentiometer operator, but it should be as short as is consistent with the determination of accurate balances of the thermopile-galvanometer circuit and of the potentiometer. The time necessary for the thermopile to reach thermal equilibrium determines the shortest permissible interval. For the thermopile used, this time is approximately 10 seconds. A time interval of 1 or 2 minutes was found to be satisfactory.

Figure 2 is for illustrative purposes only, and in actual use a definite time interval is used and the average of two adjacent light-off readings is subtracted from the average of the corresponding adjacent pair of light-on readings to obtain the response to the energy being measured; for example, the average of points *A* and *D* subtracted from the average of points *B* and *C*. Obviously, the average of points *D* and *E* subtracted from the average of points *C* and *F* also represents the response to the energy being measured. The 3 days shown in the figure include a day on which the initial light-off reading was comparatively large and the drift was negative, a day when the drift was small, and a day when the drift was strongly positive.

The data shown in figure 2 indicate that results of fair precision may be obtained from a light-off, light-on, and light-off reading at approximately equal time intervals. It is also obvious that when the response is large, say 50 to 100 μv, the necessity for accurate timing is greatly reduced. For example, in the section of figure 2 for November 1, 1939, the entire time is over half an hour; and it is apparent that if a light-off reading were taken at point *A*, and a light-on and light-off reading were taken at any time during the next half hour, an error of less than 1 μv would be caused by neglecting time altogether and considering the average of the two light-off readings as representing the light-off conditions. If the vertical separation were 100 μv, as it may often be, this 1 μv would represent an error of only 1 percent. Usually, readings may be taken in a time interval of a few minutes rather than half an hour. If an uncertainty of 1 or 2 percent can be tolerated, it is possible to simplify the procedure and use more rugged, but less sensitive, electric equipment.

IV. EXPERIMENTAL TESTS

The physical photometer was tested experimentally by measuring spectrally selective filters to verify the adequacy of the luminosity filter and thermopile and by measuring rotating sector disks to be sure that the rotating lamps would be evaluated correctly.

1. MEASUREMENT OF SPECTRALLY SELECTIVE FILTERS

The glasses measured were chosen from types that are very selective in their transmission and were selected so as to include transmission bands distributed throughout the visible spectrum. The group included those designated as selenium red, selenium yellow, signal yellow, cobalt blue, signal green, and signal blue, the glasses ranging from 2 to 50 percent in transmission, and also signal-purple filters some of which transmitted only one-half of 1 percent of the incident light from an incandescent lamp at 2,848° K. Their spectral transmissions and the computed luminous transmissions had been carefully determined by others, and the data for many of them have been published.[7]

In the measurement of the luminous transmission factor, F_V, of a glass filter, four measurements have to be taken, corresponding to eq 3, with the glass in the beam and with it removed. The value of F_V is given by the ratio

$$F_V = \frac{\left(P_{LT} - \frac{P_{LI}}{F_I}\right)_{\text{glass in}}}{\left(P_{LT} - \frac{P_{LI}}{F_I}\right)_{\text{glass out}}}. \qquad (4)$$

The comparison of the results of measurements made with the physical photometer according to eq 4 and the values obtained by computation from spectrophotometric data by the use of the ICI luminosity factors is given in table 1. The values calculated from spectrophotometric data were computed by the usual summation method with 10-mμ intervals, although this computation by discrete intervals may slightly reduce the accuracy of the final result. The response of the physical photometer is equivalent to a continuous intergration rather than to the summation used in the computations. On the other hand, the physical photometer data were obtained at room temperatures, whereas the spectrophotometric data, on which the computations are based, were obtained at 25° C. It so happens that the selenium red and yellow glasses, which are subject to appreciable summation errors, are also the least uniform in transmission (through different parts of a given filter) and subject to the largest temperature effects.[8] The discrepancies between the two columns of values are well within the combined experimental errors of the two methods for all of the glasses.

The test with these 22 filters justifies the conclusion that the physical photometer gives results which are consistent with the ICI luminosity factors and verifies the performance of the combination of luminosity filter and thermopile-galvanometer-potentionometer system.

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[7] K. S. Gibson and Geraldine K. Walker, Signal Section, Proc. Am. Ry. Assn. **30**, 405, 420 (1933).

[8] The purple glasses are also subject to appreciable summation errors and important temperature effects but are uniform in transmission.

TABLE 1.—*Comparison of values of luminous transmission of spectrally selective glasses obtained by direct measurement with the physical photometer and by computation from spectrophotometric data with ICI luminosity factors*

Color designation of glass	Luminous transmission for 2,848° K		Color designation of glass	Luminous transmission for 2,848° K	
	Physical photometer	Spectrophotometer		Physical photometer	Spectrophotometer
Selenium red	0.088	0.089	Signal green	0.182	0.184
Do	.103	.101	Do	.200	.201
Do	.135	.139	Do	.251	.252
Selenium yellow	.505	.500	Do	.268	.270
Signal yellow	.378	.376	Signal blue	.0356	.0356
Do	.506	.508	Do	.0215	.0216
Cobalt blue	.163	.161	Signal purple	.0049	.0051
Do	.244	.242	Do	.0050	.0049
Do	.291	.290	Do	.0063	.0059
Do	.374	.374	Do	.0115	.0120
Do	.402	.400	Do	.0200	.0206

2. MEASUREMENT OF ROTATING SECTORED DISKS

When sectored disks are used, the light reaching the receiver varies from zero, when the opaque portion is in the path of the light, to full intensity, when the open portion is in the path of the light. Obviously, the use of sectored disks is a more severe test of the physical photometer than the evaluation of a rotating lamp for which the changes in intensity are small.

The transmissions of two sectored disks, one with four openings, transmitting about 10 percent, and one with two openings, transmitting about 1 percent, were measured on the physical photometer. The transmissions of the sectored disks were also calculated from the angular openings.[9] The calculated and measured transmissions are compared in table 2.

The results given in table 2 indicate that the physical photometer will correctly evaluate an intermittent light when the periods of fluctuation are short compared with the response period of the thermopile-galvanometer circuit (about 10 seconds). Any period can be used provided it is not great enough to cause perceptible flicker of the galvanometer spot.

TABLE 2.—*Comparison of transmissions of sectored disks*

Disk designation	Transmission factor	
	Calculated from angular opening	Measured by the physical photometer
10 percent	0.1000	0.1001
1 percent	.00979	.00975

[9] The angular openings were determined by the Length Section of the Weights and Measures Division of the Bureau.

3. STABILITY

One important consideration is the stability of the physical photometer. In measuring lights it is desirable to have an instrument which can be calibrated and then used for a period of time before recalibration. The length of time between calibrations is governed by the possible aging effects of the component parts of the physical photometer.

The surface of the receiver is well protected from mechanical damage, and there is no reason to expect that rapid changes will occur from aging of the surface. The chemicals used in the luminosity filter are all stable in the concentrations used in the solution. Most of the constituents have been carefully studied by other investigators.[10] The properties of the glass are not likely to change.

Nevertheless, the stability was investigated by two separate tests. A seasoned lamp was placed at a fixed distance from the receiver and measured over a period of 2 weeks. The results are given in table 3. A study of these data shows a maximum variation from the mean of 0.35 percent and an average deviation of 0.17 percent. These variations are within the experimental error, and this test shows that during this length of time there was no appreciable change in the emf of the thermopile for a given density of luminous flux.

TABLE 3.—*First test of stability*

Date	Response
	Percent
March 23	100.17
March 25	99.92
March 28	100.30
March 31	100.04
April 1	99.65
April 6	99.92
Mean	100.00

The second test was made as part of a series of measurements on a group of standardized lamps. The period of time covered by this series of measurements was nearly 6 months. The response for a given density of luminous flux during this period did not vary by as much as 0.4 percent from the mean, and the average deviation from the mean was less than 0.2 percent.

V. APPLICATION TO MEASUREMENT OF LAMPS

The results obtained in measuring highly selective filters, given in table 1, indicate clearly that the physical photometer may be used to measure the light from all spectral types of sources, including fluorescent lamps, mercury, neon, sodium, and similar gaseous-discharge lamps. Parker [11] has already used a similar physical photometer for work with mercury and sodium lamps.

[10] R. Davis and K. S. Gibson, Filters for the Reproduction of Sunlight and Daylight and the Determination of Color Temperature, Misc. Pub. BS 114 (1931).

[11] Allan E. Parker, *Measurement of illumination from gaseous discharge lamps*, Illum. Eng. **35**, 883 (1940).

The values obtained for the rotating sectored disks (table 2) show that fluctuating sources, such as rotating lamps and gaseous-discharge lamps (operating on alternating-current circuits), will be correctly integrated when the period of the fluctuation is not long compared with the response period of the thermopile-galvanometer circuit.

The work done with the physical photometer indicates that, when once calibrated, it will enable the candlepower of a lamp to be determined without the use of other lamps as standards and without the use of accessories, such as color-matching filters. Visual observers must balance a lamp against other lamps of known candlepower in order to determine the candlepower of the unknown lamp; little time can intervene between the photometric balances for the different lamps; and when the lamps being compared differ in color, it is necessary to use accessory filters to equalize the color. The use of a previously calibrated physical photometer to determine the candlepower of a lamp will be of considerable advantage in conserving the life of standard lamps and will result in a saving in the time required to determine the candlepower of a single lamp. In addition, it will be unnecessary to take time to obtain and to calibrate a color-matching filter, when such a filter is required as an accessory for visual observations.

Another advantage of the physical photometer is that one person, experienced in using sensitive electric-measuring equipment, can make the measurements required and thereby save most of the time and trouble involved in obtaining and using a group of visual observers who have photometric experience and nearly normal luminosity functions.

Work leading to the use of the physical photometer for the determination of the candlepower of lamps operating at 2,046°, 2,360°, and 2,727°K to give three points on the new proposed photometric scale [12] is under way.

VI. SUMMARY

The experimental results show that a physical photometer composed of three elements—a luminosity filter, a spectrally nonselective receiver, and a sensitive electric measuring apparatus attached to the receiver—gives photometric results which are practically the same as those which should be obtained by a standard observer having the characteristics represented by the ICI luminosity factors.

The luminous transmission of a spectrally selective filter can be determined with the physical photometer in a much shorter space of time than that required to obtain the spectrophotometric data and perform the necessary calculations. The two methods are comparable in accuracy. It is often unfeasible to make such determinations by direct visual observation.

WASHINGTON, July 1, 1941.

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[12] E. C. Crittenden, *Terminology and standards of illumination*, J. Opt. Soc. Am. **29**, 103 (1939).