New Color Corrected Photronic Cells for Accurate Light Measurements

By MARLIN E. FOGLE

Some of the problems encountered in the measurement of light with Photronic photoelectric cells are discussed. A new solid glass "Visual Correction" color filter, to correct the spectral sensitivity of the Photronic cell to that of the average human eye, is described. Calculated and measured values of the relative current output of the cell, with and without the correction filter, are given for various commercial light sources. It seems probable that a cell with this new correction filter will in use, at normal incidence, be able to measure with an accuracy approaching ± 2.0 per cent for light from tungsten lamps, ± 3.5 per cent for light from all continuous sources, and ± 5.0 per cent for all commercial monochromatic sources.

THE present paper is concerned in general with problems encountered in the measurement of light with the Photronic[1] cell, and in particular with the use of a new glass color-filter (called a "Visual Correction" filter) which has just been developed to correct for the deviation in spectral sensitivity of the Photronic cell from that of the average human eye.

The solid (dry-disc, barrier-layer) type of photocell has definitely established itself in the field of light measurements in the four to five years of its commercial existence. This type of cell converts light energy directly into electrical energy with an efficiency that enables a permanent-magnet movable-coil type of instrument to be operated directly from the current of photoelectricity generated by the cell—no amplification or external source of current being necessary.

The Weston Photronic cell, a typical solid cell, and its component parts are shown in Fig. 1. Two models of illumination meters using this cell are shown in Fig. 2. One has a single cell as the light receiving target which can be used in any plane from horizontal to vertical. The other model is regularly supplied with a two-cell target on a flexi-

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[1] *Photronic*—A copyrighted name used to designate the photoelectric cells and devices manufactured exclusively by the Weston Electrical Instrument Corporation.

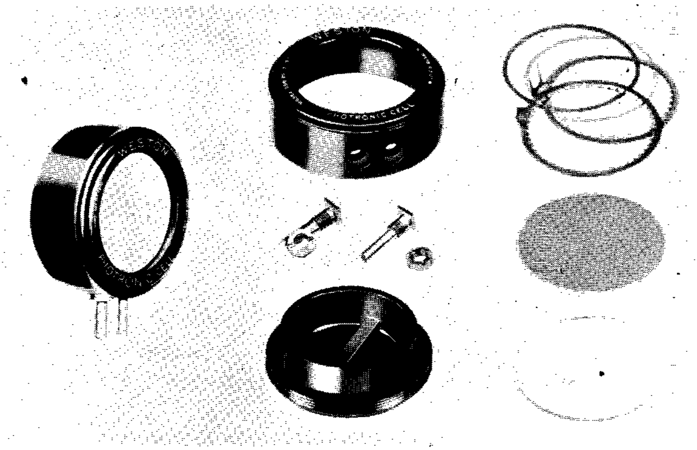

FIG. 1—Photronic cell and component parts: Case, contacts, photosensitive disc and glass window.

ble cord that permits the measurement of low light intensities from any angle and in almost any location. For measuring extremely low intensities, a target with more cells is used.

The chief attributes of the solid photocell type of illumination meter are: simplicity, portability, ruggedness, automatic and direct measurement of light values, speed of operation, an accuracy comparable to visual type illuminometers, and a comparatively low cost. The general characteristics of the first Photronic Illumination Meter were

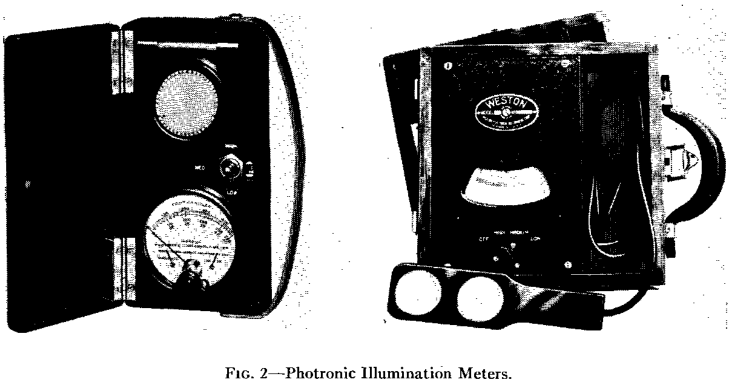

FIG. 2—Photronic Illumination Meters.

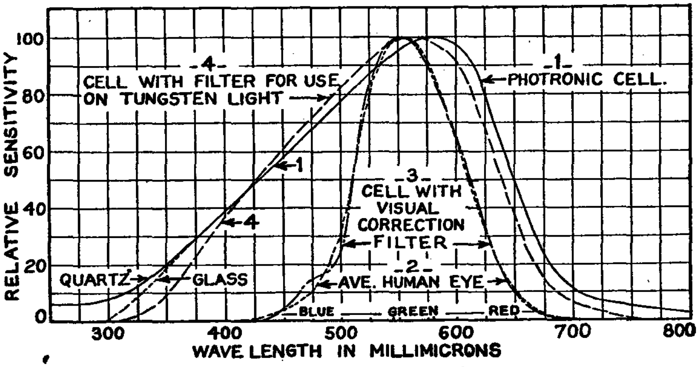

FIG. 3—Spectral sensitivity of photronic cell with and without filters.

discussed in the TRANSACTIONS of this Society in 1932 by W. N. Goodwin, Jr.[2] and will not be repeated at this time.

SPECTRAL SENSITIVITY OF THE HUMAN EYE

The entire process of seeing is dependent upon the fact that human eyes are sensitive to some of the electromagnetic radiations that enter the pupil of the eye. This sensitivity is limited to a narrow range of frequencies or wave-lengths of the known ether spectrum, roughly between 400 and 700 millimicrons of wave-length as shown by Curve 2 in Fig. 3.

The human eye is most sensitive near the center of this band at about 555 millimicrons. The sensitivity of the eye decreases as the wave-length either increases or decreases from 555 millimicrons, becoming zero at both edges of the visual band. Of course, lights of different wave-lengths not only produce different amounts of eye sensitivity or luminosity, but also produce different color sensations in the eye. That is, a normal eye observes a change in hue for each change in wave-length. Of course, for color-blind eyes there are regions of the spectrum where there is no apparent change in hue for a change in wave-length.

FACTORS AFFECTING ILLUMINATION

The mechanism of light reactions involved in producing illumination can be broken down into at least three divisions: (1) The source

[2] W. N. Goodwin, Jr., TRANS. I. E. S., XXVII, No. 9, 828–835 (1932).

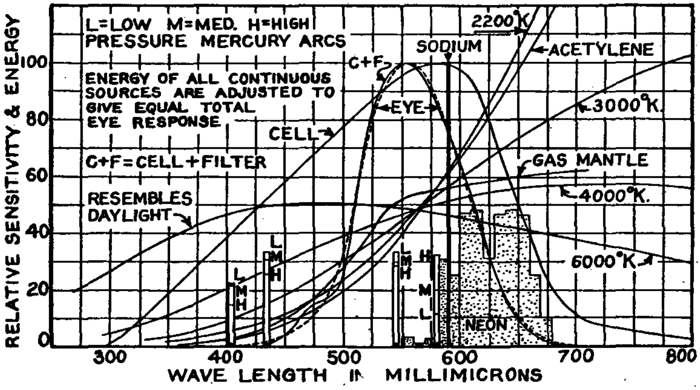

FIG. 4—Relative energy distribution for various commercial illuminants.

of the light, (2) the path of the light, and (3) the receiver of the light.

The Source

A source of light operating under a given set of conditions emits light of a definite spectral composition. The relative amounts of energy emitted at each wave-length from 300 to 800 millimicrons by a black body source at 2200, 3000, 4000, and 6000 K; by an acetylene flame; and by a Welsbach mantle are shown by respective curves in Fig. 4. The curves for these sources, which all emit continuously throughout the visible spectrum, are so adjusted that the total eye response to each is the same. The relative amount of "red energy" is seen to decrease and the amount of "blue energy" to increase as the color temperature of the source increases.

The relative amounts of energy emitted in the visible region by several monochromatic sources is also shown in Fig. 4. Practically all of the light from a sodium lamp is in a narrow band at about 590 millimicrons and produces a yellow color sensation. The visible energy from high, medium, and low-pressure mercury lamps is mainly in four bands at 405, 436, 546, and 578 millimicrons as shown—the total energy in the four bands being adjusted to 100 per cent for each source. The relative distribution for neon which emits almost continuously over a wide band in the orange-red region is also given.

These curves show how widely various commercial sources of illumination differ in their spectral composition, and emphasize how essential it is to know the composition of a given light in order to interpret its effects.

The Path

The path that a ray of light takes in reaching the eye also has a large effect upon the results. It is seldom that light passes unaltered from a source to a receiver. It usually passes through some colored gas, liquid, or solid; is reflected from a colored surface; or is absorbed and re-emitted by a colored substance before reaching the eye or other light receiver. As a result the spectral composition of the light is often radically altered before it reaches the receiver.

The Receiver

Radiations that enter the pupil of the eye produce luminosity in proportion to the amount of radiant energy entering, its spectral distribution, and the sensitivity of the eye to each wave-length. Almost any other receiver will evaluate the luminosity of light from various sources quite differently than the human eye. This is because the spectral sensitivity of other receivers, such as photocells or photosensitive emulsions, differ appreciably from that of the eye. Of course all human eyes differ somewhat among themselves, the sensitivity ascribed to the eye being an average for a large number of eyes.

The relative intensity of two different lights, or the relative brightness of two different surfaces, will therefore depend upon (1) the quantity and spectral composition of light being emitted by the source (or sources), (2) the distance and spectral nature of the path of the light, and (3) the relative sensitivity of the receiver.

SPECTRAL SENSITIVITY OF A PHOTRONIC CELL

The relative sensitivity of an average Photronic cell is given by Curve 1 in Fig. 3. The cell sensitivity is seen to span the eye visibility range and to extend slightly into the ultra-violet and near infrared regions. That is, certain radiations are visible to the cell that are not visible to the human eye; and those radiations which are visible to both the eye and the cell are not equally visible to both. The result is that the cell and the eye do not evaluate equally different lights varying in spectral composition. They approximate each other, sometimes quite closely, when measuring light from continuous sources such as from the sun, an acetylene flame, a gas mantle, or a tungsten lamp; but may differ considerably when measuring light from more monochromatic sources such as neon, sodium, or mercury lamps.

The cell can be made to agree with the eye for all measurements of light by multiplying the cell output by the proper factor. This method is quite unsatisfactory however, first, because it is practically impossible to tell what factor to use when light from several sources is involved or where colored walls, colored shades, or even colored bulbs alter the composition of the light.

The obvious method of making the cell agree with the human eye is to use a color filter (a selective radiation filter) in front of the cell to filter out or remove that part, or all, of the rays of any given wave-length necessary to make the response of the cell to the remainder just equal the eye sensitivity at that wave-length. With a cell and filter combination having an effective sensitivity identical to that of the average human eye, it matters not what the spectral composition of the light may be because the sum total response to all the different wave-lengths will be the same for the cell plus filter as for the eye.

COLOR CORRECTION FILTERS

The transmission of the ideal visual correction filter for a Photronic cell is given by Curve 1 in Fig. 5. A visual correction filter consisting of two pieces of colored glass cemented together with balsam has just been developed which closely approximates this ideal. The spectral calculations for this new filter were made by the author working in conjunction with Dr. H. P. Gage of the Corning Glass Works who developed the special blue glass component after existing glasses proved inadequate.

A colored-liquid filter and a dyed-gelatin filter were previously developed, both of which also quite closely approximate the ideal correction filter. A liquid filter is undesirable for most commercial applications; and the gelatin filter used in the past being transparent to infrared rays sometimes led to an appreciable error because of the infrared response of the cell. Calculations and measurements indicate that the new glass filter is by far the best one yet developed for this purpose and that it is entirely satisfactory for commercial use. Results on this filter will be discussed later.

The spectral sensitivity of a cell with a partial correction filter is shown by Curve 4 in Fig. 3. It is an Aklo-type Corning Glass filter which removes most of the infrared rays and alters the sensitivity of

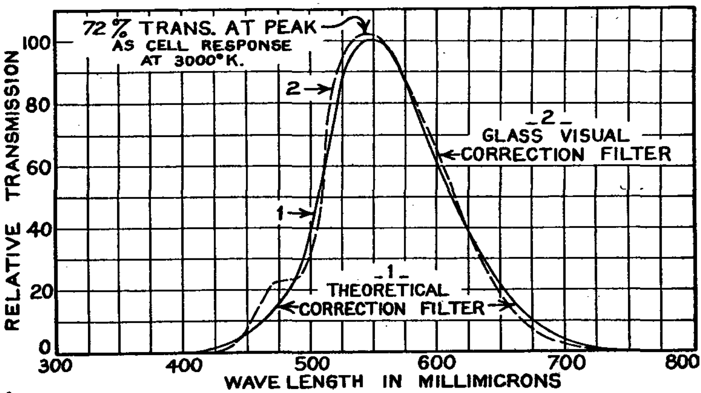

FIG. 5—Theoretical and glass visual correction filters for Photronic Cell.

the cell so that it will measure tungsten light of all ordinary color temperatures with a fair degree of accuracy. It has a high transmission, which is desirable when measuring low light intensities, and is less expensive than the visual correction filter. It does not correct for sources other than tungsten and is therefore limited in its use.

In respect to the need for color correction, the Photronic cell had much in common with the visual type illuminometer, the accuracy of which is considerably impaired when measuring light of any color temperature other than that of the comparison lamp in the illuminometer. Correcting for the spectral differences encountered with the cell has been relatively simple when compared with the problem of correcting for spectral differences encountered with the visual type illuminometer. One filter to change the cell sensitivity to the eye sensitivity eliminates the usual difficulty in making heterochromatic matches thereby enabling the cell to measure light of any spectral composition directly and accurately; but with the visual type instrument, a different filter on the comparison lamp is required for the measurement of each light having a color differing appreciably from that of any other light measured. Furthermore the transmission of each filter changes every time the color temperature of the comparison lamp alters a small amount with use so that a calibration curve must be obtained for each filter over a range of color temperatures.

THE GLASS VISUAL CORRECTION FILTER

One component of the new correction filter is a yellow glass which removes the excess blue response of the Photronic cell, and the other is a blue-green glass which removes the excess red response. The spectrophotometric curve of the glass visual correction filter and the calculated ideal filter are compared in Fig. 5. It is possible to make the two curves conform more closely, by altering the thickness of the component glasses, and thereby increase the accuracy on continuous light sources. However, by allowing a small inaccuracy in continuous source measurements it was possible to improve the accuracy of measurements on commercial sources more monochromatic in nature. The calculated spectral sensitivity of an average cell with a glass visual correction filter is given by Curve 3 in Fig. 3 whereas Curve 2 represents the average eye sensitivity.

The largest variation of the glass filter from the ideal filter is in the region of 485 millimicrons. The cell and filter have a sensitivity greater than and again lower than the eye within a narrow band of the spectrum on either side of 485 millimicrons, so that for continuous sources the variations tend to cancel out. Furthermore, no commercial monochromatic source emits energy in this region and none is likely to be developed because the eye sensitivity, or luminous efficiency, is too low.

The total transmission of the filter is about 37.5 per cent for light from tungsten at 3000 K—measured as cell response. The peak of the transmission is about 72 per cent (78 per cent of the theoretical maximum) at 545 millimicrons. This is quite high for a filter having complete cutoffs at both ends of the visible spectrum.

The infrared sensitivity of the Photronic cell (a sensitivity which may produce a response as large as 10 per cent of the total for light rich in the near infrared rays) is eliminated by the glass correction filter. This also tends to retard heating of the cell, since only a portion of the heat is able to reach the disc by conduction, and thereby reduces errors caused by changing temperature.

Glass is quite stable chemically and therefore the filter does not affect the sensitive surface of the cells disc. The blue-green component, being more easily scratched and fogged by moisture than the yellow component, is placed inside of the cell for protection.

CALCULATIONS AND MEASUREMENTS ON FILTER AND CELL

Calculations were made in order to predict the accuracy of a filter in use with the Photronic cell when measuring light from tungsten lamps, acetylene flame, gas mantle, daylight, neon, sodium, and mercury lamps. The relative energy emitted by each illuminant every

10 millimicrons between 400 to 800 millimicrons was multiplied by the eye sensitivity at the corresponding wave-length and the products added to obtain the total eye response for each illuminant. Substituting the cell sensitivity (as altered by the filter) for the eye sensitivity, values of total cell response were obtained which allowed the theoretical accuracy of the cell to be calculated for each illuminant—assuming one illuminant as a basis of comparison.

Calculations on the final filter are given in Table I. The reliability of such calculations can be judged by the close agreement between calculated values obtained in a similar manner for a cell without a filter, and actual measurements listed in Table I. Since the measured values for the monochromatic sources may be in error by at least ± 5.0 per cent, because of inaccuracies in the visually determined standard intensities, the small differences between calculated and measured values are unimportant. Of course, the calculated accuracy does not take into account instrument errors, variations in spectral response of individual cells, calibration errors, temperature errors, and fatigue, all of which affect measured values.

Table I also contains partial results of tests that are being made by the Electrical Testing Laboratories on four cells equipped with glass visual correction filters. The measured values, obtained by comparing cell output with visually determined quantities of light, agree quite closely with calculated values at color temperatures of 2360, 2855, 4820 K and for mercury vapor. At 6535 K they differ by 3.3 per cent. The accuracy of the measured value at 6535 K is in greater doubt than for the others because its accuracy is dependent upon the Davis and Gibson filter used to convert 2855 degrees to 6535 degrees and upon the maintenance of the proper color temperature, as well as upon the candlepower standardization of the lamp itself. The candlepower values assigned to the lamps were considered uncertain by about ± $\frac{3}{4}$ per cent.

The four cells were not measured for spectral sensitivity but the results indicate that they are close to the average cell, although they were purposely chosen to represent opposite extremes so far as their physical appearances and time of manufacture were concerned.

INTERPRETATION OF RESULTS

Calculated results on the cell with and without a correction filter, for light emitted by a black body radiator between 2200 and 6500 K, are plotted in Fig. 6. The measured values for the four visually-corrected cells are also plotted. The curve for the corrected cells

TABLE I—ILLUMINATION MEASUREMENTS WITH THE PHOTRONIC CELL

Light Source	Photronic Cell Without Filter			Cell With Glass Visual Correction Filter	
	Measured Output*	Calc. Output*	Calc. Correction Factor	Calc. Output*	Effect of Filter Variations
					%
2200 K		106.2	.94	99.7 ±	.3
2300	106.7	105.5	.95	99.8 ±	.2
2600		102.0	.98	100.0 ±	.1
2700	100.0	100.0	1.00	100.0 ±	.0
2848 (Ill. A)		98.3	1.02	100.0 ±	.0
3000	97.6	97.2	1.03	100.1 ±	.1
4000		95.7	1.04	100.4 ±	.3
4800 (Ill. B)		98.6	1.01	100.5 ±	.5
6000		101.5	.99	100.7 ±	.6
6500 (Ill. C) Daylight	101.0	103.0	.97	100.7 ±	.7
Acetylene		105.5	.95	99.9 ±	.2
Gas Mantle	90.0	86.0	1.16	100.4 ±	.3
Sodium	74.0	70.0	1.43	100.7 ±	2.0
Neon	106.0	107.0	.94	99.5 ±	2.0
Mercury: High Pres.	71.0	74.0	1.35	99.3 ±	2.0
Mercury: Inter. Pres.	77.0	82.0	1.22	99.4 ±	2.0
Mercury: Low Pres.		87.0	1.15	99.6 ±	2.0

* Relative values of current output based on Tungsten light source at 2700 K.

MEASUREMENTS ON FOUR CELLS WITH GLASS VISUAL CORRECTION FILTERS[a]

Light Source	Relative Measured Output of Cells[b]				Average
	#1	#2	#3	#4	
2360 K	98.9	98.8	99.1	99.1	99.0
2855	100.0	100.0	100.0	100.0	100.0
4820	100.0	100.9	100.7	98.7	100.7
6535	103.2	103.3	105.6	104.1	104.0
Gas Mantle					
Mercury	101.0	100.6	99.4	96.7	99.6
Sodium					
Neon					

[a] Measurements by Electrical Testing Laboratories.

[b] Basis of comparison 2855 K. These four cells were purposely selected as being dissimilar in regard to time of preparation and physical characteristics. Even so, their spectral characteristics appear to be quite uniform.

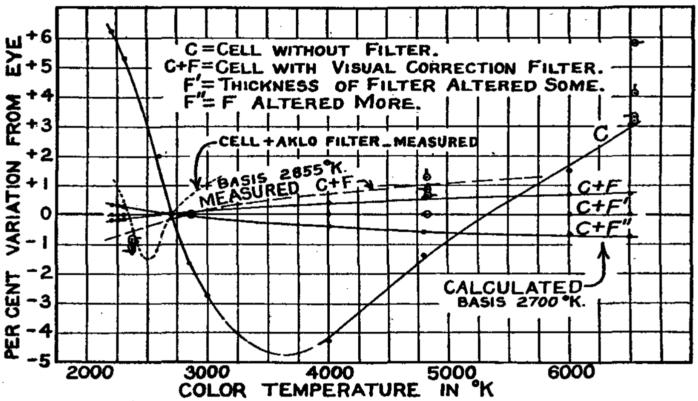

FIG. 6—Calculated and measured variations in photronic cell accuracy with color temperature of light.

was not extended to 6500 K nor drawn through the values obtained at 6500 because it appears the curve should be a smooth one and because the accuracy of the measurements at that point are in greater doubt than for any of the other points. Slight variations from the curve at other points may be due to errors in the calibration lamp and in the meter used for measuring the output of the cells, as well as in the cell or filter. In fact the closeness of the agreement between cal-

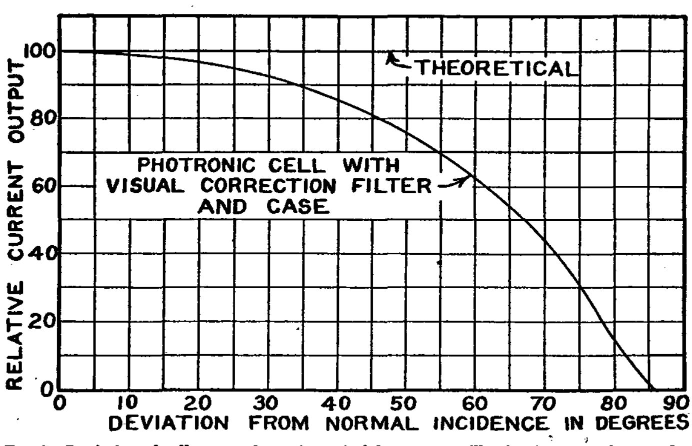

FIG. 7—Deviation of cell output from theoretical for constant illumination at various angles of incidence.

culated and measured values indicates all errors are equally small and for most applications negligible. Furthermore, it is possible to correct for any general deviation of measured values from calculated values by altering the filter thickness slightly, as from $C + F$ to $C + F'$ or to $C + F''$ as shown by the curves in Fig. 6.

It appears from these preliminary measurements that a visual corrected cell can be calibrated with an accuracy approaching ± 2.0 per cent for light from tungsten, ± 3.5 per cent for all continuous sources, and ± 5.0 per cent for all commercial monochromatic sources. It must be remembered, however, that such high accuracy would hold only for light falling upon the cell at normal incidence. As the angle of incidence increases, the cell output falls off more rapidly than the cosine law requires for a light beam of constant flux density, as shown by Fig. 7. This is partly because the length of the path of light through the color filter increases, partly because of shading by the cell holder, and partly because of other reasons inherent with the cell itself. A slight loss in color correction also occurs at the larger angles because of the increased length of path through the filter.

Once the accuracy of the visually corrected cell is known, it is possible to check an illumination meter in a few minutes at one point with a standard tungsten lamp. The meter can then be used with assurance on sources such as mercury or neon which can not be measured rapidly or accurately by ordinary visual methods.

Variations in spectral response between individual visually corrected cells in the regions of sodium and neon radiation can hardly be more than plus or minus 2 per cent. Larger variations in existing visual methods have so far prevented their being used to accurately evaluate the absolute error of the cell for these sources. It seems that if cells and correction filters were individually measured and selected they would prove a more reliable means than existing visual methods for measuring the more monochromatic light.