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The Standardization of Photo-Electric Cells for the Measurement of Visible Light

H. H. Poole and W. R. G. Atkins

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I—The Standardization of Photo-Electric Cells for the Measurement of Visible Light

By H. H. Poole, *Sc.D.*, *Registrar*, *Royal Dublin Society*, *and* W. R. G. Atkins, *Sc.D.*, *F.R.S.*, *Head of the Department of General Physiology*, *Marine Biological Laboratory*, *Plymouth*.

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[Plate 1]

Introduction

During the last ten years we have been engaged in making photo-electric measurements of illumination in the open, in woods, and under water. For the most part relative measurements sufficed; thus, under water the percentage of the blue light in air was given,* and later for each colour.† In woods, the light-habitat is best expressed by means of the daylight factor‡, namely, the illumination, received on a horizontal surface expressed as a percentage of the diffuse illumination, similarly received, in the open. A fuller statement involves giving the daylight factor for each colour separately,§ or else the "colour factor." Thus, if we decide to regard as "white," *i.e.*, as standard, any given type of illumination, by the use of appropriate photo-electric cells and colour filters we can find ratios green/blue, yellow/blue, and red/blue for this illumination, and also for any other illumination whose colour we wish to specify. The ratio of the ratio green/blue for the given illumination to the ratio green/blue for the standard may be called the "colour factor" for the green filter, and so on. The blue filter has been taken as a standard since all our early work was, of necessity, done with blue-sensitive cells. If we now adopt the diffuse light in the open as the standard, and determine the daylight factor for blue light in a wood and the colour factors for the same spot, it is evident that multiplying the daylight factor for blue by the several colour factors gives the daylight factors for those colours. Of this we have previously given examples.

In addition to such relative measurements, we have all along ventured to give standardized measurements of daylight in metre-candles (lux) or thousand metre-candles (k.m.c. or kilo lux), using an open carbon arc, of intensity calculable from

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* Poole, 'Sci. Proc. R. Dub. Soc.,' vol. 18, p. 99 (1925).

† Atkins and Poole, 'Phil. Trans.,' B, vol. 222, p. 129 (1933).

‡ *Ibid.*, 'Sci. Proc. R. Dub. Soc.,' vol. 18, pp. 277 (1926).

§ *Ibid.*, *Loc. cit.*, vol. 20, p. 13 (1931).

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its current, as a source whereby to rate a potassium vacuum cell. Cells of other types were then compared in daylight, usually mixed sunlight and sky-light, with a potassium cell thus standardized.

This " carbon arc potassium cell " standard gives values which may differ from those of visual measurements, though, for reasons given later, the agreement is far closer than would at first sight seem probable. The choice of a visual standard is, however, purely arbitrary, for our work was undertaken primarily with the idea of correlating photo-synthetic and other biological activities with the intensity of the radiant energy received at the site. For a full solution of the various problems which may be encountered measurements would be required of the energy, in absolute units, received from each part of the spectrum, together with their time and space integrals. As a practical proposition, however, we have contented ourselves with (*a*) the setting up of convenient standards in tolerably close agreement with the visual estimations ; (*b*) the determination of percentage factors, viz., daylight and colour factors ; (*c*) the determination of the energy received over the whole spectrum ; and (*d*) approximate allocations over wide spectral bands. AURÉN's method, using the sun as a standard, was also tried.

In this paper we are only considering the measurement of visible light as received on a plane diffusing surface set either normal to the beam or, for daylight, horizontally. The consideration of the total illumination falling on a spherical photometer, the integration of the illumination over lengthy periods, and the measurement of the energy in absolute units in various bands of the spectrum is deferred.

The necessity for accurately reproducible standards and the use of standardized cells becomes more urgent as measurements are made over widely separated regions of the globe. Thus the seemingly very high values, 250-325 k.m.c. over six-hour periods, reported by TEEGAN and RENDALL* for Rangoon, assume altogether different proportions when one ascertains that they were made using a potassium cell, calibrated against a " Pointolite " electric lamp, namely, on a scale widely divergent from the visual.

In the past, biological investigations have been vitiated by the want of precise measurements which differentiate light from total energy, if even that has been measured. The light of a bright July day—in Sweden—has been taken by LUNDEGÅRDH† as an ecological standard, for lack of a better one. WIESNER,‡ DORNO§ (1919), and RÜBEL|| have given precision to photographic and other radiation measurements. Photo-electric methods have, however, many advantages for work of this type, as was found by DORNO¶ for the ultra-violet. In particular

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* ' Nature,' vol. 125, p. 447 (1930) and ' Ind. J. Phys.,' vol. 4, p. 585 (1930).

† " Klima und Boden in ihrer Wirkung auf das Pflanzenleben." Jena, 1925.

‡ " Der Lichtgenuss der Pflanzen." Leipzig, 1907.

§ " Physik der Sonnen-und Himmels-strahlung." Braunschweig, 1919.

|| " Abderhalden's Handbuch der biol. Arbeitsmethoden." Part 279, pp. 233-292. Berlin, 1928.

¶ " Ire Conf. int. Lum.," Lausanne-Leysin. Paris, 1928.

the work of Aurén* † deserves attention ; as a unit he adopted the radiation from the sun and sky, under clear weather conditions, with sun at 45° altitude, as received upon a de-polished opalized plate set horizontally and measured with a photo-electric cell.

Photo-Electric Cells Used

The cells were mounted in suitable boxes with apertures closed by surface-flashed opalized glass (opal). This we have found to be an excellent diffusing medium ; some tests on its adequacy are given later. It acts as a secondary source of illumination, the light from which always reaches the cell with a constant angular distribution, irrespective of the distance and dimensions of the source. The opalized layer is turned to the outside, so that its distance from the source may be known and set accurately. In mounting the cells the projecting hemispherical windows or cylindrical surfaces are placed as close as possible to the diffusing surface. The aperture was kept as small as possible without seriously shading the cell, in order to minimize the correction for size of photometer. The outer surface of the face, around the opal aperture, was, for standardization, covered with matt black paper to lessen reflection back on to the source and its surroundings.

The cells used were as follows :

(*a*) *Emission type.*—The varieties considered here are all vacuum cells, since for use as standards the vagaries of the gas-filled cell rule it out. We did, nevertheless, use gas-filled cells for certain measurements under water, but they were compared before and after use, and at intervals during use, against vacuum cells. The best conditions for obtaining a reasonably consistent behaviour with gas-filled cells were also studied.‡

The earliest stable cells we used were of the type in which the cathode consisted of a film of potassium, and the anode a metallic ring placed below the window, which was from 1 to 3 cm in diameter; these cells, denoted by letters G, H, and L, were made by the General Electric Co. in 1924, 1925, and 1927, respectively. They appear to have undergone little or no change in sensitivity, though exposed for several hours at a time to full daylight, including summer sunlight. It is particularly necessary to note that these early vacuum cells were made with a plain potassium surface, which has a very light grey colour when the interior of the cell is viewed. The more recently made cells have a sensitized potassium surface, and this has a decided blue tint. These sensitized cells are not stable when exposed to full sunlight, but are now usually supplied by the makers unless unsensitized cells are ordered.

The wave-length sensitivity curves found for the earlier types of emission cells we examined are shown in fig. 2 of our 1928 paper.§

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* ‘Medd. met.-hydr. Anst., Uppsala,’ vol. 5, No. 4 (1933).
† ‘Ark. Mat., Astr. Fys.,’ vol. 24A, No. 4 (1933).
‡ Atkins, ‘Sci. Proc. R. Dub. Soc.,’ vol. 20, p. 67 (1931).
§ Poole and Atkins, ‘J. Mar. Biol. Ass.,’ vol. 15, p. 455 (1928).

Much use was made of large sodium cells prepared by Dr. R. C. Burt. These are of high sensitivity, and have proved quite stable ; one has been exposed to the sun and sky for nearly five years without measurable deterioration. They appear to have a rather flat region of maximum sensitivity between 3400 and 3600 A in their wave-length sensitivity curve. The cells are prepared by electrolysis of the glass under special conditions. The film is therefore of great purity, and its good contact throughout its whole extent enhances the sensitivity. There appear, however, to be definite differences, from cell to cell, in the extent to which these cells are sensitive to different parts of the spectrum. The walls are of soda glass, which transmits well down to about 3300 A, and is not opaque altogether even at 2900 A.

The cells resemble electric light bulbs in shape, and the sodium cathode is on the glass. Two metal prongs serve as anode, with a cross-wire connection. In later models this connecting piece is supported on a glass rod; but even in this type the cross-wire sometimes comes away in transit. Connecting the two prongs externally restores approximately the original sensitivity. Otherwise the prong left insulated becomes charged up to the negative potential, and tends to cut down the sensitivity of the cells somewhat, or to raise the saturation potential. Since the cells are mounted in a radio valve socket, the anode and cathode leads are not very far apart, and even with bakelite insulation 60 volts anode potential may give rise to a leak of the order of 10^{-9} ampere, which has to be allowed for in standardizing by means of a lamp of low intensity. In sunlight these cells give 30–100 μa under opal glass, and such leaks or " dark currents " are negligible.

A marked advance was made in the production of the thin film caesium-on-silver oxide cell, type C.M.V. 6, as shown by Campbell and Ritchie,[*] their fig. C in frontispiece. The metal plate cathode and wire grid anode give a cell with a good conducting base for the sensitive film together with good spatial relations for collecting all the electrons, so that a linear relationship between current and illumination is obtained to a high degree of accuracy. The saturation voltage is also low, about 12 volts in some cells. We have, however, used these cells, like the others, at 60 volts as a rule. Their sensitivity extends throughout the spectrum, with a maximum at about 7200, and another in the violet, with a minimum at about 5000 A. The curve for one of these cells used by us is shown in fig. 3 of our 1931 paper,[†] together with that for its combination with a Corning heat absorbing filter, which gives approximately uniform colour sensitivity from 4400-6400 A, namely, through the region in which the response of the eye is considerable. The figure also shows the curves for an early type of thin film potassium-on-copper cell, K.M. 2, which has now lost its red sensitivity, and for the Burt cell which has a negligible sensitivity beyond 5000 A. The advent of type C.M.V. 6 enabled us to measure the colour of light in woods, and the absorption of light of different colours in sea-

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[*] " Photo-electric Cells." London, 1929.

[†] ' Sci. Proc. R. Dub. Soc.,' vol. 20, p. 13 (1931).

water. The cell is, however, of no use as a standard, as it has now after some years lost a large part of its sensitivity.

The thin film potassium-on-silver cell, type K.M.V. 6, has a secondary hump of emission about 6000 A. According to Campbell it is the most stable cell known, save the unsensitized potassium cell. We have no experience of the prolonged exposure of this type of cell, one of which was kindly lent to us by the General Electric Co.

An extremely sensitive cell, type X, has been produced by Mr. E. Bolton King of Oxford. Its maximum response is around 8500 A, and it still has 16% of its maximum sensitivity at 11,000 A.

Its sensitivity extends throughout the visible spectrum, but, as it is much lower in this region, its useful range is perhaps limited to the red and infra-red. We have used two shapes, namely, X 16, with sensitive surface of undisclosed composition on the glass wall of a tube, the anode being a rectangular wire, and X 41, a large bulb of similar construction, kindly lent by Mr. King. This, alone among emission cells we have tested, is of the same order of sensitivity as selenium rectifier cells.

(*b*) *Rectifier or Sperrschicht Cells*—In this type of cell, introduced by Lange,[*] a crystal layer of a semi-conductor lies between a metal plate and a metal film. No external potential is applied. A good account of their properties has been given by Hughes and Dubridge.[†] Their high sensitivity, convenient shape, and freedom from electrical leaks (" dark currents ") render them specially suited for field work. The relation between current and illumination is not, however, linear. We have already[‡] examined this relation for a variety of cells of the cuprous oxide type, as well as for the selenium rectifier cell of Bergmann[§], which has many advantages, such as greater sensitivity, a lesser temperature coefficient, and a wave-length sensitivity curve with a maximum at about 595 mμ, so that a good agreement is given with visual measurements. Further work has shown that the Bergmann cell, as prepared under licence by the Weston Electrical Instrument Co., may be exposed for over a month to sun and sky without changing its sensitivity, save for a small reversible temperature effect. Like C.M.V. 6, this cell has proved suitable for determining the penetration of different portions of the solar spectrum into the sea.[||] Like the emission cells, no two are of exactly the same sensitivity or colour sensitivity, though the differences in sensitivity at least seem smaller.

All rectifier cells apparently suffer from the drawback that the response is not truly linear, the curvature of the light/current characteristic and the effect of temperature on the sensitivity of the cell increasing with increase in the resistance of the measuring instrument. This point is discussed in the next section.

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[*] ' Phys. Z.,' vol. 31, p. 139 (1930).

[†] " Photo-electric Phenomena." New York, 1932.

[‡] ' Sci. Proc. R. Dub. Soc.,' vol. 20, p. 537 (1933), and vol. 21, p. 1.

[§] ' Phys. Z.,' vol. 32, p. 286 (1931).

[||] Poole and Atkins, ' J. Mar. Biol. Ass.,' vol. 19, p. 727 (1934).

The statement commonly made that the current given by rectifier cells is proportional to the illumination, applies only to such low illuminations as are ordinarily met with in artificial lighting indoors, and is by no means correct for the high natural illumination encountered in well-lighted rooms or out of doors.

We have not so far worked with the Bernheim rectifier cell, on account of its high cost, but the Bergmann-Weston cell possesses adequate sensitivity for ordinary field work. The Bernheim cell is apparently also a selenium cell and is two to five times as sensitive as the Weston cell, according to size.

Neither the cuprous oxide nor the selenium rectifier cell is uniform in sensitivity over its surface, and photo-electric action may take place at either or both the front and back boundaries of the semi-conducting layer as found by SCHOTTKY.* This may result in a reversal in the direction of the photo-electric current as the spectrum is traversed.† No such reversal has been found with the selenium cell, but differences in sensitivity may be demonstrated, just as in the cuprous oxide cell, when its surface is explored with a small pencil of light. Sometimes the higher sensitivity values were obtained near the middle of the cell, but the distribution was irregular, the maximum value being near one side. Taking the minimum response, for constant illumination by a sub-standard tungsten filament lamp, as 100, the maximum was found to be 141 in the cell studied, which was of the newer type without a central electrode. Taking the average of thirty-six measurements the half of the sensitive surface nearer the terminals was found to be less sensitive than its fellow in the ratio 100 : 116. The possibility of such differences should be remembered by those who use the halves of such cells differentially according to HILL's‡ method.

THE MEASUREMENT OF THE PHOTO-ELECTRIC CURRENT

We have already§ described the final form in which the potentiometer-telephone-amplifier null-point method has been used at sea for measurements involving a wide range of intensities as determined with emission cells. The method has also|| been adapted for use with rectifier cells, measuring the drop in potential over relatively low resistances, 10 ohms, and upwards. The potentiometer-telephone method proved difficult to use in the laboratory, because of disturbances due to alternating town supply current. Even when this had been cut off from one end of the building, it was still hard to obtain silence in the telephone on account of the A.C. hum. Sheathing the apparatus in copper and earthing the boxes proved

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* 'Phys. Z.,' vol. 31, p. 913 (1930).

† AUGER and LAPICQUE, 'C.R. Acad. Sci.,' Paris, vol. 193, p. 319 (1931); POOLE and ATKINS, 'Nature,' vol. 131, p. 133 (1933).

‡ HILL, 'J. Sci. Instr.,' vol. 8, p. 262 (1931), and 'Nature,' vol. 133, p. 685 (1934).

§ 'Phil. Trans.,' B, vol. 222, p. 129 (1933).

|| 'J. Mar. Biol. Ass.,' vol. 19, p. 67 (1933), and vol. 19, p. 727 (1934).

ineffective. It was finally found that consistent measurements could be obtained with the three-valve amplifier and a resistance of even as much as two megohms by passing external leads through the spiral metal-rubber tubing commonly sold as gas flex. This reduced the hum to a negligible intensity. Reading the potentiometer to one scale division, or 0·1 millivolt, accordingly gave a current reading of 5×10^{-11} amp per scale division.

These difficulties had, however, not been overcome when we adopted our final arrangement for the standardizations.

The 1932 standardizations were made, using a galvanometer with the Onwood type of suspension. With scale at one metre distance 1·00 mm deflection was produced by $2 \cdot 87 \times 10^{-9}$ amp. This sensitivity was maintained constant, as shown by tests at intervals; but it was not great enough to obtain satisfactory standardizations with the early type of potassium cell which had been used as a reference standard from 1924 (G) and 1928 (H) when used with the sub-standard lamp.

Attempts were made to use a Paschen galvanometer, but, as suitable magnetic screens were not available, stray fields due to various laboratory currents rendered its use impossible. For determining the wave-length sensitivity curves of the cells, we used, in Dublin, a Zernicke type C galvanometer set with scale at 2·4 m distance. Although this is a low-resistance instrument (24·5 ohms), being designed primarily for thermo-couple work, its sensitivity at this distance was 1·0 mm for $2 \cdot 4 \times 10^{-10}$ amp., the scale being readable to 0·1 mm. It was not available in Plymouth where these standardizations were carried out.

The arrangement adopted finally was a potentiometer null-method, similar in principle to our outfit for work at sea, but using a Tinsley box and scale galvanometer of sensitivity 12·3 mm per micro-amp and period 2·0 seconds.

For small currents the sensitivity was increased by the use of an electrometer valve amplifier, as designed by G. Winfield and B. S. Platt of the Department of Physiology, Leeds University, for glass electrode measurements and made by Messrs. H. Tinsley. The arrangement proved satisfactory for measurements over a wide range of current, and enables one to work with great rapidity as compared with the use of any highly sensitive galvanometer. According to the sensitivity of the cell and the intensity of the illumination, measurements were made of the drop in potential across resistances of from 10,000 ohms up to nearly 100 megohms. For these we used a subdivided 100,000-ohm set or a subdivided megohm, or a 10-megohm unit resistance such as is used for valve circuits. The latter was mounted on uprights embedded in paraffin wax, and as a check upon its constancy, its resistance, 9·86 megohms, was measured at intervals, using a potentiometer. For measuring the smallest currents, nine similar 10-megohm resistances were connected in series and suspended by quartz pieces in a desiccator over calcium chloride. The heavily rubber-coated leads emerged from the top of the vessel embedded in paraffin wax with a bar of ELO resin across the middle of the opening. The total resistance was approximately 96 megohms in the desiccator, but in air the nine lay between 9·73 and 10·13 megohms, total 89·39. With such a resistance the sensitivity is approximately 10^{-11} ampere per potentiometer scale division, or 10^{-12} with the plug in the × 0·1 position.

In measuring the photo-electric current by this method the high resistance was as usual in the photo-cell circuit; the E.M.F. to be measured is that across this resistance, so its terminals should be connected to the electrode terminals of the electrometer valve set, taking care to screen the leads right up to the cell when very small currents are being measured. For this purpose armoured gas tubing is suitable. In any case the whole apparatus is mounted on a table covered with tinned iron sheets, and earthed to a rod buried in the ground outside. In making the connection to the electrode terminals the negative, viz., the one marked "half-cell," should be connected to the same terminal of the resistance as the H.T. negative, while the lead marked "glass electrode" goes to the other resistance terminal, to which one also connects the lead from the cathode of the photo cell. The other connections, between electrometer valve set, potentiometer and short period galvanometer, are made exactly as for glass electrode work, the terminals of the set being marked.

With cells of high sensitivity such as the Bergmann selenium rectifier or the X 16 and X 41 emission cells, calibrated micro-ammeters were found suitable, though when convenient the null method was also used with low resistances across which to measure the potential drop.

When rectifier cells are employed to measure bright light, it is essential to use a low-resistance circuit, as the curvature of the light/current characteristic and the disturbing effects of temperature variations would otherwise be unduly large. We have hitherto used a 10-ohm circuit for bright light, only increasing the resistance across which the P.D. is measured, or alternatively using a higher resistance and more sensitive micro-ammeter, where the weakness of the light rendered this necessary and allowable.

There can be little doubt, however, that the circuit recently described by Campbell and Freeth,* being of zero effective resistance, is in every way preferable. We have recently adapted our marine outfit so as to employ a slightly modified form of this circuit, and find that we can readily combine the advantages of zero effective resistance with a sensitivity limited only by that of our detecting instrument, which may have any resistance whatever.†

METHODS OF TESTING THE PROPORTIONALITY OF RESPONSE OF VARIOUS CELLS

Before choosing a standard source for fixing the scale for any cell, it is well to test how far that scale is linear. Several highly accurate methods have been described by other workers for this purpose. Unfortunately, they do not yield illuminations

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* 'J. Sci. Instr.,' vol. 11, p. 125 (1934).

† 'Nature,' vol. 131, p. 810 (1934), and 'Sci. Proc. R. Dub. Soc.,' vol. 21, p. 133 (1934).

of the order of full sunlight, which we need for our work. The simple method of placing the photometer window at various known distances from a steady small powerful source appears to be the best. For sodium and potassium emission cells the only source that is bright enough is the carbon arc. All our experience with these cells goes to show that their response is approximately linear up to full daylight, provided that a sufficiently high anode potential is used to ensure approximate saturation in the brightest light; *see* Table I, Photometer H tests on 20/6/1934.

With rectifier cells, however, the response is not linear, and the curvature of the characteristic must be measured and allowed for. Fortunately, the selenium rectifier cell is very sensitive to the light of a filament lamp, and possesses a plane sensitive surface whose position can be measured with accuracy. It is thus possible to carry out the "Curvature" test on the bare cell, and so, by means of a suitable projector type filament lamp, to obtain intensities equal in effect to full sunlight on the cell as used under opal glass.

The cell is mounted on a photometer bench so that it can readily be placed at any known distance from the plane of the lamp filament. A 60-volt 150-watt projector lamp was used, run off a large battery at 55 volts. The filament of this lamp is coiled in a close spiral which is itself wound zig-zag so as to occupy a plane vertical rectangle about 7 mm square. A water cell about 1 cm thick is placed just in front of the cell to reduce the rise of temperature. For the same reason it is well to take readings as quickly as possible, or to cut off the light with a shutter between readings. Of course, the usual precautions must be taken to avoid errors due to scattered or reflected light. It is also necessary to remember that the water cell reduces the effective distance between the source and the cell by an amount which can readily be found from the thicknesses of the glass and water layers, and which, in our cell, amounted to 5·8 mm.

Two further sources of error remain, and may become important at short distances, namely, the effects of the sizes of the source and the cell window, and the possibility of refraction in the lamp bulb affecting the effective position of the filament. The latter error is hard to calculate, as any variations that may exist in the thickness of the lamp bulb are unknown, but from parallactic observation of the real image of a pin point formed inside the bulb in the plane of the filament the displacement of the image due to refraction in the bulb would seem to be small—possibly 1 or 2 mm.

Correction for Sizes of Source and Photometer Window

The "size of source" correction is considered in the "Dictionary of Applied Physics," Vol. 4, p. 421. Here the correction is given for a source in the form of a disc and also for a single filament. In the present instance we must also correct for the size of the photometer window. It is probably sufficiently accurate to obtain the total correction by adding the "source" and "window" corrections. The magnitude of the latter will depend, not only on the radius of the circular window, and in a cell mounted behind an opal window, on the extent to which different parts of it affect the cell, but also on the distribution of light from the lamp filament.

If the lamp radiates as a small plane surface so that the intensity in any direction is proportional to the cosine of the angle with the normal to the plane, it is easy to see by a simple integration that, for a small lamp and a cell window of radius r_1 of uniform efficiency all over, we can correct for the size of the latter by adding r_1^2 to d^2 when finding the illumination, d being the distance from source to window. A similar correction can be made for the lamp, so that the total correction is given by using $d^2 + r_1^2 + r_2^2$ instead of d^2, where r_2 is the radius of the disc occupied by the lamp surface.

Should the lamp, however, radiate equally in all directions, the cell window correction is reduced to $3r_1^2/4$, while for a set of parallel filaments, as in a standard lamp, the cell window correction would be intermediate in value. With a projector type lamp, with its closely coiled filament, it is difficult to predict how the radiation will vary with the angle, as this must depend on the variations in the screening of the back parts of the spirals. The coiled filament lamp was accordingly mounted so that it could be rotated through known angles, first about a vertical axis passing through the centre of the filament plane, and then about a horizontal axis. A Weston cell at a distance of about 55 cm indicated the variations in candle-power over angles up to 15° with the normal to the filament plane, which is about the maximum that would be subtended by the edge of the cell at the nearest distance used with this lamp. Since the axes of the filament coils are vertical, the individual turns being horizontal, we should expect small variations in the vertical angle to have much more effect on the screening of the backs of the coils than similar variations in a horizontal plane. This was found to occur, the maximum deviations from the mean values being 8% and 2% respectively. The reading for the normal to the filament plane was very close to the mean, for both vertical and horizontal planes, so apart from irregular fluctuations we may treat the lamp as radiating equally in all directions when finding the correction for the sizes of the source and cell window, so that the value $d^2 + \frac{3}{4}(r_1^2 + r_2^2)$ should be used in place of d^2 with this lamp, for which r_2^2 being only about 0·15 sq cm is practically negligible.

With the sub-standard lamp described in a later section, however, the filaments are straight and nearly vertical, occupying a plane rectangle about 6·5 cm by 3·3 cm. When we integrate the effect of each filament separately for a point on the normal through the centre of the rectangle, we find that the size of this source can be corrected for with sufficient accuracy by adding 8·7 sq cm to d^2. Since this source radiates as a plane as regards deviations from the normal in the plane of its greatest dimension, it is best to add r_1^2 rather than $3r_1^2/4$ to correct for the cell window, provided that we use a value of r_1 that is a fair measure of the window size, as with a window larger than the cell pupil the marginal parts are much less effective. The total correction for this lamp is accordingly $8{\cdot}7 + r_1^2$ sq cm.

LIGHT SOURCES SUITABLE FOR STANDARDIZATION

Since we are concerned at present with the measurement of visible daylight, it is desirable that our scale should not differ too widely from the visual scale. This at once rules out the use of a filament lamp for the standardization of cells whose colour sensitivities differ widely from that of the eye. The only cell that we have so far come across for which this method of standardization is even approximately suitable is the selenium rectifier cell. For our early work with blue sensitive potassium and sodium cells, we chose the carbon arc as the only available source which did not differ too widely from daylight in colour. As this has some obvious disadvantages, we later tested the possibilities of " artificial mean noon sunlight " as specified by the Seventh International Congress of Photography.* This is obtained by means of a sub-standard filament lamp at 2360° K and a Davis-Gibson double filter cell. When this is interposed 7·5 mm has to be subtracted from the actual distance to obtain the optical distance from source to opal of photo-cell. We obtained a filter cell of standard dimensions with apertures 101·6 mm diameter in order that light might be transmitted from the whole of the length of each filament of the sub-standard lamp. The visual transmission of the filter for 2360° K, old scale, is 0·1352. No corrections have been applied for differences in the transmission of the filter, occasioned by variations in its temperature from the standard 25° C, since the coefficient is small.

Natural " mean noon sunlight " is based upon C. G. ABBOT's measurements at Washington. The artificial mean noon sunlight, as specified, duplicates the natural fairly well right out to 900 mμ, according to data in the Smithsonian Physical Tables, 1933 edition ; this is important in dealing with red sensitive cells. The agreement is not so good for the violet end, the ratio of the energy in the artificial to the actual sunlight being 0·871 at 420 mμ, falling to 0·579 at 380 and to 0·304 at 360 mμ.† The discrepancy is of no importance in visual estimations, since the eye is so insensitive in this region, but it is serious for potassium and more especially for sodium cells on account of their violet and ultra-violet sensitivity. The results shown in Table III make this clear.

We have also tested our cells with the bare lamp, and the results show the great difference in the scale obtainable with most cells using sources having dissimilar spectral energy distributions.

THE CARBON ARC AS A STANDARD SOURCE

This source, though possessing obvious disadvantages owing to its general unsteadiness, also possesses some advantages which are not shared by any other. It is very simple and cheap to set up, and, so far as our experience goes, gives consistent results at any time, provided that suitable precautions are taken and good quality

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* " 7th Int. Congr. of Photography," London (1929). DAVIS and GIBSON, ' Bur. Stand., U.S.A.,' Misc. Publ. No. 114 (1931).

† DAVIS and GIBSON, *loc. cit.*, Chart 2.

solid carbons are used ; cored carbons should never be used. The arc's chief advantage, however, is the ease with which intensities can be obtained approaching, or in some cases equal to, that of full sunlight. This is especially valuable in calibrating rectifier cells, whose light/current characteristics are not linear, and also small vacuum cells of early types, which, though exceedingly stable, are rather insensitive, so that with the very low intensities available with other sources highly sensitive current-measuring methods must be used.

A hand-fed lamp with solid carbons 7 mm in diameter is mounted with the carbons vertical, the positive being above ; the current is supplied by an 84-volt storage battery, regulated by a rheostat, and is measured by means of an accurate ammeter. A voltmeter connected across the arc is advantageous. An image of the arc is projected on a vertical screen at a distance of 3·6 m by means of a photographic objective about 20 cm in focal length, the magnification being about 16 : 1. The cell to be tested is mounted with its window (usually of opal flashed glass) normal to the line joining its centre to the tip of the positive carbon, this line making an angle of 45° with the vertical. The distance from the centre of the window to the centre of the carbon tip is measured to the nearest millimetre ; this distance may be as small as 10 cm for cells with small windows (1-2 cm diameter), but for larger photometers larger distances are desirable.

Readings are best carried out by two workers, one adjusting the arc by observation of the projected image and reading the current and, if so desired, the voltage, the other balancing the potentiometer used for measuring the photo-electric current. The arc should be adjusted so that the image of the glowing tip of the positive carbon is brought to an exact position, that the end is horizontal and as nearly plane as possible, and that the arc is just long enough to ensure that the negative carbon casts no shadow at 45°. This is rendered easy by suitable markings on the screen. The most suitable value for the current with 7 mm carbons is about 7 to 7·5 amperes, and almost all our measurements have been made with currents between 6 and 8 amp. With 7·5 amp. and a 3 mm arc the voltage was about 52 to 54.

The photographs (negatives) reproduced in figs. 1 and 2, Plate 1, were taken by mounting the screen so that it could be dropped, thus exposing a sheet of " gaslight " paper pinned just behind. Fig. 1 shows the bare arc for an exposure of about 1/20th sec., as estimated from the size and position of the aperture in the falling screen ; the actual size may be judged by the millimetre squares ruled on the print, the magnification in the reproduction being about 8 : 1.

It will be seen that most of the " light " affecting this paper comes from the arc itself. That this is chiefly ultra-violet is shown by the fact that when a Jena G.G. 3 filter was introduced the image for 1/20th sec. exposure was too weak for reproduction, and showed only the carbon tips. This filter has a fairly sharp cut-off about 425 mμ, transmitting freely above 450 mμ, and scarcely at all below 400 mμ.

Fig. 2 shows the result of a 1-second exposure through the G.G. 3 filter. This caused over-exposure of the carbons, so that the relative importance of the arc is exaggerated. To the eye the image of the arc is scarcely visible compared with those of the carbons. The photographs illustrate the well-known fact that almost all the visible light comes from the carbons, but most of the ultra-violet from the cyanogen bands in the arc itself.

It will be seen that the arc length was about 2·7 mm in fig. 1, and 3·2 mm in fig. 2. The former length is slightly above the minimum (2·5 mm) necessary to ensure absence of shading, and is almost an ideal length for working ; the latter is slightly too long, as a long arc increases the curvature of the positive carbon end, and increases also the importance of the ultra-violet radiation from the arc, which is probably more affected by slight variations in the purity of the carbons than is the light from the carbon tip.

The photographs show that the positive tip was about 3·5 mm in diameter. This was for a current of about 7 amperes, giving a current density rather over 0·7 amp per sq mm, agreeing well with ALLEN's[*] value 0·746 amp per sq mm which we have always used in conjunction with FORREST's[†] value for the luminosity of the positive " crater," *i.e.*, 173 candle-power per sq mm in a direction normal to the face.[‡] Combining these results, we get the value 232 candle-power per amp normal to the surface, or 164 candle-power per amp at 45°, which we have always used in calculating the intensity of our standard source.

When this value is used for standardizing potassium and sodium cells and the latter are then employed to measure daylight, the scales of intensity obtained do not differ so widely from the visual scale as one might expect from the fact that, as the colour temperature of the carbon tip is only about 3780° K, whilst that of sunlight at the earth's surface is about 5600° K, the light from the glowing carbon is relatively weak in the blue end of the spectrum. But the arc light is much richer in blue than is that of a filament lamp, whose colour temperature may range from 2350° (vacuum) to 2900° (gas-filled).

Both FORREST and ALLEN used a special Y arrangement of carbons with two negatives, so that the positive " crater," which they showed was very nearly plane, could be viewed normally. Such a complication does not appear to be necessary for our purpose, and would greatly detract from the simplicity and cheapness which are among the arc's advantages. With the simple arc of suitable length and carrying a suitable current the carbon end is also very nearly plane, though the necessary obliquity of the line of illumination, with consequent importance of the exact angle of the end, is undoubtedly a disadvantage.

Other values for the intrinsic brightness are quoted by FOWLE in the Smithsonian Physical Tables, 1933, Table 351, ranging from 310 candle-power per sq mm

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[*] ALLEN, ' Proc. Phys. Soc.,' Lond., vol. 33, p. 62 (1921).

[†] FORREST, ' Electrician,' vol. 71, p. 729, 1007 (1913).

[‡] The value given in FORREST's original paper is 162 cp per sq mm, but the revised value, 172-174, was quoted by Professor J. T. MACGREGOR-MORRIS, Principal of the Electrical Engineering Laboratory of East London College, in which both FORREST's and ALLEN's work was carried out, during the discussion of ALLEN's paper in 1921.

(Barrows) to 130 candle-power per sq mm (Ives and Luckiesh). These are, however, taken from *Data*, 1911, and the conditions are not stated, so that there seems to be no reason to doubt the substantial accuracy of Forrest and Allen's later work. In any case, we are here concerned chiefly with showing that the carbon arc is a standard that can be reproduced with fair accuracy, whatever value may be adopted for the intrinsic brightness of the glowing carbon.

The relatively high sensitivity of sodium and potassium cells to the light of the arc lamp is, of course, due to their sensitivity to the near ultra-violet emitted by the arc itself. The maximum sensitivity of the sodium cell occurs in this part of the spectrum, and that of the potassium cell is not very remote from it. This is one of the chief objections to the use of the arc lamp as a standard, as one is making considerable use of ultra-violet in a standardization which is supposed to refer to the visible spectrum. The agreement with measurements made with selenium cells standardized in artificial "mean noon sunlight" is, however, very close, when both types are used to measure bright mixed daylight.

Selenium rectifier cells have a much smaller ultra-violet sensitivity. Under quartz this is given as amounting at 3500 A to 20% of the maximum response. The maximum is found at about 5900 A, so that with them the effect of the arc itself is not very important. The cell that we tested (Weston) did not differ very greatly in its sensitivity to the arc (on the above assumption as to its candle-power), to a sub-standard filament lamp at 2360° K, and to the same lamp with the special filters designed to give "mean noon sunlight"; thus, the cell did not differ greatly from the eye in its estimation of the relative intensities of blue and yellow light.

Some results of tests made with the arc on different dates are shown in Table I.

Each line of Table I represents the mean of a set of readings, of the arc and photo-electric currents, made in rapid succession; from 3 to 10 pairs of readings were made in each set according to the constancy of the arc. It is evident that comparatively small changes in the angle of the carbon end will produce appreciable errors, so that where difficulty was experienced in getting the arc to burn steadily, the mean of a large number of readings was taken. Under the conditions of working in 1933 and 1934, these difficulties were greatly reduced, and these later measurements must be regarded as more reliable than the earlier ones.

All the cells were mounted behind opal glass windows of various sizes, except for the readings entered in the last two lines, for which the Weston selenium cell, here marked WB, was used bare. In finding the intensities given in the table, allowance was made for the finite size of the photometer window, as explained above.

The photometers tested are denoted in the table by letters. H contains a vacuum potassium cell which we have always used as our standard for daylight measurement since 1928; before this we used a similar but less sensitive cell, G. It will be seen that the latest test only differs by about 2% from the value 40·0 found in 1928, which has been used in our subsequent work. We now take the value 40·7, the mean of our most accurate series on June 20, 1934. B. 299 is the photometer which has been exposed since December, 1929, on the roof of the laboratory in Plymouth for the continuous recording of daylight. It contains a Burt sodium vacuum cell, end-on aperture. As this cell was not available in Dublin for restandardization, it was directly compared in daylight with another Burt cell,

TABLE I—ARC STANDARDIZATIONS

Date	Photometer	Arc length mm	Arc current amp	Distance cm	Intensity mc	Anode potential volts	Photometer constant mc per μa
7.6.1928	H	—	6·05	21·3	21,850	74·5	38·85 × 10^3
7.6.1928	H	—	—	—	—	60	*40·0 × 10^3
8.6.1934	H	—	6·85	13·9	58,000	60	43·3 × 10^3
8.6.1934	H	—	6·90	36·6	8,440	60	39·7 × 10^3
20.6.1934	H	2·5	7·37	32·7	11,270	60	40·6 × 10^3
20.6.1934	H	2·5	7·40	25·3	18,900	60	40·4 × 10^3
20.6.1934	H	2·5	7·12	18·0	36,000	60	41·1 × 10^3
20.6.1934	H	2·5	7·34	10·75	104,500	60	41·2 × 10^3
15.7.1929	B. 299	—	7·0	18·6	31,900	46	3·70 × 10^3
15.7.1929	B. 299	—	7·0	18·6	31,900	57·5	3·55 × 10^3
15.7.1929	B. 299	—	7·0	18·6	31,900	69	3·36 × 10^3
15.7.1929	B. 299	—	7·0	18·6	31,900	80·5	3·13 × 10^3
15.7.1929	B. 299	—	7·0	18·6	31,900	92	3·02 × 10^3
16.7.1929	B. 299	—	6·0	18·6	27,300	70	3·50 × 10^3
16.7.1929	B. 299	—	6·0	18·6	27,300	94	3·08 × 10^3
16.7.1929	B. 299	—	6·0	18·6	27,300	119	2·99 × 10^3
16.7.1929	B. 299	—	6·0	18·6	27,300	142	2·96 × 10^3
16.7.1929	B. 299	—	—	—	—	60	†3·55 × 10^3
5.6.1934	B. 188	3	6·46	22·2	11,060	60	3·26 × 10^3
5.6.1934	B. 188	4	5·89	22·2	10,080	60	3·20 × 10^3
5.6.1934	B. 188	5	6·89	22·2	11,800	60	2·86 × 10^3
8.6.1934	B. 188	—	7·01	64·0	2,776	60	3·21 × 10^3
23.5.1930	C.M.V. 6	—	6·5	21·6	22,800	62	1·00 × 10^3
14.6.1934	C.M.V. 6	—	6·98	28·5	13,950	60	2·26 × 10^3
12.4.1933	W	—	6·2	31·2	10,380	—	13·55
30.5.1934	W	—	6·85	26·7	15,670	—	12·38
30.5.1934	W	4	6·74	27·2	14,890	—	12·37
30.5.1934	W	6	7·25	27·2	16,000	—	12·02
8.6.1934	W	—	6·92	33·4	10,070	—	12·75
12.4.1933	WB	—	6·2	31·8	9,980	—	5·85
30.5.1934	WB	—	6·92	27·7	14,700	—	5·63

* By reduction. † Interpolated mean for two days.

B. 188, on May 1, 1934, and the latter standardized against the arc on June 5 and 8 as shown in the table. It will be seen that, taking the 1929 value for B. 299 and the 1934 value for B. 188 at an anode potential of 60 volts in each case, the ratio of the sensitivities should be 3·26/3·55, *i.e.*, B. 299 should have only 0·917 of the sensitivity of B. 188. The ratio found in daylight was 0·924, so that here again we have excellent evidence of the stability of these cells.

The effect of varying anode potential on B. 299 is well shown. There can be no doubt but that a potential as high as 120 volts would be advantageous with Burt cells, especially in very bright light, if it were not for the fact that the relative importance of leakage currents would be increased by this high voltage. We have always adopted 60 volts as a convenient standard for emission cells. At this voltage the change in sensitivity is no more than 0·4% per volt for the Burt cells and is much less with most of the others, save the large cell X 41.

The effect of arc length is shown by the readings with B. 188, which is very sensitive to the ultra-violet from the arc itself. It will be seen that there is little difference between 3 and 4 mm arcs, though the 5 mm arc gave an appreciably larger effect, as shown by the reduced value of the constant in the last column. Where the arc length is not given it lay between 2·5 and 4 mm.

The results with the caesium monomolecular vacuum cell C.M.V. 6 show that it had lost more than half its sensitivity in four years.

W represents the Bergmann-Weston selenium rectifier cell No. 21104-2 exposed under opal glass. This cell is of the type possessing a central electrode. As with all rectifier cells, the response is not truly linear, and the constants given are the values for very weak light, obtained by assuming that $S = S_0 (1 - 0{\cdot}0027 \times \sqrt{c})$ where S and S_0 are the sensitivities (*i.e.*, the reciprocals of the constants) for a cell current c and for very small currents, respectively. This empirical relation was found to represent the curvature of the characteristic of this particular cell for a 10 ohm galvanometer to within 1 or 2%. The most accurate tests on this cell were those of 8/6/1934, and it will be seen that they fall between those with short arcs for 30/5/1934 and 12/4/1933. The 6 mm arc gave a slightly lower constant. There is no evidence of any change in the cell during a period of over a year, as the small apparent gain in sensitivity must be an experimental error, or a temporary change due to alteration of temperature.

WB represents the same cell without opal glass. It will be seen that the 1934 constant is again slightly lower than that for 1933, indicating a small apparent gain in sensitivity. The effective transmission of this piece of opal glass with this cell was 45%.

The Vacuum Tungsten Uniplane Filament Sub-Standard Lamp

As previously mentioned, the specification adopted for a standard light source by the Congress of Photography includes a lamp, as above, run at a colour temperature of 2360° K. The light from this is modified to reproduce sunlight, but in addition to this artificial sunlight we standardized with the bare lamp. Two lamps were used ; both were obtained from the General Electric Co. and were aged and standardized at the National Physical Laboratory. The change during use is under 4% per 100 hours, and they were run for short periods only in standardizations.

No. 62 A, 1930, when operated at 107·5 volts and taking a current of 0·7641 ampere, matched the radiation from a black body at 2360° K, the colour temperature being certified as accurate to within ± 10° and the horizontal candle-power, 71·05, as accurate to within ± 0·25%. These figures give an efficiency of 0·865 candle-power per watt. This was used up to December 29, 1933, when the filament was broken. No. 61A, 1934, when at 96·20 volts and 0·7300 amp was stated to have a colour temperature 2360° K, accuracy not certified, and a H.C.P. 51·05 within ± 0·25% ; the efficiency is therefore relatively low, namely, 0·73 cp per watt. The lamp was thus used in the subsequent work. Good agreement was obtained between standardizations carried out with these two lamps upon a selenium rectifier cell, which gives results not very different from the visual. When using a type C.M.V. 6 cell, which is predominantly red-sensitive, it was found that there was a lack of agreement which indicated a difference in colour temperature between the sub-standard lamps as might be expected from their respective efficiencies. We are much obliged to the Director of the National Physical Laboratory for informing us that the temperature scale had been altered by 40°, so that the second lamp had been standardized at 2320° K on the old scale.

The alteration was made in 1932, as a result of the comparison of the colour temperature of a black body immersed in freezing platinum with the colour temperature previously considered to be that corresponding to 2046° K (the freezing point of platinum). The difference was such that it corresponded to about 40° at 2360°. The value attached to the second lamp is believed to be correct to well within 20°. In consequence the second lamp had a redder light and was acting less efficiently.

In order to restore the exact mean noon sunlight colour for the new lamp combination, as it is run at a lower temperature, it should be used with a bluer filter, suitable for 2320° K on the old scale. For this a different transmission factor must be used, which is necessarily a lower value, thus further reducing the already low intensity. Alternatively current and voltage for running it at 2400° K, viz., the old 2360° K, might be obtained from the N.P.L. This has not been done as yet, since the difference in colour temperature is not sufficient to cause any appreciable error with the selenium cell on which we have based our daylight measurements. Furthermore, we have already had two sub-standard lamps broken in transit from London and do not wish to risk the loss of our present lamp, for which the constants and corrections have been determined so carefully.

The current to operate the sub-standard lamp was in 1932 obtained from a D.C. generator driven by a gas engine, since adequate storage batteries were not available. It was regulated by hand rheostats, coarse and fine, and was measured by means of a four-terminal ohm resistance and potentiometer.

As the source was far from constant, one worker regulated the lamp current while another measured the photo-electric current by galvanometer deflections. For the 1933 and subsequent standardizations, the D.C. generator was driven from a motor worked from the town A.C. supply. The constancy was so much improved that it was possible for one observer to regulate the lamp current and make the photo-electric measurements, using a second potentiometer. The lamp current as specified was maintained constant during measurements to within ± 0·0004 amp and usually the agreement was closer.

The Standardizations of the Cells by Sub-Standard Lamp, alone or with Mean Noon Sunlight Filter

These standardizations were carried out with the lamp at various distances from the opal in front of the photo-cell. Owing to the low intensity of the source and to the moderate sensitivity of some of the older cells, originally we had to work at times at a distance of 10–20 cm. This had the disadvantage of introducing relatively large corrections for size of source and size of photometer. With the more sensitive current-measuring system finally adopted, namely, the potentiometer and electrometer valve null method, we were able to work at up to 50 cm distance with the least sensitive cell and bare lamp, and up to 20 cm with the filter ; this series could have been carried to greater distances as only one megohm was used across which to measure the potential drop. There is, however, uncertainty as to the constancy of the 10 and 90 megohm sets, though the variations were not found to be large.

One has also to consider the electrical leaks (dark currents) of the cells or their mountings, which, though negligible in strong illumination, may be important at very low intensities. Such leaks were always directly measured. They were of importance only in the Burt cells, as previously mentioned.

On switching on the current, the sub-standard lamp took about two minutes to attain a constant emission. The current was regulated as previously described, and its constancy during each reading of the photo-electric current was immediately checked upon the conclusion of the latter. Readings made with variations beyond the limits already given were, of course, rejected, but the possibility remains that, during the minute or half-minute occupied by the photo-electric measurement, the lamp current may have gone up—or down—and reverted to its original value again ; such rapid fluctuations may possibly account for a few discordant values obtained in what appeared entirely satisfactory measurements. These do not, however, in any way affect the accepted final values.

Table II illustrates the method of working, and gives the results for one cell at various distances, and the corresponding values reduced to a 1 m distance according to the inverse square law corrected for the sizes of source and window.

In this case the agreement with the inverse square law is excellent, but better agreement between the two series would be obtained if we assumed that the resistance of the 96 megohm set had increased to 100 megohms since measurement, owing to further drying of the surfaces. With most cells the agreement with the inverse square law is not so good, the results at 10 cm being generally too small by some 5 to 10% compared with the values found at 40 or 50 cm, even when the calculated correction has been made for the sizes of the source and window.

Several suggestions may be offered to account for this discrepancy, but none of them is very convincing: (1) It does not appear probable *a priori* that we are underestimating the "size of source" correction, as we are treating the lamp as radiating as a plane surface when estimating the effect of the window size, and, by disregarding the fact that the centre of the latter is generally more effective than the edge, we are probably over-estimating its effective diameter. (2) It is possible that refraction in the glass of the lamp bulb may have slightly increased the effective distance, but the test made with the projector lamp, already referred to in this connection, would seem to indicate that this effect is small. (3) If the diffusing power of the opal glass were inadequate it would not be correct to take the distance from the filament to this glass as the effective distance, but rather something greater, as the cell is behind the glass. To test this point a selenium rectifier cell was mounted in a box at about 4·7 cm behind a 4 cm opal window so that the whole could be rotated about a vertical axis through the centre of the window. Even with the cell at this distance from the window, the reading was proportional to the cosine of the obliquity to within 1 or 2% over a wide range of values when allowance had been made for the increase in reflection loss with obliquity. The diffusing power of the opal glass would therefore seem to be adequate. (4) In view of the tests already described in bright light, it seems to be most unlikely that lack of proportionality of response in this weak light was responsible for the discrepancy; in the rectifier cells the curvature of the characteristic found from the projector lamp tests was allowed for. (5) With the Davis-Gibson filter in position, the light is reduced at

TABLE II—STANDARDIZATION IN MEAN NOON SUNLIGHT

Submarine photometer, containing sodium vacuum cell Burt No. 299 under opal; window, 7·6 cm; anode potential, 61·0 volts, coefficient 0·4% per volt. Voltage drop measured across 96·0 megohm set in desiccator or, alternatively, across standard megohm. Optical distance, D, is 0·75 cm less than actual distance with Davis-Gibson double filter cell in position. Combined factor for size of source and of photometer $= f$.

D cm	V (obs) volt	f	V at 1 metre $= VfD^2 \times 10^{-4}$ volt	
29·25	0·8544	1·024	0·0749	With R = 96 megohms. 0·0752 volt. C = 0·785 × 10^{-9} amp.
39·25	0·4781	1·015	0·0746	
49·25	0·3120	1·009	0·0764	
69·25	0·1555	1·005	0·0748	
9·25	0·06880	1·281	0·000754	With R = 1·00 megohm. 0·000752 volt. C = 0·752 × 10^{-9} amp.
19·25	0·01905	1·063	0·000751	
29·25	0·00854	1·024	0·000750	

Since the horizontal candle-power of lamp, through filter, is 9·61, taking the visual transmission of the filter as 13·52%, the above figures with the two resistances give respectively 12·24 and 12·78, mean 12·5 metre candles per 10^{-9} ampere.

short distances by the increased absorption of the more oblique rays ; the effect does not seem to be very important, as results with the filter agree rather better with the inverse square law than those with the bare lamp (*see* Table III). (6) It is almost impossible to get rid of *all* scattered light, and this is more important at the longer distances.

In view of the difficulty in explaining away the discrepancy otherwise than as the cumulative effect of a number of small factors, we decided to take 40 cm as a standard distance for testing all cells except the potassium one, which, being very insensitive and having a small window, was best tested at 20 cm when the filter was in use. The " size of source " correction was thus limited to within 2·1%.

The results of these filament lamp standardizations for a number of cells have been collected in Table III along with the most reliable arc tests and daylight

TABLE III

Constants (*i.e.*, reciprocals of sensitivities) of photo-cells, *as mounted* and under opal filters in metre candles (lux) per 10^{-9} ampere for various sources. Anode potential 60 volts for emission cells. Standardizations with the 1934 (new) lamp are marked N.

			Source of illumination, normal incidence.			
			Lamp at 2360° K			
Type of cell	Mark	Aperture cm diam	No filter	Sunlight filter	Carbon arc	Daylight‡‡
Potassium . . .	H	1·2	142·1	47·6	40·7§	40·7
Sodium	B. 188	10·0	29·3	6·32	3·21‖	3·485
,, ...	B. 223	9·9	4·83	1·37	—	—
,, ...	B. 224	10·1	7·51	1·93	—	—
,, ...	B. 299	7·0	55·5	12·5	3·55	3·71§§
K.M.V. 6 . . .		9·6	3·03	1·68	—	2·59
C.M.V. 6 . .		3·6 × 2·4	2·18	3·19	2·26¶	3·70
C.M.V. 6 . .	—	3·6 × 2·4	1·54N	3·52N	—	—
X 16	435	5·0	0·0533	0·141	0·216**	0·348
,, ...	498	9·0	0·021N	0·040N	0·056	—
,, ...	498	4·6	—	—	0·122	—
,, ...	498RG5*	4·6	—	—	0·156	—
X 41	612	10·0	0·0115	0·0275	—	—
Selenium . . .	W. 21104-2	4·0	0·0143‡	0·0164N	0·128††	0·0164‖‖
	W. 21652-8	4·0	0·0146	—	—	—
	W. 21931-4†	4·0	0·0123N	0·0177N	—	0·0195¶¶

* Red filter, 2 mm thick.

† No central electrode.

‡ Exact agreement between results with old and new sub-standard lamp.

§ Mean of the June, 1934, determinations.

‖ This June, 1934, value, by daylight comparison gives 3·53 for B. 299 ; *cf.* with 3·55 below, as found on July 15, 1929.

¶ June, 1934, *cf.* 1·00 as found 23.5.1930.

** A.P., 92·5 volts, 21.7.1933.

†† 8.6.1934.

‡‡ All based on arc value for H.

§§ Mean of ten observations, 1.5.1934.

‖‖ Mean of six, 1.5.1934.

¶¶ Mean of four, 1.5.1934.

comparisons with the potassium arc scale. We see how greatly the sensitivity has increased from the early potassium vacuum cell up to the red-sensitive X 16 and X 41 and the rectifier selenium cell. From its wave-length sensitivity curve the last named is obviously to be preferred for obtaining a visual estimate.

As already mentioned, all our early work was done taking the carbon arc standardization of the potassium cell as a measure of visible daylight. This cell will, being blue sensitive, over-rate blue-sky light and under-rate sunlight. It appears to be less sensitive to " mean noon sunlight," artificially produced, than to arc light, because though the latter is poorer in blue it is much richer in ultra-violet. The " Daylight " column in Table III takes the carbon arc value for the potassium cell as correct, and comparisons with the other cells in bright mixed daylight, on May 1, give the figures which are shown in this column. It may be seen that the sodium cells are considerably more sensitive to both the carbon arc and to daylight than to artificial sunlight, more so even than the potassium cell. But the agreement is quite good for these sodium cells, between direct carbon arc standardization and daylight comparison with the potassium-carbon arc scale. With the lamp at 2360° K, both the sodium and potassium cells show low sensitivity on account of its richness in red ; the relative sensitivities to the m.n.s. (mean noon sunlight, artificial) source and to the 2360° K lamp are as follows : potassium cell, 2·98 ; sodium B. 188, 4·64 ; B. 223, 3·58 ; B. 224, 3·89 ; B. 299, 4·44. Thus the sodium cells differ slightly in colour sensitivity in the visible spectrum, B. 223 being more sensitive to green and yellow than the others. The first three Burt cells have a yellow stain over a large portion of the aperture, this apparently cuts down their sensitivity to ultra-violet considerably*. With daylight and the carbon arc the ratio for B. 188 is 1·085, and for B. 299 it is 1·054 ; the agreement is quite good.

The thin film potassium-on-silver cell is about as sensitive to daylight and mean noon sunlight as are the Burt cells. It is considerably more sensitive to the 2360° K lamp.

C.M.V. 6 was not mounted so as to exhibit its best performance, from which it had also fallen off with age. Its daylight sensitivity is now very close to that of B. 299, though its good response to red makes it far more sensitive to the arc and the 2360° lamp, between the figures for which there is good agreement. It would therefore enable one to make a fairly accurate comparison of such sources. The agreement between its constants in daylight and m.n.s. is tolerable. Comparison of the values found with the old and the new sub-standard lamp shows that the latter was being run at a considerably lower temperature, giving a redder light. It seems very unlikely that the colour sensitivity of this cell could have changed in the four months' interval between the two tests sufficiently to give such a discrepancy. Its decrease in total sensitivity was over a period of four years. The increase in

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* Thus, B. 188, which has about twice the effective area of B. 299, is about twice as sensitive for the filament lamp with or without the daylight filter. With arc or daylight, however, the increased importance of ultra-violet makes the sensitivities of these two cells more nearly equal, the ratio of the sensitivities being approximately the same with either of these illuminants.

red found in the new lamp is in agreement with the values for the efficiencies of the two lamps, which, as previously mentioned, were 0·865 and 0·727 candle-power per watt respectively. This cell is quite free from temperature errors, and over a short period its stability is adequate for accurate work.

The type X cells are of a different order of sensitivity to all the foregoing. The X 16 size is 40–70 times as sensitive as C.M.V. 6 to lamp (2360°) light, 10–20 times as sensitive to arc light and about 10 times as sensitive to daylight—this figure should really be higher as the daylight was afternoon light in February with a sun/sky ratio about 0·2. Being predominantly a red-sensitive cell, we have decided to use it always with a red or orange colour filter. The cell shows a small reversible temperature effect, being slightly less sensitive when hot.

The larger X 41 is unsuited for use with strong daylight, since it requires a very high anode potential to saturate it, and would probably suffer damage. Its sensitivity is great—of the same order as that of the selenium rectifier cell. We are indebted to Mr. E. Bolton King of the Oxford Instrument Co. for lending us this beautiful cell.

Their small size, high sensitivity and colour response with a maximum at about 5950 A render the Bergmann selenium cells, Weston make, of great utility. The colour response maximum is subject to small variations; at least one of the newer cells without central electrode is rather more red sensitive than the earlier type, which is a slight disadvantage for visual comparisons, but an advantage for work on the red end with colour filters. It may be noted that for the earlier type, No. 21104-2, the agreement between the various standardizations, lamp at 2360°, m.n.s., arc, and daylight, is very close. It is particularly to be observed that the figure, 0·0164 obtained with the m.n.s. combination, albeit with the new lamp, agrees exactly with the value found from the May 1 comparisons (viz., in bright mixed daylight) with the potassium cell standardized by the carbon arc method. This is fortunate for our work, since it has hitherto been based upon potassium cell carbon arc standardizations. Results obtained by the two very different methods of standardization agree perfectly in bright mixed daylight; for blue sky the potassium cell would give an over-estimate on the visual scale, whereas the selenium cell would given an under-estimate. Through the courtesy of Dr. K. Mees and Dr. H. L. Jones, we have recently obtained a green colour filter which has been produced to reduce the colour sensitivity of the Weston cell to a close approximation to that of the eye. It was received, however, too late for inclusion in these standardizations and we have as yet no data as to its stability in continuous bright sunlight. The cells themselves seem quite stable, for one of them, when exposed for 30 days to summer daylight, showed no change, beyond the reversible temperature effect, within the limit of accuracy of our arc standardizations. It should be added that our 1928 potassium arc scale was based upon the constant 40·0 mc per 10^{-9} amp, whereas the mean of our recent determinations, more numerous and more precise, gives 40·7 mc. As regards the newer type selenium cell, W 21931-4, the bare lamp and m.n.s. standardizations indicate greater red-sensitiveness, but the m.n.s. and daylight figures are not in so good accord as with W 21104-2. This may very easily be due to the fact that the curvature correction, as found for the latter, may not be quite great enough for the former, and so in bright daylight may lead to the not very important difference found.

We have omitted from the Table III the standardizations of the cuprous oxide cells in " mean noon sunlight," as we found the loss in sensitivity which they undergo in daylight render them useless for anything but comparative values at one time. By comparison in daylight on February 26, 1932, we found a cell of this type, kindly given to us by Dr. P. Auger, was highly sensitive and 32-metre candles on the potassium carbon arc scale gave 1·00 μa. This cell had a gold film over the oxide. A similar cell, by Siemens and Halske, but with a silver film, gave 1·00 μa for 45 mc. The behaviour of these cells has been considered by us in two earlier papers.*

Correction for Reflection Losses at Front Surface of the Diffusing Window

Since it is necessary for much of our work that the diffusing properties of the window should not be affected by water, we use a glass which is polished on each face. It is necessary, therefore, to correct for the increased reflection loss at the upper surface due to obliquity, when measuring the vertical component of light of moderate altitude. The constants given above refer to light making an angle not exceeding 35° with the normal to the surface. The following figures† show the correction factor f by which the reading of a horizontal photometer should be multiplied for light of altitude α°.

α	5°	10°	15°	20°	25°	30°	35°	40°	45°	50°	55°	60°	65-90°
f	2·50	1·56	1·30	1·16	1·10	1·06	1·03	1·02	1·015	1·01	1·005	1·005	1·00

Integration of the effect of a uniform sky shows that for such the factor should be 1·06, *i.e.*, the same as that for sunlight of altitude 30°. For many daylight measurements, therefore, it is sufficiently accurate to multiply the constant of the cell, as found for illumination at normal incidence, by 1·06. This has, in fact, been our usual practice, except in a few cases in which we have been especially interested in comparing sunlight and sky light, for each of which we have then used the appropriate factor.

Sensitivity of the Cell Surfaces

In order to get an idea of the intrinsic sensitivity of the surfaces of the various cells, tests were made, using definite areas or apertures, upon the bare cells. As sources the lamp at 2360° K (new scale) was used, both alone and as modified to give " mean noon sunlight."

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[*] ' Sci. Proc. R. Dub. Soc.,' vol. 20, p. 537 (1933), and 'Nature,' vol. 131, p. 133 (1933).

[†] 'J. Marine Biol. Ass.,' vol. 14, p. 177 (1926).

Since the rectifier cells presented suitable plane surfaces, and the areas could be measured, they were used alone ; but with the emission cells a small circular aperture was placed immediately in front. To minimize effects due to the curvature of the bulbs, the apertures were only a few square centimetres in area.

The distance from source to aperture or rectifier cell was 50 cm. Accordingly, each square centimetre of aperture admitted 0·0204 lumen, since the source was 51·05 candle-power. With the filter in position, the luminous flux was 0·00276, assuming the visual transmission of the filter to be 13·5%.

The results in micro-amperes per lumen are shown in Table IV. It may be seen that the only emission cell exhibiting the same order of sensitivity as the rectifier cells is type X 16, which is considerably more sensitive than the cuprous oxide cells in lamplight. Type C.M.V. 6, when tested, had lost about half its original sensitivity ; it is, nevertheless, over twice as sensitive as K.M.V. 6 in "mean noon sunlight." In this the sodium and potassium cells are of low sensitivity, but are relatively far more sensitive than in lamplight ; in daylight they show up better for the reasons given before. The value actually found for the sensitivity of the sodium cell in "m.n.s." was rejected, since it gave an impossibly high value for the transmission of the filter cell and a large dark current was present during the determination ; though this was measured before and after the filter determination,

TABLE IV

Comparison of sensitivities of vacuum and rectifier photo-electric cells without opals, in light from sub-standard lamp at 2360° K and in "mean noon sunlight." Results expressed in micro-amperes per lumen. Effective percentage transmission of the m.n.s. filter cell is also shown. The visual transmission of the filter cell is taken as 13·52%.

Type of cell	2360° K	m.n.s.	Transmission %
Sodium, B. 188*	0·021	(0·095)	(62·6)
Potassium, L.	0·056	0·24	56·5
K.M.V. 6	1·14	1·78	21·0
C.M.V. 6†	6·66	3·81	7·73
X 16, No. 498	91·3	50·4	7·48
X 41, No. 612	37·3	14·5	5·28
Selenium, W. 21931-4	154·0	121·2	10·7
Cuprous oxide, S*x* 81‡	31·4	53·3	24·0
,, S*x* 80‡	26·9	49·7	24·8
,, P.A.‡	29·9	49·3	22·3
,, S. & H.§	34·2	54·4	21·5
,, Wh.§	25·8	9·5	5·2

* Other similar cells were more sensitive, *see* text ; (0·095) and (62·6) deduced from Table III, *see* text.

† Had lost about half its sensitivity with age.

‡ Was considerably more sensitive when new.

§ Little used, as new. S*x* denotes French Serpidox cell. P.A., a cell made by Dr. P. AUGER. S. & H., Siemens and Halske. Wh., Westinghouse.

it was felt that an uncertainty existed. The value given in brackets was calculated from the 2360° K value, using the transmission, 62·6%, derived from Table III. Though the surface of the sodium cell tested here, B. 188, was less sensitive than that of the potassium cell, yet two other similar cells were, over their whole areas and under opal glass, 4·61 and 3·26 times as sensitive as B. 188 under the same conditions. Since the areas were approximately the same in each of the three, it seems just to rate these two as giving 0·44 and 0·31 micro-amperes per lumen, namely, more sensitive than the potassium cell tested which gave 0·24 μa per lumen.

Table IV also shows the effective transmission of the filter for each cell. It may be seen that the cells which are predominantly blue sensitive record the transmission as greater than it is on the visual scale, namely, somewhat under 13·5% for the new lamp. To this the selenium rectifier cell comes nearest with 10·7%. The thin film caesium and type X cells follow—X 41 being apparently less blue sensitive than X 16. Finally, we have the Westinghouse cuprous oxide cell, which is apparently of the original Lange type and exhibits only a back-layer photo-electric effect. The wave-length sensitivity curves of these cells we have previously examined, fig. 4, in our 1933 paper.*

Observations on Photo-Electric Cells with Electrodes Reversed

A point of interest, though foreign to our original theme, was the determination of the current given when the " anode potential " is applied to the cathode. It was the study of such an effect that led Campbell to the discovery that certain thin film deposits had a wider spectral sensitivity than normal thicker films. We accordingly tested a number of cells. A knowledge of the magnitude of this effect may save one from error due to a chance wrong connection, as, for instance, in our experience when a K.M.V. 6 cell was found to give an unexpectedly low sensitivity—in reality a very high value for the reverse effect.

According to Campbell, the reverse sensitivity is due to an active layer on the glass wall of the cell sufficiently in contact with anode to give a current ; sensitivity of the actual anode, the gauze in K.M.V. 6 and C.M.V. 6, is unusual. The effective layer in either case is invisibly thin. With the older type of cell in which the glass carries the sensitive surface of the cathode, it looks as if the anode itself must carry a film also, but in this case the reverse sensitivity is usually very low. Thus, with the largest cell we tested, X 41, it amounted only to 0·4% of the direct effect in 2360° K lamplight. With the small potassium cell of photometer H the reverse effect was 11·2% in bright mixed daylight. Under similar conditions a large sodium cell, B. 188, gave 4·0% inverse effect, and a type C.M.V. 6 cell showed only 2·5%. The highest value found was with a K.M.V. 6 cell, which gave 56·9% in 2360° K lamplight and 48·1% in artificial " mean noon sunlight." This difference indicates that the reverse effect is more sensitive to red light than is the direct.

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* ' Roy. Dub. Soc.,' *loc. cit.*

We desire to acknowledge our indebtedness and to express our thanks to the Government Grant Committee of the Royal Society for assistance in the purchase of photo-electric cells and other apparatus. For general laboratory facilities we are indebted to the Royal Dublin Society and to the Marine Biological Association, Plymouth. We desire also to express our thanks to Dr. N. R. Campbell and members of the Staff of the General Electric Company for much helpful advice, and to the Company for the loan of a thin film potassium cell ; to the Director of the National Physical Laboratory for information concerning sub-standard lamps ; and to Mr. E. Bolton King for the loan of his new cell of high sensitivity to red light. Dr. P. Auger also most kindly presented us with one of his cuprous oxide cells.

Summary

Representative types of vacuum emission and of rectifier photo-electric cells were examined and standardized in light from different sources. Constants relating to nineteen such cells have been selected for inclusion in the tables given.

The photo-electric current was measured with standardized micro-ammeters or other galvanometers, or by a potentiometer null method using, when required, an electrometer valve to increase the effective sensitivity of the null point indicator. The sensitivity thus obtained was 10^{-11} ampere per scale division of the potentiometer, and the method permits of very rapid working. Alternatively, our submarine potentiometer-amplifier-telephone null method could be used down to a sensitivity of 5×10^{-11} ampere per scale division.

As light sources the following were used : open solid carbon arc ; vacuum sub-standard filament lamp at 2360° K ; artificial " mean noon sunlight " derived from the latter by interposing special filters. The cells were also compared in mixed daylight. For sodium and potassium cells, only the carbon arc gives a scale of values reasonably close to the visual. Accordingly, a critical account has been given of this method, which is also suitable for other emission and rectifier cells. Selenium rectifier cells have colour sensitivities close enough to that of the eye to allow of the use of the mean noon sunlight source also, or with rather less accuracy of the bare filament lamp. Close agreement is given by the selenium rectifier cell standardized in mean noon sunlight and the potassium cell in arc light, when both are used to measure bright mixed daylight.

Vacuum potassium and sodium cells were found to have preserved their sensitivity constant for over five years. The selenium cell has remained constant for over a year, save for reversible temperature effects.

It was established that the sodium and potassium emission cells used maintained a rectilinear proportionality between illumination and current up to full summer daylight. The curvature of the illumination/current characteristic of the selenium and other rectifier cells is important and must be allowed for.

The thin film caesium cell has proved useful for work throughout the spectrum, but its sensitivity falls off slowly. King's type X cell is of high sensitivity, comparable

with that of rectifier cells, especially in the red. Stability data over a prolonged period are as yet wanting.

For measuring daylight the perpendicular illumination, in metre candles, required to give a current of one micro-ampere was as follows with a few of the photometers: potassium, 40,700 mc; sodium, 3710 mc; thin film potassium, 2590 mc; thin film caesium (old cell), 3700 mc; King's type X 16, 348 mc; selenium, 16·4 mc. The size of cell factor enters into these measurements, which are on the potassium cell carbon arc scale.

The intrinsic sensitivity of the cell surfaces, expressed in micro-amperes per lumen, are as follows: sodium, 0·095-0·44; potassium, 0·24; thin film potassium, 1·78; thin film caesium, 3·81; type X 16, 50·4; selenium rectifier, 121·2; cuprous oxide rectifiers, 49·3-54·4 front film type; ditto, back film type, 9·5. The source was artificial mean noon sunlight.

When the electrodes are reversed, so that the normal cathode is made the anode, some types of cell give a high reverse effect; thus a thin film potassium cell gave as much as 56·9% of the direct effect and the reverse effect showed greater red sensitivity than the direct.

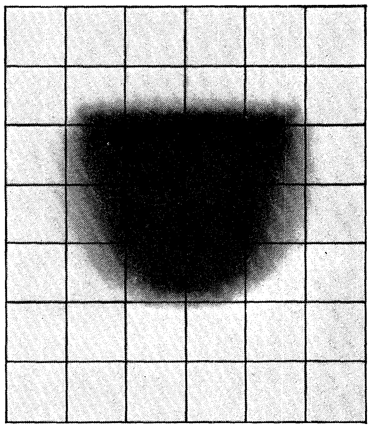

FIG. 1

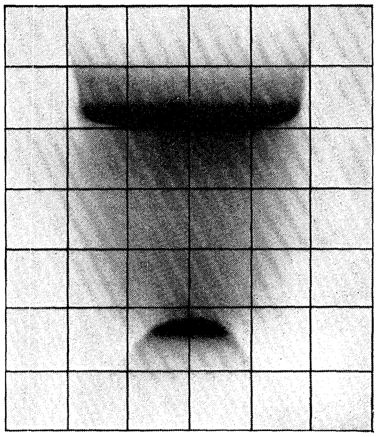

FIG. 2

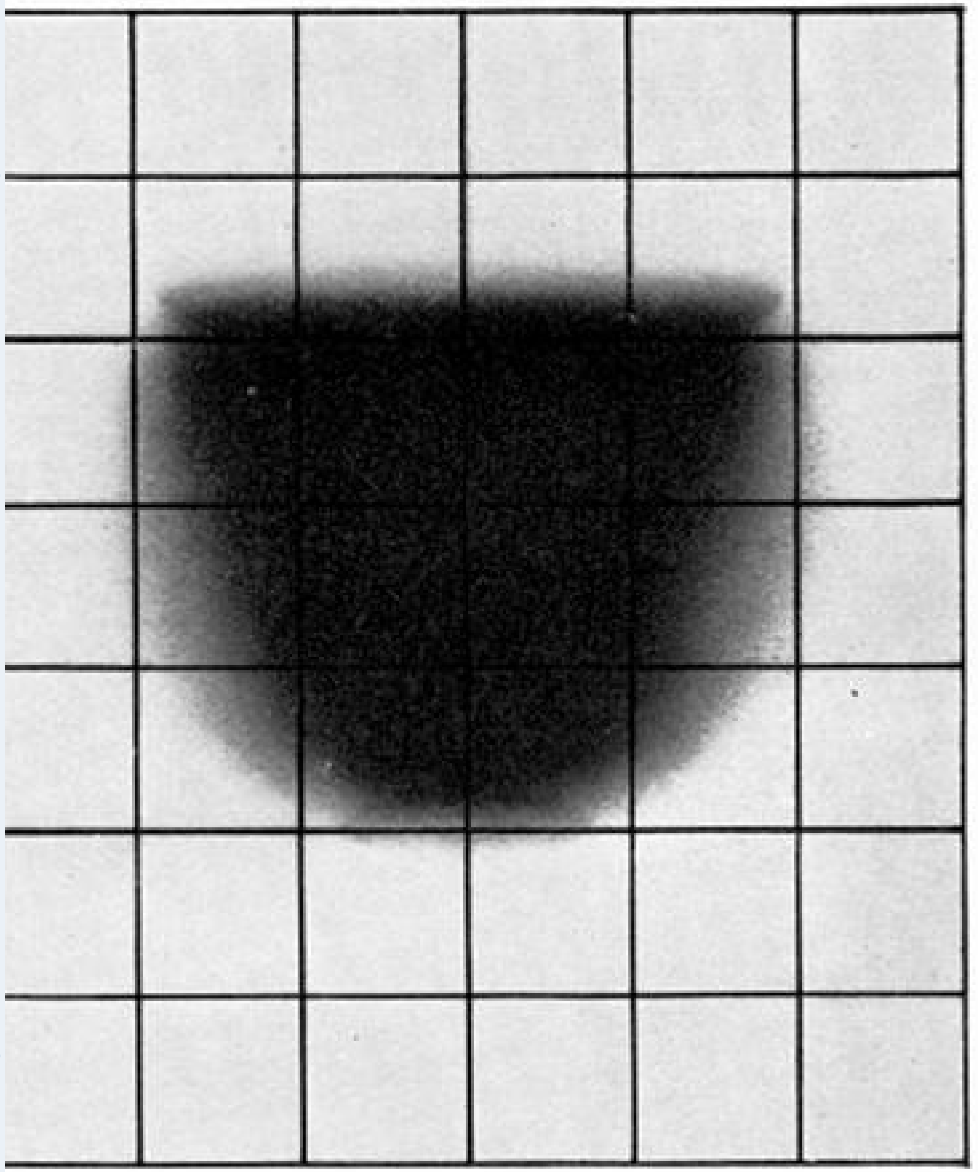

FIG. 1

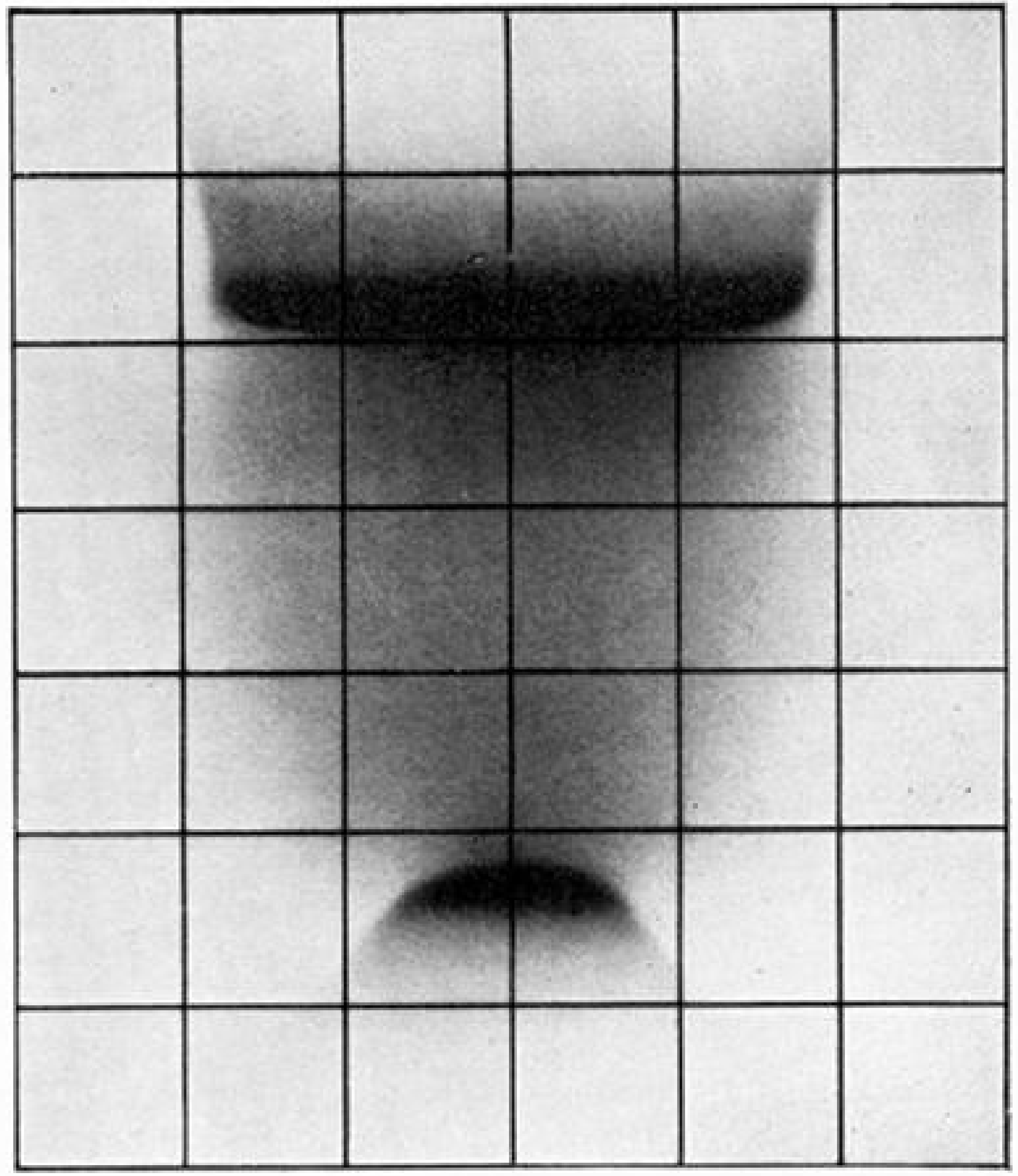

FIG. 2