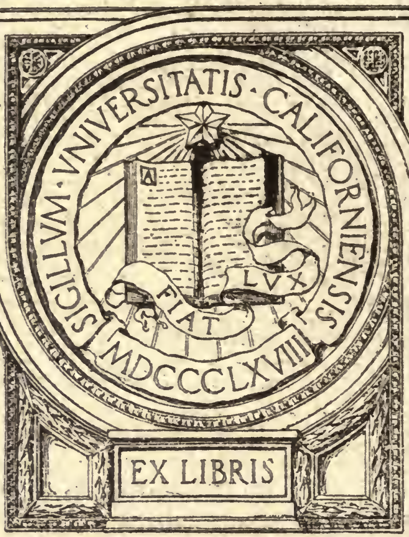

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ELECTRICAL PHOTOMETRY AND ILLUMINATION.

A TREATISE ON LIGHT AND ITS DISTRIBUTION, PHOTOMETRIC APPARATUS, AND ILLUMINATING ENGINEERING.

BY

HERMANN BOHLE,
FELLOW OF THE ROYAL SOCIETY OF SOUTH AFRICA;
MEMBER OF THE INSTITUTION OF ELECTRICAL ENGINEERS;
MEMBER OF THE VERBAND DEUTSCHER ELEKTROTECHNIKER;
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PREFACE.

This book is primarily intended as a text-book for second year engineering students. It contains in an amplified form the lectures delivered by the author during the session 1911.

The subject of photometry and illuminating engineering has been somewhat neglected in the past, and whereas one finds scores of books on electrical machinery, there have been very few on photometry and lighting. Yet this subject is as important as, or even more so than, the design of dynamos and motors. It is useless to raise the efficiency of generators and motors by 1 or 2 per cent. and afterwards to waste the power by improper illuminating engineering.

Illuminating engineering is a combined science of physics and physiology. This has been far too little understood in the past, with the result that physiology has hardly been considered. Our knowledge of physiological science is still very meagre. We neither possess any apparatus with which we can measure the physiological quality of an illumination, nor have we been able to remove the difficulties which we encounter when lights of different colours are compared. For a long time —while engineers were busily engaged in perfecting the generating plant and the light-producing devices—the subject of illuminating engineering was left in the background, with the result that one often finds the finest buildings poorly lighted, not so much from the physical, as from the physiological standpoint. Especially, architects are to blame in this direction; any illumination is often considered good enough, as will be gathered from the fact that for a particular building costing £20,000 the sum allocated by the architects for the lighting was only £100, in spite of the building being largely wanted for entertainments at night.

Although the book is primarily intended for college students, it is hoped that it will be found useful by others interested in illuminating engineering, such as medical men, architects, teachers, and even the general public. The mathematics have been kept as elementary as possible, and persons not acquainted with higher mathematics may skip the deductions of the formulæ without detriment.

Much material has been collated from various sources, and of these I should like to mention the writings of Messrs Steinmetz, Trotter, Norden, Högner, Monasch, Dow, Sharp, Bloch, Bell, Hyde, Drysdale, J. T. Morris, Millar, and last, but not least, the articles appearing in the *Illuminating*

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Engineer. Since the appearance of this paper and the formation of the Illuminating Engineering Society by Mr Leon Gaster, method has been introduced into the researches for the advancement of illuminating engineering science, and it is to be hoped that in future valuable information will be obtained from this source.

A great many of the tests described in this book were carried out in the laboratory of the South African College, Cape Town; some of them appear here for the first time. Where the results of tests of other experimenters are included, mention is made in the text or by foot-notes wherever possible. Although the metric system of units has been employed throughout the book, all principal figures are supplied with two scales, so that the book will be found equally useful by persons preferring the English system. Figures are numbered according to chapters, *i.e.* fig. 5·06 indicates the sixth figure of the fifth chapter. Time-wasting explanations and errors are thereby largely avoided. As no definite system of photometric units has so far been adopted, the system mainly employed in Europe has been used.

The author is very much indebted to Mr Leon Gaster, Editor of the *Illuminating Engineer*, and to various other persons and firms mentioned in the text, who have so kindly supplied particulars of their apparatus or experiments, supplied electrotypes, or in any other way assisted in the production of this book; and especially to his colleagues, Professor T. P. Kent, M.A., and Professor A. E. Snape, M.Sc., and his senior student, Mr P. J. de Wet, for checking the manuscript. Without such co-operation the book would lose much of its value.

H. B.

CAPE TOWN,
July 1912.

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ILLUMINATING ENGINEERING.

ABBREVIATIONS.

J.I.E.E.	Journal of the Institution of Electrical Engineers.
E.T.Z.	Elektrotechnische Zeitschrift.
Proc. Roy. Soc.	Proceedings of the Royal Society of London.
Verh. d. D. Phys. Ges. .	Verhandlungen der Deutschen Physikalischen Gesellschaft.

LIST OF PRINCIPAL SYMBOLS.

A = emissivity
a = absorption coefficient
$2a_1$ = distance between lamps
c, c_1, c_2, c^1 = constants
d = diameter
E = illumination
$\bar{E}$ = average illumination
E_h = horizontal illumination
E_{vertical} = vertical illumination
h = height of lamp above testing plane
i = intrinsic brightness
I = intensity in any direction
$\bar{I}_H$ = horizontal intensity (mean)
I_n = normal intensity
$I_{\circ}$ = mean spherical intensity
$I_{\ominus}$ = mean hemispherical intensity (lower)
I_c = current in amperes
T = time illumination
K = reflection coefficient
K_r, K_1, K_2, etc. = constants
$K_u = \dfrac{\text{maximum illumination}}{\text{minimum illumination}}$
l, l_0, L, L_1, L_2, L_0 = lengths

n = number of divisions
p = percentage voltage fluctuation
P, P_1, P_2 = power absorbed
P_R = radiated power
Q = quantity of light
R, r, r_0 = radii or distances
S, S_1, S_2, s = areas
t = time
t° = temperature
t_f = temperature at the finish
t_b = temperature at the beginning
V = voltage
V_0 = constant voltage
α, β, θ = angles
$\gamma = \dfrac{\text{distance between lamps}}{\text{width of street}}$
ω = spherical angle
ϕ = flux
ϕ_r = reflected flux
ϕ^θ = flux included in region swept out by rotating θ round the vertical
$\phi^1 = \dfrac{\phi_\theta}{2\pi}$
λ = wave-length
$\pi = 3{\cdot}14159$
$\epsilon = 2{\cdot}71828$
η = watts per candle
$\cos\phi$ = power factor

Any other symbols are fully explained in the text.

ELECTRICAL PHOTOMETRY AND ILLUMINATION.

CHAPTER I.

PHOTOMETRIC UNITS AND STANDARDS.

1. **GENERAL CONSIDERATIONS.**—In photometry we compare sources of light with regard either to their luminous intensity or their power of producing illumination. These comparisons cannot be made directly: all we can do is to compare the brightness of two surfaces, one of which is illuminated by some arbitrary standard of light (an absolute unit does not exist), and the other by the light to be compared. Such measurements, or rather comparisons, depend therefore upon the properties of the human eye, which has to judge the relative brightness of the two surfaces, the accuracy of the judgment becoming the more difficult the more the lights differ in colour.

Photometric measurements require the possession of

(*a*) Photometric Units.
(*b*) Standards of Light.
(*c*) Photometers.
(*d*) Systems of Measurements.

For simplicity we shall assume that all sources of light are points, this assumption being allowable if the distance of the photometer from the light is more than twenty times the greatest dimension of the light.

2. **PHOTOMETRIC UNITS.**—These are :—

Luminous intensity, or candle-power, the standard of which is called a "candle."

Luminous flux is the amount of light emanating from a source. The practical unit, called the "lumen," is the flux which passes through a unit solid angle, emitted from a point source of the intensity one candle-power.

The luminous flux from a point or spherical source of intensity I is $4\pi I$, since the solid angle surrounding a point is 4π. Thus luminous flux

$$\phi = 4\pi I,$$

and

$$I = \frac{\phi}{4\pi} \quad . \quad . \quad . \quad . \quad . \quad 1{\cdot}01$$

Illumination.—The unit of illumination is called the candle-metre * or candle-foot, this being the illumination produced on a white surface of unit area (one square metre or one square foot) when a flux of one lumen, uniformly distributed, falls perpendicularly upon it. Let its symbol be E, then, $E = \frac{\phi}{S}$, where S is the area and, since the surface of a sphere is $4R^2\pi$,

$$E = \frac{\phi}{4R^2\pi} = \frac{4\pi I}{4R^2\pi}$$

$$= \frac{I}{R^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad 1{\cdot}02$$

(It is only for a hollow sphere that all rays are perpendicular.)

Intrinsic brightness is the ratio of the normal intensity I, measured in candle-power, to the surface s of the source. Let its symbol be i, then

$$i = \frac{I}{s} \text{candles per unit area} \quad . \quad . \quad . \quad 1{\cdot}03$$

s is the apparent area, which is usually much larger than the actual surface.

Quantity of light is the name given to the product of the flux of light and its duration, and is therefore measured in lumen-seconds or lumen-hours.

We have $$Q = \phi t = 4\pi It \quad . \quad . \quad . \quad . \quad . \quad 1{\cdot}04$$

Time illumination is the product of the illumination of a surface and the time of exposure, and is measured in candle-metre-seconds or candle-feet-seconds. Its symbol is T.

We have $$T = Et = \frac{I}{R^2}t \quad . \quad . \quad . \quad . \quad . \quad 1{\cdot}05$$

Consider now a source of light I. The illumination at a distance L_1 is $\frac{I}{{L_1}^2}$; at a distance L_2 it is $\frac{I}{{L_2}^2}$, whence

$$\frac{E_1}{E_2} = \frac{{L_2}^2}{{L_1}^2} \quad . \quad . \quad . \quad . \quad . \quad 1{\cdot}06$$

i.e. the illumination varies inversely as the square of the distance away from the light.

Again, let two sources of light, I_1 and I_2, produce the same illumination

---

* The candle-metre is also termed "Lux."

E, and let their distances away from the illuminated surfaces be L_1 and L_2 respectively, then

$$E = \frac{I_1}{L_1^2} = \frac{I_2}{L_2^2},$$

whence

$$\frac{I_1}{I_2} = \frac{L_1^2}{L_2^2} \quad . \quad . \quad . \quad . \quad . \quad 1{\cdot}07$$

which says that the intensities of two sources of light, producing the same illumination, vary as the square of the distances.

Let a uniform luminous flux ϕ strike a surface S perpendicularly; then the illumination is $\frac{\phi}{S} = E$. This same flux illuminates an inclined surface $S_1 = \frac{S}{\cos\theta}$ (see fig. 1·01), the illumination being now $E_1 = \frac{\phi}{S_1}$, whence

$$E_1 = E\cos\theta \quad . \quad . \quad . \quad . \quad . \quad 1{\cdot}08$$

We see that the illumination is proportional to the cosine of the angle of incidence. The latter is the angle between the ray and the normal to the plane of incidence.[*]

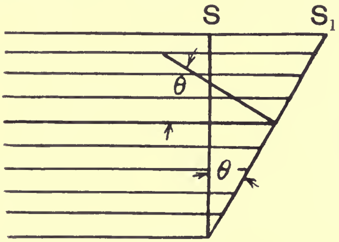

Fig. 1·01.—Lambert's Law.

3. **STANDARDS OF LIGHT.**[†]—The most important standards are the British, German, and French candles, or the pentane, amyl-acetate, and colza oil or carcel lamps.

Besides these flame standards there exist a number of incandescent standards of which we shall consider the platinum and the carbon standards.

4. **FLAME STANDARDS.**—A flame standard should fulfil the following conditions:—

(1) The combustible should be pure and easily procurable.

(2) It should be burnt under conditions which can be easily controlled and defined.

(3) Changes in atmospheric conditions should have no influence on the candle-power, or the variation should be capable of being easily defined.

(4) The colour of the light should be such that no difficulty is experienced in comparing it with the more common sources of light.

It may be said that none of the above flame standards fulfil all these conditions.

5. **THE BRITISH OR PENTANE STANDARD.**—This lamp was invented by Vernon-Harcourt[‡] and is made for 10 candle-power. It is used for reference at the National Physical Laboratory; hence we may

---

[*] Lambert's law, which is, however, only approximately accurate.

[†] See also Mr C. C. Paterson's paper, *Journal of the Inst. Elect. Engrs.*, vol. xxxviii. p. 271.

[‡] *Proc. of British Assoc.*, 1877, pp. 51 and 426; 1898, p. 845.

express the British candle as the tenth part of the 10 candle-power pentane lamp. The lamp is illustrated in figs. 1·02 and 1·03. Liquid pentane is contained in the rectangular saturator at the top of the lamp. Air passes in at one of the cocks, and, being drawn round baffle plates over the surface of the pentane, mixes with pentane vapour and passes by gravity down a rubber tube to an argand burner. The air supplied to the outside of this flame is drawn through the cylindrical box enclosing the steatite burner, whilst that feeding the inside of the flame is heated by its passage up the annular space between the outer and inner metal chimneys. It then passes through the rectangular box seen at the top of the chimneys, and down the centre of the supporting pillar to the middle of the burner. The extent to which a variation in the dimensions of any part of the lamp affects the candle-power is being investigated at the present time, but no results have as yet been published.

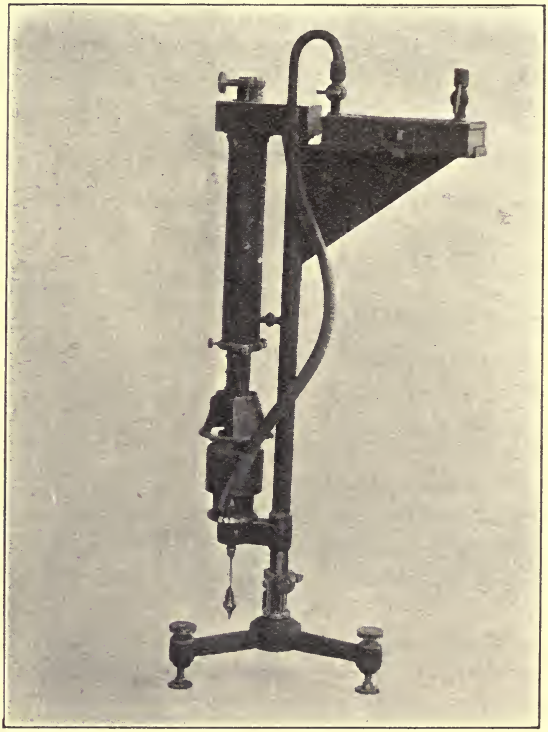

FIG. 1·02—The Pentane Standard.

The chimney tube CC should be turned so that no light passing through the mica window near its base can fall upon the photometer. The lower end of this tube should, when the lamp is cold, be set 47 millimetres above the steatite burner.

A cylindrical boxwood gauge, 47 millimetres in length and 32 in diameter, is provided with the lamp in order to facilitate this adjustment. The conical shade G should be so placed that the whole surface of the flame beneath the tube C may be seen at the photometer through the opening.

The adjustment of the lamp is as follows:—

The lamp is set up plumb at the end of the bench by means of a plumb-line passed through the chimney, and made to coincide with its central axis by means of a centring plug at the top. The lamp is then levelled till the plumb-bob hangs exactly over the middle of the burner. The exact distance of the lamp from the photometer is measured by means of a scale having at one end a pin which fits accurately into the centre of the burner, and at the other end a shoe, the top of which must graze some known point on the photometer.

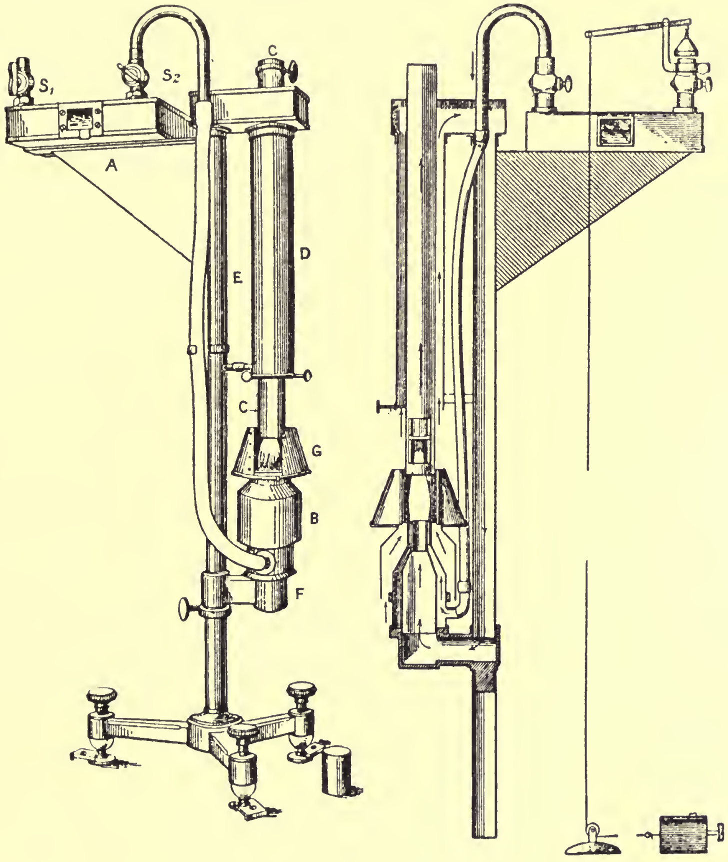

FIG. 1·03.—The Pentane Standard.

The manipulation of the lamp is extremely simple. All that is necessary is to put into the reservoir a pint of pentane, to open both the stop-cocks, and after a few moments to light the jet of vapour at the burner, and then to regulate the flow of air and vapour by the stop-cocks until the tip of the flame is seen at the middle of the mica window.

By affixing a piece of rubber to the air inlet cock, and regulating the flow of air through it by an ordinary screw clip, a most sensitive means of flame adjustment is obtained. The candle-power of the lamp is a maximum when the flame is at its proper height, but a slight increase or decrease does not materially affect the candle-power.

6. THE AMYL-ACETATE OR HEFNER LAMP (GERMAN OFFICIAL STANDARD).—A section of this lamp is shown in fig. 1·04. The combustible is amyl-acetate ($C_7H_{14}O_2$), which has a very mobile flame, so that—since the lamp is used without a chimney—it must be carefully protected from draughts. The combustible is contained in a cylindrical reservoir which forms the base of the lamp. A wick dips into this and passes up the thin-walled German silver tube projecting from the centre of the base, into which it fits without being screwed. The tube is of 8 millimetres inside, and 8·3 outside diameter, and is 25 millimetres high. The wick consists of 15 to 20 strands of untwisted cotton yarn, which just fill the tube without squeezing. The wick, however, does not rise above the top surface of the tube, but, keeping about level with it, serves to conduct the liquid to the point of ignition.

The exact height at which the flame gives one Hefner candle (0·9 English candle) is 40 millimetres.

In order to adjust the flame to the correct height, the lamp is fitted with a sighting arrangement, by means of which an image of the top of the flame is cast on a ground glass disc, and adjusted to a cross line.

Considerable care and skill must be employed in judging whether the flame is at its correct height, since the flame shows a tendency to vary its shape from one which is high and pointed to one which is somewhat depressed and flattened at the top.

The height of the flame is of great importance, since a variation of 1 millimetre alters the candle-power by 2·3 per cent.

As the lamp is also widely used in Great Britain, on account of its simplicity and cheapness, it is advisable to describe fully how the height of the flame is adjusted to exactly 40 millimetres.

Each lamp is provided with a gauge, shown in fig. 1·05. When it has been placed over the tube containing the wick and the observer looks through the slot S in the gauge, he should just be able to distinguish a light between the tube and the wall of the gauge, the space being less than one-tenth of a millimetre. The upper edge of the gauge then just reaches to the little mark in the middle of the sighting arrangement.

The lamp should be burnt at least ten minutes before it is used, and the temperature of the room should be between 15 and 20 degrees C. The height of the flame is correct when the visible tip of the flame just touches the mark on the ground glass in the sighting arrangement.

The residue which collects at the top of the German-silver tube near the wick should be taken off before the lamp has cooled down, and the lamp should be frequently cleaned in order to ensure accuracy.

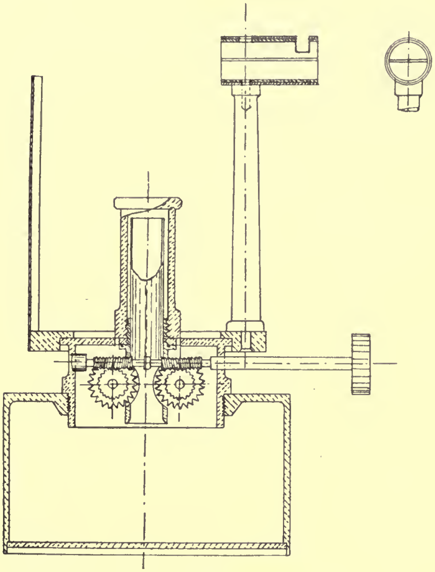

FIG. 1·04.—The Hefner Standard.

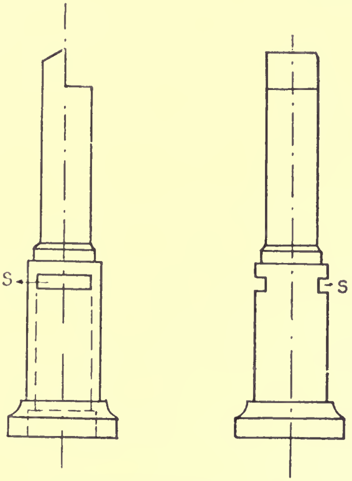

FIG. 1·05.—Gauge for Hefner Standard.

7. **THE CARCEL LAMP.**—A photograph of this lamp, the working standard of the French gas industry, is shown in fig. 1·06. It has a glass chimney and a wick of annular cross section, to which a continual supply of pure colza oil is maintained by means of a clock-work pump. According to the official instruction, the wick should stand 10

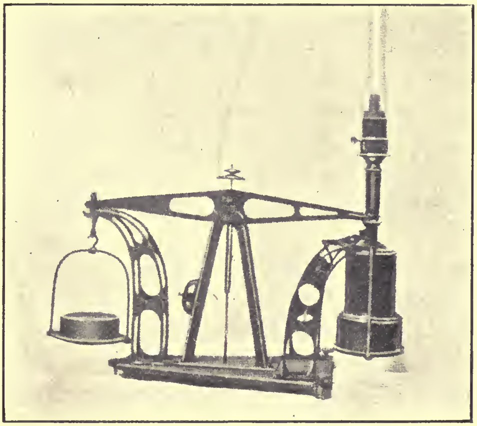

FIG. 1·06.—The Carcel Standard.

millimetres above the wick-holder, but in practice this is found to give too great a consumption of oil, and it is necessary to lower it to 7 or 8 millimetres. The chimney is made of thick glass and reduced in diameter to 7 millimetres above the wick.

The lamp should give its standard candle-power when consuming 42 grams of oil per hour. This adjustment is difficult to obtain, and a correction is made if the consumption falls within 37 to 46 grams.

For each experiment the oil and wick must be new, and the latter must be perfectly dry. As soon as a full stream of oil is circulating over the wick, the latter should be charred to an even depth of about 2 millimetres all round by means of a flat flame burner. The lamp may then be lighted, turned very low, and the chimney fixed so that the neck presses close down on to the wick.

Under these conditions there is only a very shallow ring of flame, which tends to equalise the intensity all round the wick. After about 15 minutes' burning in this condition, the chimney is raised, and the wick turned up; after 20 minutes' burning the lamp is counterpoised on a balance on the photometer bench. A weight of 10 grams is then added to the scale on which the lamp is fixed, and the time observed before the balance again swings over.

The correct time for a consumption of 10 grams is 14 minutes 17 seconds.

Mr Paterson, of the National Physical Laboratory, states that even with extraordinary care he was unable to make readings from the lamp agree with certainty to within ± 3 per cent.

8. **INFLUENCE OF ATMOSPHERIC CONDITIONS ON THE CANDLE-POWER OF FLAME STANDARDS.**—(*a*) **Variation Due to Carbon Dioxide.** — According to the latest investigations by W. J. A. Butterfield, J. S. Haldane, and A. P. Trotter,[*] the candle-powers of the pentane and Hefner lamps are reduced by 1 per cent. when the amount of carbon dioxide reaches 0·035 and 0·045 per cent. respectively. The diminution in light is practically uniformly proportional up to about 2 per cent. of carbon dioxide. We see therefore that good ventilation is essential.

(*b*) **Water Vapour.**—The results obtained by C. C. Paterson[†] have been practically confirmed by the above experimenters. The effect of moisture on the pentane and Hefner standards is shown in figs. 1·07 and 1·08 respectively. As it is necessary to know the aqueous pressure in order to find the amount of water vapour, fig. 1·09 has been plotted, which holds for a wet and dry thermometer.

(*c*) **Barometric Pressure.** — According to the investigations by Mr Paterson, the candle-power falls uniformly with a reduction in the barometric pressure, as shown for the pentane and Hefner lamps in

---

[*] *J.I.E.E.*, vol. xxxviii. p. 271.

[†] *The Illuminating Engineer*, 1911, p. 509.

figs. 1·07 and 1·10 respectively. The latest investigations by the above three experimenters show, however, somewhat different results, as is indicated in the same figures.

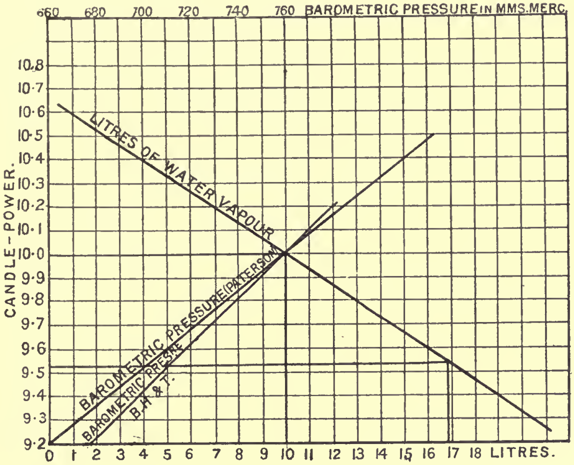

Fig. 1·07.—Variation in Candle-Power of the Pentane Lamp with Humidity and Barometric Pressure.

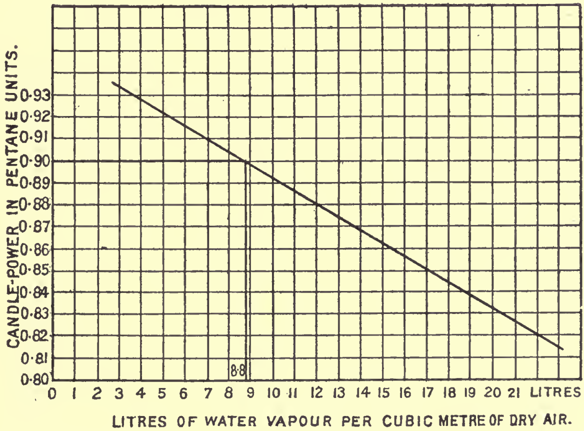

Fig. 1·08.—Variation in Candle-Power of the Hefner Lamp with the Humidity.

(*d*) **General Formulae for Corrections.**—According to the investigations by Butterfield, Haldane, and Trotter we have :—

For the pentane lamp—

$$I = \frac{100 - \left(\frac{a - A}{0{\cdot}16} + \frac{c - C}{0{\cdot}035} - \frac{b - B}{12{\cdot}5}\right)}{100} \times I \quad . \quad . \quad . \quad 1{\cdot}09$$

For the Hefner lamp—

$$I = \frac{100 - \left(\frac{a-A}{0{\cdot}16} + \frac{c-C}{0{\cdot}045} - \frac{b-B}{25{\cdot}0}\right)}{100} \times I \quad . \quad . \quad . \quad 1{\cdot}10$$

in which

A = the accepted normal percentage of aqueous vapour in the air (10 litres per cubic metre of dry air for the pentane lamp, 8·8 litres for the Hefner lamp).

B = normal barometric pressure (760 millimetres).

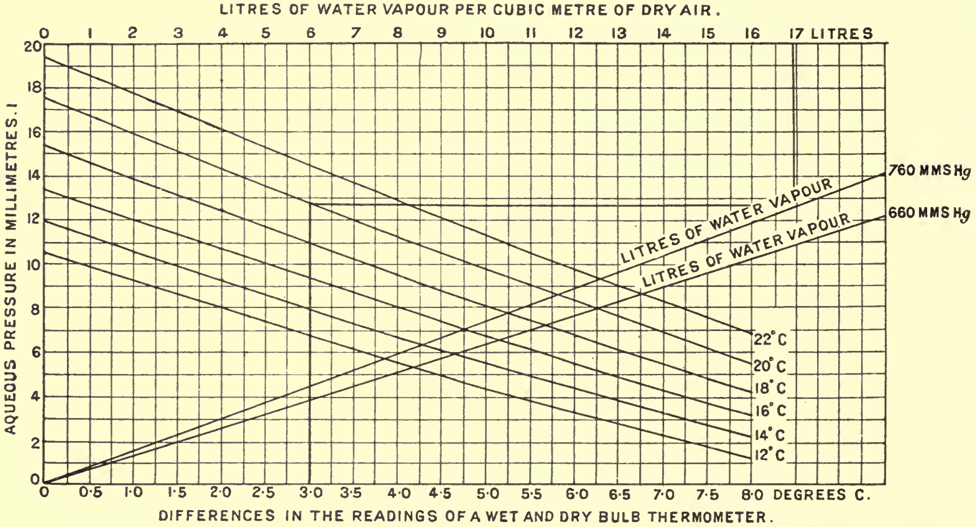

Fig. 1·09.—Aqueous Pressure for Different Readings of a Wet and a Dry Thermometer.

C = the accepted normal percentage of carbon dioxide in the air; no standard value is given, and with good ventilation the influence of carbon dioxide may be neglected. *No flame standard should be relied upon which has been burned for over* 15 *to* 20 *minutes in a closed room.*

a = the prevailing percentage of aqueous vapour in the air when the lamp is in use.

b = the prevailing atmospheric pressure.

c = the prevailing percentage of carbon dioxide in the air.

I = normal candle-power (10 for the pentane, 0·9 for the Hefner lamps).

(*e*) **Height of Flame.**—The variation of the candle-power of the Hefner lamp for different heights of the flame is shown in fig. 1·10. For the pentane lamp no reliable results are available, but the influence on the candle-power of a slight increase or decrease in the height of the flame is small.

In the Hefner lamp, which is not guarded against draughts, great care has to be taken to keep the height of the flame constant. A variation in the height is best noted with a thermo-electric couple fixed about 5 millimetres above the tip of the flame (when the flame is 40 millimetres high) and connected to a galvanometer. There is then a certain deflection corresponding with the correct position and height of the flame. If the flame sinks or moves to one side, the reading of the galvanometer changes. The galvanometer may be combined with an audible signalling arrangement.

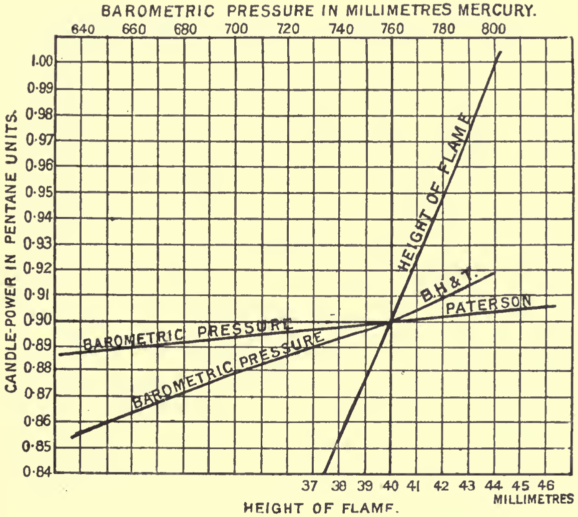

FIG. 1·10.—Variation in Candle-Power of the Hefner Lamp with Barometric Pressure and Height of Flame.

Example.—For the pentane lamp let $A = 10$, $a = 20$, $b = 710$, $B = 760$; then (neglecting the influence of carbon dioxide) we have

$$I' = \frac{100 - \left(\frac{2 - 1}{0{\cdot}16} - \frac{710 - 760}{12{\cdot}5}\right)}{100} \times 10$$

$$= 8{\cdot}975 \text{ candles.}$$

9. **COMPARISON AND CRITICISM OF THE VARIOUS LAMPS AS STANDARDS.**—The accompanying table shows the relationship between the values of the various standards in use.

10. **GENERAL CONSTRUCTION.**—The Hefner lamp is much simpler than the pentane lamp, smaller in size, and more easily manufactured to standard dimensions. Its price is about £2, against £14 for the pentane lamp. (The Carcel lamp does not give sufficiently accurate readings, and will not be further considered.)

Ease of Regulation and Working.—The pentane lamp is easier to adjust, and its candle-power remains more constant while observations are

TABLE I.—CONVERSION TABLE FOR STANDARDS OF LIGHT.*

1 Pentane Candle = 1 American Candle = 1 International Candle = 1 Bougie Décimale = 1·11 Hefner Candles = 0·104 Carcel Candle.

Results expressed in	Factors for Conversion into				
	1. German Lux.	2. Hefner Candle-foot.	3. International Candle-foot.	4. International Candle-metre. or Lux.	5. Carcel Candle-metre.
1. Hefner candle-metre (German lux)	1·	0·0929	0·0837	0·9009	0·093
2. Hefner candle-foot	10·76	1·	0·9009	9·71	1·001
3. International candle-foot	11·95	1·11	1·	10·76	1·034
4. International candle-metre, bougie-metre, lux	1·11	0·103	0·0929	1·	0·104
5. Carcel candle-metre	10·75	0·9986	0·966	9·61	1·

being made than that of the Hefner lamp, because the latter, burning as it does without a chimney, is not guarded against draughts.

Effects of Atmospheric Changes.—As regards changing humidity, the two standards are nearly equally affected. The pentane lamp is, however, more sensitive to barometric variations than the Hefner.

The Nature of the Light.—The pentane lamp has a whiter light than the Hefner lamp.

The fact that the candle-power of the pentane lamp is about eleven times that of the amyl-acetate lamp makes it of about the same order of magnitude as the lights which are tested against it.

This—and the better colour of the light—are advantages not to be underrated.

Incandescent Standards of Light.†—It would go beyond the scope of this book to consider the many incandescent standards which have been suggested. It may suffice to consider the two principal ones—the primary platinum standard by M. Violle, and the secondary carbon standard due to Dr Fleming.

11. **THE PLATINUM STANDARD.**—M. Violle proposed in 1881 to define the unit of light as the light radiated normally from one square centimetre of platinum at its melting-point. The essential conditions for the reproduction of the platinum standard are that:—

(1) The platinum must be chemically pure.

(2) The mass must not be less than 500 grams.

(3) The crucible must be made of pure lime.

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* Dr B. Monasch, *Illuminating Engineer*, 1909, p. 742.

† See also J. S. Dow, *Electrician*, vol. lvii., 1906, p. 855. Dr Fleming, *J.I.E.E.*, vol. xxxii., 1903, p. 119.

(4) The hydrogen burnt must contain no carbon.
(5) The gases should be burnt in the ratio of 4 volumes of hydrogen to 3 of oxygen.

The process of producing the unit of luminous intensity by the platinum standard consists in melting this mass (500 grams) under the above conditions. This is, however, extremely difficult and could be done only at National laboratories.

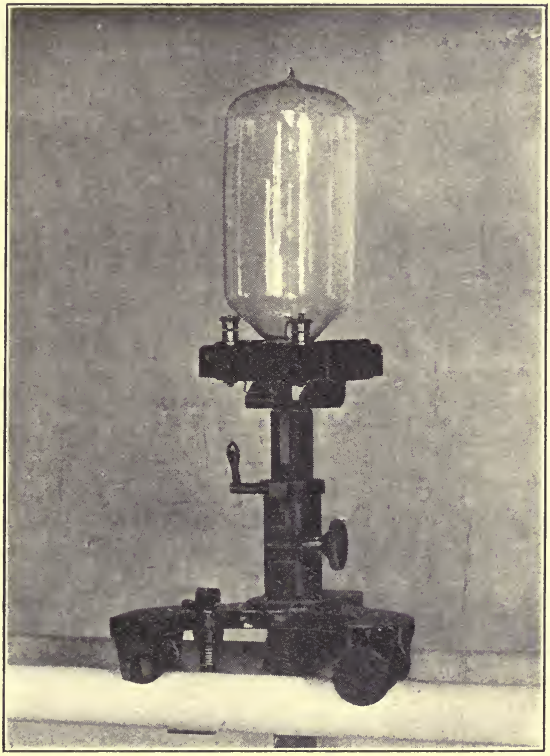

FIG. 1·11.—Fleming's Electric Lamp Standard.

The candle-power of the platinum standard is about twenty English candles.

A modification of the Violle standard was suggested by Messrs Lummer and Kurlbaum. It was to be the light emitted from a square centimetre of solid platinum when brought by an electric current to such a temperature that 10 per cent of its radiation, as measured by a bolometer, could pass through a layer of water two centimetres in thickness contained in a cell with quartz sides. The apparatus was established at the Reichsanstalt, Berlin, and is used at present as a standard of reference for Hefner lamps. The spectral quality of the light is, however, not very satisfactory for a standard, and the adjustments are very difficult.*

12. **FLEMING'S INCANDESCENT STANDARD.**—This consists of an ordinary incandescent carbon electric glow lamp, with a specially aged filament in a large glass bulb, as illustrated in fig. 1·11.

The candle-power of the glow lamp alters with

(1) Changes in electric resistance of the filament.
(2) The nature of the surface of the filament.
(3) The deposit of carbon on the interior of the bulb.
(4) The temperature of the atmosphere surrounding the lamp.

When, however, a good filament is run in a lamp at normal, or slightly above the normal, voltage for 50 hours or so, it attains a condition in which a small further use will not much alter the candle-power of the filament. By this time the glass globe has been somewhat blackened and the lamp is reduced in candle-power. The filament is then taken out and placed in a large clear globe, for which the blackening on account of the large size is practically negligible. The lamp is then calibrated with a pentane standard for a definite voltage, and the voltage and candle-power are marked on the globe. The statement of a definite temperature would appear to be necessary, since an increase of the surrounding temperature slightly augments the candle-power. Subsequent tests seem, however, to indicate that the influence due to external temperature fluctuations is negligible.

Experiments on carbon incandescent standards made by C. C. Paterson show that such lamps are suitable for low voltages up to 110 volts, if they are properly manufactured and if they are not used more than ten minutes a day for five days in the week; in this case they will last for two to three years without re-calibration, provided no excess voltage is ever applied.

High voltage lamps have not yet proved a success for standards.

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* See J. E. Petavel, *Proc. Roy. Soc.*, vol. lxv. p. 478.

CHAPTER II.

RADIATION AND ITS EFFECTS.

13. **NATURE OF LIGHT.**—According to Newton, light consists of minute particles thrown off at great velocities by light-giving bodies. The modern theory, originated by Euler, considers light to be a wave-motion; this is now generally accepted, and can be proved; but if there is motion, there must be a medium which is moving, and, as the movement is of extraordinary rapidity, it follows that the medium must have an extremely high elasticity; it must also have a very low density, so as to penetrate all substances. To this hypothetical medium has been given the name "ether." It is essentially a carrier of energy, and hence, looked at from this standpoint, we may consider ether to be matter.

There are two kinds of wave-motions to be considered: longitudinal and transversal. Light is of the latter type, since it shows different properties in two directions, at right angles to each other and to the direction of propagation; whereas for longitudinal motion, such as sound, the air particles vibrate in the direction of propagation only.

The speed of light, which can be fairly accurately calculated, is 3×10^{10} centimetres per second. Experience shows that light, or radiation, possesses different wave-lengths, and hence also different frequencies, since the speed is constant.

Within the visible range this shows itself by different colours. Red light has a greater wave-length than yellow light, and blue or violet lights still shorter wave-lengths.

When the wave-length attains values lying within certain limits, the radiation becomes visible. The visible part of the spectrum is however very small compared with its whole length. The wave-length lies between 75×10^{-6} and 38×10^{-6} centimetres,* which gives frequencies of

$$\frac{3 \times 10^{10}}{75 \times 10^{-6}} = 4 \times 10^{14} \text{ to } 7{\cdot}9 \times 10^{14}.$$

Radiation however commences long before it becomes visible, *i.e.* long before the red light appears. This radiation is called ultra-red, whereas

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* The wave-length is sometimes expressed in terms of μ, which is equal to $\frac{1}{1000}$th of a millimetre, or $\mu\mu$, equal to one millionth of a millimetre.

that which takes place beyond the other limit, the violet, is called ultra-violet. Beyond the latter occurs a gap, after which come the X-rays. If we divide the whole range of radiation into octaves, we have about twenty-two between the commencement of the ultra-red and the X-rays, differing in wave-length from $30{,}000 \times 10^{-6}$ to $0{\cdot}01 \times 10^{-6}$ centimetres, and of these somewhat less than one octave is visible. Of sound waves, on the other hand, the ear distinguishes eight octaves, so that the eye is relatively less sensitive than the ear.

Light radiations consist of radiations of different frequencies, distinguished by different colours. The eye however notices mostly the resultant of these radiations. That is to say, if all the radiations from the red to the violet are present, the eye sees the resultant colour only, which is white. Or, if orange and green radiations occur, the light appears yellow. The eye differs remarkably in this from the ear, which distinguishes all the different sounds in a harmony.

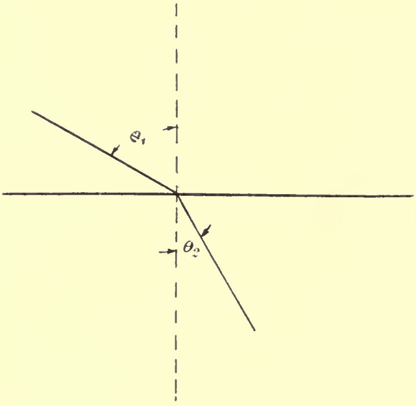

FIG 2·01.—Refraction of Light.

Light travels at a speed of 3×10^{10} centimetres per second in air and gases. When it strikes denser media, the speed is reduced, and, since the vibration takes place at right angles to the direction of travel, it follows that the edge of the beam, which strikes the denser medium first, is retarded, in the same way as the near side of a vehicle when turning a corner. We say that the light is refracted, and the ratio of the sine of the angle of incidence to the sine of the angle of refraction (see fig. 2·01) is called the refractive index between the two media.

14. **SPECTRA.**—We notice further that the waves of higher frequency decrease more than those of a lower order, as one would naturally expect. If we send a current of a very high frequency through a choking coil the damping action is enormous, whereas for a frequency of one or two cycles per second it is hardly noticed.

It is this phenomenon which makes it possible to resolve a resultant ray into its constituent components, *i.e.* into a *spectrum.*

Light from different sources produces different spectra. For a tungsten filament, the spectrum is a continuous one, *i.e.* it shows all the radiations from the red to the violet without separate lines. But the spectrum from a mercury vapour lamp shows only a number of lines on the dark background, of which the yellow-green and the indigo-violet are the most pronounced; the red lines being almost completely absent.

A third spectrum is the band spectrum, which shows a number of bright bands, separated by dark spaces; but each band usually shows a number of colours, or radiations of different frequencies. Such spectra are obtained with gases at high pressure.

If we have two lights of which one is a gas through which the other is studied by means of a telescope, it will be found that the gas absorbs those radiations of the other, which it produces itself, while it is transparent for all other radiations. The minute particles of the gas, which are of the same frequency as the radiations of the other light, are set in motion and absorb the energy of the impinging rays, whereas the other radiations do not respond. We may therefore expect that the spectrum, looked at through a vapour light, will appear either as bright lines on a dark background, or as dark lines on a bright background. In the latter case absorption has taken place, and we have a "reversed" spectrum.

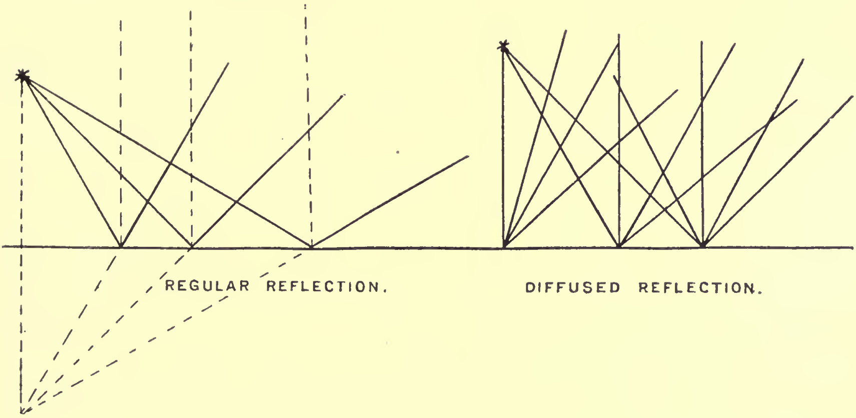

FIG. 2·02.—Reflection of Light.

15. **REFLECTION.**—Besides refraction and absorption we have reflection, which may be of a twofold nature. If we use a polished silver mirror, it will be found that a beam of light which impinges on it is reflected as a single ray, and that the angles of incidence and of reflection are equal. If however we take a sheet of white drawing-paper, the beam of light is scattered into many irregular parts. The first reflection is called regular, the latter irregular or diffused (see fig. 2·02). In both cases it will be observed that the intensity of the reflected light is less than that of the incident ray, showing that either absorption or transmission, or both, have taken place. In the case of the silvered mirror it will be absorption only, at least as far as visible radiation is concerned, whereas for the drawing-paper it will be both.

If all the frequencies which make up the beam of sunlight are reflected, the reflecting surface appears white; if none, it is black; and if the percentage reflection of a certain frequency is higher than that of others, the body shows that particular colour.

If part of the light is reflected, but in equal proportion for the various radiations, the surface appears grey. As radiation is energy, it follows that surfaces which absorb light must become heated, and black bodies more so than coloured and grey ones. This is the reason why we wear white clothes in summer, dark ones in winter.

Substances which reflect all the light are called opaque, and those which transmit all radiations, transparent. Perfectly opaque or perfectly transparent substances probably do not exist. Quartz is very transparent, whereas glass is so for a number of radiations, but opaque for others. For instance, invisible ultra-violet rays of all frequencies are passed by quartz, but only those of lower frequency pass through glass. Other substances reflect light irregularly within themselves, but do not transmit it; they are termed *translucent.* As light is reflected and transmitted, we distinguish between reflected or opaque colours, and transmitted or transparent colours. If we look at a piece of cloth, and if it appears, say blue, it means that a greater percentage of the blue is reflected than of any other radiation. This however does not mean that a substance shows always the same colour, which depends largely on the nature of the light in which the body is viewed. For instance, an opaque red substance, viewed in the green light of a mercury vapour lamp which possesses few red radiations, appears black. It would therefore be useless to employ such light where colours have to be distinguished, unless the missing radiations are supplied by other illuminants, as is the case in the Bastian lamp to which is added an underrun incandescent carbon filament, rich in red rays.

TABLE II.—DAYLIGHT COLOURS AS THEY APPEAR IN ARTIFICIAL LIGHT.

Daylight Colour.	Colour of Incident Light.					
	Red.	Orange.	Yellow.	Green.	Blue.	Violet.
White . .	Red	Orange	Yellow	Green	Blue	Violet
Red . .	Intense red	Scarlet	Orange	Brown	Violet	Violet, with a red tint
Orange . .	Orange-red	Intense orange	Yellow-orange	Yellow with a green tint	Violet-brown	Light red
Yellow . .	Orange	Yellow-orange	Yellow	Yellowish green	Green	Brown, with a slight red tint
Green . .	Reddish grey to black	Yellowish green	Yellow-green	Intense green	Greenish blue	Blue-grey
Blue . .	Violet to purple	Orange-grey	Green to slate	Green-blue	Intense blue	Violet-blue
Violet . .	Purple	Red-maroon	Yellow-maroon	Bluish brown	Blue-violet	Intense violet
Black . .	Purple-black	Deep maroon	Olive-yellow	Brown (green tint)	Blue-black	Violet-black

Table II. will give some idea of how some daylight colours will appear under various artificial lights.

In Table III. are given the relative intensities of the various frequencies for different illuminants.

TABLE III.—RELATIVE INTENSITIES OF VARIOUS FREQUENCIES FOR DIFFERENT ILLUMINANTS.

Type of Light.	Red.	Yellow-green	Green.	Blue.
Daylight	1	1	1	1
Petroleum	2·1	1	0·73	0·12
Incandescent gas	1·21	1	0·88	0 22
Incandescent electric (mean)	1·7	1	0·77	0·22
Pure carbon arcs, with vertical carbons . .	1·35	1	0·97	0·45
Flame arcs, with inclined carbons (white light)	0·97	1	1·21	1·05
Mercury vapour arc	...	1	0·78	0·58

It will be seen from this table that for colour-distinguishing purposes the flame arc with white light is nearest to daylight. The pure carbon arc with inclined carbons is however even better, and should certainly be employed where the recognition of colours is of great importance.

16. **PRODUCTION OF LIGHT.**—As far as electric lighting is concerned, we have to consider, in the majority of cases, temperature radiation. If we heat a substance more and more, the frequency of radiation is increased until the radiation itself becomes visible. This commences in the red, passes then into the yellow, and finally into the white. A further increase in the temperature produces a bluish white light, *i.e.* the blue-violet rays predominate if the substance has not already fused. For a given power input the temperature keeps on increasing, but the rate of increase decreases with the rise in temperature due to dissipation, and when a given temperature has been reached, the rate of dissipation of energy equals the rate of generation and no further increase in the temperature takes place.

The dissipation is due to radiation, convection, and conduction. If the radiator is placed in a vacuous globe, as is the case with most incandescent lamps, the dissipation can take place by radiation only, so that the power of radiation must be equal to the input. This radiated power is, according to Stefan, expressed by

$$P_R = AS(t_f^4 - t_b^4) \quad . \quad . \quad . \quad . \quad 2{\cdot}01$$

in which t_f is the absolute temperature of the radiator, t_b that of the surrounding media, S the radiating surface, and A a constant.

The latter varies with the nature of the surface and the surrounding media. As in lighting we usually deal with high temperatures, we may neglect t_b and find approximately

$$P_R = ASt_f^4 \quad . \quad . \quad . \quad . \quad . \quad 2{\cdot}02$$

Example.—Let $t_f = 1000$, $t_b = 300$,

then $t_f - t_b = 1 \times 10^{12} - 8{\cdot}1 \times 10^9 = 9{\cdot}919 \times 10^{11} \fallingdotseq 1 \times 10^{12}$.

In most cases the temperature is much higher than 1000 degrees C. For black bodies, and when the power radiated is expressed in watts per square centimetre, the value of A is $5{\cdot}32 \times 10^{-12}$.*

With the aid of the above equation, we are able to calculate the temperature of an incandescent lamp. As an example let us take 100-watt carbon filament lamp with a radiating surface of one square centimetre.

$$t_f = t^0 = \sqrt[4]{\frac{100 \times 10^{12}}{1 \times 5{\cdot}32}}$$

$$= 2080 \text{ degrees absolute, or } 1807 \text{ degrees C.}$$

This equation holds if the temperature inside the globe is low, which is, however, doubtful, because glass is not transparent for all radiations, and reflection takes place, causing the inside temperature to be fairly high.

1807 degrees C. is about the temperature at which carbon lamps glow. Carbon, the most refractory body known, unfortunately deposits carbon on the inside of the vacuous globe, which absorbs the light partly, and, as the resistance increases with a reduction in the size of the filament, a further decrease in the current and in the candle-power results. When a reduction of 20 per cent. has been reached, the lamp is usually considered useless.† This reduction is obtained the sooner, the higher we raise the temperature, and hence the latter is limited for commercial reasons. Where the price per unit of current is high, it pays to run the lamps at a high efficiency, even if they last for a comparatively short time. 500 to 700 hours may be considered an average economical life for carbon filament lamps. Wherever light is to be produced, we should see that all the power input is radiated and none conducted away or lost by convection; consequently the use of a vacuous globe, even if a filament would last in air, is still to be recommended to prevent conduction and convection losses.

Although carbon is the most refractory body we have, it does not follow that it is the best material for incandescent lamps. A material may have a lower melting-point than carbon, and yet the temperature at which it commences to evaporate may be higher. Carbon cannot be worked commercially at a higher temperature than 1800 degrees C., but tungsten can, since its evaporation point does not lie much below its melting-point, which is above 3000 degrees C. Hence we can raise the temperature of a tungsten lamp until it absorbs 1·25 watts per candle against 3 for the carbon lamp. As tungsten does not evaporate, the lamp does not blacken as long as the vacuum remains good, and it may be kept on until the filament breaks. A blackening is always caused by an imperfect vacuum, which however does not always develop immediately after the installation of the lamp, but may occur after the lamp has been worked for a considerable time.

* Kurlbaum, 1898.

† See also Chapter V.

We see from these remarks that the efficiency of incandescent lamps can be further increased by discovering a substance which is still more refractory than carbon and tungsten, and has an evaporation point near its melting-point.

Equation 2·02 holds for normal radiations only, *i.e.* for black and grey body radiations. The constant A will be different for these two. A black body absorbs all the radiations impressed upon it and radiates a maximum for a given temperature.

Grey bodies absorb less in the same proportion in which they reflect light and consequently radiate less. Coloured bodies absorb different parts of the impinged radiation ; consequently they will radiate different fractions of black body radiations, according to the frequency, *i.e.* according to the temperature.

For such radiations the coefficient A is therefore no longer a constant. Radiations of this type are termed "Selective Radiations."

We have seen that the radiation increases with the temperature. Wien [*] has connected the intensity of radiation, the wave-length, and the temperature of a black body by a formula :—

$$P_R = AS\lambda^{-5}\epsilon^{-\frac{C}{\lambda t}} \quad . \quad . \quad . \quad . \quad 2{\cdot}03$$

in which P_R is the power radiated, A and C are constants, S is the radiating surface, λ the wave-length, t the absolute temperature. The value of C is 1·47.[†]

If we consider this equation, we see that when λ is large, the first factor $(AS\lambda^{-5})$ decreases very rapidly, and is zero for $\lambda =$ infinity. But the other factor $\left(\epsilon^{-\frac{C}{\lambda t}}\right)$ rises to unity for $=$infinity. On the other hand, when $\lambda = 0$, the second factor is 0 and the first one grows to infinity. Between these two limits, P_R rises and falls. If we integrate from $\lambda = 0$ to $\lambda =$ infinity, we get

$$P_R = ASt^4 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad 2{\cdot}04$$

For

$$\frac{dP_R}{d\lambda} = 0, \quad t\lambda_{\text{max.}} = \frac{1{\cdot}47}{5} = 0{\cdot}294$$

and

$$\lambda_{\text{max.}} = \frac{0{\cdot}294}{t} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad 2{\cdot}05$$

With this equation we can find the wave-length of a black body for any given temperature, or find for a given wave-length the temperature. In the above example $t = 2080$ degrees absolute, hence

$$\lambda_{\text{max.}} = \frac{0{\cdot}294}{2080} = 141 \times 10^{-6} \text{ centimetres,}$$

which is outside the visibility of light.

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[*] See Wiedmann's *Annalen*, lviii. p. 662 (1896).

[†] Lummer and Prengstein, *Verhandlungen der deutschen Physikkalischen Gesellschaft*, 1899.

The eye is most sensitive to wave-lengths of the order of about 54×10^{-6} (for average intensities), whence

$$t_{\text{max.}} = \frac{0{\cdot}294}{54 \times 10^{-6}} = 5420 \text{ degrees absolute}$$
$$= 5693 \text{ degrees C.} \quad . \quad . \quad . \quad 2{\cdot}06$$

which is far above the temperature even carbon will withstand, but which is about the temperature of the sun.

17. **EFFICIENCY OF RADIATION.***—If we divide the visible radiation by the total power, we get the luminous efficiency of the radiator. This efficiency is still very low for even the best illuminators, and does not exceed 5 per cent. for the tungsten, and 13 per cent. for the flame arc lamps.† This is due to the fact either that the greater part of radiation is invisible or else that the energy is partly conducted away or lost by convection. The efficiency can be increased by raising the temperature; but, as we have seen, this reduces the life of the lamp until the latter becomes commercially impossible.

18. **LUMINESCENCE.**—In incandescent lamps, substances are heated until they show visible radiation. Light is however also obtained by luminescence. Here we are concerned with electro-luminescence of gases only.

Electrical energy is now converted directly into radiation without being first converted into heat. The colours of the light are therefore no longer due to temperature, but depend upon the capability of the vapour for vibrating, *i.e.* upon the chemical composition of the vapour.

When a gas is being used as a conductor of electricity, it becomes luminescent under certain conditions. The conduction may be continuous or intermittent. The former type is illustrated by luminous arcs in arc or mercury vapour lamps; the latter by luminous discharges in Geissler or Moore tubes.

19. **CONTINUOUS CONDUCTION.**—The arc which is set up between two electrodes is a stream of vapour, which has to be produced before conduction can take place. This "starting of the lamp" may be accomplished by increasing the potential difference between the electrodes until it is high enough to bridge the space, or by bringing the electrodes momentarily into contact. The starting could also be effected by temporarily conducting an auxiliary vapour stream between the electrodes. Lamps of this nature are evidently direct-current lamps, as a stoppage of the current or the passing of an alternate current through zero would extinguish the arc, and it would require fresh starting. An exception is the carbon arc, which consists of particles of carbon which form a bridge between the electrodes and which do not disappear simultaneously with

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* See also Chapter V.

† See *Elektrotechnischer Anzeiger*, 1908, p. 11.

the current, so that, when the alternate current increases again, the bridge is still present. The frequency of the current must, however, not be lower than 30 cycles per second.

The vapour which is set up, once the starting has been accomplished, is supplied from the negative electrode, the cathode, and moves towards the positive pole, the anode; and the spectrum therefore depends on the material of the cathode, unless the anode melts at a temperature lower than that of the arc. This happens in flame arcs, so that their spectra are the combined ones of positive and negative carbons. Where this is not the case, it would appear that the positive electrode ought not to be consumed. This is really the case, and if we make this pole large enough so that it is sufficiently cooled, consumption can at any rate be made very small. In the magnetite arc lamp the positive electrode consists of copper, large enough to keep sufficiently cool to prevent oxidation and consumption, and hot enough for preventing condensation of the vapour. The negative pole consists of an iron tube, filled with powdered oxide of iron (magnetite), oxide of titanum, and oxide of chromium. The tube acts as a conductor, the oxide of iron gives conductivity to the mixture when cold, the oxide of chromium prevents the otherwise rapid consumption and the flickering of the arc—the latter by keeping the melted magnetite in a constant position. The oxide of titanium makes the arc luminous. The lamp is suitable for outdoor work only. The oxides are completely converted, but they condense immediately after leaving the arc as a reddish soot. It is therefore essential that the lamp be provided with such ventilation as will carry this soot away into the atmosphere. The maximum amount of light comes from the flame and the negative electrode, as one would expect.

20. **ORDINARY ARC LAMP.**—In the ordinary type of arc lamp with two carbon electrodes the flame or arc and the negative electrode give very little light, 85 per cent. of the luminosity coming from the incandescent part of the positive pole. This is due to the fact that this pole becomes very hot, the temperature being near the melting-point of the carbon. Where the temperature is highest, a crater is formed, which is the maximum light producer. Its light is white with a slight bluish tint, and from this point of view it is best for distinguishing colours, as it approaches the colour of daylight. Even the latter has a bluish tint where there is reflected sky-light.

On account of the high temperature of the positive electrode, a rapid consumption takes place by combustion which is about twice as high as that of the negative carbon. This combustion may be reduced by enclosing the arc in an air-tight glass globe, with just enough ventilation to keep an equilibrium of pressure. The arc must now be supplied with a higher pressure (75 volts against 45), the length of the arc is greater, and as the temperature of the positive electrode is now less, no crater is being formed and consequently the quantity of light emitted is less. The colour of the light is bluer than before, since a greater portion is obtained from the arc itself, and it is the latter that chiefly supplies the blue part of the spectrum.*

21. **MERCURY VAPOUR LAMP.**—Amongst continuous conduction lamps must be mentioned the mercury vapour lamp. It consists of an exhausted glass tube, with a positive metal electrode—iron or mercury—and a negative electrode of mercury. On tilting the lamp, so as to bring the mercury in contact with the positive electrode by a thread of mercury, the circuit is closed, and mercury vapour is produced which afterwards keeps the current flowing when the lamp has been tilted back. The voltage required depends on the length of the tube. With a tube 120 centimetres long and $2\frac{1}{2}$ in diameter, a P.D. of about 120 volts is required. The lamp then uses about 3 amperes. The resistance of the lamp consists of three parts: (1) the resistance of the anode, (2) the resistance of the vapour, (3) the resistance of the cathode.

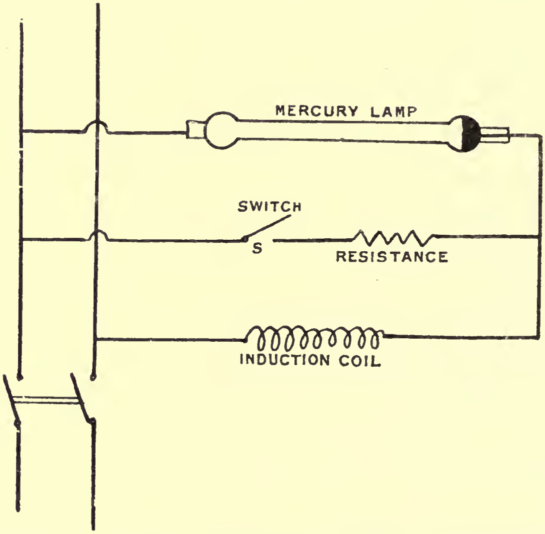

Fig. 2·03.—Connections for a Self-starting Mercury Vapour Lamp.

The resistance of the anode is inversely proportional to the current, so that the drop across it is practically constant for all currents, being about 8 volts. The same holds for the cathode, as long as the current is not too small, the drop of potential being about 5 volts. The resistance of the vapour is proportional to the length of the tube, but decreases with an increase in the diameter, although not exactly inversely. The decrease is rapid if the current is small and the diameter is small. It also decreases with an increase in the current, and more rapidly when the current and diameter are small and the vapour pressure high. The latter

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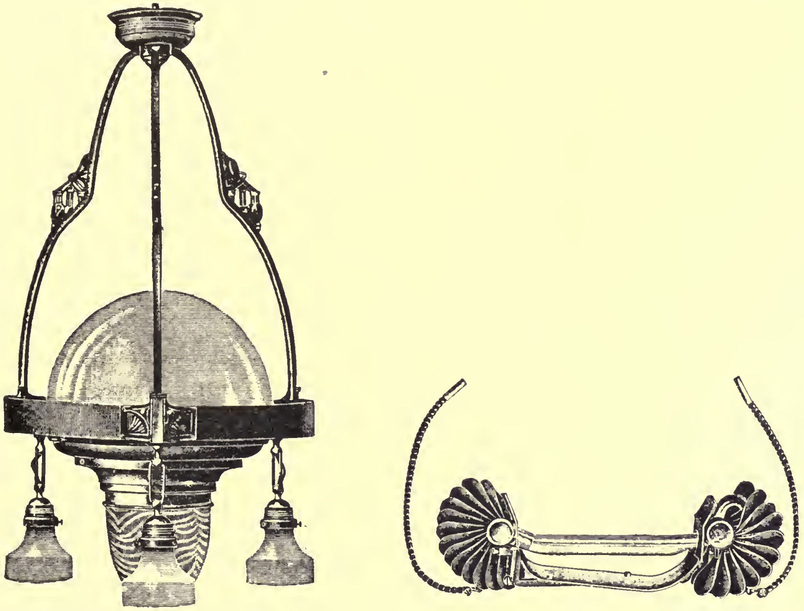
* For further information see Chapter IV.

is usually one millimetre of mercury, as it has been found that for this pressure the light-giving efficiency is a maximum. The consumption of the lamp is about 0·8 watt per candle (M.S.C.P.).

The connections for a mercury vapour lamp are shown in fig. 2·03. In this case tilting is not required. By closing the switch S the induction coil is charged, and discharged through the lamp when the switch is pulled out. The starting band, consisting of a narrow metallic strip round the glass near the cathode, facilitates the starting. As, on account of the heat produced, mercury is always evaporating, the positive pole is constructed as a condensing chamber, *i.e.* it is made large enough so as to present a large cooling surface, in order to keep the gas pressure constant.



Quartz Lamp for Inverted Light. Burner for Quartz Lamp.

Fig. 2·04.—Kuch's Quartz Lamp.

The great disadvantage of the mercury vapour lamp lies in the peculiar colour of the light, since it contains practically no red rays. Various endeavours have been made to remedy this—for instance, by including other metals in the mercury; it has, however, been found that the element which is added collects on one of the poles, and the mixed spectrum at the beginning soon makes room again for the pure mercury one.

If mercury vapour lamps are joined to high voltages, the heat produced is enormous and the glass vessels are no longer suitable. Quartz is in this case employed. The tube can then be made much shorter, and intensities of 2000 to 3000 candles (M.S.C.P.) are reached with tubes less than 10 centimetres long. The terminals must now be specially constructed, with long radiators, to conduct away the heat generated. Küch's quartz lamp is illustrated in fig. 2·04.* The efficiency of such a lamp is almost as high as that of a flame arc lamp. Against the ultra-violet rays of such lamps protecting globes are essential, as quartz is transparent to them.

Whereas the temperature of the glass vapour lamp is very low so that one can touch the tube, that of the quartz lamp is extremely high. Up to 60 volts the temperature has been found to rise proportionally with the voltage, so that—since for 60 volts the temperature is already 1700 degrees C.—for 200 to 250 volts it will probably reach 5000 to 6000 degrees C.—*i.e.* the temperature of the sun. The pressure inside the tube is about that of the atmosphere, at which the specific consumption of the lamp, including steadying resistance, is about 0·35 watt per candle. The variation of this consumption is illustrated in fig. 2·05, from which it will be seen that the consumption can be still further reduced by increasing the current consumption—*i.e.* by raising the voltage. For lighting purposes, however, it is not advisable to increase the pressure inside the tube beyond that of the atmosphere, to prevent the mercury vapour, which is poisonous, from leaking out. The light of the quartz lamp is whiter than that of the glass lamp, but still largely deficient in red rays. On account of the smallness of the quartz tube, the tilting can easily be accomplished automatically.

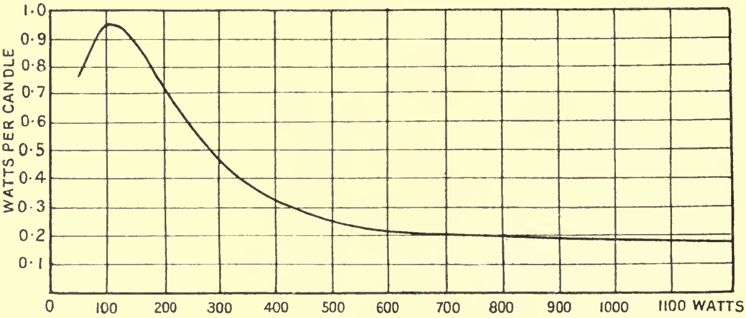


FIG. 2·05.—Specific Consumption of a Quartz Mercury Vapour Lamp.

22. **INTERMITTENT OR DISRUPTIVE CONDUCTION.**—In the Geissler tube the gas enclosed carries the current whereby it becomes luminous. Hence the spectrum depends on the nature of the gas, and has nothing to do with the electrodes, as long as these do not melt.

For intermittent conduction, it is necessary that a certain potential difference should be applied before *any* conduction takes place. We call this the "disruptive voltage."

23. **MOORE TUBE.**—The resistance of such a circuit is thus a variable quantity, being infinite for low voltages and low for voltages above the disruptive potential difference. This resistance, or rather impedance,

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* See *E.T.Z.*, 1907, p. 932.

varies with the temperature and pressure of the gas, so that for a constant terminal potential difference the current will vary inversely proportionally to it. This makes it necessary to provide mechanisms which tend to keep the circuit in equilibrium. In the Moore Tube lighting system, the efficiency is a maximum when the pressure of the gas enclosed is about 0·11 millimetre mercury. On the passage of the current through the gas (which is usually nitrogen) part of the latter is used up, whereby the impedance of the circuit is reduced, its value becoming a minimum when the pressure is about 0·08 millimetre. The flow of the current would then be a maximum. This increase in the vacuum is due to a solidification of the enclosed gas. A special valve must thus be supplied, which automatically feeds the tube with nitrogen when the pressure has dropped from 0·11 to 0·01 millimetres.

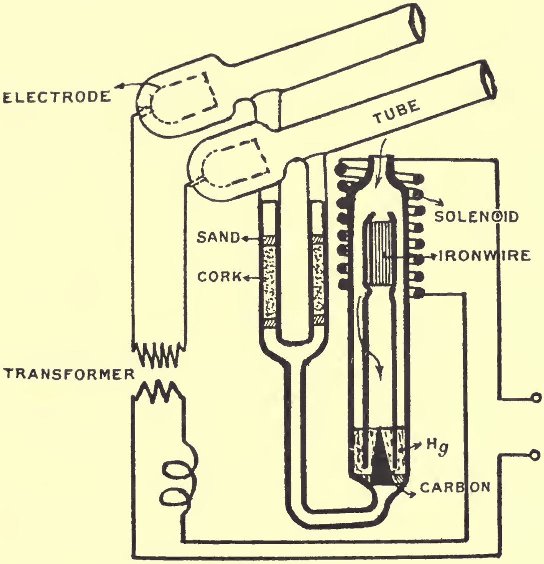

Fig. 2·06.—Moore's Tube Lighting.

The system is illustrated in fig. 2·06.

The valve consists of a porous carbon plug, placed at the bottom of the glass tube (in communication with the main tube, into which dips a hollow glass plunger, which forces the mercury up to cover the plug and closes up the entrance to the vacuous tube). The inner glass tube carries a number of iron wires, and as the whole valve is surrounded by a solenoid in series with the primary of the transformer which supplies the tube with current, it follows that the position of the plunger depends upon the load on the transformer. As the load increases with a decrease in the vacuum, the plunger is drawn further into the solenoid, and as this causes the mercury to drop, part of the porous plug is exposed and gas or air can filter through the plug into the vacuous tube. Where nitrogen is the gas wanted, it is only necessary to place the valve in an air-tight box with a few holes, before which phosphorus is placed. The latter absorbs the oxygen of the air, and an unlimited supply of nitrogen becomes available. The colour of the light depends on the gas enclosed; it is a golden colour for pure nitrogen, orange-pink for ordinary air, and a whitish-blue when fed with carbon dioxide. With a variation of the pressure of the enclosed gas not only does the rate of the flow of the current change but also the visible part of the radiation, as one would naturally expect; hence the flow of current must be so regulated that the visible radiation becomes a maximum. Also, the potential difference depends on the gas pressure, to which it is approximately proportional.*

Temperature has also some influence on the disruptive voltage, lowering the same, when it is high.

The P.D. required for a Moore tube is approximately represented by the following table:—

TABLE IV.—P.DS. REQUIRED FOR MOORE TUBE LIGHTING SYSTEMS.

Length in metres . .	7·5	15	22·5	30	45	60
R.M.S. Volts . .	2100	4000	5500	7000	9500	12,000

The light of the Moore tube is well diffused on account of the great length of tube, especially as the diameter is also considerable, being about 4·5 centimetres. It flickers however in unison with the feeding alternating current, unless the frequency is higher than 50 cycles per second.†

The consumption is about 2 watts per candle; the system is therefore less economical than lighting with tungsten lamps.

Voltage variations have little influence on the candle-power, since the latter is practically directly proportional to the voltage, whereas the candle-power of even a tungsten lamp varies as the fourth power of the supply pressure.

24. **MANUFACTURE OF INCANDESCENT LAMPS.**—The carbon filament is made from amorphous cellulose, which is dissolved in sulphuric acid, washed during the next four to six weeks to remove the acid, and squirted through dies. The thread is then wound on a perforated drum and slowly dried. It is next cut to the required length and wound on rods of carbon or porcelain. A number of these rods are then embedded in charcoal, within crucibles; the latter are placed in furnaces, the temperature of which is raised to 300 or 500 degrees C., this temperature being maintained for ten hours, and then to 2500 degrees C., lasting six hours. This process is called *carbonising*. The filament is now hard and homogeneous, but requires uniformity in thickness. This is obtained by flashing—a process in which the filament is placed in an atmosphere of

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* See *Transformers*, p. 128, by Bohle and Robertson (Chas. Griffin & Co.).

† See Chapter V.

hydrocarbon gas, such as coal gas, or benzine, and heated to incandescence by the electric current. The thinner and consequently hotter parts of the filament receive a greater share of the carbon deposit from the gas than others, and uniformity in thickness results. The latter is usually shown by the automatic opening of a switch in the circuit of the lamp.

Carbon has a negative temperature coefficient, from which it follows that the candle-power of such a lamp varies greatly on a variable supply pressure. The filament may, however, be metallised by firing it in an electric furnace after squirting, at a temperature of over 3000 degrees C. before and after the flashing process. In this way a coating is produced which, although it consists of carbon, possesses the qualities of metals, *i.e.* it has a positive temperature coefficient. Its resistance is also lower than that of ordinary carbon. The specific current consumption for commercial working is about 2·5 watts per candle.

After flashing the filament, it is placed in a bulb which is exhausted, first with a powerful air pump and completely with mercury pumps. The final flashing occurs in the bulb. To remove all traces of oxygen, a solution of red phosphorus in alcohol is forced from an orifice in a revolving vertical tube into the sealing tubes, which are placed over it in turn. On heating the bulb with a burner, the phosphorus evaporates, combines with the remaining oxygen, and is deposited in a transparent state inside the bulb. Connections to the filament through the glass are made by means of platinum wires, which have the same expansion coefficient as glass.

25. **TANTALUM FILAMENT.**—The tantalum filament consists of drawn tantalum, obtained originally as a black powder, which is reduced to the metallic form in the electric furnace with the exclusion of air. In this state it is sufficiently ductile to be drawn into thin wires. Its specific resistance is about 12 microhms per cubic centimetre at ordinary temperature, and more than five times this value at proper incandescence. The thickness of the filament for a 25-candle lamp is about 0·05 millimetre, and it requires a length of about 6 millimetres per volt.

26. **THE TUNGSTEN LAMP** is made by different processes, that of the Osram lamp being as follows: Paste of finely divided tungsten with gums of dextrine is squirted through diamond jets under very high pressure. The resulting thread is heated with the exclusion of air, by means of the electric current, which causes the filament to sinter. This sintering is carried out in gases which attack the binding material, so that finally pure metal is left.

The diameter of the jet is 0·055 millimetre, that of the resulting thread 0·05. This shrinks after sintering to 0·03 millimetre. The amount of shrinking depends upon the quantity of the binding material. It is usually 84 per cent. in volume and 65 per cent. in length.

The filament is elastic, but brittle; it can be bent round rods one centimetre in diameter, and after bending it returns to its old form. It is fastened to the leading-in wires by melting the ends of the latter to globules to surround the filament. This is accomplished with the electric arc.

The exhausting of the globe takes longer than that of the carbon filament, as more gas is occluded.

27. **JUST-WOLFRAM LAMP.**—The manufacture of the Just-Wolfram lamp is somewhat different. A thin carbon filament of 0·02 to 0·06 millimetre in diameter is placed in an atmosphere of volatile tungsten compounds and hydrogen. The compounds are chlorides and oxychlorides of tungsten. The filament is then heated by the electric current, causing tungsten to be deposited on it and the compounds to be reduced by the hydrogen. To reduce the filament to pure tungsten, it is placed in hydrogen gas, having a pressure of about 20 millimetres mercury, and heated by means of the current to a white incandescence. The carbon then combines with the tungsten to form a carbide, and the change is so complete that the filament is left tubular, without a trace of carbon being detectable. The filament is next placed in an atmosphere of hydrogen with a little steam and raised to a high temperature, which causes the carbon to oxidise so that tungsten alone remains. The filament is fixed to the leading-in wires by a paste consisting of finely divided tungsten and coal tar or gum. These paste mounts are dried and made red-hot before the filament is placed into the bulb.

Drawn tungsten filaments are now also produced, similarly to tantalum lamps.*

28. **PHYSIOLOGICAL EFFECTS OF LIGHT.**—It is surprising that up to the last few years the physiological effects of light have been so little considered by engineers, architects, and the public in general. When buildings, such as schools, halls for entertainments, libraries, etc., are planned, very great care is taken as regards the architectural features, and little with the lighting. Small windows, and usually in the wrong place, bring the daylight illumination down to a minimum, and the appearance of a slightly foggy day makes the use of artificial illumination necessary. Yet there is no reason why a maximum amount of light should not enter a room. The eye is so constructed that it can fully protect itself against any amount of well-diffused light, such as daylight; *i.e.*, it can pass from a room with an illumination of 100 candle-metres into the sunshine where it is many hundred thousands. There is therefore no reason for installing insufficient light, and the statements that artificial illumination should not exceed 70 to 80 candle-metres is absurd. "Glare," however, should be avoided.

29. **GLARE.**—An exact definition of glare is difficult. Some people define it as the intrinsic brilliancy which, when it exceeds a certain value—a value which somewhat depends on the individual—causes dazzling and pain to the eyes. But this definition is not sufficient. If we look at the filament of an incandescent electric lamp in the evening, we experience a

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* See Appendix.

dazzling sensation; if we look at it during the day, especially in the open, the glare is absent. As a matter of fact, a bright lamp in the sunshine is hardly noticeable. And yet the light is there all the same. Again, if we place a light in front of a white screen, even at night, little of a glare is experienced when looking at it, but when studied before a black board, the glare appears strongly. We see that contrast plays an important part in what constitutes glare, which may be explained as follows:—

When looking at a lamp in front of a white screen which makes the illumination appear high, or when studying the lamp in the road on a sunny day, the nerves of the eye are less sensitive, and as the pupil has contracted, the sensation is small; whereas in looking at a light in front of a black board the pupil extends to take in the dark background, and as the illumination is small, the nerves of vision are rested and therefore more sensitive. Glare occurs thus only when a rested or sensitive eye experiences simultaneously a high intrinsic brilliancy and sharp contrasts.

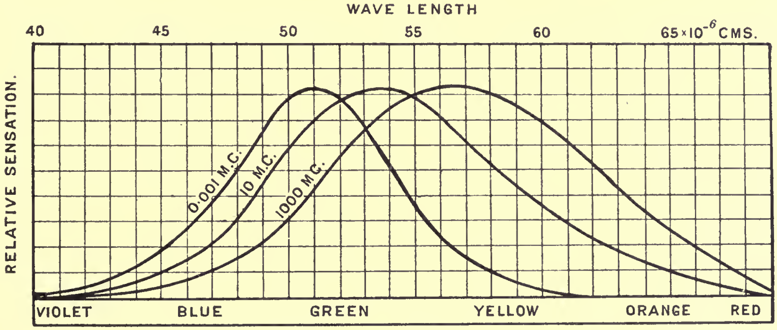

Fig. 2·07.—Sensation of Light.

30. **WAVE-LENGTH AND FREQUENCY.**—The sensitivity of the eye depends also upon the nature of the light, *i.e.* upon the wave-length and frequency. It begins with the red, then gradually increases, becoming a maximum between the yellow and green (see fig. 2·07).

The sensation depends however somewhat on the intensity. Its peak moves towards the red for high intensities and towards the blue for low ones. These curves will also explain why it is impossible to compare, with the ordinary equality photometer, lights of different colours, especially if they differ largely in intensity. For high intensities the sensitivity is highest for yellow light; in the case of low ones, for the green. But even if we produce on the two sides of a photometer screen equal illuminations, it will be obvious that it is impossible to compare a yellow light with a greenish blue one—for instance, an incandescent carbon lamp with the mercury vapour lamp—since for the former the sensitivity of the eye is higher, *i.e.* the sensation on the eye is greater with less candle-power for yellow light than with blue light. The application of the Flicker photometer, however, overcomes this difficulty (see notes on Flicker photometer);

or we can compare the lights by finding out the distances at which given colourless letters (black on white or *vice versa*), arranged out of order, can be read equally well by the two lights. This method of comparing lights is not used, because the distances differ so much for individuals. From the curves we see also that as for high intensities the sensation is a maximum for yellow light, for low intensities it is a maximum for greenish blue light. Both lights when of equal intensities will look differently bright when viewed from different distances. Thus the mercury vapour lamp will appear much brighter from a great distance and less bright than the carbon lamp when studied close by. For search-lights, etc., we should therefore install lights of a greenish blue colour, if it were not for the fact that they penetrate the fog less effectively than yellow lights.

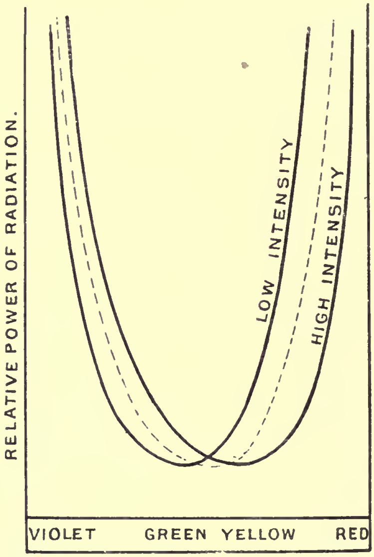

Fig. 2·08.—Power required for Radiations of Different Frequencies.

We have seen that the average sensitivity of the eye is greater for the yellow-green part of the spectrum than for the red and the violet. It follows, therefore, that for a given sensation the maximum power is required for red and blue-violet radiations, as is approximately illustrated in fig. 2·08.

As the light enters the eye, its power is changed, mostly into heat. If the rate of conversion becomes too great, the heating becomes excessive and the eyes give pain. Continued "overheating" causes inflammation. If the time of overheating seems short, a few hours will see full recovery. Temporary blindness is also due to excess power absorption. Looking at the curve it will be obvious that for red and violet light the absorption of power for a given sensation will be much greater than for yellow-green lights; consequently the danger of overheating is also greater. Yellow-green lights are therefore preferable, especially where the intensities are great. At the same time, less harm is done by red radiation than by violet and ultra-violet. The latter is invisible, yet the radiations may be there all the same and the invisibility makes it all the more difficult to guard against such rays. The harm done by ultra-violet rays is greater than that due to red and ultra-red radiations, on account of the greater frequency and shorter wave-lengths. As long as the wave-length is great, the eye, or rather its constituent particles, are able to respond to, or resonate with, the impressed motions; but when the frequency becomes too high, as is the case with the ultra-violet rays, a response is no longer possible, and dissociation results. It is therefore absolutely essential that lights which produce largely ultra-violet rays, such as open arcs of all kinds, discharging across spark gaps, should be studied with protecting glasses.

Ordinary clear glass gives sufficient protection in some cases, as it is opaque to ultra-violet rays of higher frequencies. These rays can be completely shut off by special glasses of a yellowish tint, or by proper globes, and it is advisable to do this where direct light has to be employed.

The metal filament incandescent lamp, which produces ultra-violet rays, is not to be employed in positions where direct rays are liable to enter the eye.

The harm done by ultra-violet rays is effective and lasting. The author remembers taking in 1905 a number of students over the Vickers-Maxim Works at Sheffield, where they were shown electric welding. Unfortunately, there were only two pairs of protecting glasses available, and as the author, who was interested in the mechanism of the machine, studied it without protection for several minutes, he received an overdose of ultra-violet rays. About twelve o'clock the following night he awoke with a maddening pain at the back of the eyes, which lasted for about an hour, and for weeks afterwards he had difficulty in keeping anything properly in focus. Even now, seven years after, he feels the effects, especially after testing arc lamps. In any case his eyes have been greatly weakened, and the least loss of tone in the system shows itself by blurred vision. Had he worn ordinary glasses, the evil effects would not have been so pronounced, or they would have been temporary only.

Overheating is experienced instantaneously, and it is cured quickly. The harm done by ultra-violet rays is noticed ten to twenty hours afterwards, but it is lasting. It is therefore essential that for open arcs the necessary protection should be applied, that glasses should be used which prevent ultra-violet rays from entering the eyes above or below them. Once eyes are weakened by such radiation, they become very sensitive to it, and the least dose causes headaches. This is also experienced in brilliant sunshine, especially in places where a large quantity of light is reflected. White sand and snow reflect a large part of ultra-violet radiations contained in sunlight, so that it is advisable to wear protecting glasses.

No ill-effects are caused by radiations above the blue, to which the organs of the eye can respond; but light which contains blue and violet radiations only cannot be tolerated for any length of time. The most sensitive part of the eye, the yellow spot, does not respond to them (it is blue-blind), and as a result these radiations are seen by the surrounding parts of the retina only, and when the latter endeavours to focus them on the yellow spot, the light disappears altogether. A greatly irritating effect is the result.

Different eyes show different degrees of sensitiveness to ultra-violet rays. If we place an arc lamp at the back of a screen consisting of a fine silver deposit on glass, no visible light will pass through, but for ultra-violet light the screen is transparent. Most people will therefore be unable to see the light at the back of the screen, whereas other persons are able to do so. This is especially the case with persons who have been subjected to an operation for cataract, involving the removal of the crystalline lens of the eye. The inability of ordinary people to see ultra-violet light may therefore be partly due to the fact that the crystalline lens absorbs it.

The lens very often changes its colour during life, and this gradual coloration seems to afford protection, since little children appear to be more susceptible to ultra-violet light than older people.

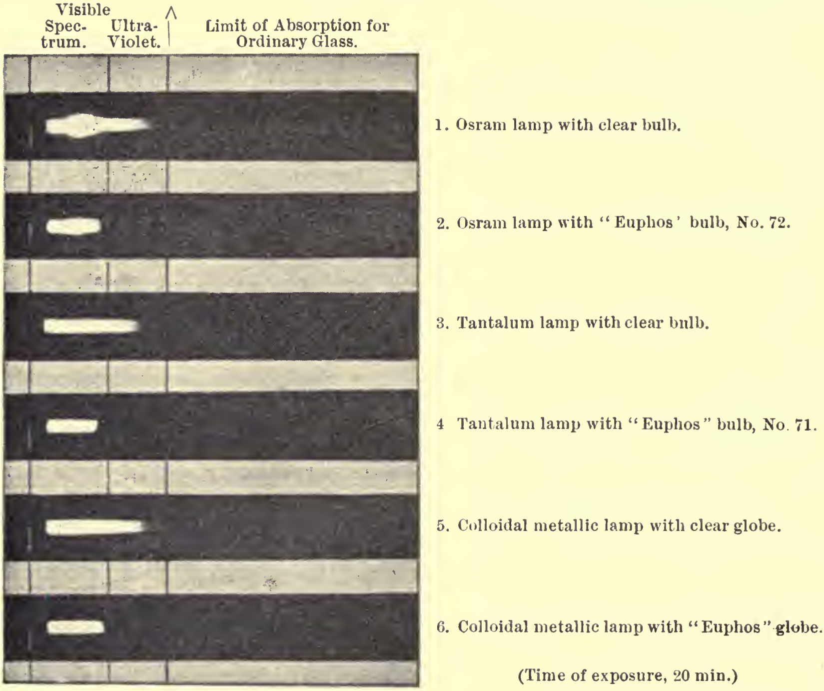

Fig. 2·09.—Effect of "Euphos" Glass on Ultra-Violet Light.

Doctors Schanz and Stockhausen have invented a glass, which they call "Euphos." It consists of a mixture of red and green glass, giving a yellowish tint, which cuts off the ultra-violet light completely, as is clearly marked in the accompanying fig. 2·09.* They also claim that this glass does not absorb more than 2 to 3 per cent. of the visible light.

The reason why daylight is so much less harmful than artificial radiation is to be found in the fact that daylight is luminescent, or selectively radiant, so that the amount of power which enters the eye, even in sun-

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* See *Illuminating Engineer*, vol. i., 1908, p. 772.

shine, is comparatively small; moreover, the light is perfectly diffused. In artificial light however the percentage of visible radiation is small, and as it is caused by temperature or black-body radiation, the amount of power that enters the eye is large.

At the extreme end of the ultra-violet light follow the X-rays, which are consequently of a very high frequency. The effect of X-rays is the same as that of ultra-violet rays, but in a greater degree. Excessive application will cause dissociation of the part treated, on account of the particles of the body being unable to respond to the rapid motions of the impinging rays. Care must therefore be taken when applying such light frequently.

Ultra-violet light is however not entirely useless; it may be employed as a germ-killer. Many pathological bacteria live in the dark, and light destroys them. The ultra-violet rays are the most effective as germicides.

Ultra-violet rays may even be employed for the purification of water, and their use in this direction is already applied on a commercial basis. The rays are produced by means of a mercury vapour lamp, enclosed in a vessel consisting of quartz. The water is so conducted that it passes at least three sides of the quartz lamp, and tests have shown that bacteria are completely destroyed in this way. The water should however be previously clarified in order to prevent an absorption of the ultra-violet rays.

The reader who wishes further information on the physiological effects of light should read the highly interesting article by Prof. Einthoven and Dr W. A. Jolly in the *Quarterly Journal of Experimental Physiology*, 1908, vol. i. No. 4, entitled: "The Form and Magnitude of the Electrical Response of the Eye to Stimulation by Light at Various Intensities"; also Dr Jolly's article on the "Electrical Response of the Frog's Eyeball to Light," in the same Journal, 1909, vol. ii. No. 4.

CHAPTER III.

PHOTOMETRIC APPARATUS.

31. **PHOTOMETERS.**—Photometers are usually classed as follows:—

(1) Intensity photometers, employed for comparing the candle-power of two sources of light.

(2) Spectro-photometers, in which selected rays from the spectra of two sources are compared as regards their luminous intensity.

(3) Illumination photometers, for measuring the illumination of streets, squares, halls, rooms, etc.

We shall confine ourselves to considering classes 1 and 3.

32. **INTENSITY PHOTOMETERS.**—There is a very large variety of this class of photometer on the market. Only a few representative types shall be discussed here.

33. **THE BUNSEN GREASE-SPOT PHOTOMETER.**—This is based on the equalisation of the illumination all over a screen, the greater part of which is opaque and the rest transparent. The transparent part, made so with grease (oil or paraffin wax), allows more light to pass than the rest of the screen, so that if a light be placed, say, on the left, the opaque part which reflects all the light will appear bright, the grease-spot darker. Viewed from the right-hand side, the grease-spot appears light, the rest of the screen dark. Suppose now we place here another light, then the distance of the screen from the two sources of light may be so adjusted that the grease-spot disappears on one side.

Next we adjust until it disappears now on the other side and take the mean of the two readings.

We then have

$$\frac{I_1}{I_2}=\frac{L_1^2}{L_2^2}$$

If I_2 be the standard lamp, the candle-power of the test lamp is given by

$$I_1=I_2\frac{L_1^2}{L_2^2}=I_2\frac{L_1^2}{(L-L_1)^2} \quad . \quad . \quad . \quad . \quad 3{\cdot}01$$

in which L_1 and L_2 are the corresponding distances, and L their sum.

The accuracy to be expected lies within ± 3 per cent. This is due to the fact that the grease-spot is not perfectly transparent. Even the above accuracy can be expected only by the employment of mirrors, as shown in fig. 3·01, in order to be able to view both sides of the screen simultaneously. Moreover, the screen should be rotatable through 180 degrees, so as to neutralise any difference in the nature of the two illuminated surfaces. The distances L_1 and L_2 must not be too small, as equations 1·02 and 1·07 hold for point sources only. Again, we should not look too long at the screen, as it tires the eyes and does not increase the accuracy. It is preferable rather to make a larger number of observations rapidly.

The difference in the nature of the two sides of the grease-spot screen may be determined as follows:—Place the screen in the middle of the bench, and on the back of it a light. The direct rays of the latter are kept off the grease-spot screen by means of an opaque disc. On the right and on the left from the grease-spot disc and at equal distances place two mirrors, cut from the same piece, which reflect the light on the photometer screen. If both sides of the latter are equal in nature, they will appear equally well illuminated; if not, the screen must be moved through a length L^1 one way or the other, until equality is obtained. If L be the distance between the mirrors, L_0 that of the light from the axis of the photometer, then, as may easily be proved, the measure of the inequality of the two sides of the screen, as regards whiteness, is given by

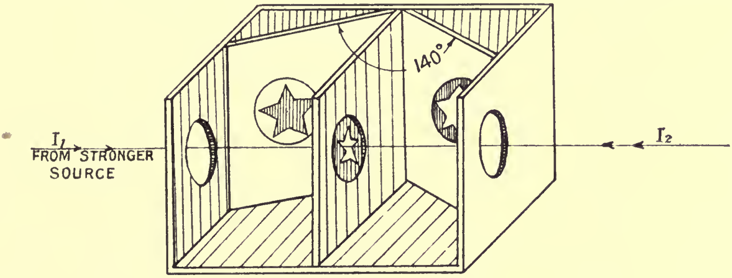

FIG. 3·01.—Bunsen Grease-Spot Photometer.

$$\frac{4L^1}{L+\frac{LL_0}{L^2}}$$

When L_0 is small this changes into $\frac{4L^1}{L}$ (nearly).

34. **RITCHIE'S WEDGE PHOTOMETER.**—This instrument is shown in fig. 3·02. Two adjacent sides of a white prism (pressed magnesia or plaster of Paris), inclined at equal angles to the incident rays, serve as the two illuminated surfaces which are to be compared. When both are equally bright, the edge disappears. Care must be taken that the latter is not blunted, as this would compel the eye to travel from a bright surface

over a less illuminated part to another bright area, whereby the accuracy is impaired.

For accurate tests it is essential that both surfaces of the wedge should be equally inclined. The best angle is about 70 degrees. If the angle is smaller, the surfaces are brighter, but less is seen of them; whereas if the angle is greater, the illumination decreases too much.

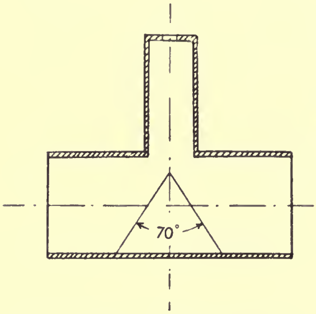

Fig. 3·02.—Ritchie's Wedge Photometer.

35. **LUMMER-BRODHUN PHOTOMETER.**—This is a superior kind of grease-spot photometer, the "grease-spot" of which is perfectly transparent. A diagrammatic sketch of this type is shown in fig. 3·03, a photograph in fig. 3·04.

A white magnesia slab S is illuminated on both sides by the lights to be compared (fig. 3·03). By means of two totally reflecting prisms, A and B, the diffused light is sent through a compound prism C D, which takes the place of the grease-spot in the Bunsen photometer. This compound prism consists of two right-angled prisms, placed base to base. One of the prisms has parts of its hypotenuse surface taken off by sand-blasting, so as to be at a lower level than the rest. The hypotenuses of the two prisms are then put together, being faced to come into optical contact where they touch. When such a prism is viewed by means of a telescope and an eye-piece in the proper position, we see the field of view divided into two parts, one of which is illuminated by the diffused light scattered from one side of the magnesia slab, and the other part by light scattered from the other side of the screen. By adjusting the distances of the lights, the brightness of the two parts of the field of view may be equalised. The accuracy

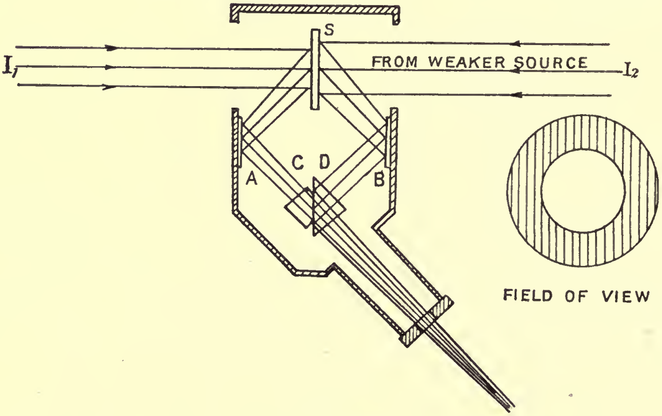

Fig. 3·03.—Arrangement of the Lummer-Brodhun Photometer.

obtainable with this type of photometer when comparing lights of similar colour lies within 1·0 per cent.

The accuracy may be further increased by employing the contrast type of photometer. In this, the hypotenuse of one part of the compound prism is shaped as shown in fig. 3·05, the lower levels being obtained with sand-blasting. The raised parts allow all the light to pass, the lower parts reflect all, as shown. The observer consequently sees the recessed parts illuminated from the right, the raised parts from the left of the screen.

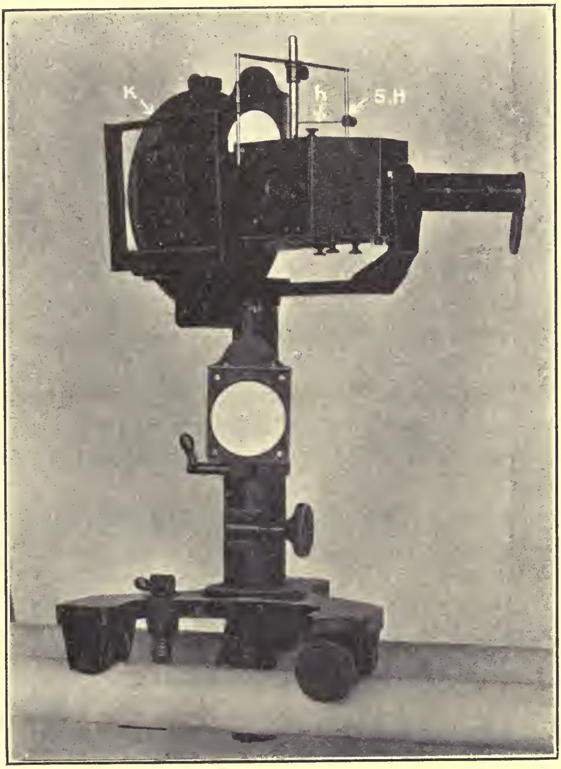

Fig. 3·04.—Lummer-Brodhun Photometer.

In order that the fields R and L may come into contrast, glass plates G_1 and G_2 are so arranged that the fields R_2 and L_2 remain uninfluenced, whereas R_1 and L_1 are somewhat darkened.

The distance of the screen from the two sources of light has been adjusted properly when the fields R_1 and L_1 stand out equally prominently from the slightly brighter background.

The photometer shown in fig. 3·04 is suitable for comparing lights under different angles, by the application of a divided circle K. In order to be able to test whether the angles of incidence of the rays from the two sources are the same, a shadow-thrower S H is employed. A steel rod is screwed into the lid of the frame and carries by means of two vertical rods the horizontal rods *h*. The magnesia slab is replaced by a white carton disc, provided with black lines (it is placed at the foot of the photometer). By a simultaneous adjustment of the rods by means of the sleeve and by turning of the photometer, the shadows of the two rods may be made to fall on the horizontal black lines of the carton. The paper disc is afterwards again replaced by the magnesia slab, and the comparison takes place as before.

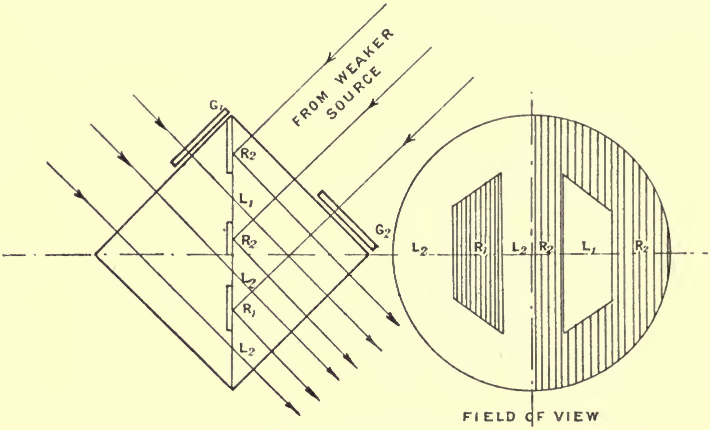

FIG. 3·05.—Contrast Type of Lummer-Brodhun Photometer.

36. **FLEMING'S TOTAL REFLECTION PHOTOMETER.**—This is a modification of the Lummer-Brodhun type, in which the two lights I_1 and I_2 to be compared are placed one in front and one at the side of the prism box (see fig. 3·06).

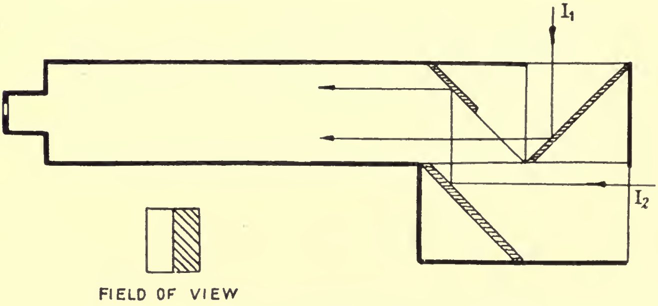

FIG. 3·06.—Fleming's Total Reflection Photometer.

37. **TROTTER'S PHOTOMETER.**—This apparatus is illustrated in fig. 3·07 and is based on the equalising of the illumination of two white surfaces inclined at equal angles (35 degrees). One screen has a hole or holes in it through which the observer looks at the other screen. The

material of the screens is white cardboard. If one hole only is used in the nearer screen, it is best to have it star-shaped, with the star distorted so that when seen at an angle it appears symmetrical. The edges must be carefully bevelled. The screens are equally illuminated when the holes apparently vanish.

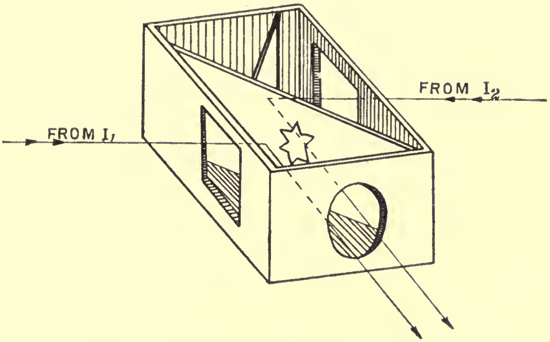

Fig. 3·07.—Trotter's Intensity Photometer.

38. **POLARISATION PHOTOMETERS.**—These instruments are based on the equalisation of two fields of light by weakening one of them by means of crossed polarising prisms. The theoretical range of such an instrument is infinite.

A ray of ordinary white light, either from the sun or from an artificial source, when passed through a crystal of Iceland spar is separated into two rays of practically equal intensities. These are called the ordinary and extra-ordinary rays. Let the two rays be received on the surface of a plate of glass held at a fairly high obliquity to the ray so as to reflect it through an angle greater than a right angle. It will be found that for most positions of the reflecting plate two rays on emerging will differ in intensity. Thus we see that the two doubly refracted rays have sides, and it is this sideness, or laterality, which is known as polarisation.

In unpolarised light the vibrations take place in all possible planes containing the ray, the sole condition being that they are perpendicular to it. When the light is passed through the doubly refracting crystal, every vibration is decomposed into two components at right angles to each other, the exact directions of which depend upon the position of the Iceland spar. The complete separation of the two is usually effected by means of a Nicol prism, which is a suitable length of Iceland spar cut along the long diagonal and joined together again by a thin layer of Canada balsam. The refractive index of the latter for any light is between the refractive indices of the Iceland spar for the ordinary and extraordinary rays. It is therefore possible to get rid of what is known as the ordinary ray by total reflection while the extra-ordinary ray passes on practically unaffected. The Nicol prism allows only one ray to pass; but this ray is polarised in a certain plane. To the ordinary untrained eye this ray does not differ from common unpolarised light. To prove that the light transmitted by the Nicol is in this peculiar condition, we take a second Nicol and view the light through it. When the two Nicols are placed so as to have the similar crystalline faces parallel to one another, the second Nicol will transmit the light which has passed through the first Nicol; but if the second Nicol is rotated through a right angle about the ray as axis, it will completely cut off the light. We may suppose the first Nicol to transmit light made up of vertical vibrations. The two together, being what is called crossed, cut the light off entirely. If either is rotated now, light will begin to appear.

The first Nicol is called the polariser, the second one the analyser, because by it the polarised condition of the ray after it has passed through the polariser is recognised.

39. **DR MARTENS' POLARISATION PHOTOMETER.***—The construction of this instrument will be seen from figs. 3·08 and 3·09. The

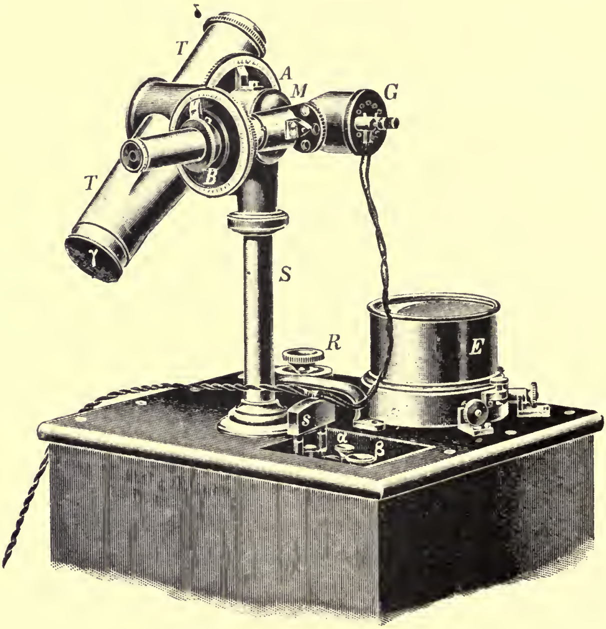

Fig. 3·08.—Martens' Polarisation Photometer (Elevation).

column S carries at its upper end a sleeve M which supports the lampholder G for the comparison glow lamp *g*, and the polarisation photometer; also the rotatable tube T, the inclination of which is read from a divided circle A. The light from the source to be compared strikes the magnesia slab F, which scatters it on the reflecting prisms P and Q. It then passes

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* *Verh. d. D. Phys. Ges.*, vol. v.

through the blend and the lens to the doubly refracting prism W on the polarising Nicol 2, and then through the analysing prism N, lenses L and H, into the eye of the observer. The light from the comparison lamp takes a similar course, except that it is polarised in the Nicol 1. Equality of the fields of view is obtained by rotating the Nicol prism N—its position with regard to the polarising prism being shown on the divided circle B—until the surfaces 1 and 2 appear equally illuminated, *i.e.* when the edge between them apparently disappears. The intensity of the source of light to be tested is then given by $I = CL^2 \tan^2 \theta$, where L is the distance of the light from the slab F, θ the angle read on the divided circle B, and C a constant of the instrument. The latter is found as follows:—

We place a standard lamp (say a 10 c.p. pentane lamp) instead of the light to be compared at a distance L_1 from the slab F, then

$$C = \frac{10}{L_1^2 \tan^2 \theta_1},$$

where θ_1 is the angle now read on the circle B. As we have two angles θ_1, we get also two constants.

We see that it is not necessary to know the candle-power of the comparison lamp as long as this candle-power is constant, *i.e.* of the same value when the instrument is calibrated and when used for comparing sources of light.

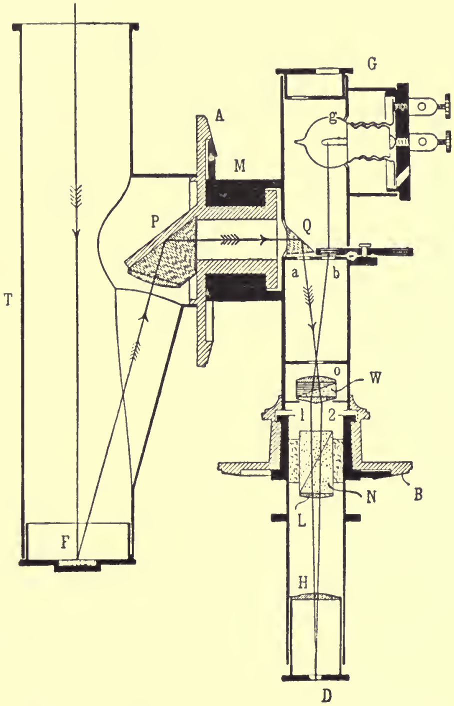

FIG. 3·09.—Martens' Polarisation Photometer (Sectional View).

The above equations are easily proved when the fact is taken into consideration that the light which emerges from a pair of crossed Nicol prisms is proportional to the square of the cosine of the angles between the principal planes of the prisms and that the vibration of the light from the comparison glow lamp is at right angles to that from the source to be compared.

40. **PHOTOMETERS FOR LIGHTS OF DIFFERENT COLOURS.**—In order to understand the difficulty connected with the photometry of lights of different colours it will be necessary to consider the following points in addition to what has already been stated in Chapter II.

We have seen that photometrical methods of testing illuminants should be carried out in such a manner as to compare the brightness of two illuminated surfaces. This is easy when both lights have the same colour; but when this is not the case, it will often be found that different persons obtain results differing often by many per cent. This might be partly due to the different distances employed by the various observers between the eye and the photometer screen. The central portion of the retina, the macula lutea or "yellow spot" is less sensitive to the green end of the spectrum than the surrounding part. If therefore we alter the distance between the eye and the screen, different portions of the retina are affected and the photometer may appear out of balance. This is especially the case when the screen is badly illuminated. The brighter the illumination the greater will be the accuracy obtained. In no case should the illumination be less than one candle-foot. This is, of course, easily obtained when dealing with laboratory measurements, but not in the case of testing street illumination, where the illumination is much less in nearly all cases.

Suppose further we have two similar pieces of red and green paper and illuminate them with white light. As long as the illumination is strong the red one appears the brighter of the two. When however the illumination is reduced gradually the papers finally change places with regard to apparent brightness. This is called the "Purkinje effect," by which is meant that with increasing light the luminous sensation produced by the red end of the spectrum increases more rapidly than that which would be produced by the green part (see also fig. 2·07). In the above experiment, the surfaces should be placed at a great obliquity to the eye, for, if the angle is small, the Purkinje effect does not take place.

Von Kries explains these phenomena as follows:—

The light-perceiving organs of the retina consist of rods and cones, of which only the latter perceive the colours. The cones are also most sensitive to yellow light and, while they do not respond to very much illumination, once they have commenced to act with increasing stimulus they keep on doing so long after the rods have ceased to do so.

The rods are unable to perceive colour and all light appears to them white. They are sensitive to weak light, to which the cones do not respond at all, but when the stimulus is further and further increased the rods become saturated and respond no further.

When light is fairly strong we see by means of the cones, and hence we have a colour sensation. Very weak light is seen through the rods and the colour disappears, everything looking grey.

From the photometric standpoint it is of importance to find out when the struggle between the rods and cones begins. As the extreme central portion of the retina contains practically only cones, then, if the image of the illuminated surfaces falls within this region, the Purkinje effect is absent. But when the angle between the eye of the illuminated surfaces is great, and the cone region is largely affected, the Purkinje effect is pronounced.

In properly constructed photometers the angle is usually small and the Purkinje effect is of little importance as long as the illumination does not drop below one candle-metre.*

It should be pointed out here that this theory of light and colour perception is not fully indorsed by all experts. Dr F. W. Edridge Green † suggests that the struggle between the rods and cones can be explained by the distribution of visual purple over the retina, and that the rods are merely concerned in the distribution of visual purple. Light falling on the eye causes the visual purple to retreat from the rods and spread over the other parts. The chemical change causes a corresponding sensation stimulus, which depends in quality and quantity on the nature of the light causing it, and this stimulus is communicated to and analysed in a special centre of the brain. Hence, according to this theory, it is in the brain and not in the eye where the sensations of light and of colour are analysed. The divergency in opinion shows that further investigations are needed.

41. **FLICKER PHOTOMETER.**—Various endeavours have been made to produce instruments for the comparison of lights in which the erratic behaviour of the rods and cones is more or less counterbalanced. An instrument of this nature, which has given satisfactory results, was invented by Professor Rood. It is based on the phenomenon that when two surfaces illuminated by lights of different colours are presented alternately to the eye, the latter requires a longer time to be influenced by a colour sensation than by one of brightness. Consequently, when the two surfaces are equally illuminated and rapidly presented to the eye in turn, the surfaces appear stationary and to be of a common tint.

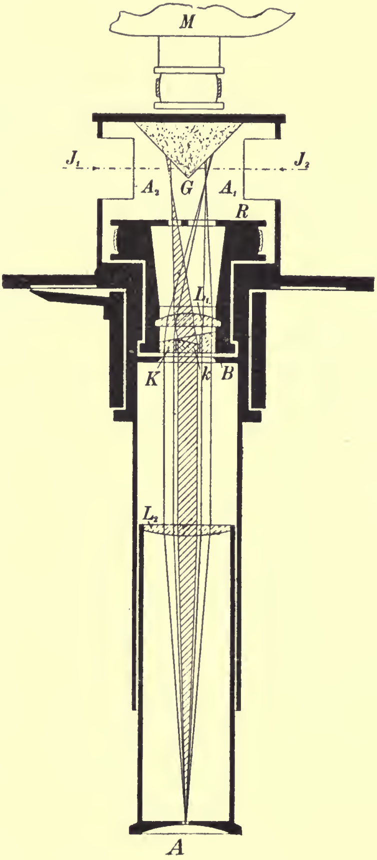

Fig. 3·10.—Flicker Photometer (Sectional View).

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* See J. S. Dow, *Illuminating Engineer*, 1908, p. 153.

† *Ibid.*, 1909, pp. 210, 741, 802.

Experience shows that a Flicker photometer gives more consistent results than any other type when comparing lights of different colours. But even in this case it will be found that different observers obtain different results.

Figs. 3·10 and 3·11 show a so-called "Flicker photometer," in which Professor Rood's discovery is applied.

G is a Ritchie wedge within the focal length of the lens L_1, A the eye-piece within the focal distance of lens L_2. Between the lenses L_1 and L_2 is placed a glass combination prism K *k*, consisting of two concentric parts with angles of similar refraction. The prisms K *k* are rigidly joined together, but with their slopes in opposite directions. They and the lens L_1 are rotated by a motor M. The speed of the latter is regulated by means of a resistance in the motor circuit Transmission takes place by two small belts.

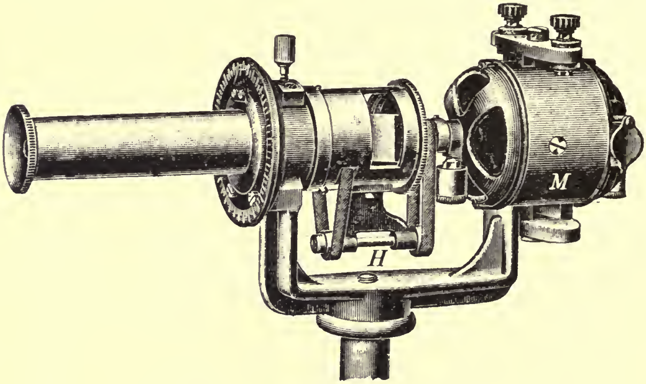
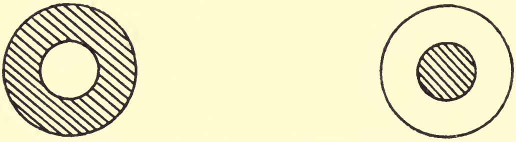


Fig. 3·11.—Flicker Photometer (Elevation).



Figs. 3·12 and 3·13.—Fields as seen in a Flicker Photometer.

By the introduction of the double prism K *k* two diametrically lying fields A_1 and A_2 are observed by A on the prism G. With a continual but slow rotation—assuming at present lights of the same tint—the field of view looks alternately like figs. 3·12 and 3·13, as long as the illuminations are equal.

When now the speed is increased a flickering is observed, which is increased by the fact that the maxima and minima appear alternately in the ring and at the centre. A proper adjustment has been obtained when the flickering disappears, or has become a minimum.

If lights of different tints are to be compared, we adjust the speed and position of the photometer until the field of view appears of an identical tint and the flickering has become a minimum.

The actual speed of the photometer depends largely upon the colour of the lights compared. If both are of the same tint, the range is large and easily determined, and the speed may be comparatively low. When the tints differ considerably, the range is greatly reduced, but a little practice will soon tell how far the speed has to be increased. Different observers usually obtain slightly different results.

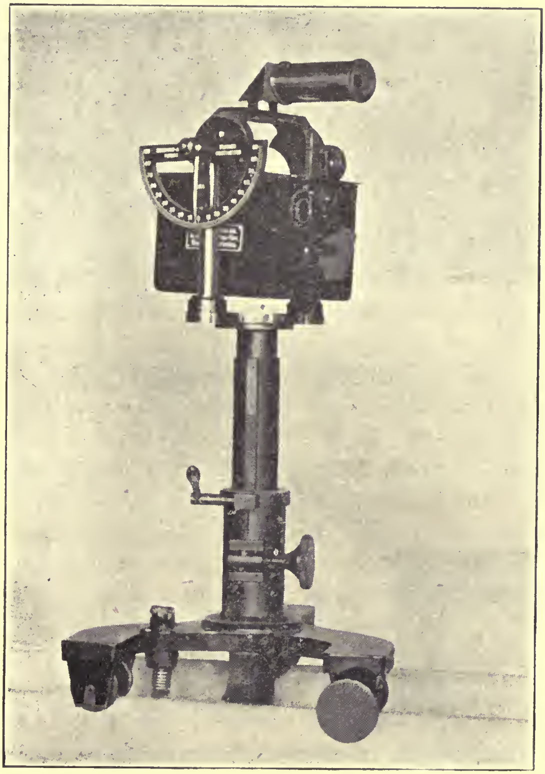


Fig. 3·14.—Simmance-Abady Flicker Photometer (General Appearance).

Another Flicker photometer, largely used in Great Britain, is the Simmance-Abady type, made by Messrs Alex. Wright & Co., London, and illustrated in figs. 3·14 and 3·15.

It consists essentially of a diffusing rotating disc viewed edgewise. The alternate diffusing surfaces of this screen cause a flicker which moves from side to side until the illuminations are balanced. The disc or screen is shown separately in fig. 3·15. The instrument can be placed at any angle, and is therefore suitable for the determination of polar curves for arc lamps.

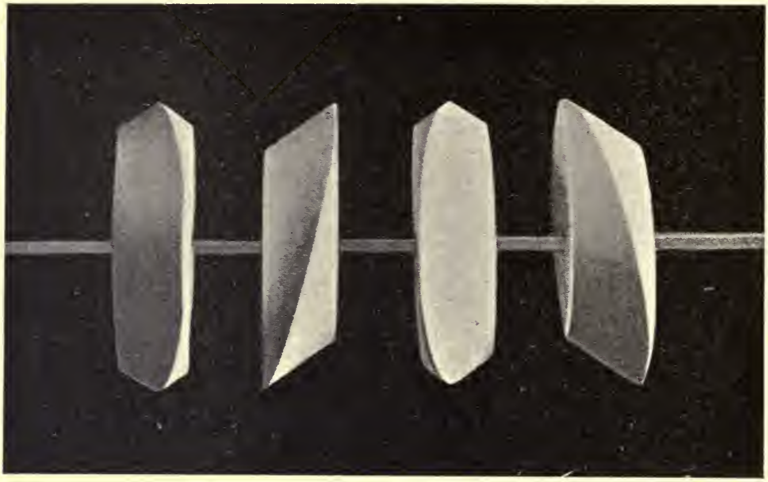


Fig. 3·15.—Sighting Wheels of Simmance-Abady Flicker Photometer.

42. **VON CZUDNOCHOWSKI'S PHOTOMETER.***—A somewhat different type of photometer for the comparison of light of different colours is suggested by Mr W. B. von Czudnochowski in the *Illuminating Engineer* of April, 1908, p. 283. His instrument is based on the following principle:—

Fig. 3·16.—Shadows caused by a Grating.

When the image of a solid object is projected on a semi-transparent screen, it appears sharply defined as long as the direction of vision is perpendicular to the screen, but it becomes indistinct when viewed obliquely, in consequence of the semi-transparency of the screen. Suppose now that we have a grating composed of parallel wires crossing under 45 degrees, those sloping to the right being illuminated from one light, those to the left by a second light; then the two shadows are formed on the screen and the points of intersection, being illuminated by neither source, appear much darker than the rest, as shown in fig. 3·16. Let further the direction of the rays coming from the left-hand light coincide with the direction of vision of the right eye, and *vice versa*, then an image formed by the left-hand source appears sharp to the right eye, and conversely, an image formed by the right-hand source appears distinct to the left eye. This gives

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* See *Illuminating Engineer*, 1908, p. 283.

rise to a stereoscopic effect, and one observes a system of apparently free black points, against a background caused by a grating. Certain conditions must however be fulfilled.

Let in fig. 3·17 A A represent two wires in the grating, L the diagonal distance between two such wires, B B be the transparent screen, L_1 the distance between the screen and the grating, θ the angle of incidence, I_1 and I_2 the two sources of light, then

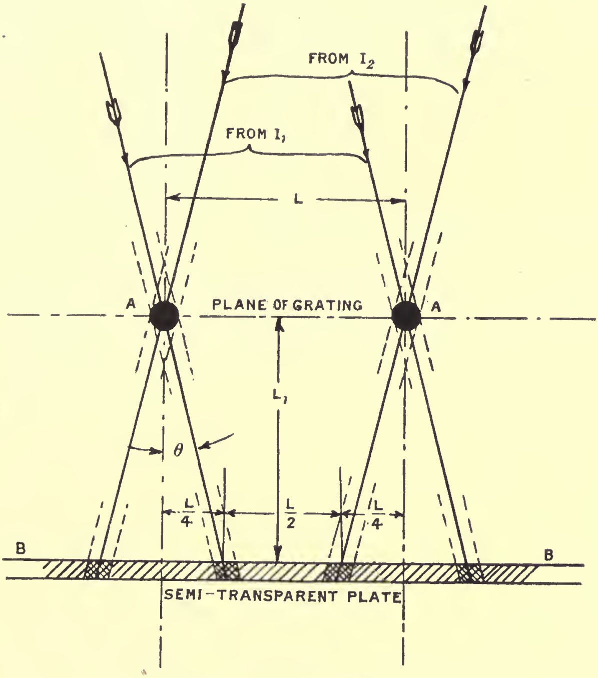

FIG. 3·17.—Principle of Czudnochowski's Photometer.

$$\tan\theta = \frac{L}{4L_1}.$$

The distance of the grating from the eye must be the smallest of distinct vision, about 250 millimetres (10 inches). Let this distance be called L_2, then

$$\tan\theta = \frac{\text{half the distance between the eyes}}{L_2},$$

$$= \frac{L_E}{2L_2}.$$

Combining these two equations, we get

$$L = L_1 \frac{2L_E}{L_2}.$$

For a normal pair of eyes $L_E = 65$ millimetres, so that for $L_1 = 10$ millimetres, $L = 5{\cdot}2$ millimetres.

We have seen before that when the illumination drops below a certain value the colour effect disappears and everything looks a ghostly grey. With a photometer built on the above principle, a colourless field is obtained without employing a low order of illumination, by using two shadow patterns, which will appear grey on a white background with black intersections. If now one of the sources is moved sensibly out of balance, one of the patterns becomes coloured.

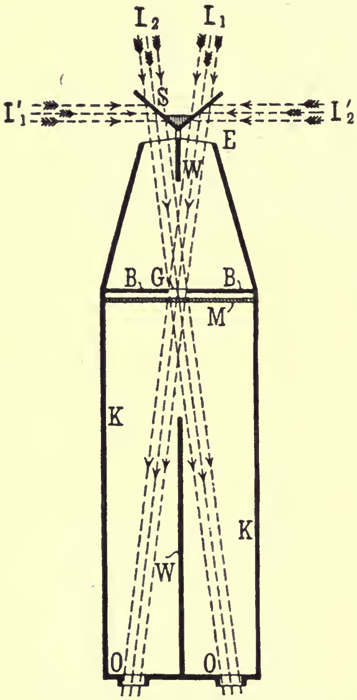

Fig. 3·18.—General Arrangement of Czudnochowski's Photometer.

The general arrangement of the photometer is shown in fig. 3·18, in which I_1 and I_2 are the two sources to be compared, B B the diaphragm with the grating G, M the transparent screen, W W screens to divide the black box K K into two sections, and S a mirror for directing the light.

The grating is best stamped out of sheet metal, wire gauze being unsuitable, since by the crossing of the wires the grating becomes too thick.

It will be obvious that, as the balancing of the photometer consists in equalising the contrast of the "shadows" against a white background, colour plays no part in the accuracy of the adjustment.

43. **ILLUMINATION PHOTOMETERS.**—These are employed to measure the illumination given by lights in regions such as rooms, halls, streets, etc., irrespective of the distance of the source away from this region. Photometers for this purpose are obtained by slight modifications of the intensity instruments. They should be portable and consequently of light weight.

Illumination photometers may be divided into two classes: diffused reflection and diffused transmission photometers. In the former the light is diffused by a screen and then reflected by mirrors to the photometer; in the latter it is diffused by a piece of ground glass and then transmitted to the photometer.

44. **PROFESSOR WEBER'S PHOTOMETER.**—A photograph of this instrument is shown in fig. 3·19, and the optical arrangement in fig. 3·20. A standard benzine lamp *b* is arranged in a box at one end of a horizontal tube A. In this tube, and capable of sliding in it, is a translucent screen of opal or ground glass. The light from *b* is reflected by means of a Lummer-Brodhun prism *p* into an eye-piece O. At the top of the vertical tube B,

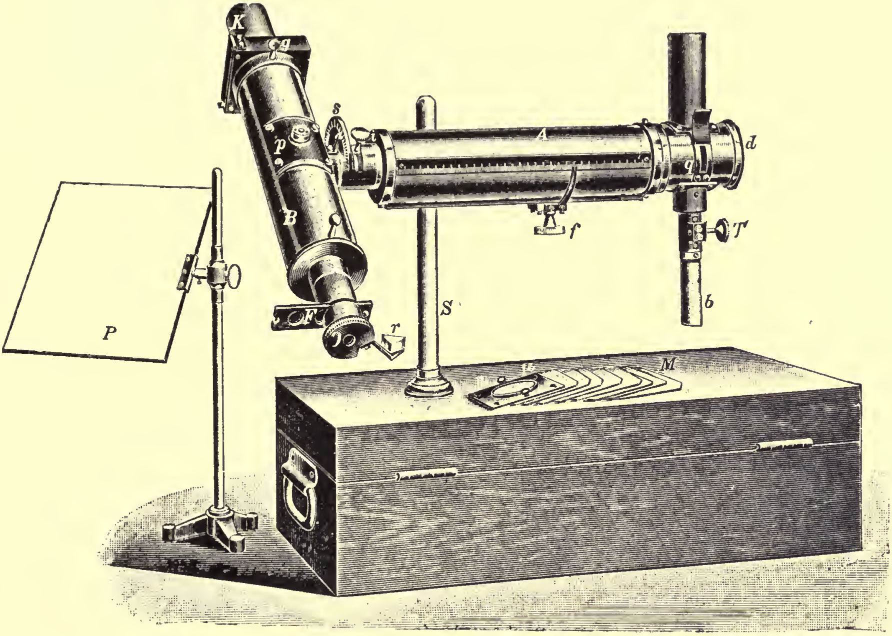

Fig. 3·19.—Weber's Illumination Photometer (Elevation).

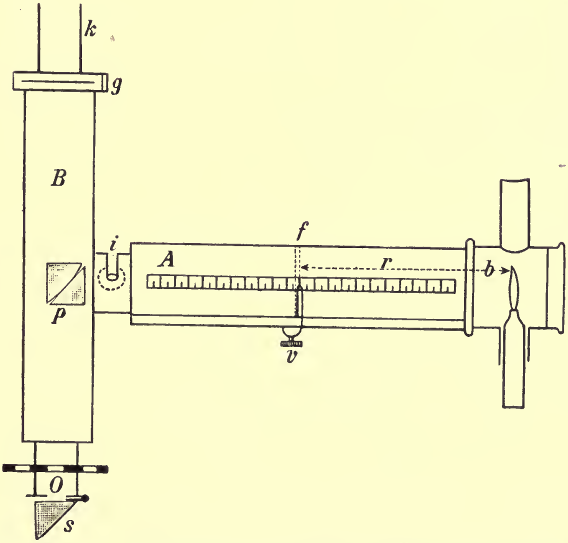

Fig. 3·20.—Weber's Illumination Photometer (Sectional View).

which can be placed at any angle, is another piece of translucent glass *g*, the light from which passes through the prism *p*. Both screens *f* and *g* are therefore viewed together. The distance *r* of the screen *f* from the comparison lamp *b* is shown on a millimetre divided scale. Equality of the field of view is obtained by altering the position of *f*.

The instrument may be used for intensity and illumination measurements. In the former case

$$I = C\,\frac{L^2}{r^2}\ \text{candles},$$

where L is the distance of the lamp to be compared from the glass plate *g*, and C a constant. The latter is found by means of a standard lamp, say a 10 c.p. pentane lamp, which gives

$$C = \frac{10 r_0{}^2}{L_0{}^2},$$

where r_0 and L_0 are now the distances indicated.

When using the apparatus as an illumination photometer, we place a white screen P at the desired angle in the region the illumination of which we desire to find, and direct the tube B towards the centre of this plate as perpendicularly as possible. The ground glass plate *g* is taken out, and the illumination—after equalising by moving *f*—is given by

$$E = \frac{C^1}{r_1{}^2},$$

where C^1 is another constant and is found again with a standard lamp.

Suppose we use a 10 c.p. pentane lamp placed at a distance of 2 metres from a white screen, the illumination of the latter is given by

$$E = \frac{10}{2^2} = 2{\cdot}5 \text{ lux}.$$

Suppose that with this illumination a balance be obtained with *f* at a distance of r_0 metres from *b*, then

$$C^1 = 2{\cdot}5 r_0{}^2.*$$

The distance of the screen P from the photometer does not figure in the calculation.

Instead of using a white screen P, the measurement may be accomplished by inserting frosted white glass plates μ at *g*, the illumination of which is found in an identical manner. The instrument then acts as a diffused transmission photometer. By placing the tube B at different angles, the illumination may be determined in any desired region and direction.

The instrument has also been employed for the comparison of lights of different colours by placing before the eye alternately red and green pieces

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* To be quite accurate, the screen should be spherical so that the rays fall perpendicularly upon it. The accuracy is however sufficient if the flat screen is placed at a considerable distance from the illuminant.

of glass, expressing the intensities in red and green candles. Such tests are however valueless, as no scientific meaning can be attached to the results.

The range of the Weber photometer is naturally small, on account of the short length of the tube A. It may however be increased by the application of Nicol prisms or opal glass discs of different degrees of transparency.

45. **TROTTER'S UNIVERSAL PHOTOMETER.***—A general view of the instrument is shown in fig. 3·21, and its optical arrangement in fig. 3·22.

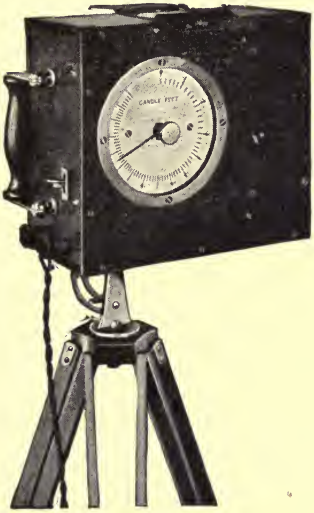

FIG. 3·21.—Trotter's Universal Photometer (Elevation).

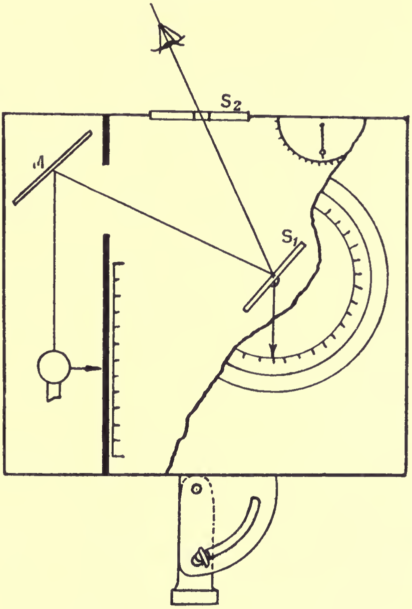

FIG. 3·22.—Trotter's Universal Photometer (Optical Arrangement).

The instrument is called universal, as it is claimed that illuminations and intensities can be accurately measured by it.

A small lamp (4 volts) throws a beam of light by means of a mirror M on the screen S_1. This is viewed through three small slits in the screen S_2, which receives the illumination to be measured. S_1 can be rotated about its axis by means of a cam, and the illumination thereby varied until a balance of brightness between S_1 and S_2 is obtained. Calibration takes place with a standard lamp, which produces a known illumination at a given distance. The scale of the photometer may be made direct reading.

For candle-power measurements the perforated screen S_2 is set directly

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* Manufactured by Everett, Edgcumbe, and Co. See also *Electrician*, 8th Nov. 1907, and the *Illuminating Engineer*, 1909, p. 799.

facing the lamp, and folding shutters or "blinkers" are provided to screen off other light. To set the screen in this position, the photometer is mounted on a tripod with a pivoted and hinged head, enabling the instrument to be turned in any direction and fixed at any angle. Since the screen faces the light, the direction of view must be other than perpendicular to it, and an angle of 20 degrees has been chosen.

The comparison lamp should be carefully aged and tested. It is fed from a 4-volt battery carried in a separate wooden case. Provision is made on the scale for a slight variation of voltage.

Screens S_1 and S_2 are interchangeable in order to test lamps of different tints.

The instrument is made suitable for colour photometry by the application of Crova's law. Crova found that if two lights, differing largely in colour, were each viewed through a yellow screen, whereby they are made practically monochromatic, the relative illumination remained unchanged.

The screen employed by Crova consisted of a solution of definite composition and thickness which only transmitted light of a certain wavelength. For practical purposes the method proved, however, unsuitable. In Trotter's photometer, the principle has been revived with success.

The weights and dimensions of the apparatus are as follows:—

Photometer:—1·8 kilograms (4 lbs.), 23 × 19 × 11 centimetres (9″ × 7½″ × 4¼″).

Battery:—2·27 kilograms (5 lbs.), 18 × 13 × 7½ centimetres (7″ × 5″ × 3″).

Stand:—0·7 kilogram (1½ lbs.), 48 × 4½ × 4 centimetres (19″ × 1¾″ × 1½″).

These figures show that the instrument is exceedingly portable.

46. **BRODHUN'S STREET PHOTOMETER.**—It is illustrated in fig. 3·23 and based upon the discovery that when a ray of light is obstructed by a rapidly rotating disc with a sectoral aperture, whereby the light is allowed to pass on at definite intervals, the intensity of the emerging ray is reduced in the ratio of $\frac{\theta}{360^\circ}$, where θ is the angle of the opening.

The comparison lamp at *g* illuminates an interchangeable frosted glass plate at *d*. A system of two lenses produces an enlarged field of this illumination on the compound Lummer-Brodhun prism W. The observer looks through the eye-piece *l* upon the separating surface of this prism and views there the rays from the two sources to be compared.

For the determination of the luminous intensity, the light is thrown on a magnesia slab S, here diffused and reflected as shown. Equality of the fields of view is obtained by reducing the light of the comparison lamp with a variable aperture disc. Two prisms *p p* are placed between *d* and W on a kind of drum which is rotated by means of a motor M and belt *c*. The rays between *p p* rotate, therefore, round the longitudinal axis of the apparatus and are screened off more or less by the variable aperture disc shown separately in fig. 3·24. The section consists of a fixed metal disc with two apertures of 90 degrees, which may be closed more or less by a second movable disc with an index.

The calibration of this apparatus takes place with a standard lamp.

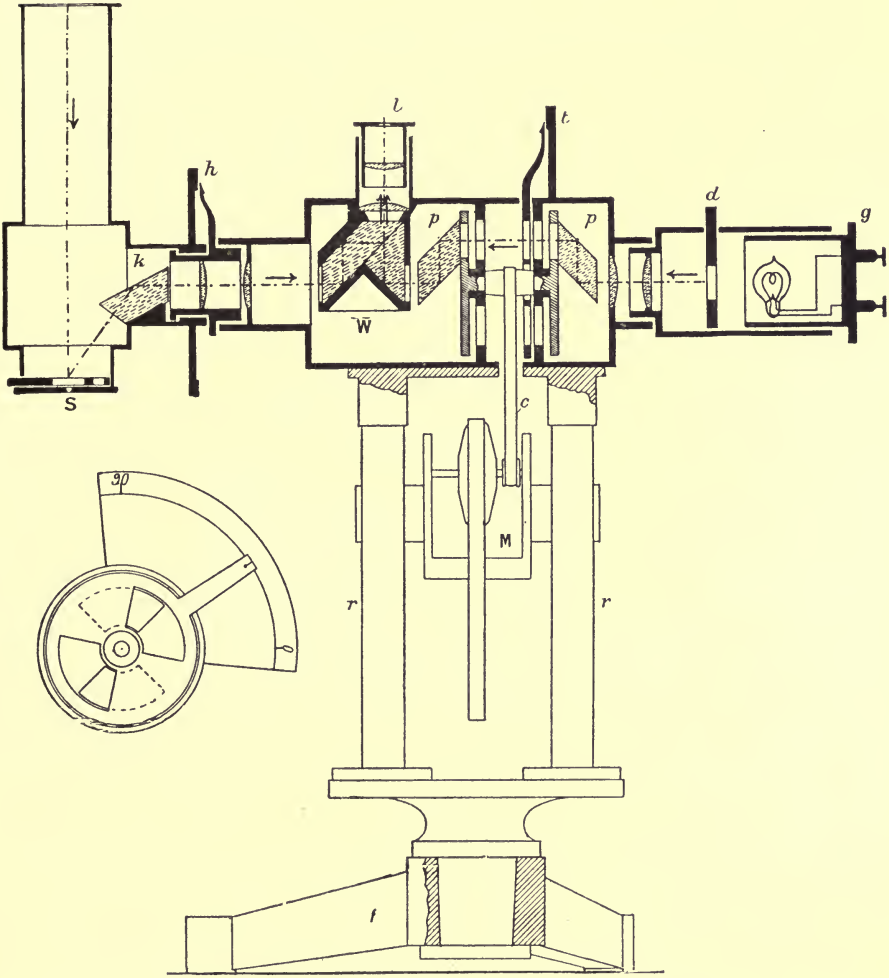

Fig. 3·23.—Brodhun's Street Photometer (Sectional View).

We have $I = C\theta L^2$, where L is the distance of the light to be tested from S, and

$$C = \frac{\text{candle-power of some standard}}{\theta_1 L_1^2},$$

θ_1 is the angle of the opening, and L_1 the distance when the standard lamp is used. When the instrument is to be used as an illumination photometer, the tube T is replaced by another tube, T_1, with a frosted glass plate, and S is replaced by a mirror to which the light is directed by a set of lenses fixed in T_1. The calibration takes place as before.

The glow lamp and the motor are fed from a six-cell portable secondary battery. This and the use of a motor make the apparatus more bulky than Weber's or Trotter's photometers.

47. **DR MARTENS' ILLUMINATION PHOTOMETER.**—This instrument is illustrated in figs. 3·24, 3·25, and 3·26, and is of a very handy and portable construction. The screen F is brought into the region of the illumination, which is to be found. The comparison lamp B (benzine) illuminates with the help of the reflecting mirrors S_1, S_2, and the prism *p* the frosted glass *m*. By moving S_1 and S_2, the illumination of *m* is altered.

The rays from F and *m* pass through the openings *a* and *b* respectively into the tube V, where they illuminate the surfaces 1 and 2 of the prism Z. Equality of the field of view is obtained by adjusting the position of the mirrors S_1 and S_2.

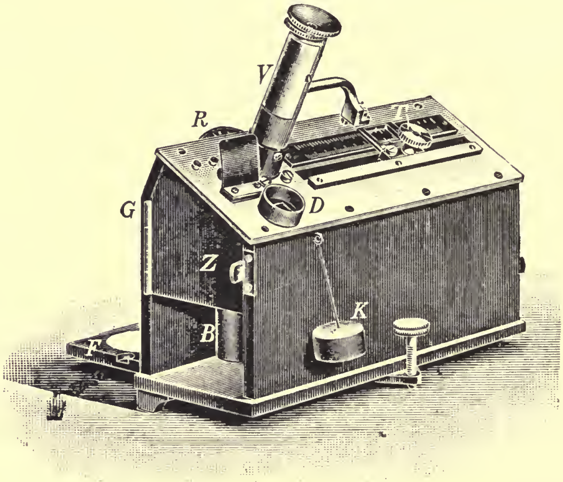

FIG. 3·24.—Martens' Illumination Photometer (Elevation).

A revolving disc R, with opal glasses *r* of different degrees of transparency, increases the range of the instrument.

The illumination E is given by the apparatus as

$$E = \frac{K}{r^2},$$

where *r* is the distance read on the scale of the instrument. On a second scale K, the illumination is read directly in lux. When inserting the revolving disc R with the constant K_3, the numbers read are correct; for K_4 the numbers must be multiplied by 10, for K_5 by 100, for K_2 by $\frac{1}{10}$, for K_1 by $\frac{1}{100}$.

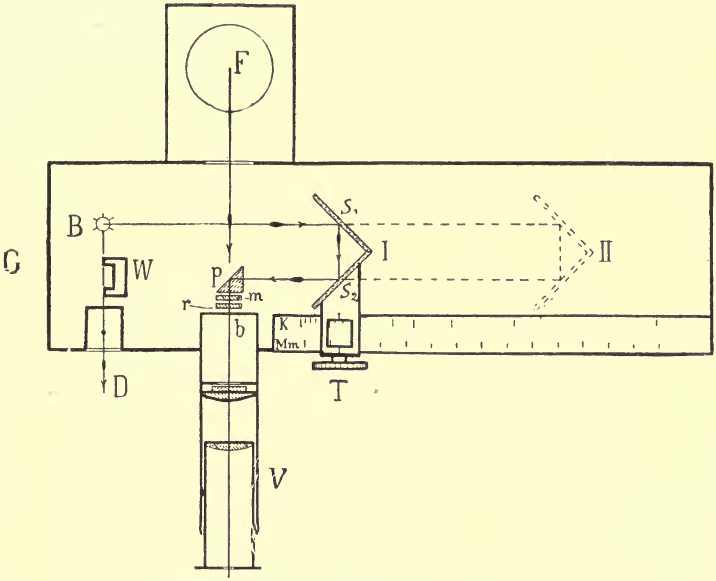

Fig. 3·25.—Martens' Illumination Photometer (Sectional View).

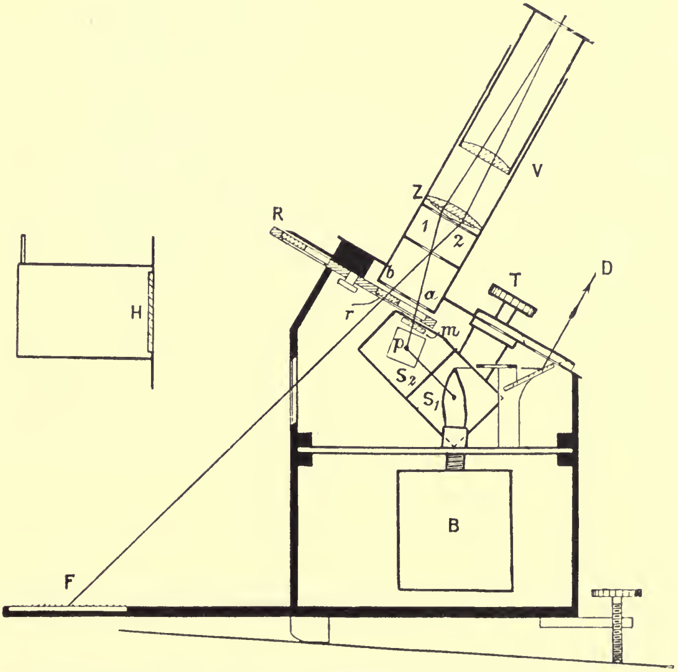

Fig. 3·26.—Martens' Illumination Photometer (Sectional Elevation).

48. **WINGEN'S PHOTOMETER.**—Another very handy illumination photometer due to Wingen is illustrated in fig. 3·27 and fig. 3·28. It consists of a box with a benzine lamp which illuminates a white screen S, the illumination of the latter being varied by altering the angle of inclination by means of a cam C. The height of the benzine flame is adjusted to a gauge line by turning up or down the wick as in an ordinary petrol lamp.

At the bottom of the box is placed a small sliding screen S_1, which receives the illumination to be tested. By means of an eye-piece at the top of the box both screens can be viewed together, and the cam is turned until the illuminations of S_1 and S appear equal.

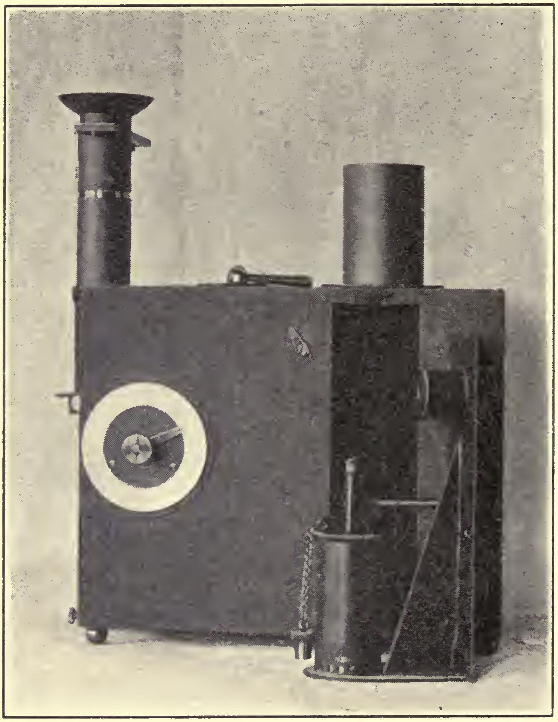

FIG. 3·27.—Wingen's Photometer (Elevation).

The instrument is calibrated in German lux, from 10 to 50 (about 1 to 5 candle-feet). By means of tinted glasses, inserted in the left-hand portion of the eye-piece tube, the range may be increased. The complete weight of the instruments is about 3 lbs., which makes it a very portable one.

The application of an eye-piece has, however, the disadvantage that the operator has to bring the head very close to the instrument, thereby often screening off part of the light for S_1. This is not so much the case with Trotter's photometer, in which the eye-piece has been discarded.

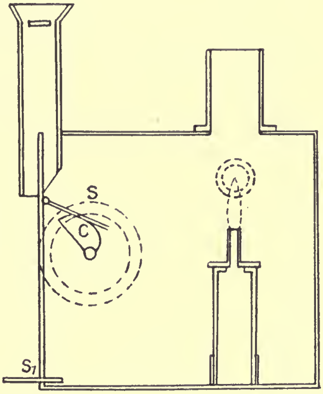

Fig. 3·28.—Wingen's Photometer (Optical Arrangement).

A very simple and for many purposes sufficiently accurate photometer, illustrated in fig. 3·29, consists of a rectangular box containing a 4- or 6-volt electric lamp illuminating the lid. The latter is made of thin metal provided with a narrow slot. This slot is covered with a sheet of drawing-paper, protected by thin glass, the illumination of which varies roughly as the cosine of the angle of the incident rays from the lamp, which is fixed near one end of the box. With a box 15 inches long a fairly large scale can be obtained.

The calibration takes place by placing a standard lamp at known distances away from the lamp.

The instrument has the advantage of simplicity and cheapness, is very portable, and may be read at considerable distance, so that there is no danger of screening off part of the light, as is frequently the case with photometers having eye-pieces. The weight of the instrument is about 2 lbs., to which must be added that of the 4-volt accumulator.*

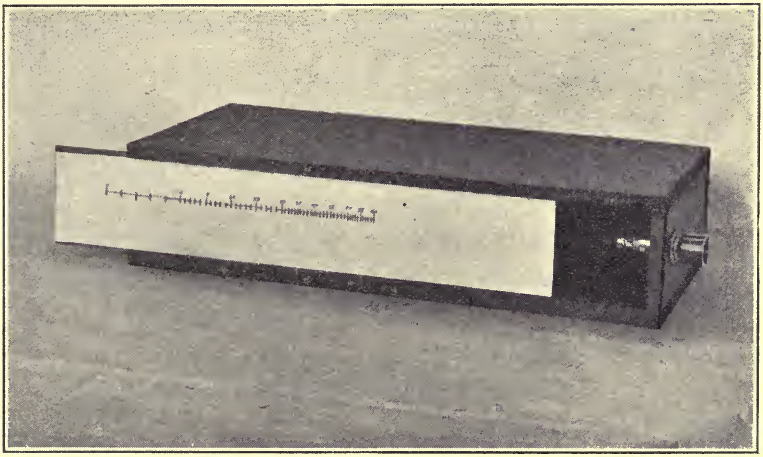

Fig. 3·29.—Illumination Photometer.

49. **PHYSICAL PHOTOMETER.**—It is beyond the scope of this volume to describe any but the most commonly used photometric apparatus.

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* A similar instrument was described by H. P. Harrison in *Illuminating Engineer*, 910, p. 373.

Mention however must be made of a selenium photometer which has been placed on the market. The use of the human eye is here abolished, and the lowering of the resistance of a selenium cell when subjected to rays of light (not heat) is applied. The principle of the photometer is at once seen from fig. 3·30. I_1 and I_2 are the lights to be compared, A and D reflecting mirrors, S_e a selenium cell, B a battery, and M a current-indicating instrument. The selenium cell is rapidly moved backwards and forwards so that it is alternately illuminated by I_1 and I_2. When both intensities are equal, the resistance of the battery circuit is stationary, but when this is not the case the pointer of the instrument M vibrates.

Commenting on the use of selenium for photometric purposes, it appears to the author that there can be a limited field only for this type of apparatus, viz., for the comparison of lights of absolutely identical colours. We have already seen that as far as the eye is concerned the brightness of surfaces, if illuminated by lights of different tints, does not increase proportionally to the square of the distance—a phenomenon first detected by Purkinje and explained above. The results obtained with a selenium photometer would therefore be altogether different from those found by the use of one's eyes, and, after all, the latter are the final judges. A further disadvantage of the use of selenium lies in the fact that the resistance is not immediately increased to its initial value when the cell is placed into darkness.

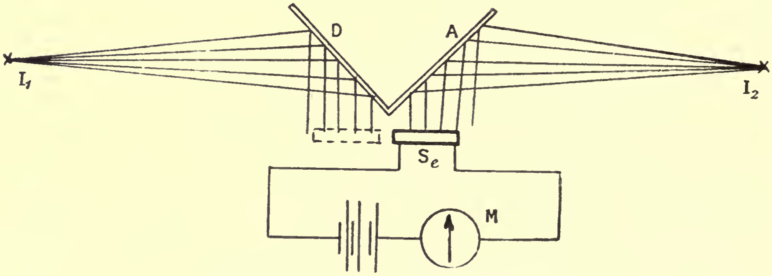

FIG. 3·30.—Selenium Cell Photometer.

50. PHOTOMETER ROOM AND AUXILIARY APPARATUS.—

Most photometric determinations should take place in a room especially reserved for such work. For outside measurements, self-contained illumination photometers, such as Weber's, Martens', Brodhun's, Trotter's, etc., are used.

A photometer room should not be too small. The space occupied by it should be not less than 50 cubic metres (1800 cubic feet) and preferably larger if possible, with a minimum length of 10 metres (32 feet). This is essential for the testing of arc lamps, since the bench must be of considerable length—at least twenty times the diameter of the globe—if the law of inverse squares is to be accurate. The ventilation of the room should be as thorough as possible, but draughts must be avoided. This is especially necessary when flame standards are used, the candle-power of which depends largely on the atmospheric conditions surrounding the lamp. The suitable size of a photometer room is 12 × 3 × 5 cubic metres (appr. 40 × 10 × 16 cubic feet).

Photometer rooms are usually painted a dead black; but this is not absolutely essential if only sufficient care is taken to prevent reflected light from reaching the photometer. A complete photometer bench for the testing of incandescent lamps is shown in fig. 3·31. Reflected light is kept from the photometer by means of aluminium screens covered with dead-black velvet. The direct light passes through holes in the screens. These holes may be fitted with dispersion lenses or smoked glasses when lights of exceedingly unequal intensities are to be compared. The carriage of the photometer is supplied with a small portable electric lamp in order to facilitate the reading of the scales. The error caused by the reflection

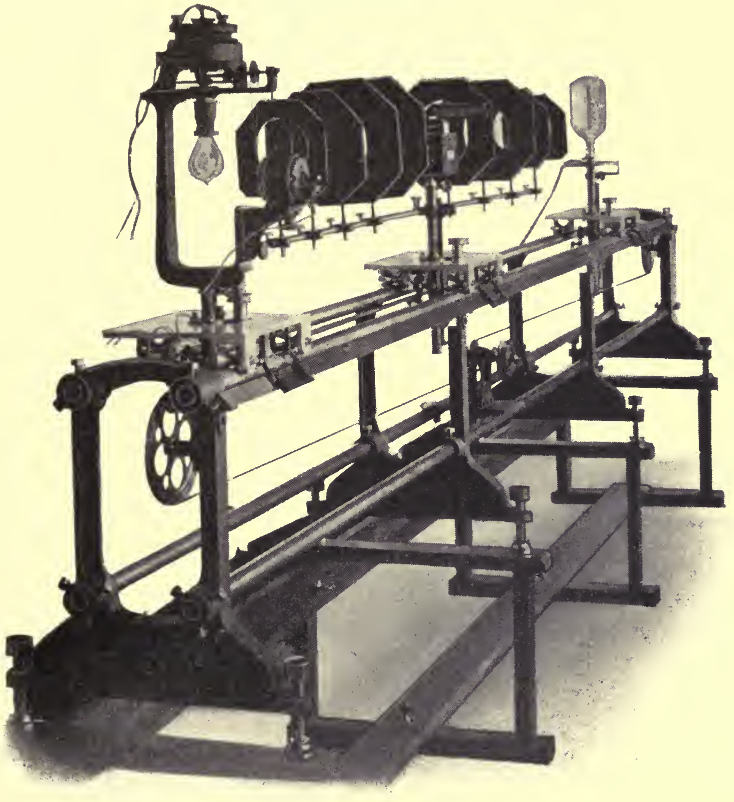

FIG. 3·31.—Standard Photometer Bench.*

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* As manufactured by Alex. Wright & Co., Ltd., London, and used at the National Physical Laboratory, London.

of light from the screens is negligible when glow lamps are tested, and also —if sufficient care be exercised—when arc lamps are compared.

Photometer, standard lamp, and the lamp to be compared rest on carriages which slide on bars accurately turned and planished. Glow lamps are usually fixed on a universal joint which allows the axis of the lamps to be placed in any direction.

The bench illustrated in fig. 3·31 is supplied with a lamp rotator, in order to enable mean horizontal candle-power tests to be rapidly carried out. This lamp rotator is shown in fig. 3·32, and is due to Mr C. C. Paterson. The scale of the bench, which consists of a strip of polished triangular brass, is provided with two graduations, one in centimetres and one for direct reading. The length of the bench is 3 metres.

The illumination of the photometer screen is suitably made 10 candle-metres (about 1 candle-foot). A 10 candle-power standard would then have to be placed at a distance of 1 metre from the photometer. Clamping the photometer to the working standard of this intensity, lamps up to 40 candles could be tested on a bench 3 metres long. The moving of the test lamp is on the whole to be preferred. As the test lamp may be at a considerable distance from the photometer, the moving of it is accomplished with rope and pulley.

For lamps larger than 40 candles the illumination on the photometer screen will be greater than 10 candle-metres. It may then be more convenient to place the standard lamp at 0 of the scale, the test lamp at 300 (centimetres). For the different positions of the photometer the accompanying table gives then the ratio of $\frac{\text{Test lamp}}{\text{Standard lamp}}$.

Table V.—For a Photometer Bench 300 Centimetres Long.

	0	1	2	3	4	5	6	7	8	9
50	25·0	23·8	22·7	21·7	20·8	19·8	19·0	18·2	17·4	16·7
60	16·0	15·4	14·7	14·2	13·6	13·1	12·6	12·1	11·6	11·2
70	10·8	10·4	10·0	9·7	9·3	9·00	8·69	8·39	8·10	7·83
80	7·56	7·31	7·07	6·84	6·61	6·40	6·19	5·99	5·80	5·62
90	5·44	5·27	5·11	4·95	4·80	4·66	4·52	4·38	4·25	4·12
100	4·00	3·88	3·77	3·66	3·55	3·45	3·35	3·25	3·16	3·07
110	2·98	2·90	2·82	2·74	2·66	2·59	2·52	2·45	2·38	2·31
120	2·25	2·19	2·13	2·07	2·01	1·96	1·91	1·85	1·80	1·76
130	1·71	1·66	1·62	1·58	1·53	1·49	1·45	1·42	1·38	1·34
140	1·306	1·271	1·238	1·205	1·173	1·142	1·113	1·083	1·055	1·027
150	1·000	0·974	0·948	0·923	0·899	0·875	0·852	0·830	0·808	0·787
160	0·765	0·745	0·726	0·706	0·688	0·669	0·652	0·634	0·617	0·601
170	0·585	0·569	0·554	0·539	0·524	0·510	0·496	0·483	0·470	0·457
180	0·444	0·432	0·420	0·409	0·397	0·386	0·376	0·365	0·355	0·345
190	0·335	0·326	0·316	0·307	0·289	0·290	0·282	0·273	0·265	0·258
200	0·250	0·243	0·235	0·228	0·221	0·215	0·208	0·202	0·196	0·190
210	0·184	0·178	0·172	0·167	0·161	0·156	0·151	0·146	0·141	0·137
220	0·132	0·128	0·123	0·119	0·115	0·111	0·107	0·104	0·100	0·096
230	0·093	0·089	0·086	0·083	0·080	0·076	0·074	0·071	0·068	0·065
240	0·063	0·060	0·057	0·055	0·053	0·050	0·048	0·046	0·044	0·042

In order to be able to plot the polar curves of lamps, *i.e.* to measure the intensity of the rays in any part of a sphere surrounding a source, an apparatus illustrated in fig. 3·33 is suitable. The emitted ray is reflected by a mirror S, and the angle at which the ray emerges is seen on a divided circle K. Further apparatus for determining the intensities of incan-

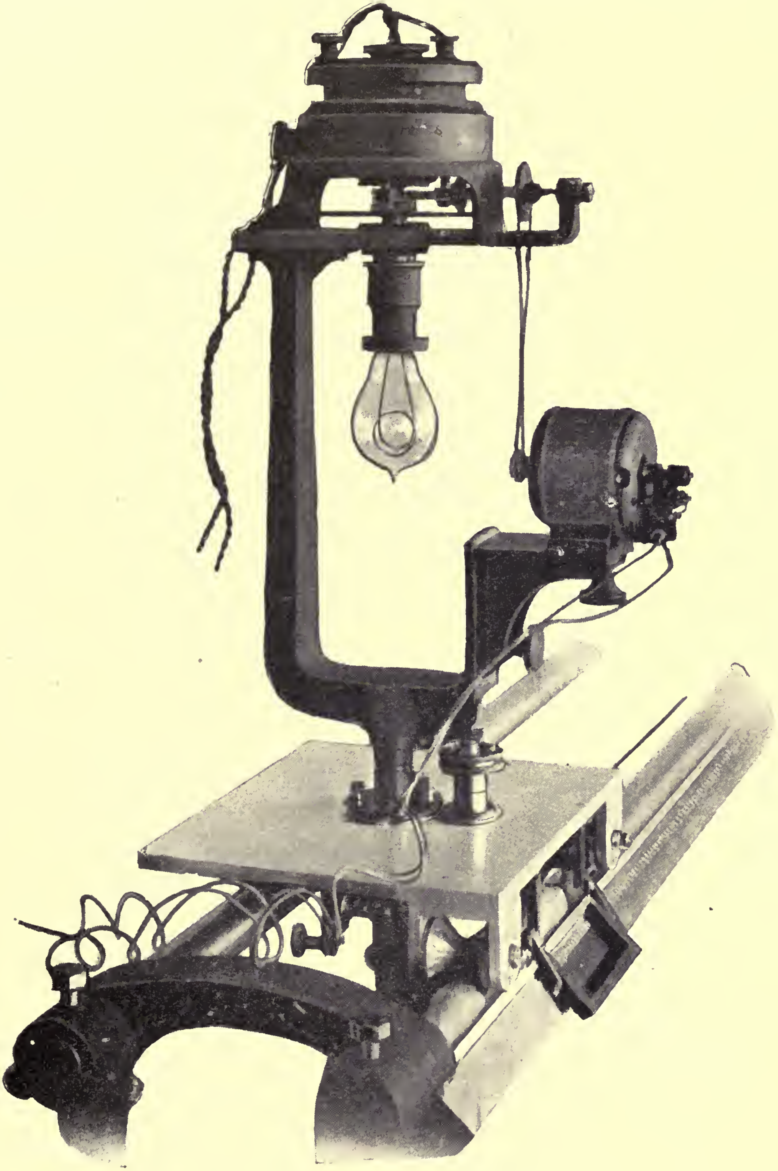

FIG. 3·32.—Paterson's Lamp Rotator.

descent lamps at any angle is shown in figs. 3·34 and 3·35, which are self-explanatory.

The spherical candle-power of arc lamps may be determined by employing the system of mirrors shown in fig. 3·36. The reflecting mirrors A B may be placed at any angle, read on the scale K. G is a balance weight, and W the carriage which is placed on the rails of the photometer bench.

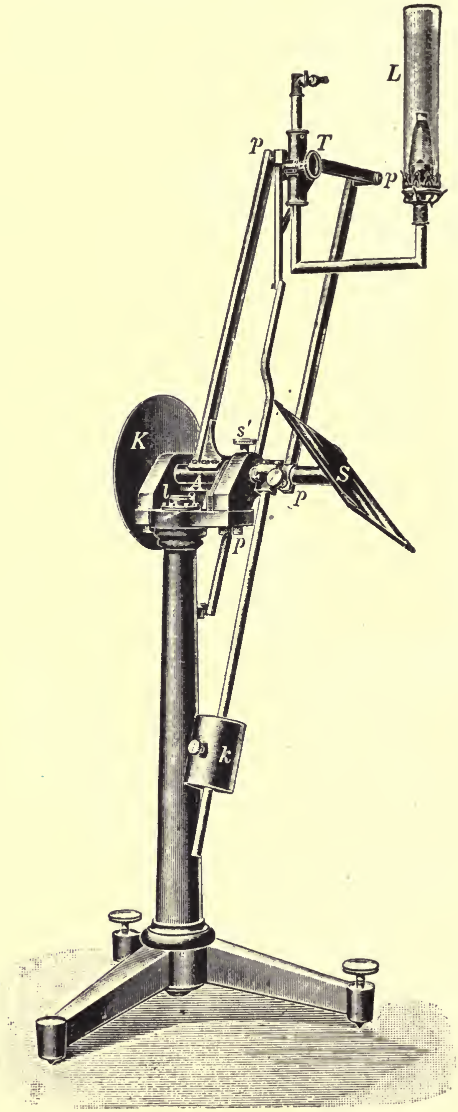

Fig. 3·33.—Universal Lamp-Holder.

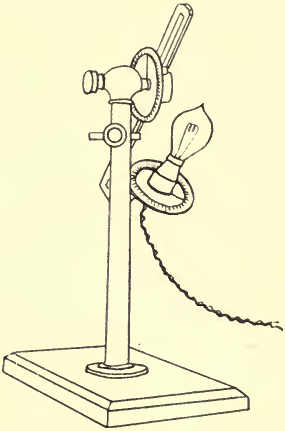

Fig. 3·34.—Universal Lamp-Holder.

Another apparatus suitable for the determination of polar curves of arc lamps is described by Dr J. A. Fleming as follows *: On a suitable base is erected a wooden gallows about 9 feet high and 3 feet wide. From the top of this the arc lamp to be investigated is suspended. In the two uprights of the gallows are two openings through which pass brass tubes or hollow bearings to which is connected another rectangular swinging frame (see fig. 3·37). The lamp is placed so that the arc A is exactly in line with the axis of

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* *J.I.E.E.*, vol. xxxii. p. 145.

these hollow trunnions. On the outside of one of the uprights is a circular scale of degrees, and the swinging frame carries a pointer by means of which its angular position relatively to the horizon is determined. The swinging frame also carries three plane mirrors, I_1, I_2, I_3, which are set at angles of 45 degrees and catch the ray from the arc lamp, and reflect it down one of the hollow trunnions. The ray therefore emerges in the same direction, no matter what may be the angular position of the swinging frame. This frame can be so set as to catch a ray coming from the arc at any angle above or below the horizon. It is quite possible, by means of a standard incandescent lamp, to determine the total and constant percentage loss of light by the three mirrors, at each of which the ray is reflected at an incidence of 45 degrees, and hence to apply the necessary correction to the intensity of the selected ray. By employing a photometer and a standard glow lamp, measurements can be made of the luminous intensity of the arc in any direction relatively to the horizontal plane through the arc. This direct measurement is often rendered difficult because the arc shifts its position continually, and there is, consequently, a

Fig. 3·35.—Lamp-Holder for Spherical Measurements.

periodic waxing and waning of the light in any direction. This difficulty may be overcome by testing the arc against itself—or, in other words, by comparing the luminous intensity of the ray coming from the arc in any direction with that of the ray coming off in a horizontal direction. This is accomplished by fixing three mirrors, H_1, H_2, H_3, to reflect round the ray coming in a horizontal direction from the arc, and make it coincide in direction with the thrice-reflected ray coming from off the arc at any angle above or below the horizon. In each case the ray suffers reflection at three mirrors placed at angles of 45 degrees; hence there is no difference in the loss by reflection, and both the rays are weakened in the same ratio. We have then to determine the ratio of the intensities of these two rays; this may be done by, for instance, employing a variable aperture disc photometer, described under Brodhun's street photometer.

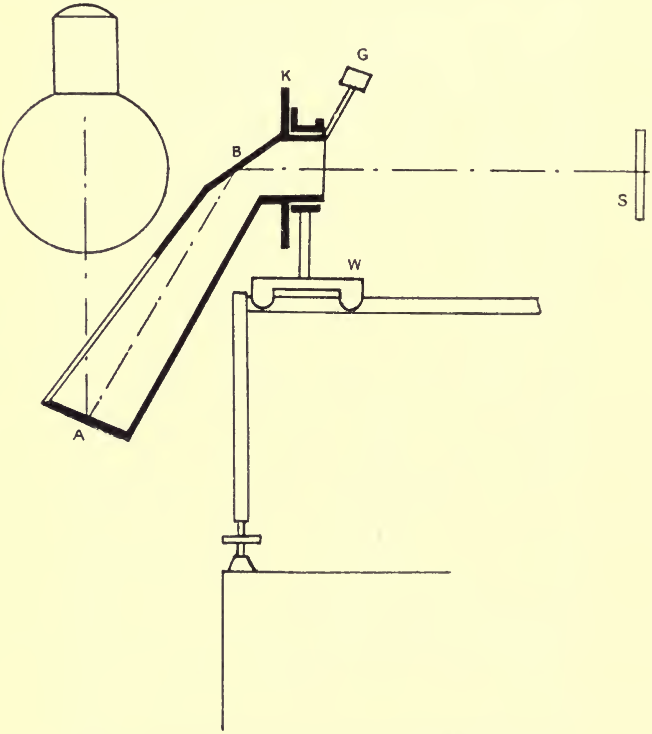

FIG. 3·36.—Lamp-Holder for Spherical Measurements.

With the aid of a standard glow lamp, and a single direct observation (or, better still, the mean result of a number of observations), we are able to determine the mean absolute horizontal luminous intensity; and hence the polar curve of luminous intensity can be plotted, as will be shown further on.

A method somewhat similar to, but simpler than, Fleming's is the following :—On a bracket is fixed a metal screen S, placed between the arc lamp I and the photometer P to keep from the latter all direct light (see fig. 3·38). To a shaft passing through the centre of S are pivoted two levers, each of which carries at its extremity a mirror M_1 and M_2. When the two arms are horizontal, the fields of view reflected by M_1 and M_2 should be equalised for equal distances. One lever, say 1, is now rotated, whereas the other one, 2, is kept horizontal, so that the light reflected from M_1 to P is emitted under different angles, seen on the metal screen. By moving M_1, equality of the field of view is easily obtained, and the intensities of the rays inclined at these angles are given by

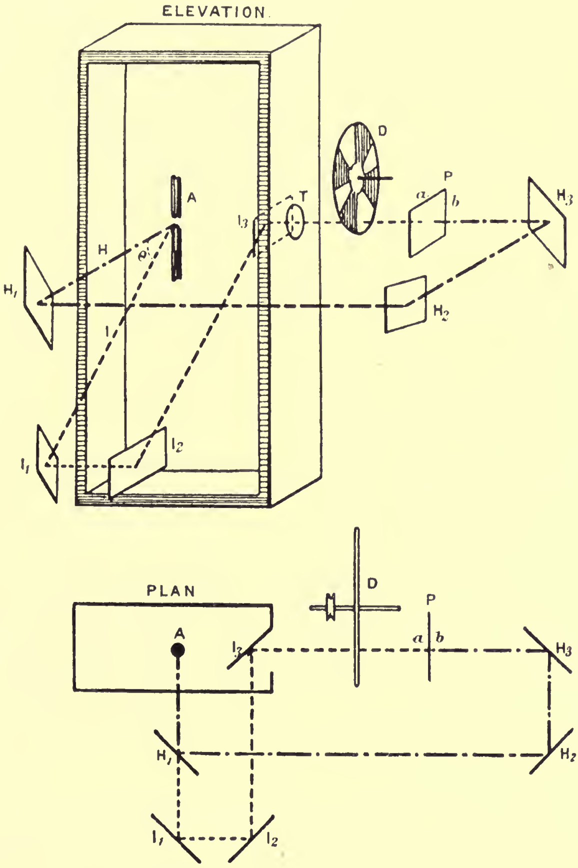

Fig. 3·37.—Fleming's Arc Lamp Testing Arrangement.

$$I_\theta = I_H \frac{L_1^2}{L_2^2},$$

in which L_1 and L_2 are the distances. I_H, the horizontal intensity, has been determined by a previous test. The photometer should be adjust-

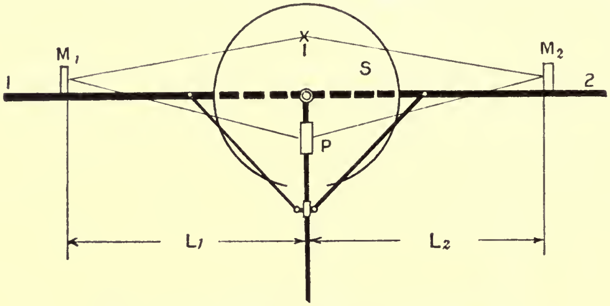

FIG. 3·38.—Arc Lamp Testing Arrangement.

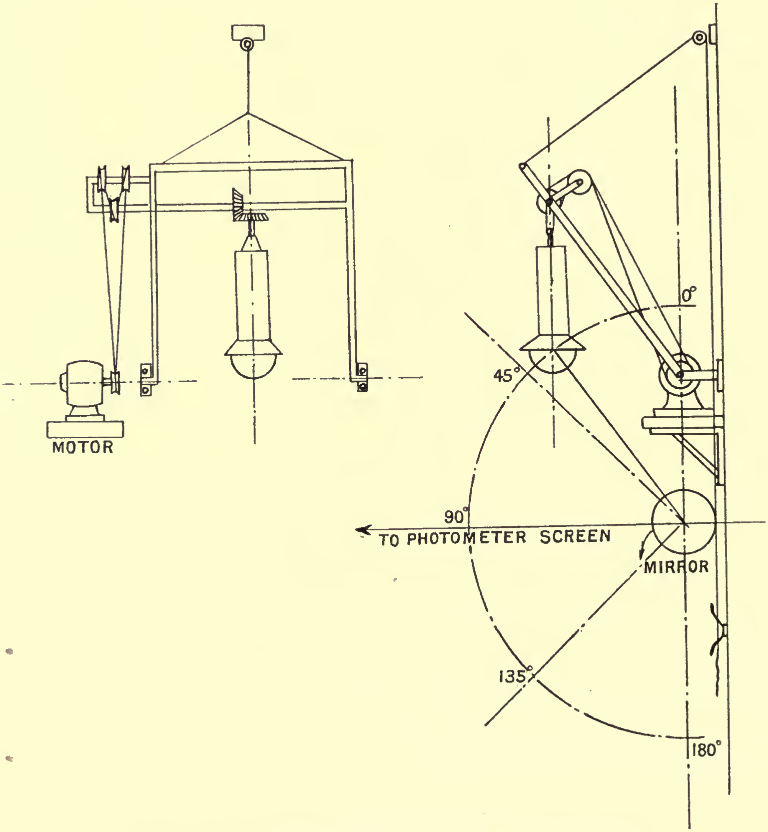

FIG. 3·39.—Drysdale's Apparatus for Testing Arc Lamps.

able so that the angles of incidence of the reflected rays from M_1 and M_2 are equal.

The absorption of light by the mirrors need not be considered, since both intensities are equally affected. The method gives correct results for symmetrical lights only, for which the horizontal intensity (along the same latitude) is practically uniform.

The previous methods possess the disadvantage that the lights must be symmetrical. Unfortunately, the position of the arc is not permanent, even for lamps with vertical carbons, and consequently the intensity of the ray under test varies. This difficulty is overcome by rotating the lamp round a vertical axis, as in the case of incandescent lamps. At the same time, the construction of the apparatus must be such that measurements can be made under any angle. Such a mechanism is shown in fig. 3·39, which has been employed by Dr Drysdale at the Northampton Institute. The illustration is self-explanatory.

51. **DISPERSION LENSES.**—When the intensities of lamps which are to be compared vary considerably, it is advisable to reduce the stronger light by means of smoked glasses, or preferably, dispersion lenses (concave). The principle involved is illustrated in fig. 3·40.

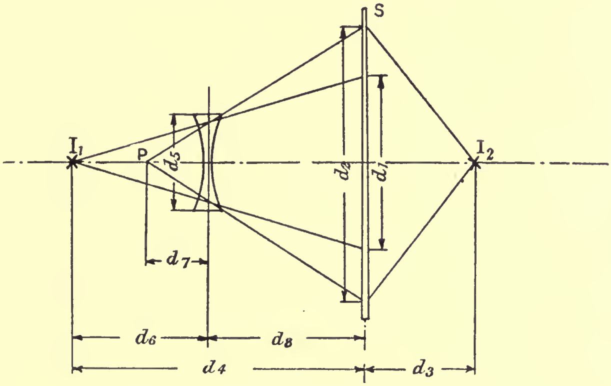

Fig. 3·40.—Principle of Dispersion Lenses.

Let us assume that in the first case the lens has been removed, then the illumination of an area with diameter d_1 is

$$E_1 = \frac{\phi_1}{d_1^2 \pi}.$$

If now the lens is inserted, the light is dispersed, so that the cone of light becomes shorter, but of a greater base—the rays appear to come from P—and the illumination now is

$$E_2 = \frac{\phi_1}{d_2^2 \pi} \quad . \quad . \quad . \quad . \quad . \quad 3{\cdot}02$$

whence

$$\frac{E_1}{E_2} = \frac{d_2^2}{d_1^2}. \quad . \quad . \quad . \quad . \quad . \quad . \quad 3{\cdot}03$$

The position of the screen is next so adjusted that equality of the optical fields is obtained; then

$$E_3 = \frac{I_2}{d_3^2} = E_2 ,$$

and

$$\frac{E_1}{E_2} = \frac{E_1}{E_3} = \frac{d_2^2}{d_1^2} = \frac{I_1}{I_2} \times \frac{d_3^2}{d_4^2} \quad . \quad . \quad . \quad . \quad 3{\cdot}04$$

We have further (see also fig. 3·40):—

$$\frac{d_1}{d_5} = \frac{d_4}{d_6} \quad . \quad . \quad . \quad . \quad . \quad . \quad 3{\cdot}05$$

$$\frac{d_2}{d_5} = \frac{d_7 + d_8}{d_7} \quad . \quad . \quad . \quad . \quad . \quad 3{\cdot}06$$

$$\frac{1}{d_7} = \frac{1}{d_6} + \frac{1}{l} \quad . \quad . \quad . \quad . \quad . \quad 3{\cdot}07$$

where l is the focal length (negative) of the lens. We also have

$$\frac{d_2}{d_1} = \frac{d_7 + d_8}{d_7} \times \frac{d_6}{d_4} ,$$

whence

$$\frac{d_2^2}{d_1^2} = \left(\frac{d_7 + d_8}{d_7} \times \frac{d_6}{d_4} \right)^2 ,$$

and

$$\frac{E_1}{E_2} = \frac{d_2^2}{d_1^2} = \left(\frac{d_7 + d_8}{d_7} \times \frac{d_6}{d_4} \right)^2 ,$$

$$= \frac{I_1}{I_2} \times \frac{d_3^2}{d_4^2} ,$$

and

$$I_1 = I_2 \frac{d_4^2}{d_3^2} \left(\frac{d_7 + d_8}{d_7} \times \frac{d_6}{d_4} \right)^2 \quad . \quad . \quad . \quad . \quad 3{\cdot}08$$

From 3·06 it follows that

$$d_7 = \frac{d_6 \times l}{d_6 + l} .$$

Substitution into 3·08 produces, after arranging,

$$I_1 = \frac{I_2}{d_3^2} \left(d_6 + d_8 + \frac{d_6 \times d_8}{l} \right)^2 \quad . \quad . \quad . \quad . \quad 3{\cdot}09$$

and, since

$$d_6 + d_8 = d_4 ,$$

$$I_1 = \frac{I_2}{d_3^2} \left(d_4 + \frac{d_6 \times d_8}{l} \right)^2 \quad . \quad . \quad . \quad . \quad 3{\cdot}10$$

The lens gives the greatest effect when $d_6 = \frac{1}{2} d_4$.

Equation 3·10 would be correct if the lens did not absorb any light. To make up for this we place on the other side of the photometer in the rays of the second lamp a piece of plane glass the thickness of which is the same as that of the thinnest part of the lens.

The focal length l is found as follows:—We employ two lamps of nearly equal intensity; place the one at zero of the photometer scale, the other at d' and the screen at d'' from zero, so as to obtain equality of the field of view. Next place the lens at $\frac{d''}{2}$ and again obtain equality by moving the second lamp further away from the screen, say to d''' from zero; the focal length is then expressed by

$$l = \frac{d''}{4} \times \frac{d_1}{d''' - d'} \quad . \quad . \quad . \quad . \quad . \quad 3{\cdot}11$$

52. **ABSORPTION OF LIGHT BY MIRRORS.**—In a mirror the image appears as far behind the mirror as the light lies actually in front of it. We must therefore add to the distance between the mirror and the photometer that from the mirror to the lamp.

As light is absorbed by a mirror, the emerging ray is reduced in intensity. The reduction coefficient may be found as follows:—Use two similar lamps and obtain equality of the optical fields without any mirrors, when

$$I_1 = I_2 \frac{L_1^2}{L_2^2}.$$

Next place I_1 at a distance L_3 from the axis of the photometer on the same level as before, and now conduct the same rays which previously reached the photometer by means of the mirror to be tested to the screen. The normal distance from the mirror to the light I_1 is L_3, that from the mirror to the screen L_4, and equality is obtained by making the distance from the photometer to the light I_2 equal to L_5; then, since part of the light is absorbed by the mirror,

$$I' = I_2 \frac{(L_3 + L_4)^2}{L_5^2},$$

whence

$$\frac{I'}{I_1} = K_r = \frac{L_2^2 (L_3 + L_4)^2}{L_1^2 \times L_5^2} = \text{reduction coefficient} \quad . \quad . \quad 3{\cdot}12$$

If it is possible to make $L_3 + L_4 = L_1$, then

$$\frac{I'}{I_1} = K_r = \frac{L_2^2}{L_5^2} \quad . \quad . \quad . \quad . \quad . \quad 3{\cdot}13$$

53. **PHOTOMETERS FOR SPECIAL PURPOSES.**—In connection with electric lighting, a knowledge of the intrinsic brilliancy and of the reflecting powers of walls, ceilings, etc., is of considerable importance. The ordinary intensity or illumination photometer is not suitable for this purpose, unless specially prepared surfaces are employed.

An instrument has however been devised by J. S. Dow and V. H. Mackinney,* with which surface brightness of any object and in any

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* See also *Illuminating Engineer*, 1910, p. 655. Manufactured by Messrs R. and J. Beck, Ltd., 68 Cornhill, London, E.C.

locality can be approximately determined. The principle of the instrument, called by the inventors a "lumeter," is shown in fig. 3·41. The observer at O_1 looks directly upon a screen S, uniformly illuminated by a glow lamp at G, and through an aperture C in S at the object. The illumination on S can be altered by screening off more or less of the opal glass at O, as is indicated.

The opaque diaphragm D allows only a sector to be exposed, and the latter is more or less covered up by the screens A and B, and thus the quantity of the light transmitted to the screen S may be very finely adjusted. With A placed fully over O, the opening is exactly one-tenth of that of the whole sector, and this is further uniformly reduced to 0 with the aid of screen B. The screen S is made by depositing a matt white precipitate on thin glass, and scraping away a central disc. It is then covered with thin glass for protection. The instrument in reality measures intrinsic brilliancy or the number of candles per unit surface. It may however also be used for determining the illumination in candle-feet which a perfectly white surface would have to receive in order to have an equivalent brightness. It is for this purpose that the instrument is most useful. The calibration then is accomplished as follows:—

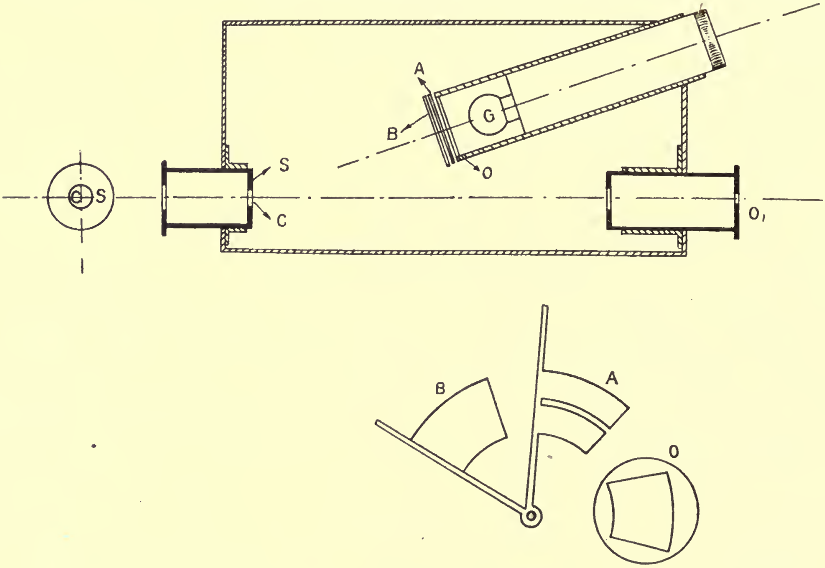

FIG. 3·41.—Principle of the Lumeter.

The position of the glow lamp, which illuminates the opal glass O, is adjusted until the brightness of the screen S is, say, 1 candle-foot, or for 10 candle-metres, determined by comparing it with another similar white surface illuminated by a standard lamp. The lamp is then fixed in position, and we may regard the scale as registering in candle-feet. The further calibration takes place by closing the screens A and B by known values.

The range of the instrument is now from $\frac{1}{100}$ to 1 candle-foot, or from $\frac{1}{10}$ to 10 candle-metres.

With the insertion of smoked glasses the range may be increased to 100 candle-feet.

To ensure accuracy it is important that the glass should be uniformly illuminated, a result achieved by enclosing the lamp in a chamber with perfectly white walls.

The instrument can of course be used for rough candle-power and illumination measurements as well as for approximate determinations of surface brightness and diffuse reflection coefficients. For relative measurements the instrument is extremely handy. We first view a white screen placed in front of the object, and then the object itself, and compare the two.

For further information the reader is referred to the original article.

54. **INTEGRATING PHOTOMETERS.**—For the determination of the mean spherical candle-power of a lamp, a large number of observations have to be made in order to obtain good results. If the light is symmetrical, it is usually sufficient to take a number of measurements along a meridian and to plot the Rousseau curve (see Chapter V.), the mean ordinate of which gives the required result. In the case of non-symmetrical lights, the tests have to take place along several meridians, making the work very laborious. All this is avoided by employing integrating photometers.

55. **MATTHEW'S PHOTOMETER.**—This instrument is shown diagrammatically in fig. 3·42 and gives reliable results for symmetrical lights only. But by rotating the lamp, for instance by means of a small motor, or by making a number of observations along various meridians, any type of lamp may be tested in this manner.

The principle of the instrument will be clear from the figure.

The rays of the lamp are reflected by means of two mirrors, M_1 and M_2, to a photometer screen P illuminated on the other side by a standard lamp I_s. Calibration takes place with a lamp of known mean spherical candle-power. For mean hemispherical measurements, only the mirrors of the lower hemisphere are employed, those of the upper ones being screened off.

The proof is as follows:—

The total flux from a point source of light is $\phi = 4R^2\pi\bar{E}$, where $\bar{E}$ is the uniform illumination on a surrounding hollow sphere. But

$$\bar{E} = \frac{I_0}{R^2};$$

hence

$$\phi = \frac{4R^2\pi I_0}{R^2} = 4\pi I_0,$$

where I_0 is the mean spherical candle-power (in this case the light is perfectly uniform all round). If this source is replaced by any other giving the same total flux, then we have

$$4R^2\pi E = 4\pi I_0 = \int E dS = \int \frac{I}{R^2} dS \quad . \quad . \quad . \quad 3{\cdot}14$$

in which I_0 denotes now the mean spherical candle-power, and E is the illumination produced on any infinitesimal area dS caused by the candle-power I at a distance R. Suppose now that we have a symmetrical light, then the illumination of any *zone* dS along any given latitude will be

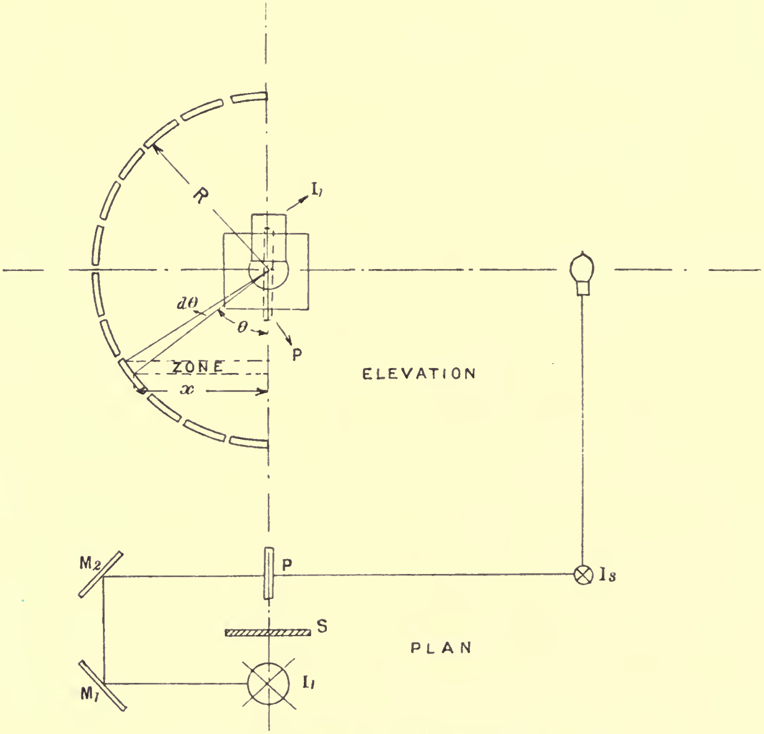

Fig. 3·42.—Matthew's Integrating Photometer.

uniform. If this zone lies at an angle θ inclined to the vertical (see fig. 3·42), then the area dS is equal to the circumference multiplied by the width, or,

$$dS = 2\pi x R d\theta,$$

and since

$$x = R \sin\theta, \quad dS = 2R\pi \sin\theta R d\theta,$$

whence

$$4\pi I_0 = \int \frac{I}{R^2} 2R\pi \sin\theta R d\theta$$

and

$$I_0 = \tfrac{1}{2}\int I \sin\theta d\theta \quad . \quad . \quad . \quad . \quad . \quad 3{\cdot}15$$

The mean spherical candle-power may be found with the aid of this equation by dividing a polar curve (see also Chapter V.) into small parts and adding up elementary products I sin θ.

If the number of parts be n for 180 degrees, then

$$\Delta\theta = \frac{\pi}{n}$$

and

$$I_o = \frac{\pi}{2n}\sum_0^n I \sin\theta . \quad . \quad . \quad . \quad . \quad 3{\cdot}16$$

Take now in the Matthew integrator a ray of light inclined by an angle θ. According to equation 1·07, the illumination is proportional to the cosine of the angle of incidence; hence the illumination on the photometer screen as caused by a reflected ray is proportional to I cos $(90° - \theta)$ or to I sin θ, since the light from the mirror in question is incident on the photometer screen at $(90° - \theta)$ degrees, and the total amount from the mirror is proportional to

$$\sum_0^n I \sin\theta .$$

56. **BLONDEL'S INTEGRATING PHOTOMETER.**—It is illustrated diagrammatically in fig. 3·43.

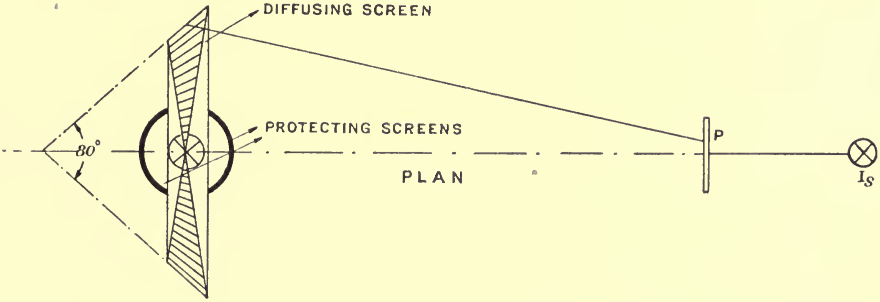

Fig. 3·43.—Blondel's Integrating Photometer.

The light from the lamp under test is thrown on a diffusing screen which has the shape of a truncated cone. From here it is reflected on the photometer screen. The illumination on the latter is, of course, proportional to ΣI, where I is the intensity in any given direction. But the mean spherical candle-power is proportional to I sin θ. Blondel obtains this result by making the screen wide in the equatorial region of the lamp and narrow near the poles, as is indicated in the figure. The calibration takes place with a lamp of known spherical intensity.

57. **ULBRICHT'S INTEGRATING PHOTOMETER.***—This instrument, which was invented by Professor Ulbricht, consists of a large opaque sphere, painted white so as to give a smooth, well-diffusing surface. The

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* See also *E.T.Z.*, 1905, pp. 512, 595, 1047 ; 1906, pp. 50, 468, 669 ; 1907, p. 777 ; 1909, p. 322.

size of the sphere should not be less than six times the diameter of the globe of the largest lamp tested. Smaller spheres are made of glass, which must be given an external coating. Larger ones are made of sheet metal and in two parts, for easy manipulation.

A light placed inside this sphere is diffused in such a manner that the resultant illumination is uniform over the whole surface; consequently the illumination of a window in the sphere is proportional to the mean spherical candle-power of the lamp inserted, as long as direct light is kept from the window. This is proved as follows:—

Assume at first the light in the centre of the sphere, as shown in fig. 3·44. Consider any small area dS, the normal illumination of which is proportional to $\frac{I}{R^2}$, where I is the intensity of the ray in that direction and R the radius of the sphere. This area acts now as a source of light to the window W, but the flux is emitted inclined at an angle θ. Its quantity to W is therefore proportional to

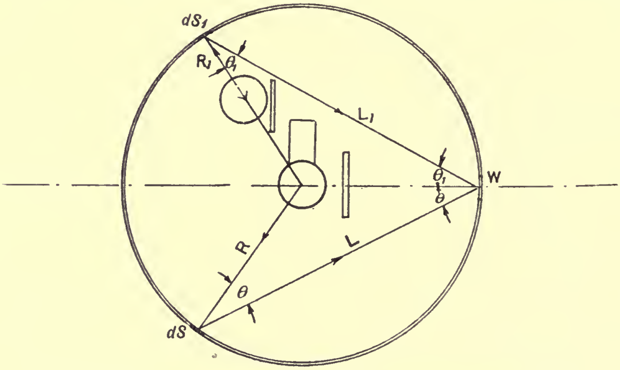

FIG. 3·44.—Principle of Ulbricht's Spherical Photometer.

$$\frac{I}{R^2}dS\cos\theta,$$

according to the cosine law, and hence the normal illumination of W is proportional to

$$\frac{I}{R^2}dS\cos\theta\frac{\cos\theta}{L^2},$$

since the illumination is directly proportional to the angle of incidence and inversely to the square of the distance L. As

$$\cos\theta=\frac{L}{2R},$$

we get the illumination of W proportional to

$$\frac{IdS}{4R^4}.$$

What applies to the area dS holds for the whole sphere; hence the normal illumination of W is proportional to

$$\frac{1}{4R^2}\int\frac{1}{R^2}dS,$$

or, according to equation 3·14, proportional to a constant multiplied by the mean spherical candle-power of the lamp.

It is not even necessary to place the lamp in the centre. Suppose it is anywhere between the centre and the circumference as indicated by the upper circle in fig. 3·44. We now have the normal illumination of dS_1 proportional to $\frac{I_1}{R_1{}^2}$, or to E_1, and the quantity of light emitted to the window proportional to

$$E_1 dS_1 \cos\theta_1,$$

while the normal illumination of W is proportional to

$$E_1 dS_1 \cos\theta_1 \frac{\cos\theta_1}{L_1{}^2}.$$

But

$$\cos\theta_1 = \frac{L_1}{2R},$$

whence the normal illumination of W becomes proportional to

$$E_1 dS_1 \frac{L_1{}^2}{4R^2 L_1{}^2} = \frac{E_1 dS_1}{4R^2},$$

and the total illumination proportional to

$$\frac{1}{4R^2}\int E_1 dS_1,$$

or to a constant multiplied by the mean spherical candle-power (see equation 3·14). This result is not changed by any absorption of light as long as the coating is perfectly uniform. Neither is it affected by the fact that the light is reflected a number of times before it reaches the window, since this can only influence the constant of the sphere, which must be determined experimentally.

The results derived here are correct as long as the surface diffuses the light uniformly and no foreign bodies are included.

A discussion which took place on this subject between members of the Illuminating Engineering Society * showed that opinions differed considerably. As regards the inclusion of foreign bodies, Professor Ulbricht has shown that the error caused by reflection of light from these bodies is negligible, as long as the sphere is made sufficiently large.†

The following precautions must however be taken. No direct light should reach the window, and the calibration of the sphere, which is usually accomplished with a large incandescent electric lamp (say a 100

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* See *Illuminating Engineer*, May 1910.

† See *E.T.Z.*, Dec. 1910, p. 1295.

candle-power metal filament lamp), must take place with the arc lamp already in position. We thus require three screens B and B_1 (see fig. 3·45)

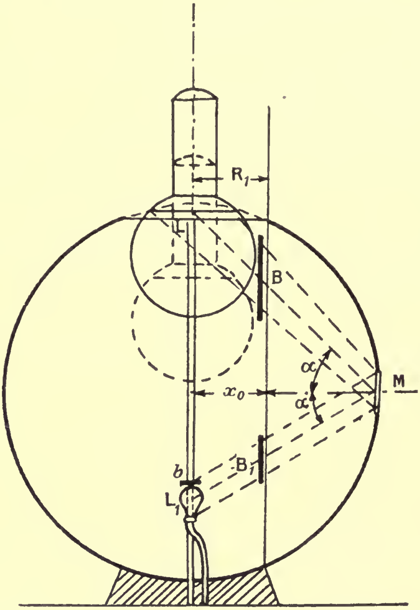

FIG. 3·45.—Arrangements of Screens in Ulbricht's Sphere.

and a screen *b* which is employed to prevent any bright parts of the lamp from reflecting light from the standardising lamp to the window W.

58. **APPROXIMATE ERRORS.**—The approximate errors caused by the screens have been evaluated by Ulbricht, and are given as follows *: —For spherical measurements

$$\text{Error} = \frac{80S - 100S_1}{R^2\pi} \text{ per cent.,} \quad . \quad . \quad . \quad 3{\cdot}17$$

which is to be added to the result.

For hemispherical determinations

$$\text{Error} = \frac{50S - 100S_1}{R^2\pi} \text{ per cent.,} \quad . \quad . \quad . \quad 3{\cdot}18$$

in which S = one-sided area of screen B in square centimetres,
S_1 = ,, ,, B_1 ,, ,,
R = radius of sphere in centimetres.

The screen B should not be larger than one-twentieth of the central cross-sectional area of the sphere and must screen off—

(*a*) For measurements without globes: the whole source of light and the reflector.

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* See *E.T.Z.*, 1907, p. 777.

(*b*) For determinations with clear glass globes: the whole source, the reflector, and any image of the source.

(*c*) For tests with diffusing globes: the whole globe.

If the screens are comparatively large, the errors may be more accurately determined with the following equations (see also fig. 3·46):—

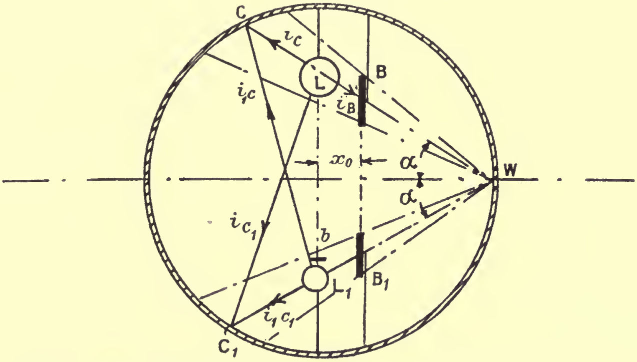

FIG. 3·46.—Determination of Errors for Ulbricht's Sphere, due to Screens.

For spherical measurements

$$\text{Error} = \frac{Sa}{R^2\pi}\left(i_B + 4i_C\right) - \frac{S_1 a}{R^2\pi}\left(5{\cdot}5 - \frac{2}{3}i_{C_1}\right) \quad . \quad . \quad . \quad 3{\cdot}19$$

and for hemispherical tests

$$\text{Error} = \frac{a}{R^2\pi}\left[S(i_B + 4i_C) - 5{\cdot}5\,S_1\right] \quad . \quad . \quad . \quad . \quad 3{\cdot}20$$

in which a represents the absorption of the diffusing surface,

$$i_B = \frac{I_B}{I_O},$$

where I_B is the candle-power of the arc lamp in the direction of the screen B,

$$i_C = \frac{I_C}{I_O},$$

where I_C is the candle-power in opposite directions to I_B and

$$i_{C_1} = \frac{I_{C_1}}{I_O},$$

in which I_{C_1} is the candle-power of the lamp in the direction of C_1, and screened off by B_1. I_O is the mean spherical candle-power of the lamp.

Example.—Direct-current lamp in clear glass globe.

$$i_B = 3, \quad i_C = 0{\cdot}5, \quad i_{C_1} = 0{\cdot}1,$$

$$S = \frac{R^2\pi}{25}, \quad S_1 = \frac{R^2\pi}{100}, \quad a = 0{\cdot}2\,.$$

Error (for spherical tests) = 2·9 per cent.

The screen B_1 has usually an area equal to 0·8 of that of B, when, according to equation 3·17, the error is nil.

All screens must of course possess white diffusing surfaces.

For hemispherical tests, the test lamp must be placed in such a position that only the light of the lower hemisphere enters the globe. For this purpose it is necessary to cover up part of the globe which lies above the radiant centre of the arc, the radius of the black covering being R_1 (see fig. 3·45).

The radiant centre is found with a special grease-spot finder. The latter is illustrated in fig. 3·47, and consists of a blackened tube containing the grease-spot G, the mirrors M_1 and M_2, and the prisms P_1 and P_2. By means of the mirrors the observer at θ views the upper and lower sides of G simultaneously. The images are brought into juxtaposition by the prisms P_1 and P_2, when the lamp is at a distance of $R_1\sqrt{3}$ from the grease-spot. A slight variation of this distance matters, however, little. The lamp is then raised or lowered until the illuminations of the upper and lower surfaces of the screen are the same. The observer is now able to determine that point in the source of the light which coincides with the plane of G, and to this point the globe must be raised so as to make the plane of the section of the globe coincide with it. Only light of the lower hemisphere is then considered in the measurement; K is a screen to guard the eye against direct light.

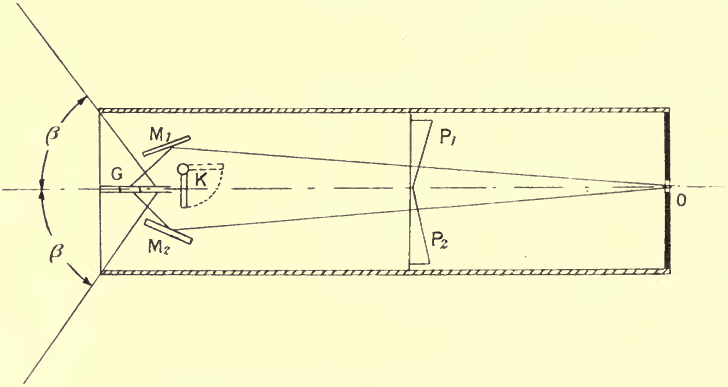

FIG. 3·47.—Ulbricht's Grease-Spot Finder.

Care must be taken that all foreign light is carefully screened off G. This result is obtained by employing the arrangement of fig. 3·48 in which T is a large black tube and S a screen.

As a result of the discussion mentioned above, further experiments were carried out in order to determine the influence of the colour of the diffusing surface of the globe on the accuracy of the test results.* The

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* See *E.T.Z.*, 1910, p. 1295.

results of these investigations show that, with proper care in carrying out the tests, a perfectly white surface is not essential as long as the surface shows uniformity. A few dark spots make little difference in the ultimate result; but should, for instance, the lower half of the globe be darker than the upper one, the error is appreciable and a new coating is required. Care must also be taken that, if flame arcs are tested, the globe is sufficiently ventilated, as otherwise the light-absorbing gases affect the test result considerably. This is a very important point, especially if the lamp is surrounded with a globe (and without globes the tests are of little importance), and it may be found that the candle-power of the lamp varies considerably during a test if the ventilation is poor. It is impossible to obtain a surface which diffuses the light perfectly, but the tests carried out by Ulbricht (see last footnote) show that the results are not much affected if the diffused reflection is somewhat mixed with regular reflection. Tests were also carried out to determine the influence of an imperfectly diffusing window: they showed that the errors caused were within the range of observation errors, as long as direct light did not reach the window. As regards the nature of the coating, satisfactory results are obtained by coating the vessel first with a white oil paint, serving as a basis, and then with white zinc paint made with lime-water, the latter acting as binding material. Such a coating can easily be washed off and renewed. Good results are also obtained if the lime-water is replaced by unboiled milk. Sulphate of barium has also been employed successfully.

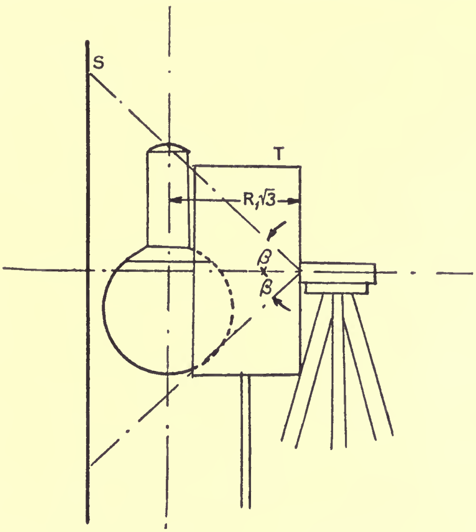

Fig. 3·48.—Determination of the Radiant Centre.

The nature of the glass used for the window is of importance. Whatever kind of milk glass is employed, care should be taken that it does not alter the colour of the light.

59. **CRITICISM ON PHOTOMETERS.**—As far as the author's experience goes, photometers such as the Bunsen grease-spot, the Ritchie wedge, and Trotter's intensity instruments, as previously described, suffice for ordinary incandescent lamp tests, so long as standards are employed which have previously been calibrated with more accurate instruments. There is little doubt that for calibration purposes the Lummer-Brodhun type can hardly be beaten, where lights of approximately equal colours are con-

cerned. The flicker photometer is scarcely to be recommended for such work, since the range over which the flickering disappears is far too large, a distance of 3 centimetres per metre length of the bench having been observed when testing a tungsten lamp against a Fleming standard.

We obtain, however, a different aspect when comparing a tungsten lamp with an arc lamp, especially a flame lamp. The ordinary equality photometers, and especially the Lummer-Brodhun type, are then unsuitable. As a matter of fact, a balance is not obtainable, since the fields of view have different colours. With the flicker type this is not the case, and the range over which the flickering disappears is extremely small, and does not exceed half a centimetre in a distance of one metre. For arc lamp tests, or, speaking generally, for tests of lamps of widely different colours, the flicker type is always to be recommended.

As regards illumination photometers, instruments without eye-pieces are preferable. The eye-piece usually brings the observer in the direction of some incident rays, so that part of the light is screened off. This however does not, on the whole, apply to the Weber type, an instrument which gives great accuracy where the colours of the fields of view differ little. Where this is not the case, Trotter's universal photometer gives good results.

Speaking generally, the accuracy, or rather the precision, obtainable in photometric work depends largely upon the individual. A person used to a Bunsen grease-spot instrument will obtain better results with it than with a Lummer-Brodhun type, to which he is unaccustomed. As in everything, experience tells also in this class of work. Even the condition of the observer is of importance, and it will be quite obvious that a person out of health will be less reliable—under otherwise equal conditions—than a healthy individual. A large number of observations in succession causes fatigue, which means that the eye becomes less sensitive. This is probably due to the continuous observation of a highly illuminated surface, the photometer screen, which is in great contrast with the surrounding blackness of a photometer room, and it is therefore advisable to rest the eye by deviation to other work. Glare should be totally avoided, as it destroys the equilibrium of the eye completely.

Looking at the photometer screen for too short a time reduces the precision, but this happens also if the period is made too long. A time of about twenty seconds is suitable with a Lummer-Brodhun contrast pattern instrument. Instrumental errors, which are constant, can be determined and neutralised. They are chiefly due to stray rays, unsymmetrical photometer screens, and inadequate distances of the sources from the screen, so that the law of inverse square holds no longer. Care should also be taken that lamps burn under normal conditions.

Errors may be systematic, or accidental. The former are partly instrumental, and may be neutralised by calibration and by taking into account influences such as those of atmospheric conditions on flame standards. Errors are largely prevented by employing a number of equally skilled operators. Accidental errors can be determined mathematically by an application of the law of least squares. In photometric work it suffices to make a number of measurements under exactly similar conditions, and to take the mean result. To go further and find the probable error of a single observation and the mean error of the result, expressed by

$$0{\cdot}6745\sqrt{\frac{\Sigma R_0^2}{n-1}} = 0{\cdot}6745M$$

and $$\frac{M}{\sqrt{n}}$$

respectively, where R_0 is the residual, *i.e.* the difference between the mean and the single observations, and n the number of observations, would in many cases be waste of time.

CHAPTER IV.

LIGHT FLUX AND DISTRIBUTION.

60. **SOURCES EMITTING LIGHT UNIFORMLY IN ALL DIRECTIONS.**—This class embraces point and spherical sources. For the former the intrinsic brilliancy is infinite, since the emitting area is nil.

For a sphere the intrinsic brilliancy is expressed by

$$i = \frac{\phi}{4\pi R^2} \qquad . \quad . \quad . \quad . \quad . \qquad 4·01$$

$$= \frac{4\pi I}{4\pi R^2}$$

$$= \frac{I}{R^2} \qquad . \quad . \quad . \quad . \quad . \quad . \qquad 4·02$$

i.e. it is inversely proportional to the square of the radius of the sphere.

61. **CIRCULAR PLANE RADIATORS.**—Such a source is to be found in the tip of the carbon of an enclosed arc lamp. Let I_n be the normal intensity, then the intensity of the light under the angle θ is

$$I = I_n \cos\theta \qquad . \qquad 4·03$$

The figure of this equation is a circle as shown in fig. 4·01.

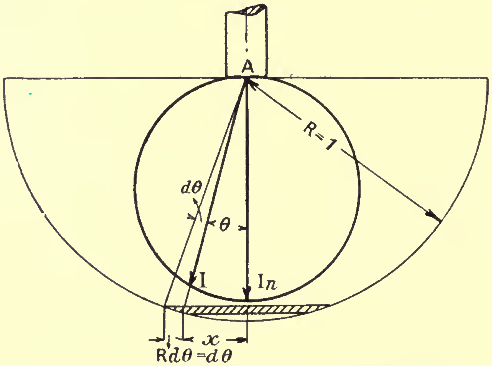

Fig. 4·01.—Light emitted by a Circular Plane.

The total light flux emitted by the radiator may be found as follows:—With A as centre draw a circle with radius unity. The length of an elementary arc formed by the angle $d\theta$ is then $Rd\theta = d\theta$, and the area swept out by it when rotating it round the vertical axis is $2\pi x d\theta$, and since $x = R\sin\theta = \sin\theta$, the area becomes $2\pi\sin\theta d\theta$. The flux striking the area is

$$\frac{I}{R^2} 2\pi \sin\theta d\theta = 2\pi I \sin\theta d\theta,$$

since $R^2 = 1$; hence the total flux

$$\phi = \int_0^{\frac{\pi}{2}} 2\pi I \sin\theta d\theta$$

$$= \pi I_n \int_0^{\frac{\pi}{2}} 2 \sin\theta \cos\theta d\theta$$

$$= \pi I_n \int_0^{\frac{\pi}{2}} \sin 2\theta d\theta,$$

and as

$$\int_0^{\frac{\pi}{2}} \sin 2\theta d\theta = 1$$

$$\phi = \pi I_n \quad . \quad . \quad . \quad . \quad . \quad 4{\cdot}04$$

The flux emitted within the angle θ against the vertical is given by

$$\phi^\theta = \pi I_n \int_0^\theta \sin 2\theta d\theta$$

or

$$\phi^\theta = \frac{\pi}{2} I_n (1 - \cos 2\theta) \quad . \quad . \quad . \quad . \quad 4{\cdot}05$$

The mean hemispherical intensity of the light is given by

$$I_{\text{◡}} = \frac{\phi}{2\pi};$$

hence

$$I_{\text{◡}} = \frac{I_n}{2} \quad . \quad . \quad . \quad . \quad . \quad 4{\cdot}06$$

The intrinsic brilliancy of the source is expressed by the flux per unit area, so that, if the radius of the radiating plane is R_1,

$$i = \frac{\phi}{R_1{}^2 \pi}$$

$$= \frac{\pi I_n}{R_1{}^2 \pi}$$

$$= \frac{I_n}{R_1{}^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad 4{\cdot}07$$

62. **CURVED SURFACE RADIATORS.** — The intensity I of an elementary area A B is equal to $I_n \cos\theta$; but $I_n = is_1$, where s_1 is the size of the small elementary area A B, whence $I = is_1 \cos\theta$ (see fig. 4·02). $s_1 \cos\theta$ is the projection of A B on the horizontal plane A C, hence the effect of the luminous curved surface A B C is the same as that of a plane surface A C with the same intrinsic brilliancy, and the intensity curve is a circle having the maximum intensity I_n as diameter.

The positive crater of a direct current arc with vertical carbons comes under this class of radiators. We see that the depth of the crater has no influence on the radiation, which depends solely on the intrinsic brilliancy and the diameter of the crater.

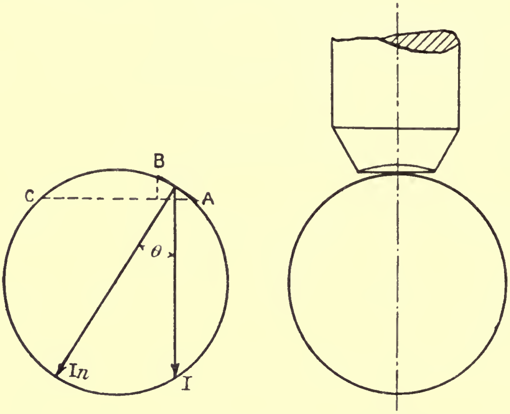

FIG. 4·02.—Light emitted by a Hollow Radiator.

63. **CYLINDRICAL RADIATORS.** — To these sources belong the luminous arcs of arc lamps, mercury vapour lamps, Moore's tube light, straight filaments of incandescent lamps, etc. We assume a uniform intrinsic brilliancy over the mantle surface of the cylinder, which is supposed to be of short length, so that the maximum intensity I_n will be in a direction perpendicular to the axis of the radiator. The intensity of a ray OI will then be expressed by $I_n \sin\theta$, being zero for $\theta = 0$ degrees. The intensity curves of such a cylindrical radiator are circles, with I_n as diameters, and having centres in an axis perpendicular to the axis of the radiator (see fig. 4·03).

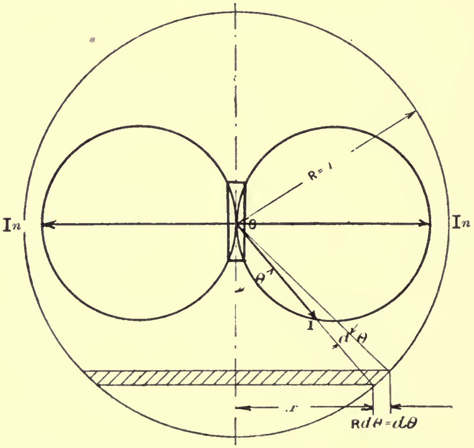

FIG. 4·03.—Light emitted by Cylindrical Radiators.

To find the total flux we proceed as under (61) and obtain :—

$$\text{Length of elementary arc} = Rd\theta = d\theta, \quad \text{for} \quad R = 1.$$

The area swept out by it when rotating it round the vertical axis is

$$2\pi x d\theta = 2\pi R \sin\theta d\theta = 2\pi \sin\theta d\theta,$$

and hence the total flux is

$$\begin{aligned}\phi &= \int_0^\pi 2\pi \mathrm{I} \sin\theta d\theta \\ &= 2\pi \mathrm{I}_n \int_0^\pi \sin^2\theta d\theta \\ &= 2\pi \mathrm{I}_n \times \frac{\pi}{2} \\ &= \pi^2 \mathrm{I}_n \quad . \quad . \quad . \quad . \quad . \quad . \quad 4{\cdot}08\end{aligned}$$

For any angle θ against the vertical, we obtain

$$\begin{aligned}\phi^\theta &= 2\pi \mathrm{I}_n \int_0^\theta \sin^2\theta d\theta \\ &= 2\pi \mathrm{I}_n \left(\frac{\theta}{2} - \tfrac{1}{2}\sin\theta\cos\theta\right) \\ &= \pi \mathrm{I}_n(\theta - \sin\theta\cos\theta) \\ &= \pi \mathrm{I}_n(\theta - \tfrac{1}{2}\sin 2\theta) \quad . \quad . \quad . \quad . \quad . \quad 4{\cdot}09\end{aligned}$$

The mean spherical intensity is given by

$$\begin{aligned}\mathrm{I}_\circ &= \frac{\phi}{4\pi} \\ &= \frac{\pi^2 \mathrm{I}_n}{4\pi} \\ &= \frac{\pi}{4}\mathrm{I}_n \quad . \quad . \quad . \quad . \quad . \quad . \quad 4{\cdot}10\end{aligned}$$

The intrinsic brilliancy follows from

$$\begin{aligned}i &= \frac{\phi}{\text{emitting surface}} \\ &= \frac{\phi}{\pi dl} \\ &= \frac{\pi^2 \mathrm{I}_n}{\pi dl} \\ &= \frac{\pi \mathrm{I}_n}{dl} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad 4{\cdot}11\end{aligned}$$

where d is the diameter and l length of the radiator.

Also

$$\mathrm{I}_n = \frac{dli}{\pi}$$

and

$$\mathrm{I}_{n_1} = \frac{di}{\pi} = \text{maximum intensity per unit length.}$$

When the length of the radiator is of great length, as with Moore's tube lighting, the calculation of the total flux is somewhat more complicated. Assuming that the light is a luminous line concentrated in the axis of the tube, Dr J. Pole * found that the flux may be expressed by

$$\phi = \pi^2 I_n l \qquad . \quad . \quad . \quad . \quad . \quad 4{\cdot}12$$

when the mean spherical intensity results in

$$I_o = \frac{\pi I_n l}{4} \qquad . \quad . \quad . \quad . \quad . \quad 4{\cdot}13$$

64. **HEMISPHERICAL RADIATOR.**—In this case the intensity in a horizontal direction is not zero, but equal to $\frac{1}{2}I_n$, since the projection of the hemisphere upon a vertical plane is equal to a semicircle. For any position intermediate between I_n and $\frac{I_n}{2}$ the intensity is $\frac{I_n}{2} + \frac{I_n}{2}\cos\theta = \frac{I_n}{2}(1 + \cos\theta)$. Fig. 4·04 also indicates that the light above the horizontal, *i.e.* for θ greater than 90 degrees is not zero, since the projection of the luminous area is not zero and only when $\theta = 180$ degrees, or $\cos\theta = -1$, does the light disappear completely. We obtain thus the intensity curve of fig. 4·04. To find the total flux we sweep out again an elementary area $2\pi x d\theta = 2\pi \sin\theta d\theta$ by an elementary arc

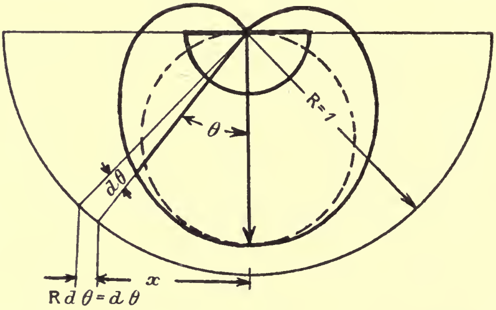

FIG. 4·04.—Light emitted by Hemispherical Radiators.

$$R d\theta = d\theta, \quad \text{for} \quad R = 1,$$

whence

$$\phi = \int_0^\pi 2\pi I \sin\theta d\theta$$

$$= \frac{2\pi I_n}{2}\int_0^\pi \sin\theta(1 + \cos\theta)d\theta$$

$$= 2\pi I_n \qquad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad 4{\cdot}14$$

If we integrate between the limits 0 and $\frac{\pi}{2}$, *i.e.* for the lower hemisphere only, we get

$$\phi = \tfrac{3}{2}\pi I_n .$$

The mean spherical intensity is given by

$$I_o = \frac{\phi}{4\pi} = \frac{2\pi I_n}{4\pi} = \frac{I_n}{2},$$

* *E.T.Z.* 1911, p. 440.

and the mean lower hemispherical candle-power is

$$I_{\circ} = \frac{1\frac{1}{2}\pi I_n}{2\pi} = \tfrac{3}{4} I_n .$$

Comparing the different sources we obtain the following table :—

Table VI.—Fluxes and Maximum Intensities of Various Sources.

	Spherical Radiator.	Plane and Hollow Radiator.	Cylindrical Radiator.	Hemispherical Radiator.
Flux emitted . . .	$4\pi I_n$	πI_n	$\pi^2 I_n$	$2\pi I_n$
Maximum intensity . .	$\frac{\phi}{4\pi}$	$\frac{\phi}{\pi}$	$\frac{\phi}{\pi^2}$	$\frac{\phi}{2\pi}$

From this follows that with the same total flux the intensities of the various sources must be in the following proportions :—

Sphere.	Plane.	Cylinder.	Hemisphere.
1	4	1·28	2

65. **P.D., CURRENT AND LENGTH OF ARC.**—In actual practice we do not obtain the results given here, as part of the light is screened off. For instance, in the case of arc lamps with vertical carbons we find that a considerable portion of the light is screened off by the negative electrode. Obviously the reduction in the light is the smaller the more we reduce the thickness of the negative carbon and the further we separate the electrodes.

Both means are limited. If the current is too large for the cross section of carbon employed, the arc extends up the sides and "hissing" takes place. This is caused by draughts of air which accelerate the combustion of carbon. The temperature of the crater is practically constant and independent of the current; an increase in the latter serves only to enlarge the size of the crater.

An equation connecting length of arc, current, and P.D. required may be obtained by plotting two sets of curves. In the first set we keep the current constant and plot the volts as a function of the length of arc. The resulting curves are approximately straight lines, according to fig. 4·05, which holds for ordinary enclosed arc lamps. These lines intersect in a point for which $V_0 = 38$ volts and $l_0 = -7{\cdot}5$ millimetres. This voltage is constant for all lengths of arc and for all currents. It represents the fall of potential from the negative carbon to the arc, and may be considered of the nature of a back E.M.F. The additional voltage is required for the vapour stream; it is directly proportional to the length of the latter. Expressing the curves by equations, we find

$$V = V_0 + c_1(l + l_0) \quad . \quad . \quad . \quad . \quad 4{\cdot}15$$

in which l = length of arc, l_0 = additional length and is equal to 7·5 millimetres in the example of fig. 4·05, and c_1 is a constant.

In the second set of curves we plot for constant lengths of arc the P.Ds. as functions of the currents and obtain curves having approximately the shape of cubic hyperbolas (see fig. 4·06), with the equations $(V - V_0)^2 I_c = c_2^2$, in which I_c is the current and c_2 a constant. The actual voltage required is then found to be given approximately by

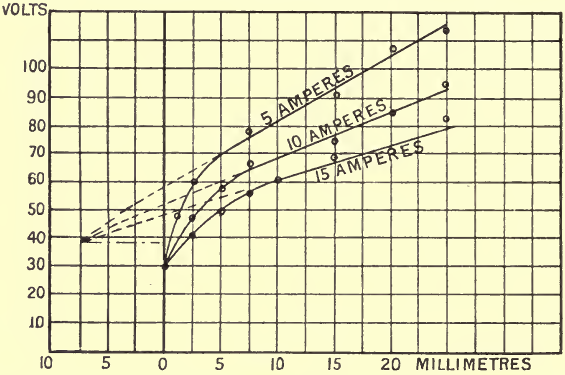

FIG. 4·05.—P.Ds. for Different Lengths of an Enclosed Arc (Current Constant).

$$V = V_0 + c\frac{l + l_0}{\sqrt{I_c}} \quad . \quad . \quad . \quad . \quad . \quad 4{\cdot}16$$

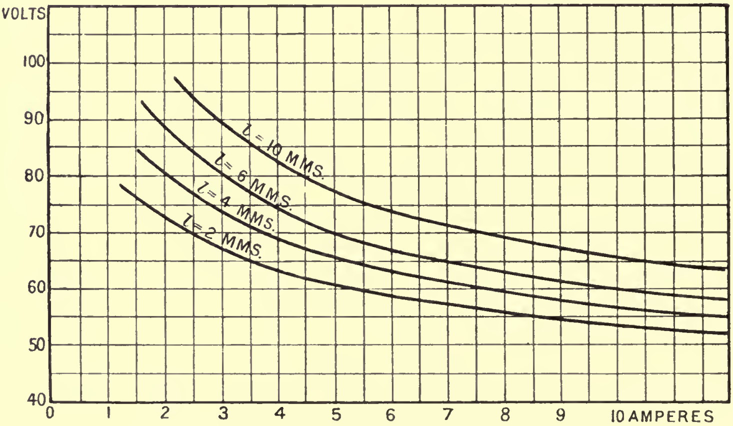

FIG. 4·06.—P.Ds. for the Different Currents of an Enclosed Arc (Length of Arc Constant).

This equation may be also found if we consider the physical conditions of the arc.

We have seen in Chapter II. that the flow of the luminous arc is from the cathode and that the nature of the arc depends on the material of this cathode. To cause this flow at all, a definite voltage V_0 must be applied. It is constant whatever the strength of the current and the length of the arc may be. When the current increases, so does the flow; hence the resistance through which the current passes decreases, keeping the fall of potential from the negative carbon to the arc constant. The power wasted thereby is therefore equal to $P_1 = V_0 I_c$, where I_c is the current.

As regards the arc proper, we may assume that its temperature is approximately constant, so that the power absorbed by it is proportional to the surface of the arc, *i.e.* to $l_1 d$, in which $l_1 = l + l_0 =$ length of arc plus the length l_0. The latter accounts for the heat carried off by the ends of the electrodes. As the diameter of the arc d is equal to $\sqrt{\frac{4S}{\pi}}$, *i.e.* proportional to the square root of the cross section S of the vapour column, and as S is proportional to the current by which the vapour is produced, it follows that d is proportional to $\sqrt{I_c}$. We have therefore:—

$$\begin{aligned}\text{Power absorbed by the arc proper} = P_2 &= c_2 l_1 d \\ &= c_2(l + l_0)d \\ &= c_2 c_3 (l + l_0)\sqrt{I_c} \\ &= c(l + l_0)\sqrt{I_c},\end{aligned}$$

$$\text{and the total power} = P = P_1 + P_2 = V_0 I_c + c(l + l_0)\sqrt{I_c},$$

whence

$$V = V_0 + c\frac{l + l_0}{\sqrt{I_c}}.*$$

It will be noticed in fig. 4·05 that, if we reduce the length of the arc below 7 millimetres, the lines bend downwards, intersecting approximately at 30 volts in the ordinate axis. This does not occur with the mercury vapour and the magnetite lamps. In both these cases consumption of the positive pole does not take place, hence it would appear that the disturbing factor lies at the positive electrode of the ordinary arc lamp. It is feasible to assume that the constant voltage $V_0 = 38$ volts is not totally absorbed at the negative carbon, but only to the extent of 30 volts, and that the difference of 8 volts is necessary to overcome the layer of mist near the positive carbon caused by the evaporation of this electrode.

The constants in equation 4·16 vary with the nature of the arc. Approximate values are given in the accompanying table.

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* The equation given by Mrs Ayrton of the P.D. for the electric arc in her well-known treatise on the electric arc is

$$V = V_0 + cl + \frac{c_1 + c_2 l}{I_c}$$

in which V_0, c, c_1, and c_2 are constants.

TABLE VII.—CONSTANTS FOR ARC LAMPS.

	Ordinary Carbon Arc.	Enclosed Carbon Arc.	Flame Arc.*	Magnetite Arc.	Vapour Arc.
V_0	$8_+ + 28_- = 36$	$8_+ + 30_- = 38$	12	31	$8_+ + 5_- = 13$
l_0	6 mms. (0·24 in.)	7·5 (0·3)	5 (0 2)	2 (0·08)	
c	5 (127)	5 (127)	4 9 (124·5)	4·8 (122)	

66. **STEADINESS OF THE ARC.**—From equation 4·16 it follows that an arc lamp cannot be worked on a voltage which is just sufficient for the current for which the lamp is built. As the electrodes are consumed, the length of the arc increases, hence for a constant P.D. at the terminals the current ought to increase (since V_0 is constant), keeping the second member of the equation constant. As however the resistance of the arc increases with its length it follows that the current must decrease, *i.e.* the second member increases so that, as V is constant, this increase takes place at the expense of V_0, and the voltage is therefore insufficient for maintaining the arc stream, and thus the lamp is extinguished. On the other hand, a slight increase in the current reduces the fall of P.D. across the arc proper, so that a decrease in the resistance takes place on account of increased production of vapour, thereby augmenting the rise in the current which goes on until the lamp short-circuits. We require, therefore, ballast or steadying resistances which prevent these variations. Moreover, without steadying resistances arc lamp mechanisms would not work. On constant potential the current of the shunt coil would also be constant and the coil thus useless.

Consider a 10-ampere flame arc lamp (of which two are usually joined in series to a 100-volt circuit). For a 5-millimetre arc the lamp itself requires 27·5 volts (see curve 1 of fig. 4·07). If we join in series with it a resistance of 2 ohms, then the voltage absorbed by the latter will be represented by the straight line in fig. 4·07. By adding curves 1 and 2 we obtain curve 3. We see that below 5 amperes the voltage actually increases with a decrease of current, hence this part of curve 3 represents the unstable condition of the lamp. Where the curve is flat, small variations in the voltage cause comparatively large current fluctuations, and it is evident that the lamp should not be worked below 8 amperes. The fluctuations could be somewhat checked by winding the steadying resistance on an iron core; the inductive effect then opposes rapid variations of the current.

The steadying resistance has the disadvantage that it absorbs power. To reduce this waste, we join as many lamps in series as possible, say three flame lamps on a circuit of 110 volts. The lamps then absorb $3 \times 27{\cdot}5 = 82{\cdot}5$ volts, so that 27·5 volts are left for the resistance. With 10 amperes this

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* The constants for this type of lamp vary considerably.

means a ballast resistance of 2·75 ohms. The conditions are represented in fig. 4·08. The total voltage curve has now become extremely flat, and the stability limit has been shifted from 5 to 8·5 amperes. The mechanism of such lamps should be extremely sensitive, *i.e.* the lamps should feed for very slight variations in the current or voltage.

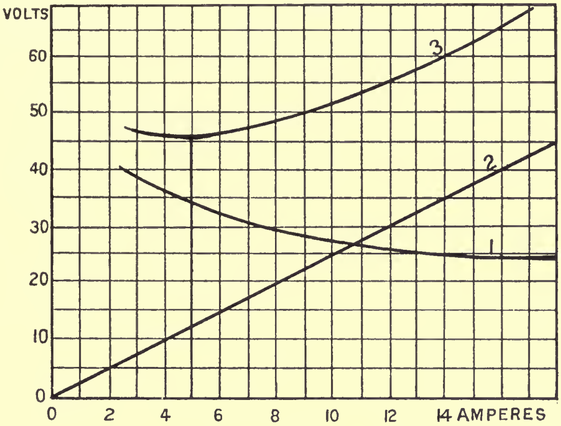

FIG. 4·07.—Flame Arc Lamp and Steadying Resistance.

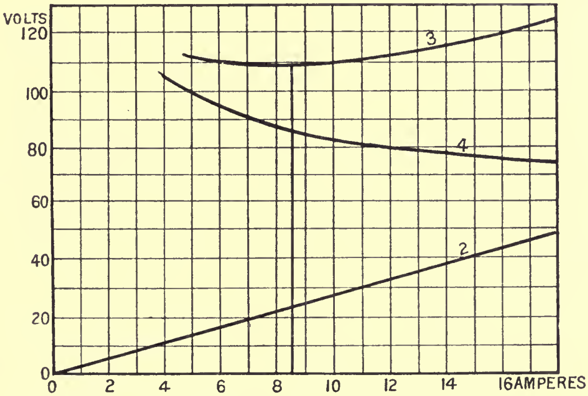

FIG. 4·08.—Three-Flame Arcs in Series on 110 Volts.

The minimum voltage required to reach the stability limit is equal to the total voltage required by the lamp plus half its variable part, *i.e.*,

$$V_{\text{min.}} = V + \tfrac{1}{2}c\frac{l+l_0}{\sqrt{I}} \quad . \quad . \quad . \quad . \quad . \quad 4\cdot17$$

Thus in fig. 4·07 we have

$$V = 33 = V_0 + c\frac{l+l_0}{\sqrt{I_c}} = 12 + 21 \text{ (for 5 amperes)},$$

and

$$V_{\text{min.}} = 33 + \tfrac{1}{2} \times 21 = 43{\cdot}5 \text{ volts.}$$

In fig. 4·08

$$V = 3 \times 12 + 3 \times 16 = 84 \text{ (for 8·5 amperes),}$$

and

$$V_{\text{min.}} = 84 + \tfrac{1}{2} \times 3 \times 16 = 108 \text{ volts.}$$

The lamps should therefore feed when the voltage variation is less than 2 volts, or $\frac{2}{3}$ of a volt per lamp. A better result would be obtained with 12 ampere lamps. In this case the minimum voltage would be $3 \times 12 + 3 \times 14 + \frac{1}{2} \times 3 \times 14 = 99$ volts, leaving a considerable margin.

It should be noted that the above deductions hold for an arc of 5 millimetres length. To change a lamp from 10 to 12 amperes would necessitate alterations in the mechanism of the lamp, especially if the same be supplied with a series solenoid. Also the carbons would have to be enlarged, as otherwise hissing might occur.

Formula 4·17 may be proved as follows:—The slope of curve 3 is nil for 5·5 amperes. It is the resultant of the slopes of curves 1 and 2 which are equal and opposite for this point. We have

$$\frac{dV_{\text{min.}}}{dI_c} = \frac{dV}{dI_c} + \frac{dV_R}{dI_c} = 0.$$

But

$$\frac{dV}{dI_c} = -\tfrac{1}{2}c\frac{l + l_0}{I_c^{\frac{3}{2}}} \text{ (see equation 4·14),}$$

and

$$\frac{dV_R}{dI_c} = R = \text{resistance of steadier,}$$

hence

$$R = \tfrac{1}{2}c\frac{l + l_0}{I_c^{\frac{3}{2}}}.$$

The total voltage required for the stability minimum is therefore

$$V_{\text{min.}} = V + I_cR = V + \tfrac{1}{2}c\frac{l + l_0}{\sqrt{I_c}}.$$

67. **LENGTH OF ARC.**—In the ordinary direct current arc lamp it is the positive electrode which produces the maximum amount of light. In the open type lamp the incandescent crater is responsible for about 85 per cent. and its light is given with a high efficiency, since the temperature of the carbon of the crater is very close to that of the melting-point. The formation of the crater is facilitated by providing the positive electrode with a core of less dense material. This also reduces somewhat the P.D. required by the lamp, on account of an increase in the conducting vapour. Unfortunately, not all the light of the crater becomes available, since the lower carbon, the negative electrode, screens off a large part of it. The amount is the larger the closer we bring the carbons together. It would therefore appear that we could increase the efficiency by burning the lamp with an arc as long as possible. This is not the case, since with an increase

in the length of the arc the P.D. and the power required to maintain the arc increase also. There is therefore a limit to the length of the arc. The best results are obtained when in the open type arc the length is about 3 millimetres ($\frac{1}{8}$ inch). That we can bring the carbons so closely together is due to the fact that the negative carbon burns to a conical shape, as is illustrated in fig. 4·09, and thereby reduces the shadow which it throws. In the enclosed arc lamp, both carbons remain flat, as the pressure inside the globe prevents the temperature from rising to the high value of the open arc and thus combustion is reduced to a minimum by the partial absence of oxygen inside the inner globe. To obtain the maximum amount of light for a given expenditure of power, the length of the arc must be increased to about 10 millimetres ($\frac{3}{8}$ inch). As the temperature of the enclosed arc is lower than that of the open type it follows that its efficiency is less, but this is largely counterbalanced by the smaller consumption of carbons (one pair lasting from 80 to 200 hours against 10 to 16 for the open type) and especially by the reduced amount of labour required for re-carboning. Where wages are high it pays to use the enclosed arc, and it is for this reason that the open type lamp has practically disappeared in North America. Where labour is cheap and coal expensive, high efficiency open arcs are chiefly used.

In alternate current lamps the polarity of the poles changes continually, hence the high temperature of the positive carbon of the D.C. arc is never reached. An alternate current lamp has therefore a somewhat low efficiency. The increase in specific consumption is partly counterbalanced by the application of choking coils instead of steadying resistances, which absorb less power than the latter.

Since the advent of the tungsten filament incandescent lamp the ordinary arcs are being gradually ousted from the market, as their efficiencies are very little higher than those of metal filament lamps if we take into consideration the power wasted in the steadying apparatus, the absorption by diffusing globes, and the expense for re-carboning. By impregnating the carbons with chemicals we can however increase the conductivity, and consequently also the production of the vapour, and lower simultaneously the P.D. required, as may be seen from Table VII. The first chemically treated carbons were placed on the market by Bremer in 1898, and to-day hardly any other lamps are installed. In these so-called flame-lamps the chief source of light lies no longer in the crater of the positive carbon, which has been much reduced, but in the vapour stream itself, as will be seen from the accompanying fig. 4·10. The light coming from the crater is only about one-fourth or one-third of the total light emitted. The efficiency is however always increased when passing from incandescence (or light due to heat evaporation) to light caused by luminescence, since in the latter case the stream may be made to consist entirely of luminescent particles whereas the carbon vapour of the ordinary arc largely absorbs the light. The carbons are often placed side by side at inclinations varying from 15 to 25 degrees. This greatly reduces the amount of light screened off by the carbons and adds to the efficiency of the lamp.

As the light comes largely from the flame itself, it is due to luminescence and this means that the electrical energy is converted directly into radiations. The colour of the arc will therefore depend chiefly upon the nature of the salts with which the carbons are impregnated. The salts generally employed are calcium fluoride, oxides, sodium, and borates, causing the light to be of an intense yellow. The lamps are frequently equally suitable for direct and alternate currents. As the light is largely due to luminescence it might appear that such lamps are unsuitable for alternate currents. This would be the case if the chemicals were used by themselves. The presence of the carbon however forms the bridge required by the alternate current as long as the frequency is not too low.

Fig. 4·09.—Open Arc.

Fig. 4·10.—Arc of a Flame Arc Lamp.

68. **REGENERATIVE LAMPS.**—The consumption of the carbons in flame arcs is fairly rapid, especially as the carbons are very thin compared with those of the ordinary type of lamp. This reduced thickness is essential as the luminescent particles have to be set free by heat evapora-

tion, and this is only possible if the whole of the tip is incandescent. The hot tips must therefore consume very rapidly. To enclose the carbons in an air-tight globe, similar to those of the ordinary carbon lamp, is difficult, because the luminescent particles condense to a smoke and deposit on the globe, thereby obstructing the light. Nevertheless enclosed flame arcs are now built; they are provided with sufficient ventilation to carry the smoke to a special depositing tube. The oxygen is partly excluded by using the same air over and over again. Lamps of this nature are called "Regenerative."

Although the flame arc has a much higher efficiency than the ordinary arc—it uses only from one-fourth to one-third of a watt per candle—in the author's opinion the lamp is overrated. The deposit from the lamp in the shape of a white opaque powder is considerable, and unless the lamps are cleaned almost daily it will be found that the light is obstructed to such an extent that the increased efficiency is mostly lost. As long as the cleansing is frequent, the deposit collects chiefly at the bottom of the globe where it does little harm (for the reason, see polar curves of Chapter V.), but when it extends up the sides the absorption of light accelerates.

For street lighting a lamp with a polar curve that has its maximum intensity in a downward direction is not altogether desirable, since it causes a high illumination near the lamp and semi-darkness halfway between lamps. The uniformity of the illumination is then of a poor order. It can be somewhat improved by fixing the lamps on very high poles. As the carbons consume very rapidly, it will be found that on long winter evenings the lamps do not hold out until the next morning, but must be recarboned during the night, which results in additional expenditure. Moreover, the fumes which are given off have a deteriorating effect on the surrounding globes and cause a clear glass globe to become gradually frosted, so that with time more and more light is absorbed. It is also difficult to provide a mechanism for inclined carbons which maintains such stable light as for vertical electrodes.

69. **ALBA FLAME LAMP.**—The disadvantages of the flame arc with inclined carbons have been largely overcome in the so-called Alba or T.B. flame lamp.* The electrodes of this lamp are of the usual thickness (about 16 millimetres—$\frac{5}{8}$ inch) placed vertically, but only the shell consists of carbon, to a thickness of about 2 millimetres, the remainder being chemicals. As a result, nearly the whole of the light comes from the luminescent arc, and the distribution is, in consequence, far more suitable for street lighting. In fig. 4·11 the polar curves of three arc lamps for 15 amperes and 825 watts are compared.

On account of the increased thickness in the electrodes, the Alba lamp lasts from 20 to 30 hours before recarboning is required. The light of the lamp is also much whiter than that of the ordinary flame arc, owing to a greater percentage of blue rays, and consequently it is more suitable for street lighting, although perhaps less so for advertising purposes. The

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* Manufactured by Siemens.

globe is kept clear for a considerable time by providing excellent ventilation, which prevents the smoke from depositing on the inside. On account of the small amount of pure carbon employed, the lamp is unsuitable for alternate currents.

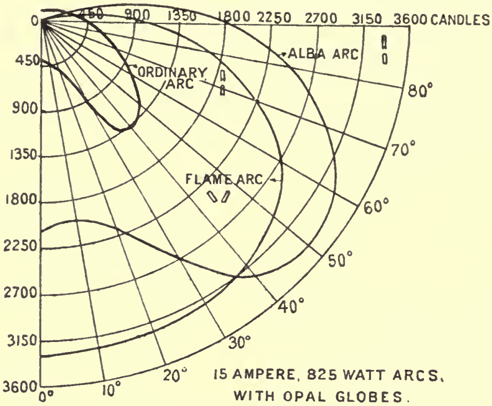

FIG. 4·11.—Polar Curves of Arc Lamps with Opal Globes.

In the magnetite arc lamp nearly all the light comes from the vapour stream and the length of the arc is limited only by the expenditure of power. The current usually employed is about 4 to 5 amperes, when the voltage is 80 to 75 volts and the length of the arc about 18 millimetres. Longer and thinner arcs are not very steady, as they are more affected by air currents.

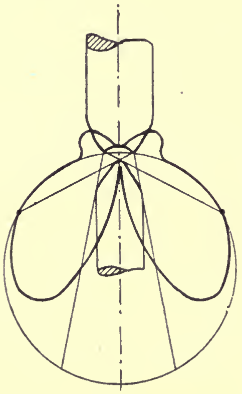

FIG. 4·12.—Screening Effect of the Lower Carbon in a D.C. Ordinary Arc Lamp.

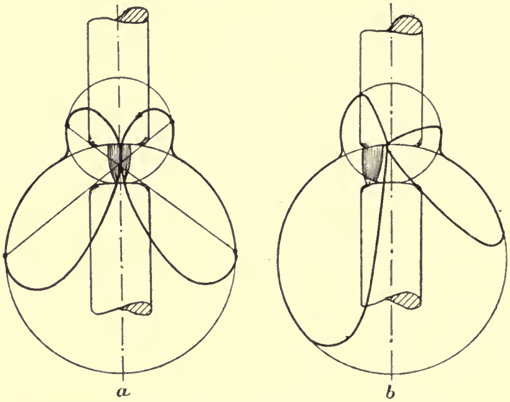

FIG. 4·13.—Screening Effect of the Lower Carbon in a D.C. Enclosed Arc Lamp.

70. INFLUENCE OF THE SCREENING EFFECT OF THE LOWER CARBON ON THE LIGHT DISTRIBUTION OF ARC LAMPS.

—The screening effects of the lower carbons are illustrated in figs. 4·12 to 4·14.

Fig. 4·12 represents the ordinary direct current arc; fig. 4·13, *a* and *b*, the enclosed type; fig. 4·14 the alternate current arc. From the latter we see that the light thrown upwards is as large as that emitted into the lower hemisphere and would therefore be wasted. A suitable reflector however directs it downwards, causing the resultant distribution as shown by the thick curve.

Fig. 4·13*a* is drawn with the arc in the centre of the carbons. In reality the arc travels round the electrodes so that the light distribution varies considerably, according to fig. 4·13*b*, in which the arc happens to be near the left edge.

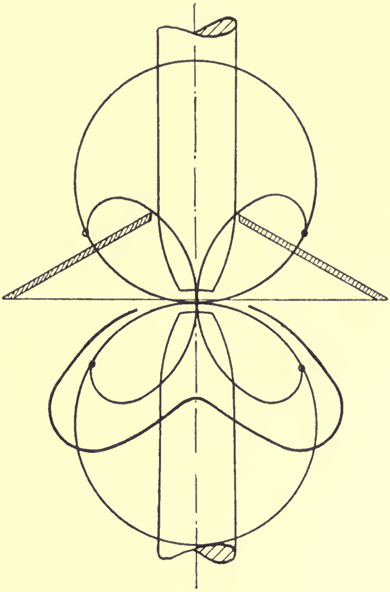

FIG. 4·14.—Screening Effect of the Lower Carbon in an Alternate Current Arc Lamp.

71. REFLECTION OF LIGHT.—Reflection of light is regular or irregular. Regular reflection is caused by mirrors, irregular by diffusing surfaces such as drawing-paper, whitewash, etc. In the former case the impinging ray is reflected with the same angle with which it strikes the reflector, but with loss of intensity, the reflected ray being weaker than the impinging ray. We thus have $I_r = KI$, in which K is the reflection coefficient. If we surround a source of light with suitable reflectors, we can redistribute the light and direct it in any desired way. The subject will be considered fully in Chapter VI., under "Design of Reflectors."

Of greater importance than regular, is irregular or diffused reflection. In this case the light is scattered, and, instead of dealing with intensities, we must now consider the fluxes. If a flux ϕ strikes a diffusing surface S, it is reflected in all directions, but not without loss.

We have

$$\phi_r = K\phi ,$$

in which K represents now the diffuse reflection coefficient. The area S is a second radiator with the flux $K\phi$.

72. REFLECTION IN A SPHERE.—Consider the simplest case, a white diffusing hollow sphere with a radiating surface ΔS, for which the polar curve (1) is a circle (see fig. 4·15).

The impinging ray I has the intensity $I_n \cos\theta$, and as the angle of incidence on ΔS_1 is θ, we obtain for the illumination of ΔS_1 the value

$$E^1 = \frac{I_n}{L_1^2}\cos^2\theta .$$

But

$$\cos\theta = \frac{L_1}{2R},$$

where R is the radius of the sphere; hence

$$\cos^2\theta = \frac{L_1^2}{(2R)^2},$$

and

$$E^1 = \frac{I_n}{L_1^2} \times \frac{L_1^2}{(2R)^2} = \frac{I_n}{(2R)^2} \quad . \quad . \quad . \quad . \qquad 4{\cdot}18$$

The normal illumination is

$$\frac{I_n}{(2R)^2} = E,$$

whence it follows that the sphere is uniformly illuminated. The total flux is therefore given by

$$\phi = SE,$$

where S is the area of the sphere.

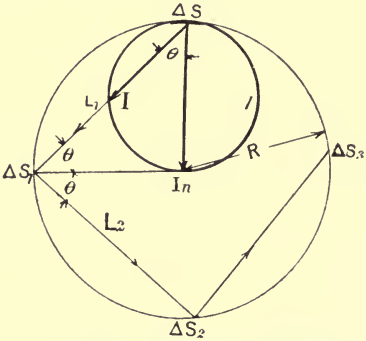

FIG. 4·15.—Reflection in a Sphere.

So far we have neglected reflection altogether. The flux ϕ which strikes unit area of the sphere is reflected the first time as $K\phi$, and as this applies to all parts of the sphere the illumination is increased uniformly to the extent of $K\frac{\phi}{S}$. On emerging again the flux is reduced to $K^2\phi$ so that the second increase in the illumination of the sphere will be $K^2\frac{\phi}{S}$. This reflection goes on indefinitely, causing a total illumination of the sphere

$$E = \frac{\phi}{S} + K\frac{\phi}{S} + K^2\frac{\phi}{S} + \cdot\cdot\cdot\cdot\cdot\; K^{\infty}\frac{\phi}{S}$$

$$= \frac{\phi}{S}\left(1 + K + K^2 + \cdot\cdot\cdot\cdot\cdot\; K^{\infty}\right).$$

As K is less than unity,

$$1 + K + K^2 + \cdot\cdot\cdot\cdot\; K^{\infty} = \frac{1}{1-K},$$

whence

$$E = \frac{\phi}{S}\left(\frac{1}{1-K}\right) \quad . \quad . \quad . \quad . \quad . \qquad 4{\cdot}19$$

Let $K = 1 - a$, where a is the absorption, then

$$\frac{1}{1-K} = \frac{1}{a},$$

and

$$E = \frac{\phi}{Sa} \quad . \quad . \quad . \quad . \quad . \quad . \quad 4{\cdot}20$$

These equations apply of course to spherical chambers only, but they indicate that for all rooms we get considerable assistance from reflection if we employ surfaces with large reflection coefficients. In the following table, the values of K, a, and $\frac{1}{a}$ have been plotted.

TABLE VIII.—REFLECTION OF LIGHT.

Reflection Coefficient, K.	Absorption Coefficient, a.	Factor of Increase, $\frac{1}{a}$.
1·0	0	...
0·95	0·05	20·0
0·90	0·10	10·0
0·85	0·15	6·67
0·80	0·20	5·0
0·75	0·25	4·0
0·70	0·30	3·33
0·65	0·35	2·85
0·60	0·40	2·50
0·55	0·45	2·22
0·50	0·50	2·0
0·45	0·55	1·81
0·40	0·60	1·67
0·35	0·65	1·53
0·30	0·70	1·42
0·25	0·75	1·33
0·20	0·80	1·25
0·15	0·85	1·17
0·10	0·90	1·11
0·05	0·95	1·05
0	1·0	1·0

The next table shows a number of diffuse reflection and absorption coefficients for various colours, as given by Dr L. Bell, in the Convention issue of the American Illuminating Engineering Society.* The table holds chiefly for wall-papers illuminated by incandescent lamps.

On studying this table we see that the light cream and yellow colours are by far the best, that apparently *light colours* such as grey and green absorb the light in an astonishing fashion, which is due to the fact that grey colours usually contain a mixture of black and red. The table was compiled for different finishes, but there appears to be little difference for all except for silk finishes, which absorb the light strongly. A polished

---

* See also the *Illuminating Engineer*, 1908, p. 72.

TABLE IX.—TABLE OF DIFFUSE REFLECTION. (BELL.)

Colour.	K.	a	$\frac{1}{a}$.
Very faint grey-cream . .	0·64	0·36	2·77
Deep cream	0·60	0·40	2·5
Deep buff	0·58	0·42	2·38
Deep cream silvery . .	0·57	0·43	2·32
Faint ecru	0·55	0·45	2·22
Faint greenish . . .	0·53	0·47	2·12
Yellow medium . . .	0·53	0·47	2·12
Light yellow . . .	0·49	0·51	1·96
Light strawberry silvery .	0·49	0·51	1·96
Light bluish . . .	0·47	0·53	1·89
Light strawberry-pink .	0·43	0·57	1·75
Light grey	0·38	0·62	1·61
Faint yellow-green-grey .	0·33	0·67	1·49
Salmon-buff . . .	0·33	0·67	1·49
Pale bluish white . .	0·31	0·69	1·45
Light green and gold . .	0·28	0·72	1·38
Pale grey	0·27	0·73	1·37
Light ecru	0·26	0·74	1·35
Light green (stripes) . .	0·26	0·74	1·35
Silvery light green . .	0·23	0·77	1·3
Light grey-green . .	0·23	0·77	1·3
Pale pink	0·19	0·81	1·24
Light green (cartridge) .	0·18	0·82	1·22
Deep yellow-grey . .	0·15	0·85	1·18
Medium crimson . . .	0·12	0·88	1·14
Light red	0·10	0·90	1·11
Medium red	0·08	0·92	1·09
Deep green	0·06	0·94	1·06
Full green	0·06	0·94	1·06
Deep red	0·05	0·95	1·05

silver mirror has a reflection coefficient of 0·90 to 0·95. White blotting-paper absorbs 18 per cent. of light, polished brass 25 to 30 per cent.

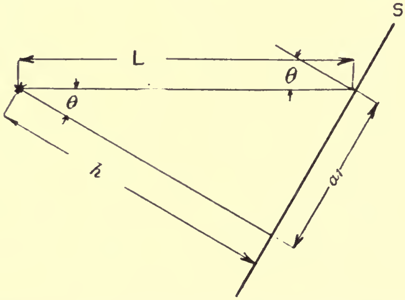

FIG. 4·16.—The Illumination of an Inclined Plane.

73. **ILLUMINATION—FUNDAMENTAL CONSIDERATION.**—The illumination E of an elementary area by an intensity I is expressed by

$$E = \frac{I}{L^2} \cos \theta \text{ (see equations 1·02 and 1·08),}$$

in which θ is the angle of the incident ray with the normal to the illuminated area, and L the distance of the source from this area. Consider the plane S in fig. 4·16. We see that

$$L^2 = a_1^2 + h^2,$$

and

$$\cos\theta = \frac{h}{\sqrt{a_1^2 + h^2}},$$

whence

$$E = \frac{I}{a_1^2 + h^2}\cos\theta$$

$$= \frac{I}{h^2}\cos^3\theta \quad . \quad . \quad . \quad . \quad 4{\cdot}21$$

$$= \frac{Ih}{(a_1^2 + h^2)^{\frac{3}{2}}} \quad . \quad . \quad . \quad . \quad 4{\cdot}22$$

This holds for any plane, whether horizontal, vertical, or inclined.

74. HORIZONTAL ILLUMINATION.

—Consider a source L_0 fixed at a distance h above the area S to be illuminated. The illumination of any point P in this horizontal plane is then given by

$$E_h = \frac{I}{h^2}\cos^3\theta,$$

in which θ is the angle by which the ray is inclined to the vertical.

For the evaluation of E_h it is convenient to know the values of $\cos\theta$ and $\cos^3\theta$ for various values of θ, especially if we know the intensities of the illuminant under different angles against the vertical.

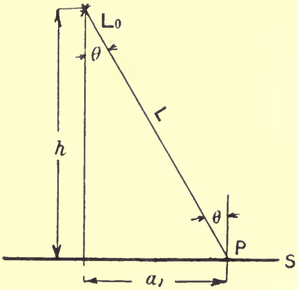

FIG. 4·17.—The Illumination of a Horizontal Plane.

TABLE X.—VALUES OF $\cos\theta$, $\cos^2\theta$, $\cos^3\theta$, AND $\cos^4\theta$.

Angles.	Cos θ.	Cos² θ.	Cos³ θ.	Cos⁴ θ.
0	1·0	1·0	1·0	1·0
5	0·996	0·991	0·988	0·982
10	0·985	0·970	0·956	0·939
15	0·966	0·933	0·901	0·870
20	0·940	0·883	0·830	0·780
25	0·906	0·822	0·745	0·676
30	0·866	0·750	0·649	0·563
35	0·819	0·671	0·550	0·450
40	0·766	0·587	0·450	0·345
45	0·707	0·500	0·354	0·250
50	0·643	0·413	0·266	0·171
55	0·574	0·329	0·189	0·108
60	0·500	0·250	0·125	0·0625
65	0·423	0·179	0·076	0·0320
70	0·342	0·117	0·040	0·013
75	0·259	0·067	0·0173	0·00449
80	0·174	0·0302	0·00524	0·000912
85	0·087	0·0076	0·00066	0·0000578
90	0·000	0·000	0·000	0·000

As an example take the Alba lamp of fig. 4·11, for which the intensities in the lower hemisphere are as follows:—

Angle against the Vertical.	Intensity in Candles.
0 degrees	2070
10 ,,	1980
20 ,,	2160
30 ,,	2700
40 ,,	3330
50 ,,	3420
60 ,,	3300
70 ,,	3000
80 ,,	2470
90 ,,	1820

If this lamp be fixed on poles 15 metres high, the ground illumination will be represented by fig. 4·18.

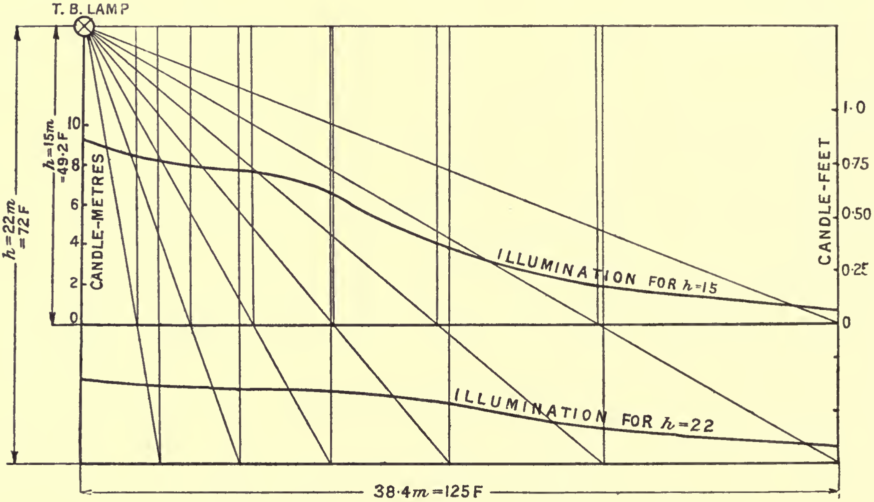

FIG. 4·18.—Illumination caused on the Road Surface by an Alba Lamp fixed on Poles 15 metres high.

We see that the illumination is a maximum for $\theta = 0$ degrees. Suppose that the lamp is to give a uniform illumination over a radius of 30 metres, what ought then to be the shape of the polar curve?

We obtain

$$I = \bar{E}_h \frac{h^2}{\cos^3 \theta} \quad . \quad . \quad . \quad . \quad . \quad 4{\cdot}23$$

$$= \bar{E}_h \frac{(a_1{}^2 + h^2)^{\frac{3}{2}}}{h} \quad . \quad . \quad . \quad . \quad 4{\cdot}24$$

in which $\bar{E}_h$ represents now the uniform illumination. For $\bar{E}_h = 6$ candle-metres and $h = 15$ metres, the result is illustrated in fig. 4·19.

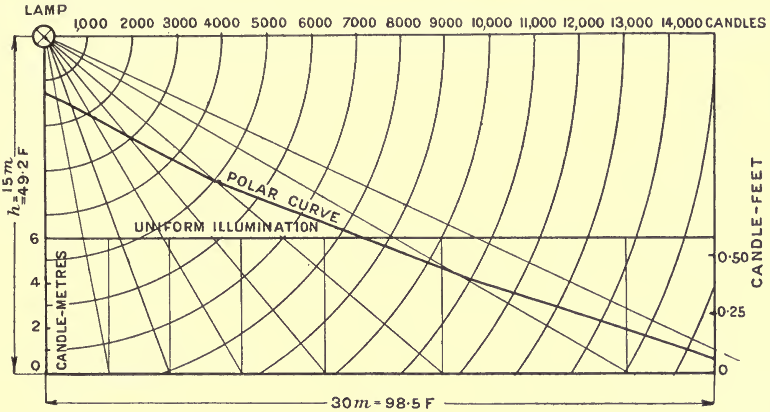

Fig. 4·19.—Polar Curve of an Arc Lamp for Uniform Illumination.

The two examples show that, if we wish to produce a uniform illumination, the light flux must be chiefly directed towards the horizontal through the centre of the arc.

75. **NUMBER OF LAMPS REQUIRED.**—In most cases the illumination by a single lamp is insufficient, and a number of lamps are required.

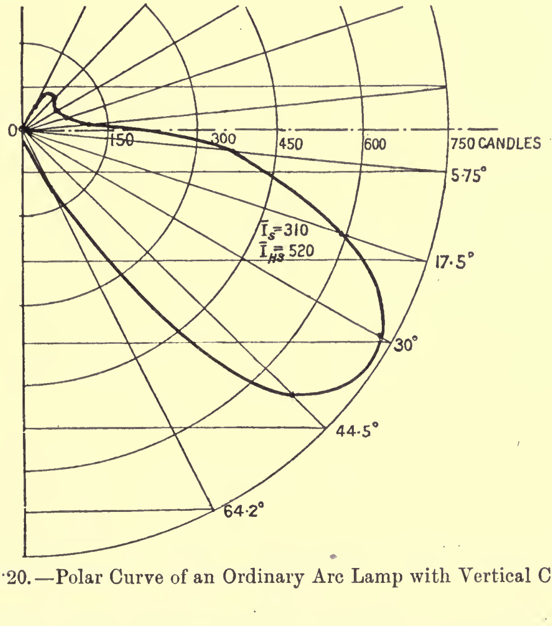

Fig. 4·20.—Polar Curve of an Ordinary Arc Lamp with Vertical Carbons.

The area which can be effectively illuminated by a single lamp depends upon the size of the lamp, the illumination required, the height of the lamp above the area, and the distribution of the light. When a number of lamps take part in the illumination, we must plot the illumination curve of each lamp and add the ordinates. For two lamps with polar curves as shown in fig. 4·20, we obtain the fig. 4·21.

If we have a single symmetrical source of light (with diffusing globes we may assume most sources to be symmetrical), the illumination will be the same for all points equidistant from the source. If we join all these points, we obtain the so-called contour or equipotential lines, which in this case are circles. Fig. 4·22 represents the contour lines obtained from an arc lamp with a polar curve as shown in fig. 4·20. Fig. 4·23 shows the contour lines for two arc lamps obtained by adding the values of two such figures as 4·22, and fig. 4·24 for three lamps placed at the corners of an equilateral triangle. The lamps are fixed in all cases 10 metres (32·8 feet) above the illuminated area.

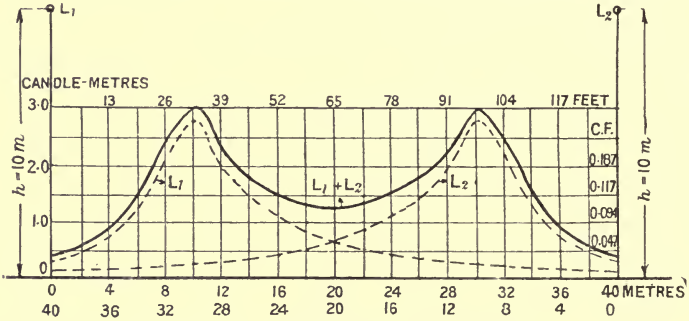

FIG. 4·21.—Illumination by Two Lamps.

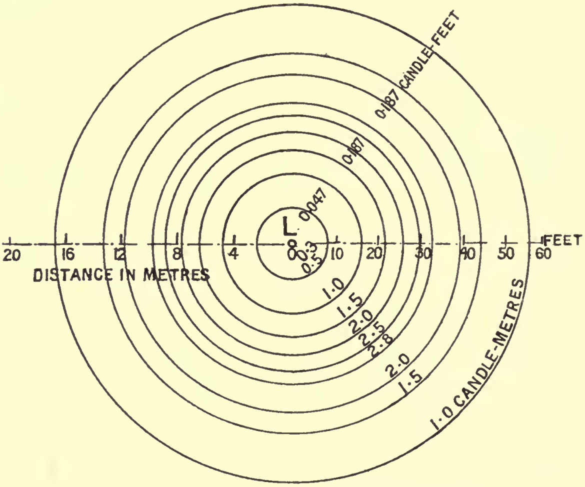

FIG. 4·22.—Contour Lines for Single Lamp.

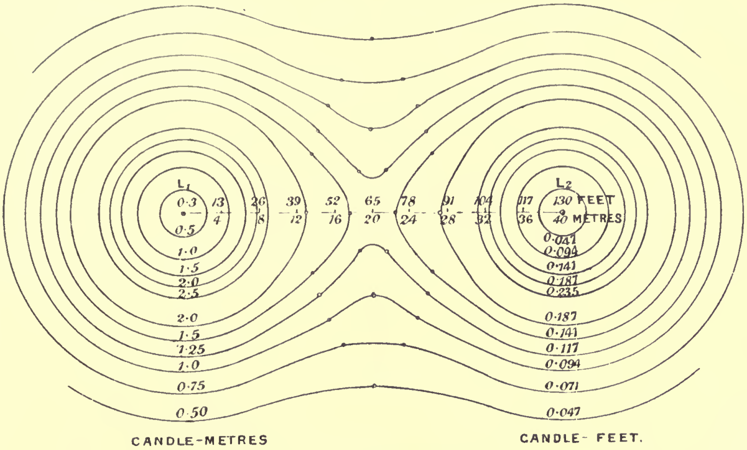

FIG. 4·23.—Contour Lines for Two Arc Lamps.

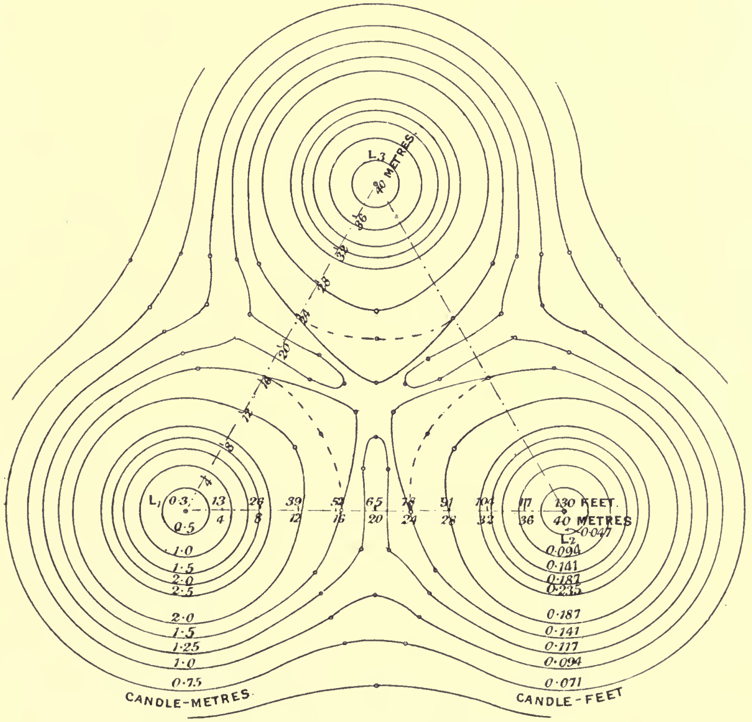

FIG. 4·24.—Contour Lines for Three Arc Lamps.

The variation in the illumination for different heights of the illuminant is illustrated in fig. 4·18. We have

$$E_{h_1} = \frac{I}{h_1^2}\cos^3\theta, \quad E_{h_2} = \frac{I}{h_2^2}\cos^3\theta,$$

whence for the same ray

$$\frac{E_{h_1}}{E_{h_2}} = \frac{h_2^2}{h_1^2} \quad . \quad . \quad . \quad . \quad . \quad 4{\cdot}25$$

i.e. the horizontal illuminations vary inversely as the square of the heights of the lamps, so that we can easily find the illumination for a given height

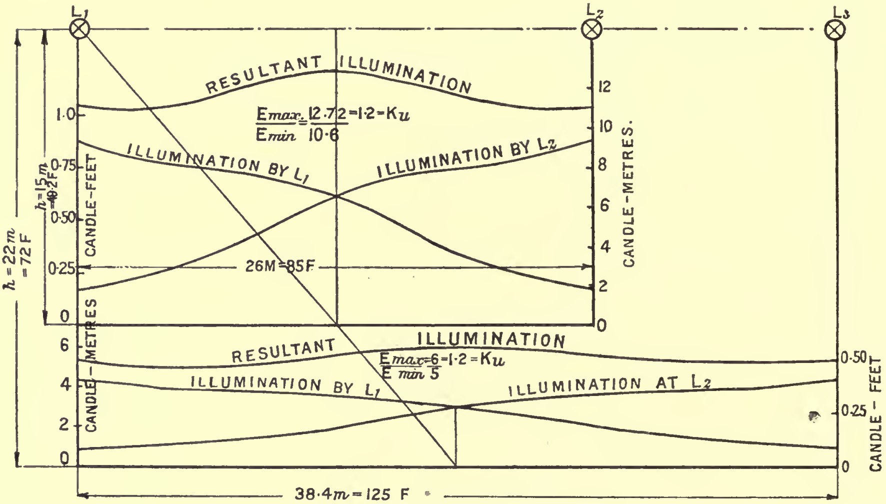

FIG. 4·25.—Uniformity of Illumination.

and type of lamp if the illumination is known for any other height. We have

$$E_{h_1} = E_{h_2}\frac{h_2^2}{h_1^2}.$$

It is also useful to know how the illumination varies if a lamp is replaced by another having the same distribution but a greater or smaller intensity.

$$E_{h_1} = \frac{I_1}{h^2}\cos^3\theta,$$

$$E_{h_2} = \frac{I_2}{h^2}\cos^3\theta,$$

whence

$$\frac{E_{h_1}}{E_{h_2}} = \frac{I_1}{I_2} \quad . \quad . \quad . \quad . \quad . \quad 4{\cdot}26$$

i.e. the illuminations vary directly as the intensities.

If the illumination is to be given by two similar lamps, its uniformity is not altered if we alter the heights of the lamps as long as we vary the distance between them in a similar manner, *i.e.* as long as $\frac{h_1}{h_2} = \frac{a_1}{a_2}$ (see fig. 4·25). The degree of uniformity of the illumination may be expressed by the following ratio :—

$$K_u = \frac{\bar{E}_{max}}{\bar{E}_{min}} \quad . \quad . \quad . \quad . \quad . \quad . \quad 4{\cdot}27$$

It is sometimes called the diversity factor. The nearer its value lies to unity, the greater is the uniformity of the illumination. In determining K_u, average maximum and minimum values should be taken, not freaks.

76. **VERTICAL ILLUMINATION.**—The illumination given by the source L_0 at any point P on the vertical plane S is expressed by (see fig. 4·26)

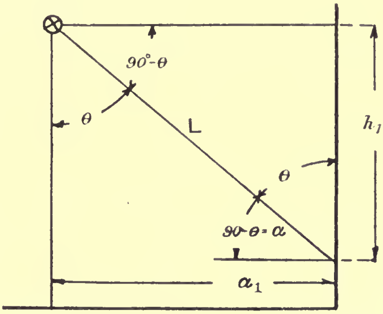

FIG. 4·26.—Illumination on a Vertical Plane.

$$E_v = \frac{I}{L^2} \sin \theta,$$

and as

$$L^2 = h_1{}^2 + a_1{}^2 = \frac{a_1{}^2}{\sin^2 \theta},$$

we obtain

$$E_v = \frac{I}{a_1{}^2} \sin^3 \theta \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad 4{\cdot}28$$

$$= \frac{I a_1}{(h_1{}^2 + a_1{}^2)^{\frac{3}{2}}} \quad . \quad . \quad . \quad . \quad . \quad . \quad 4{\cdot}29$$

The determination of the illumination of a vertical plane offers therefore nothing new. We may even use Table X. if we call the angle (90° − θ) = α and replace in the table θ by α.

77. **INDIRECT ILLUMINATION.**—The greatest degree of uniformity in the illumination is obtained when employing the indirect method. By means of a reflector below the radiator, light is directed upwards against another reflector, or against the ceiling, where it is scattered and reflected downwards more or less perfectly diffused.

78. **ILLUMINATION BY A SMALL ILLUMINATED AREA.**—Let an elementary area ΔS be struck by a flux Δφ, then its own illumination

is $\frac{\Delta\phi}{\Delta S}$, and the flux which it radiates again is $K\frac{\Delta\phi}{\Delta S}$, where K is the reflection coefficient. Suppose now this illuminant area illuminates another surface at a distance L (see fig. 4·27). The candle-power of the illuminant is $\Delta S i$, where i is the brightness, whence the illumination at O in S_1 is

$$E_1 = \frac{\Delta S i}{L^2},$$

and since

$$\frac{\Delta S}{L^2} = \Delta\omega = \text{the spherical angle},$$

it follows that

$$E_1 = \Delta\omega i \qquad . \quad . \quad . \quad . \quad . \quad . \qquad 4{\cdot}30$$

It will be noticed that in this nothing is altered if we replace ΔS by

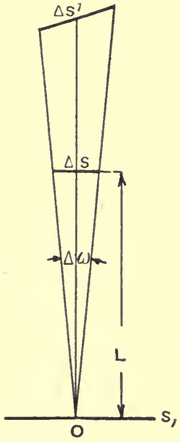

FIG. 4·27.—Illumination by a Small Illuminant Area.

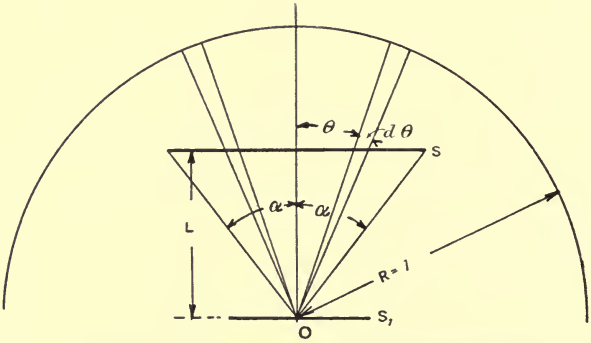

FIG. 4·28.—Illumination by an Illuminant Surface.

ΔS^1 (since the angle $\Delta\omega$ is unchanged) as long as the brightness remains constant.

Take next a larger area S illuminating an area S_1 at a distance L (see fig. 4·28). The question is, what will be the illumination of the point O in S_1? We determine the illumination as caused by an elementary circular *zone* ΔS which, as we have already seen, is expressed by i multiplied by the spherical angle multiplied by the cosine of the angle of incidence. The spherical angle is $2\pi \sin\theta R d\theta$, and for $R=1$ it is $2\pi\sin\theta d\theta$; hence the illumination is

$$dE = i 2\pi \sin\theta \cos\theta d\theta$$
$$= \pi i \sin 2\theta d\theta,$$

and

$$E = \int_{\theta=0}^{\theta=\alpha} dE = \pi i \int_0^{\alpha} \sin 2\theta d\theta$$
$$= \pi i \sin^2\alpha \qquad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad 4{\cdot}31$$

For $a=90$ degrees,

$$E=\pi i \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad 4\cdot32$$

This is the case when $L=0$, *i.e.* when S_1 coincides with S, or when S is infinitely large. It also holds approximately for rooms in which all walls and ceilings radiate uniformly with a brightness i, and also for the sky if the latter is uniformly clouded. The sky brightness on a cloudy day may thus be determined by measuring the illumination of the ground and dividing it by π.

Equations 4·30 and 4·31 hold for the point O only. As we move away from this point, the illumination decreases. If we consider the light concentrated on a small area, for which the distribution curve is a circle

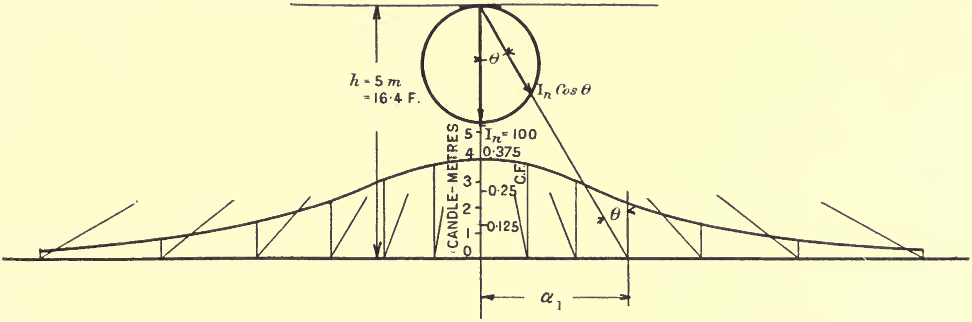

FIG. 4·29.

with I_n as the maximum intensity, then the illumination for any point P is expressed by

$$E=\frac{I_n \cos\theta \cos\theta}{L^2},$$

and as

$$L=\frac{h}{\cos\theta}=\sqrt{a_1{}^2+h^2}$$

$$E=\frac{I_n}{h^2}\cos^4\theta \quad . \quad . \quad . \quad . \quad . \quad . \quad 4\cdot33$$

$$=\frac{I_n h^2}{(h^2+a_1{}^2)^2} \quad . \quad . \quad . \quad . \quad . \quad 4\cdot34$$

The results are plotted in fig. 4·29 for $I_n=100$ candles and $h=5$ metres (16·4 feet).

In most cases the radiating surface is of considerable extent, so that for the same total intensity the illumination will be smaller directly under the lamp, and greater as we move away from point O. This means that the illumination improves in uniformity. Its value under the lamp can be obtained with the aid of equation 4·31. Suppose the diameter of the radiating surface is 2 metres, then for $h=5$ metres,

$$\sin a=\frac{1}{\sqrt{26}}.$$

For $I_n = 100$, and $S = R^2\pi = 1^2\pi = 3{\cdot}14$, and $i = \frac{100}{3{\cdot}14} = 31{\cdot}8$, we obtain directly under the lamp

$$\begin{aligned} E &= \pi i \sin^2 a \\ &= 31{\cdot}8\pi \times \frac{1}{26} \\ &= 3{\cdot}85 \text{ candle-metres,} \end{aligned}$$

whereas according to equation 4·32 it is 4 candle-metres. In this case the reduction is only about 4 per cent. With $R = h$ we should have found $E = 2$ candle-metres, which means a reduction of 50 per cent. The degree of uniformity has, however, now greatly improved.

Practical examples in illuminating engineering will be found under Chapter VII.

CHAPTER V.

TESTING OF ELECTRIC LAMPS.

79. **INCANDESCENT LAMPS.**—The candle-power of an incandescent lamp depends upon the temperature at which the filament is run, the surface area of the filament, and the nature of the surrounding globe. The temperature varies with the current, and the latter with the P.D. and the resistance of the filament. In order to be able to apply the law of the inverse square with regard to illuminations, we consider the illuminants as point sources. This is, of course, only approximately correct, but when the distances of the sources from the photometer screen are considerable, such as can be obtained for the ordinary lamps in a bench 3 metres long, the error lies easily within the error of observation. Again, hardly any source of light gives a uniform distribution—*i.e.* if we place the source in the centre of a hollow sphere, and measure the candle-power in different parts of the surface of this sphere, the values obtained are not equal. In order to judge the quality of a lamp as an illuminant, we must know its mean spherical candle-power (M.S.C.P.), *i.e.* the candle-power measured in any part of the surface of an imaginary hollow sphere given by a source emitting the same total luminous flux as the lamp, but which is equally distributed over the whole sphere. Commercially important is also the mean horizontal candle-power, although it does not give a true indication of the lamp as a light-giving source. The ratio $\frac{\text{mean spherical candle-power}}{\text{mean horizontal candle-power}}$ is called the spherical reduction factor. It has the following values:—

Carbon lamp . . .	0·86 (average).
Tantalum lamp . . .	0·80 (new), 1·0 (old).
Osram lamp . . .	0·82 (average).

For the Osram lamp this ratio varies but little with age.

80. **RELATIONSHIP BETWEEN CANDLE-POWER, P.D., CURRENT AND WATTS.**—The test lamp is compared with a Fleming standard, or with a lamp which has been burning for some fifty hours and has been calibrated with a standard. Although for various states of incandescence the lamps have not the same tint, no difficulty is experienced

with ordinary intensity photometers. The voltage is best regulated with a volt slide, according to fig. 5·01.

The mean horizontal candle-power is obtained by placing the lamp in a universal joint and testing it under different angles in a horizontal plane, taking finally the mean results of tests through 360 degrees. It can be achieved with one measurement if the lamp be rotated. The best speed is about 180 to 230 revolutions per minute. If the speed is too slow, results are unreliable, since a flickering takes place; and if it is too high, the filament expands by centrifugal force, and for long suspensions may extend to the wall of the globe. This causes a new distribution; moreover, brittle filaments are liable to break.

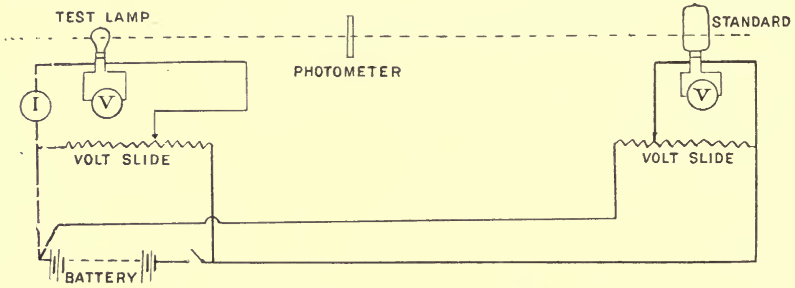

Fig. 5·01.—Testing Incandescent Lamps.

Another method frequently employed for determining the mean horizontal candle-power consists in the arrangement of two mirrors at the back of the test lamp, 9 centimetres away from the axis of the lamp and forming an angle of 120 degrees. The lamp with which the test lamp I_1 is compared should be one of the same type and size, carefully aged by burning it for 50 to 100 hours. An actual calibration is not required. Equality of the fields of view is now obtained, the distances from the photometer screens to the lamps being L_1 and L_2 respectively (see fig. 5·02). Next we replace I_1 by another lamp, the mean horizontal candle-power $\bar{I}_H$ of which is accurately known, and obtain equality of the fields of view by adjusting the distance of this lamp from the photometer screen to L^1_1, without however altering the distance L_2. The mean horizontal candle-power of the first lamp is then given by

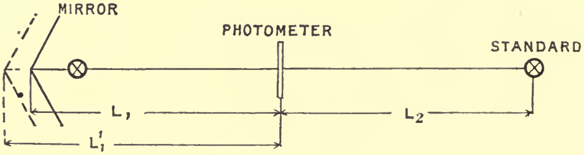

Fig. 5·02.—Testing Lamps for Mean Horizontal Candles.

$$\bar{I}_{1H} = \bar{I}_H \times \frac{L_1^2}{L_1'^2} \quad . \quad . \quad . \quad . \quad . \quad 5·01$$

Testing in this manner makes it unnecessary to take into account the absorption of light by mirrors. The method gives sufficiently accurate results as long as the lamps which are compared are of exactly the same type and differ little in size. It would be useless to test in this manner a lamp with a straight filament against one with a loop in it, or a carbon lamp against one having a metal filament of different shape. For lamps of similar type, candle-power, and distribution, the method is to be recommended on account of its simplicity and the rapidity with which measurements can be carried out.

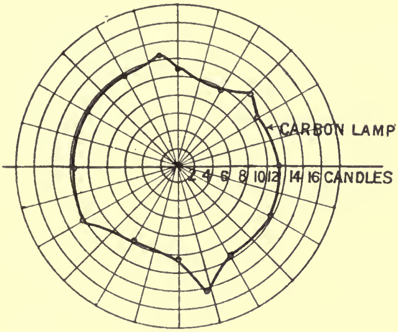

Fig. 5·03.—Horizontal Distribution of a Carbon Filament Lamp.

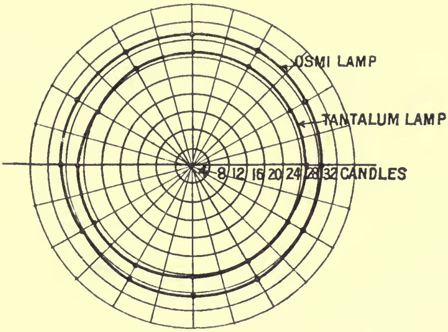

Fig. 5·04.—Horizontal Distributions of Metal Filament Lamps.

In the following table results of tests giving mean horizontal candles for various types of incandescent lamps have been analysed.

Table XI.—Results of Tests on Incandescent Lamps.*

Carbon Lamp.	Nernst Lamp.	Tantalum Lamp.	Osram Lamp.
$\bar{I}_h = 5{\cdot}08 \times 10^{-16} V^{7}$	$\bar{I}_h = 0{\cdot}28 \times 10^{-20} V^{9{\cdot}35}$	$\bar{I}_h = 0{\cdot}11 \times 10^{-7} V^{4{\cdot}4}$	$\bar{I}_h = 0{\cdot}16 \times 10^{-6} V^{4{\cdot}0}$
$= 16{,}000 I_c^{5{\cdot}5}$	$= 536 I_c^{2{\cdot}6}$	$= 16{,}700 I_c^{6{\cdot}0}$	$= 16{,}000 I_c^{6{\cdot}0}$
$= 39{\cdot}2 \times 10^{-6} P^{3{\cdot}1}$	$= 3 \times 10^{-3} P^{2{\cdot}15}$	$= 6{\cdot}4 \times 10^{-3} P^{2{\cdot}15}$	$= 5{\cdot}8 \times 10^{-3} P^{2{\cdot}32}$
$= 124 \eta^{-1{\cdot}476}$	$= 160 \eta^{-1{\cdot}87}$	$= 80{\cdot}7 \eta^{-1{\cdot}87}$	$= 52 \eta^{-1{\cdot}77}$
$R = 610 I_c^{-0{\cdot}214}$	$R = 310 I_c^{-0{\cdot}72}$	$R = 580 I_c^{0{\cdot}36}$	$R = 562 I_c^{0{\cdot}5}$

in which $\bar{I}_h$ = luminous intensity in candles,
V = volts at the terminals of the lamps,
I_c = current in amperes,
P = watts absorbed,
η = watts per candle,
R = resistance in ohms.

The tests showed that the exponent is practically constant for lamps of the same class, and independent of age. The coefficients vary however considerably, chiefly on account of the blackening of the globe.

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* See also Appendix.

Of great importance is the relationship between voltage and candle-power, and we see that in this respect the metal filament lamps are the best.

In fig. 5·05 is shown a voltage curve of a supply network, in fig. 5·06 the resulting candle-power variation for various lamps, and in fig. 5·07 the

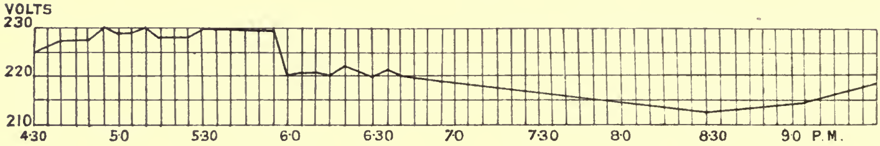

Fig. 5·05.—Voltage Fluctuation of a Supply Network.

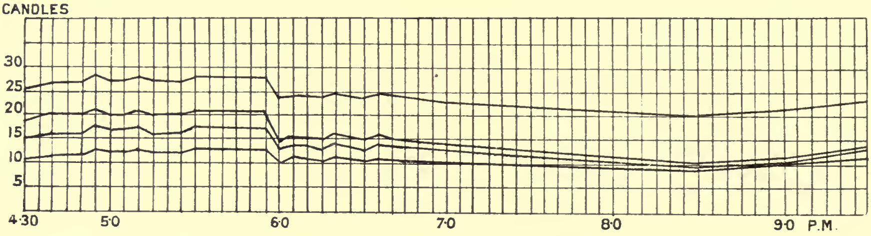

Fig. 5·06.—Candle-Power Variation Resulting from Voltage of fig. 5·05.

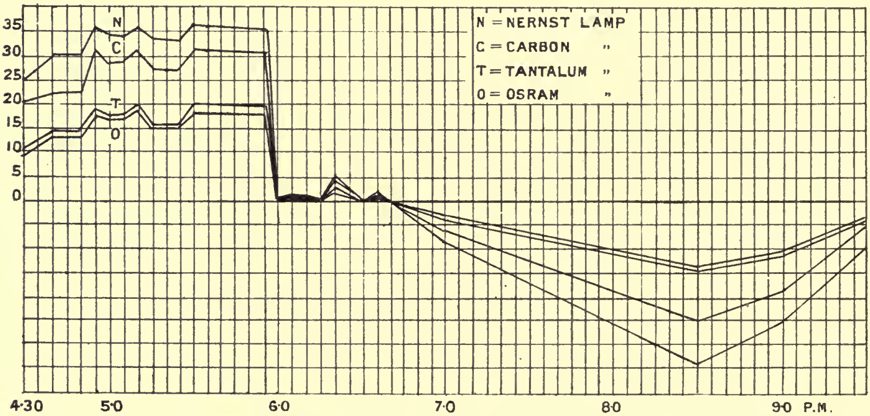

Fig. 5·07.—Percentage Candle-Power Variation Resulting from Voltage of fig. 5·05.

percentage candle-power variation. In analysing the latter, we find that the percentage candle-power variation is equal to $2px$, where p is the percentage voltage variation on either side of the normal and x the exponent in the candle-power-voltage equation. This may also be proved as follows:—

We have

$$\text{candle-power equals } I = cV^x \quad . \quad . \quad . \quad 5{\cdot}02$$

Suppose now the voltage is increased or decreased by p per cent., then

$$I_1 = c\left(V + V\frac{p}{100}\right)^x \text{ for an increase,}$$

$$I_2 = c\left(V - V\frac{p}{100}\right)^x \text{ for a decrease.}$$

The total variation in candle-power is then expressed by

$$I_1 - I_2 = cV^x\left\{\left(1 + \frac{p}{100}\right)^x - \left(1 - \frac{p}{100}\right)^x\right\}.$$

According to the binomial theorem,

$$\left(1 + \frac{p}{100}\right)^x = 1 + x\frac{p}{100} + \frac{x(x-1)}{2\,!}\left(\frac{p}{100}\right)^2 + \frac{x(x-1)(x-2)}{3\,!}\left(\frac{p}{100}\right)^3 + \cdot\cdot\cdot\cdot\cdot ,$$

$$\left(1 - \frac{p}{100}\right)^x = 1 - x\frac{p}{100} + \frac{x(x-1)}{2\,!}\left(\frac{p}{100}\right)^2 - \frac{x(x-1)(x-2)}{3\,!}\left(\frac{p}{100}\right)^3 + \cdot\cdot\cdot\cdot\cdot ,$$

whence

$$\left(1 + \frac{p}{100}\right)^x - \left(1 - \frac{p}{100}\right)^x = 2x\frac{p}{100} + 2\frac{x(x-1)(x-2)}{3\,!}\left(\frac{p}{100}\right)^3 + \cdot\cdot\cdot\cdot\cdot$$

This series converges rapidly, so that even the second member may be neglected, since for $x = 9{\cdot}35$ the result is affected by less than 1 per cent. We get therefore—

$$I_1 - I_2 = cV^x 2x\frac{p}{100},$$

and for the percentage candle-power variation,

$$100\frac{I_1 - I_2}{I} = 100\frac{cV^x 2x\frac{p}{100}}{cV^x}$$

$$= 2xp \quad . \quad . \quad . \quad . \quad . \quad 5{\cdot}03$$

Thus, with a 2½ per cent. voltage variation to either side of the normal, the candle-powers vary as follows :—

Carbon Lamp.	Nernst Lamp.	Tantalum Lamp.	Osram Lamp.
35	46·75	22	20 per cent.

The difference in the behaviour of the lamps is due to the nature of the material of the filament. Those with positive temperature coefficients, such as the metal filament lamps, are naturally superior to lamps with negative coefficients. On the whole, the gradual intensity variation of a lamp should not be more than 15 per cent., as the eye will adapt itself to such a change without trouble. Rapid changes in the intensity of less than 5 per cent. cause flickering, and must be avoided. Moreover, where a voltage *drop* occurs, care must be taken that the light is sufficient at the lower voltage. With a 15 per cent. light variation we obtain the following percentage voltage fluctuations :—

Carbon lamp . . .	1·07 on either side, or	2·14 total.
Nernst lamp . . .	0·8 „ „ „	1·6 „
Tantalum lamp . .	1·7 „ „ „	3·4 „
Osram lamp . . .	1·87 „ „ „	3·74 „

Where the supply pressure is 220 volts, the regulation must be within—

Carbon lamp	217·65 to	222·35 volts.
Nernst lamp	218·24 „	221·76 „
Tantalum lamp	216·26 „	223·74 „
Osram lamp	215·89 „	224·11 „

The consumption of power for the different lamps varies considerably. In Chapter II. it was shown on what conditions the consumption depends. On an average, we may reckon about 3·5 watts per mean horizontal candle for the ordinary carbon, 2·0 for the Nernst, 1·7 for the tantalum, and 1·25 for the tungsten lamps. For equal light intensities this would require an expenditure of power in the proportions of 1·0, 0·57, 0·49, and 0·36 respectively, and for the above given voltage drops the cross sections of the mains would be in the ratios :—1·0 ÷ 0·77 ÷ 0·308 ÷ 0·234. This shows that carbon and Nernst lamps are sure to disappear, unless means are found which will enable us to raise their working temperatures, and consequently their efficiencies, considerably.

81. **RECORDING THE FLUCTUATIONS IN THE CANDLE-POWER OF LAMPS.**—The testing of the fluctuations in the candle-power of a lamp when carried out in the laboratory is extremely laborious. The work may however be considerably reduced by the application of a selenium cell placed in a suitable position where the light of the lamp can easily fall upon it. The cell is joined in series with a recording milliameter of the permanent magnet-moving coil type, and also with a secondary battery of constant voltage. As we have seen in Chapter III., the selenium cell is not suitable for absolute measurements, but by making the cell extremely thin it is possible to reduce its inertia almost to vanishing point, and for *relative* measurements it is then quite suitable. According to the increase or decrease in the illumination, the resistance of the selenium cell decreases or increases correspondingly, and hence the current varies approximately as the illumination Actual tests carried out in this manner * have shown that the slightest variations in the intensities of illuminants are indicated by the recording instrument, so that the method is to be recommended where on a somewhat irregular supply P.D. a steady illumination is required, and where it is necessary to study the steadiness of light as given by different illuminants.

82. **MEAN SPHERICAL CANDLE-POWER (M.S.C.P.).**—In order

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* See E. Presser, *E.T.Z.*, 1910, p. 187.

to obtain a true indication of the quantity of light given by a source, we must determine its mean spherical candle-power. For a point source or sphere of uniform brilliancy, the total flux is expressed by $4\pi I$, where I is the candle-power and 4π the solid angle surrounding the source. In practice we have no lights of which the distribution is uniform in all directions.

If we surround the source by an imaginary hollow sphere with the source as centre, and find that the illumination is of equal intensity as far as points on the same latitude are concerned, we call the light symmetrical. For a source of this nature we can find the M.S.C.P. by plotting first the

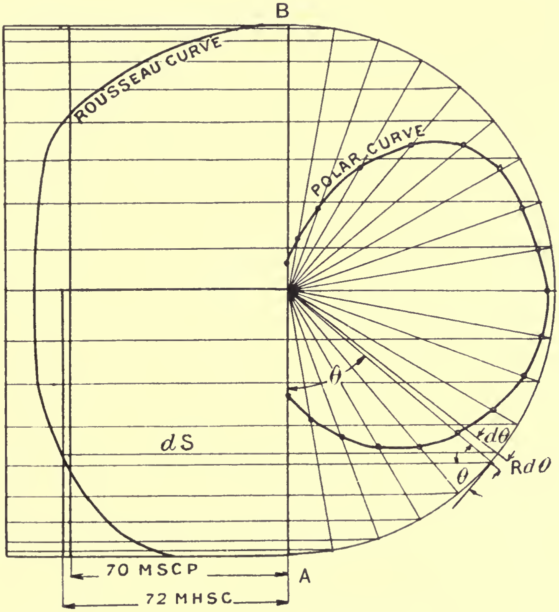

FIG. 5·08.—Polar Curve of a Tungsten Lamp.

polar curve and from this the Rousseau curve. The mean ordinate of the latter gives the M.S.C.P.

The polar curve is obtained by determining the intensities of a symmetrical source along a meridian of the imaginary hollow sphere. For a tungsten lamp, fig. 5·08 shows such a curve. Curves of this nature are however misleading as regards the total flux, since their areas do not determine its magnitude. For instance, if we have two curves of similar shapes, but of which the first one has radii equal to half of those of the second curve, then the area of the latter is four times that of the former, whereas the candle-power is only double.

Again, if we consider two polar curves as shown in fig. 5·09, which are identical in shape and size except that the one is more inclined to the vertical axis than the other, we might expect the same intensity in both cases, but in reality this is not so. Curve 2 has a horizontal axis, consequently the intensity deals with an area of the circumference $2R\pi$ whereas for an inclination θ the area is only of the circumference $2R\pi \sin \theta$. Hence the lamp with the horizontal polar curve will give a greater flux than the other lamp. This is strikingly illustrated when the Rousseau curve is drawn, the construction of which is as follows:—

Draw a suitable semicircle and, through each point in which the radii intersect the semicircle, draw horizontal lines; then plot along these from A B the corresponding lengths of the radii, as cut off by the polar curve. The new curve thus obtained is the Rousseau curve (see also fig. 5·08).

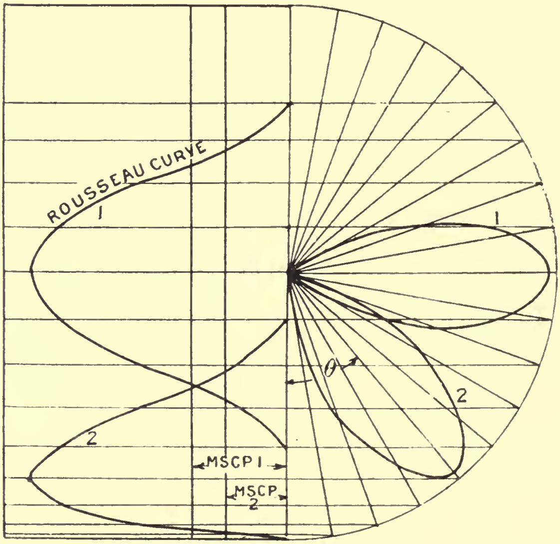

Fig. 5·09.—Polar Curves of Different Inclinations

The proof of this has already been given under Matthew's integrator, where we found that

$$I_0 = \frac{1}{2}\int_0^\pi I \sin \theta d\theta .$$

But the area of the Rousseau curve is

$$R\int_0^\pi I \sin \theta d\theta ;$$

so that the M.S.C.P. is found by dividing this area by 2R, *i.e.* by the diameter of the semicircle.

83. **MEAN HEMISPHERICAL CANDLE-POWER (M.H.S.C.P.).**—The spherical distribution of an incandescent lamp may be converted into a hemispherical one by supplying the lamp with a suitable shade. This is frequently done in street lighting. The M.H.S.C.P. is found in exactly the same way as the spherical, except that we plot the lower half of the polar and the corresponding part of the Rousseau curves only. The area

of the latter, divided by R, then gives the M.H.S.C.P. Where light is reflected from ceilings, directly or indirectly, the term M.H.S.C.P. is misleading and gives no true indication of the quantity of the flux emitted.

The construction of the Rousseau curve has the disadvantage that its area has to be estimated, either with a planimeter or in some other way. It has however been shown under Matthew's Integrator that the determination of I_0 and $I_\cup$ can be accomplished by measuring the lengths I sin θ. We divide the polar curve into a number of parts, as shown in fig. 5·10, and project the points a_1, a_2, a_3, etc., on to the horizontal, then the mean hemispherical candle-power is expressed by

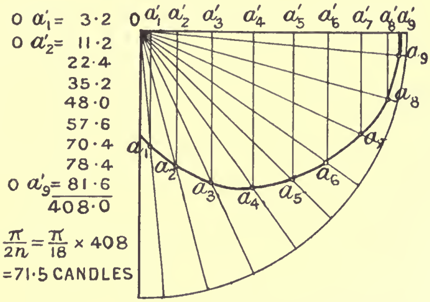

FIG. 5·10.—Determination of the M.S.C.P.

$$I_\cup = \frac{\pi}{2n}\sum_0^n \theta a \quad . \quad . \quad . \quad . \quad . \quad 5\cdot 04$$

where n is the number of divisions.

This holds also for spherical measurements, except that the construction is made for both the hemispheres.

Another method which also does away with a planimeter (it shall be described for an arc lamp, but holds for glow lamps as well) is the following:—

After plotting the polar curve, we draw a quadrant with a radius unity (say, 1 decimetre). For each angle θ we obtain then on the vertical the corresponding cosine θ if we project the point of the intersection of each ray with the quadrant upon the vertical, since the triangle is a right-angled one. For instance, $OB = \cos\theta$, since the radius R is unity (see fig. 5·11). If moreover we divide O A into ten parts, then each part is equal to $0\cdot 1 = \Delta(\cos\theta)$. To each middle point of these divisions correspond the various luminous intensities as seen from the polar curve. If now we multiply $\Delta(\cos\theta)$ by I, we get

$$I\Delta(\cos\theta) = I \times 0\cdot 1$$

for each of the ten sections. By adding up the resulting values from below upwards, we get

$$\Sigma I\Delta(\cos\theta).$$

Previously we found that

$$\text{M.S.C.P.} = I_0 = \tfrac{1}{2}\int_0^\pi I \sin\theta d\theta$$

$$= \tfrac{1}{2}\int_0^\pi I d(\cos\theta)$$

$$= \tfrac{1}{2}\sum_0^n I\Delta(\cos\theta) \quad . \quad . \quad . \quad 5\cdot 05$$

If therefore we make this construction for both hemispheres of the polar curves and take the mean result, we have the M.S.C.P.

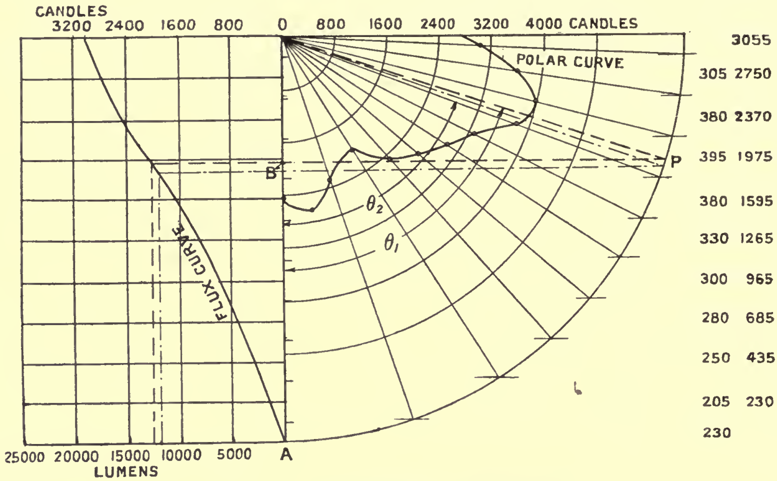

Fig. 5·11.—Determination of M.S.C.P.

The mean hemispherical intensity is expressed by

$$I_o = \sum_{0}^{n_1} I \Delta \cos\theta, \quad . \quad . \quad . \quad . \quad . \quad 5·05a$$

found for the lower hemisphere only.

Weinbeer* has constructed a special slide rule for these determinations, based on the previous considerations, with trigonometrical instead of exponential functions (see fig. 5·12).

He determines the intensities under the following angles:—85 degrees, 75 degrees, 65 degrees, down to 5 degrees against the vertical, and then adds the quantities I Δ (cos θ) for the zones lying between these, *i.e.* from 90 to 80 degrees, 80 to 70 degrees, etc., for which Δ (cos θ) is expressed in the following table:—

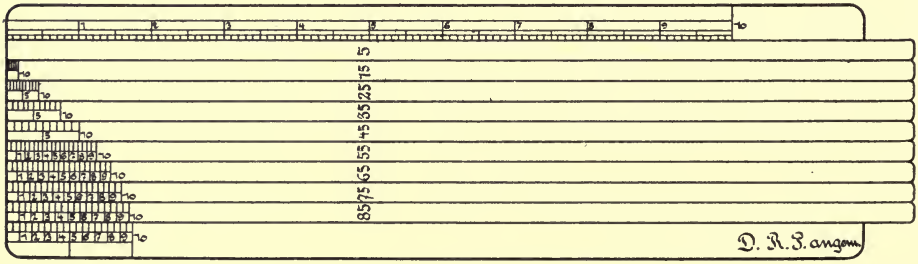

Fig. 5·12.—Weinbeer's Slide Rule for Spherical Determinations.

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* *The Illuminating Engineer*, 1908, p. 559.

TABLE XII.—COSINES.

$\Delta(\cos\theta_1) = (\cos 80° - \cos 90°) = 0{\cdot}1736$
$\Delta(\cos\theta_2) = (\cos 70° - \cos 80°) = 0{\cdot}1684$
$\Delta(\cos\theta_3) = (\cos 60° - \cos 70°) = 0{\cdot}1580$
$\Delta(\cos\theta_4) = (\cos 50° - \cos 60°) = 0{\cdot}1428$
$\Delta(\cos\theta_5) = (\cos 40° - \cos 50°) = 0{\cdot}1232$
$\Delta(\cos\theta_6) = (\cos 30° - \cos 40°) = 0{\cdot}1000$
$\Delta(\cos\theta_7) = (\cos 20° - \cos 30°) = 0{\cdot}0737$
$\Delta(\cos\theta_8) = (\cos 10° - \cos 20°) = 0{\cdot}0451$
$\Delta(\cos\theta_9) = (\cos 0° - \cos 10°) = 0{\cdot}0152$

which sums up to unity.

The rule possesses two fixed scales, each divided into 10 (or 100) divisions, but the lower one is reduced in the ratio 0·1736 to 1. In addition to these there are 9 movable rules, of which the first has no scale; the second one, the same scale as the upper fixed one but reduced in the ratio 0·0152 to 1; the third one, a similar scale reduced in the ratio 0·0451 to 1, and so on. To find the M.H.S.C.P., we proceed as follows:—Place the zero of the lowest movable scale (85) opposite the value of I_{85} on the scale below it; the zero of the second movable scale (from below, marked 75) opposite the value of I_{75} on the lowest movable scale; the zero of the third movable scale from below opposite the value of I_{65} on scale (75), and so on, until eventually the last movable scale shows on the upper fixed scale the result.

For spherical measurements the determination is repeated for the upper half, and the mean of the two results is taken.

84. **FLUX FOR REGIONS BELOW THE HORIZONTAL.**—The method illustrated in fig. 5·11 possesses the advantage that it gives us the flux for any region below the horizontal. Take for instance any angle θ, then if we project the point of intersection P of the ray O P with the quadrant upon the curve on the left in fig. 5·11, which represents the values tabulated on the right, we cut off the value

$$\int_0^\theta \mathrm{I}d(\cos\theta) = \phi^1,$$

which, when multiplied by 2π, will give us the flux. If we multiply the ordinates by 2π and plot a new curve or alter the scale, we obtain this value directly. The figure also indicates a method for finding the average illumination, as given by a single lamp, for any given circular area lying within a given angular region 2θ, viz.,

$$\bar{\mathrm{E}} = \frac{2\pi}{\mathrm{S}}\int_0^\theta \mathrm{I}d(\cos\theta) \quad . \quad . \quad . \quad . \quad . \quad 5{\cdot}06$$

$$= \frac{2\pi}{\mathrm{S}}\phi^1 \quad . \quad . \quad . \quad . \quad . \quad . \quad 5{\cdot}07$$

$$= \frac{\phi^\theta}{\mathrm{S}} \quad . \quad . \quad . \quad . \quad . \quad . \quad 5{\cdot}07a$$

85. **LIFE TESTS.**—All incandescent lamps age, *i.e.*, their candle-power

decreases with age. This is due to vaporisation of the filament. When the intensity has been reduced to 80 per cent., the lamp is usually considered useless. The interval is called the "life" of the lamp (in burning hours). Life tests are therefore of importance. They are mostly carried out for constant voltages, special automatic regulators being employed to ensure constancy. Results obtained in this manner are commercially of little importance. Lamps should be tested under normal conditions, *i.e.*, they should be joined directly to the supply pressure, without regulators, and should be periodically switched on and off.

Lamps for life tests are usually joined to a rack with two stout copper leads, to which are soldered sockets carrying from one to four dozen lamps. A single row is preferable to a number of rows above one another, to prevent abnormal heating of the upper lamps. During the first hundred hours, tests should be made every ten hours, as the candle-power changes considerably during this time (usually increases); afterwards observations at intervals of from 50 to 100 hours suffice. In the following figures the life curves of metal filament lamps are represented; they are self-explanatory.

As regards the tungsten lamp, it will be found that little blackening of the globes takes place so long as the vacuum of the lamp is maintained. The increase in the specific consumption is consequently also small.

The economical or commercial life of a lamp may be approximately predetermined for a given amount of light if we know the curve (watts per candle-time). Assume, for instance, that this curve is a straight line (which is often the case) and shows an increase of 0·5 watt per candle for 350 burning hours (curve 36B in fig. 5·13), so that the rate of increase is

$$p=\frac{b}{t}=\frac{0·5}{350},$$

then the area enclosed by this curve and the horizontal represents the increased consumption, and is equal to

$$\tfrac{1}{2}bt=\tfrac{1}{2}pt^2,$$

and when the cost of this consumption amounts to the price of the lamp per candle, the lamp should be thrown away. If $£_0$ be the cost per candle and $£$ the price per kilowatt hour, $\frac{£}{1000}$ per watt hour, then we have

$$\tfrac{1}{2}pt^2\times\frac{£}{1000}=£_0,$$

whence

$$t=\sqrt{\frac{2000£_0}{p\times £}} \quad . \quad . \quad . \quad . \quad . \quad 5·08$$

Let $£_0=1$ penny, $£=$ fourpence, then

$$t=\sqrt{\frac{2000\times 1\times 350}{0·5\times 4}}=594 \text{ hours.}$$

This of course is only approximate and assumes that a given amount of light is asked for. In domestic lighting, as the light decreases, this is usually accepted without troubling much about it. Where light however is installed on a scientific basis, the original illumination should be exactly what is required, plus the decrease which would take place in the time *t*. At the end of this time, the proper amount of light is still available, but a further decrease would bring it below the requirements, so that new lamps are now essential.*

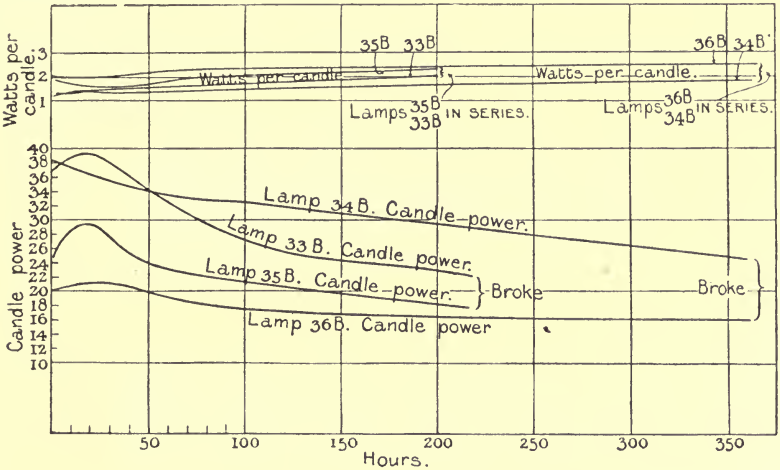

FIG. 5·13.—Life Curves of Tantalum Lamps.

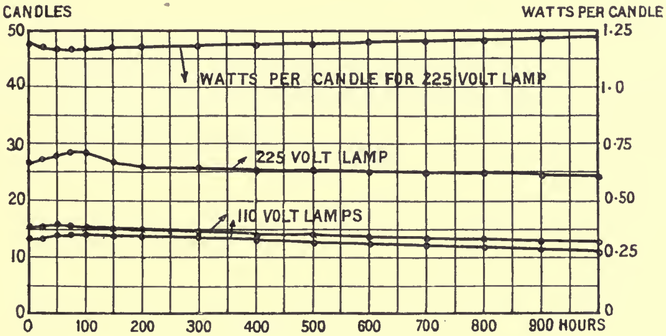

FIG. 5·14.—Life Curves of Tungsten Lamps.

86. **METAL FILAMENT LAMPS** do not behave in the same way on direct as alternate current circuits, and on the latter erratically for different frequencies. The life of tantalum lamps on alternate current circuits is shorter than on direct current networks, this being probably due to crystallisation caused by repeated heating and cooling. As these lamps

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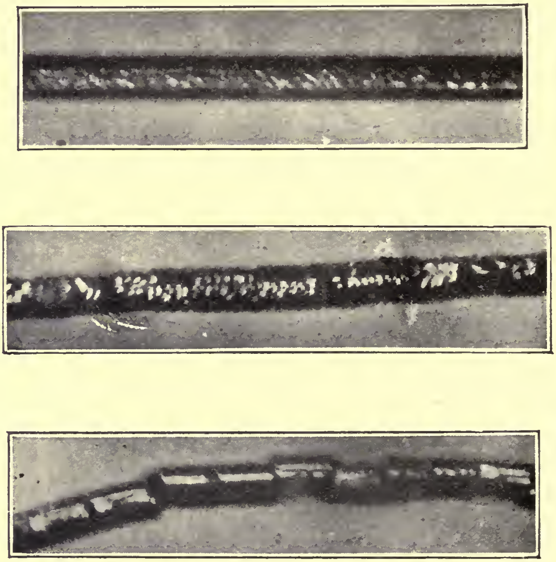
* See also a paper by F. H. Reakes Lavender, M.Sc., *Journal I.E.E.*, 1909, vol. xliv. p. 181.

will withstand on a direct current circuit a temperature much higher than that occurring when the alternate current wave is at its maximum, the fault is only partly to be found in excessive temperature. This is also proved by the fact that with an increase in the frequency the life is reduced, showing that the *frequency* of heating and cooling is the disturbing factor.

The accompanying photographs* show how drawn filaments appear before and after use. Fig. 5·15 represents a new tantalum filament, fig. 5·16 one which has been running on a direct current circuit, and fig. 5·17 a filament joined to an 83-cycle network. The greater the frequency, the shorter are the sections† in which these filaments separate. These sections join themselves again, but only imperfectly so.



Figs. 5·15 to 5·17.—Deteroriation of a Tantalum Lamp on Alternate Currents of Different Frequencies.

If the filament of a metal lamp breaks, it is often possible to weld it together again by carefully shaking the lamp. This usually reduces the length of the filament, hence its resistance, and thus causes an increase in the candle-power. Considerable additional life may be in this way obtained out of the lamps.

As metal filaments possess positive temperature coefficients it follows that on switching them on the full voltage, the current rises to several times its normal value, until the metal has had time to heat up. Fuses must thus be liberally dimensioned. The behaviour of various lamps on

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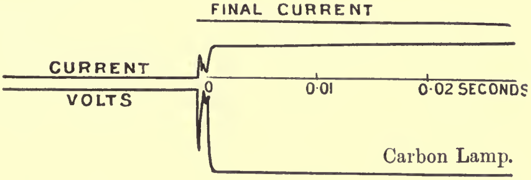
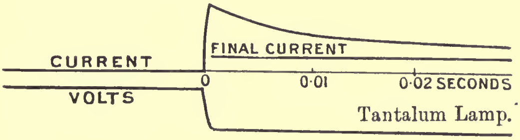
* H. M. Sayers, *J.I.E.E.*, vol. xxxviii. p. 260.

† See also Dr C. Sharp, *Electrical World*, 1907.

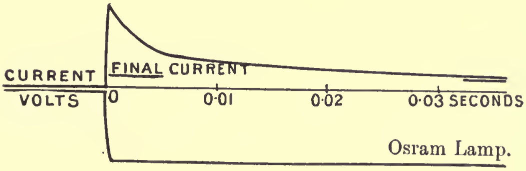
switching them on is represented in the accompanying fig. 5·18,* which is self-explanatory.



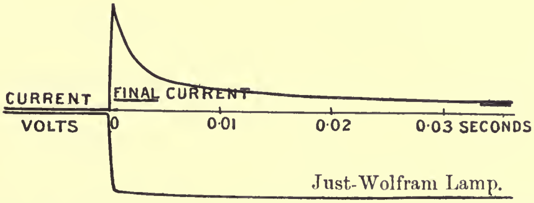
Carbon Lamp.



Tantalum Lamp.



Osram Lamp.



Just-Wolfram Lamp.

FIG. 5·18.—Behaviour of Lamps on Switching them into Circuit.

87. **ECONOMICAL EFFICIENCY.**—Another question arises:—Do we run our lamps at the most economical efficiency? To determine this we must find the relationship between the watts per candle and the useful life of a lamp. A curve connecting the two for a carbon lamp is represented in fig. 5·19. If then we know the economical life of the lamps and the increase in the candle-power of the same lamps with a reduction in the specific consumption (due to voltage increase), the initial cost of the lamp per candle-power, and the price per kilowatt hour, we can easily determine the most economical specific consumption. Take, for example, fig. 5·19, which illustrates the relationship between watts per mean horizontal candle and the useful life of a carbon lamp, normally manufactured for 4 watts per candle. The useful life of this lamp is about 1000 hours, but this is reduced in the manner indicated when the voltage is increased. Suppose

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* See J. T. Morris, *J.I.E.E.*, vol. xxxviii. p. 254.

we have an installation of forty-two 220-volt 25 c.p. lamps at 4 watts per candle, giving a total light of 1050 candles. Let the price per lamp be one-twenty-fifth of a shilling per candle, or one shilling per lamp, then during 1000 burning hours we have the following results:—

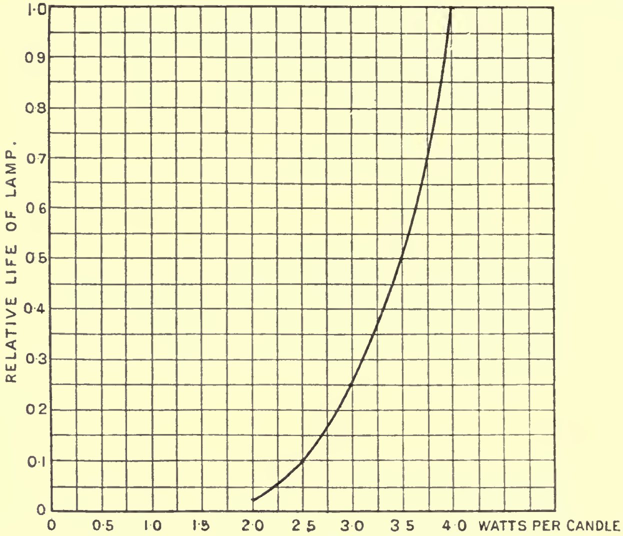

Fig. 5·19.—Relative Life of a Carbon Lamp for Different Specific Consumptions.

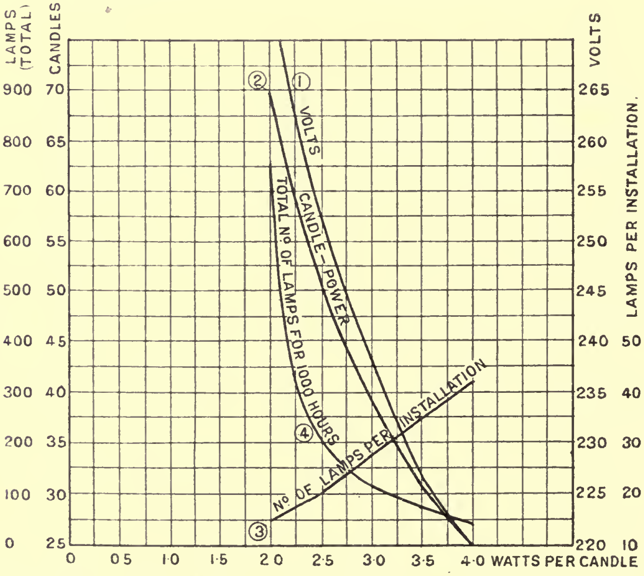

Fig. 5·20.—Voltage, Number of Lamps, and Candle-Power as Function of the Specific Consumption.

(1) The voltage must be increased according to curve 1 of fig. 5·20.

(2) The candle-power increases according to curve 2.

(3) The number of lamps required per installation decreases according to curve 3, and the total number of lamps wanted during the 1000 hours increases according to curve 4.

If we reckon 6, 5, 4, and 3 pence per unit of current consumption, we obtain fig. 5·21 as the total cost results.

We see that the carbon lamp has not been worked at its most economical specific consumption, and that commercially a better result would be obtained if on a 220-volt circuit we used a lamp normally made for 200 volts. The lamps would then have to be renewed every 100 hours, but this would still effect a saving of about 30 per cent.

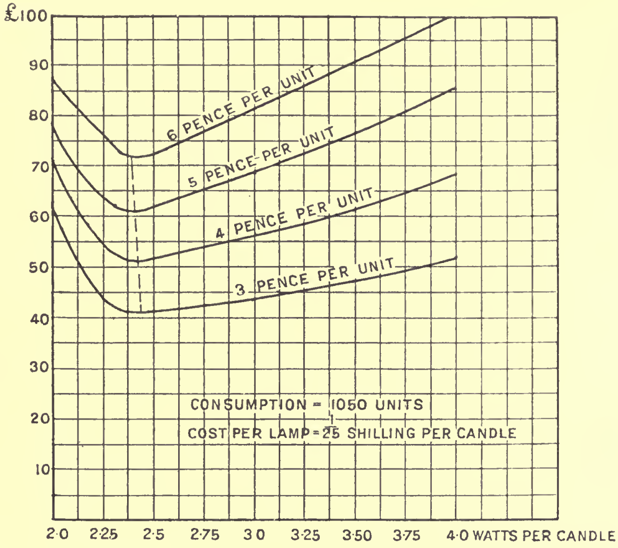

Fig. 5·21.—Cost of a 1050-candle Lamp Installation during 1000 Hours of the Specific Consumption.

The expense for labour required to exchange the lamps has been disregarded.

It is somewhat surprising to find the curves of fig. 5·21 with their minimum values practically on the same ordinate. This is due to the high price of the current compared with the low price per lamp, and does not hold for tungsten lamps, for which curves similar to those in figs. 5·19 to 5·21 have been plotted in figs. 5·22 to 5·24. It will be noticed that in this case the minimum value moves very much to the right as the price per kilowatt-hour is reduced. The installation is the same as in the example for the carbon lamp except that the time of burning is 10,000 hours and the price 2s. 6d. for a 50-candle lamp. The average life of the lamp has been taken as 1000 hours. We see that at fourpence per unit we should burn the lamps approximately at the normal specific consumption, *i.e.* at 1·2 watts per mean horizontal candle. At sixpence it would pay to reduce the consumption to about 1·03 watts per candle, which would mean that we should run a 200-volt lamp on a 220-volt circuit, and at twopence we should increase the consumption to 1·35 watts per candle, *i.e.* run 227-volt lamps on 220-volt circuits. In the latter case, the

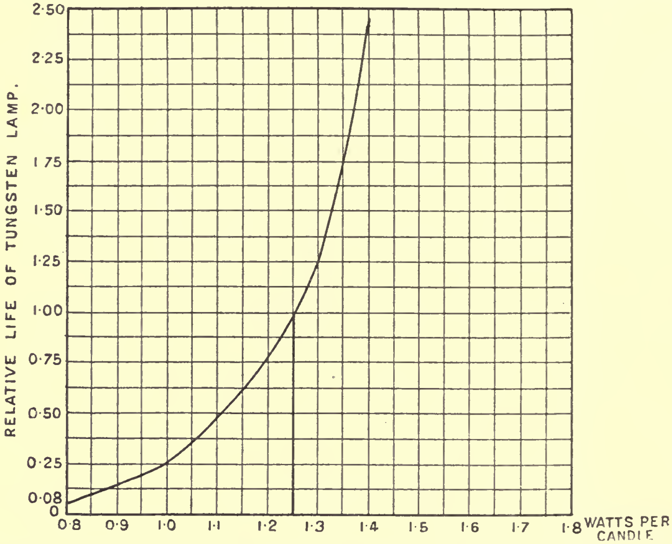

Fig. 5·22.—Relative Life of a Tungsten Lamp for Different Specific Consumptions.

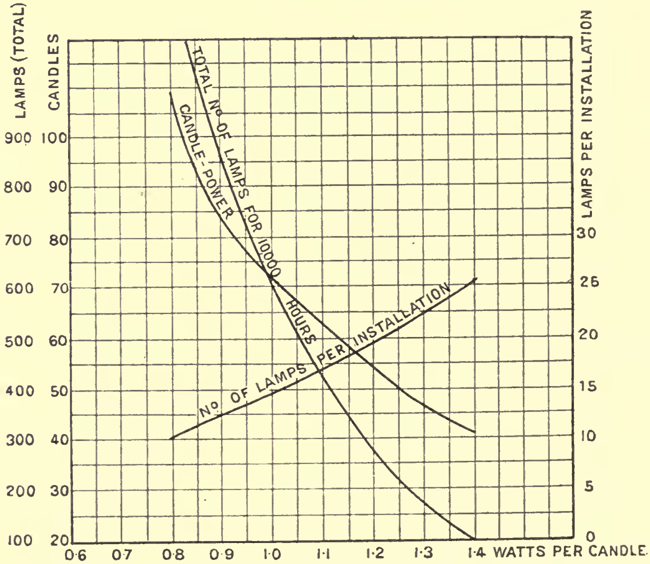

Fig. 5·23.—Voltage, Number of Lamps, and Candle-Power as Function of the Specific Consumption.

saving in wages for not having to renew the lamps so frequently would be an additional advantage.*

The useful life of a tantalum lamp is about 700 to 800 hours, *i.e.*, in this time the candle-power has decreased so much that it pays to insert fresh lamps. The useful life of a tungsten lamp is in most cases greater than the actual life. Although one sees reports of tests showing lives of 3000 and more hours, these are not borne out in actual practice, except in isolated cases. As a matter of fact, the life of a tungsten lamp is not much more than 1000 hours, unless the lamp is placed in a vertical position where it cannot be touched. Lamps which are fixed to rising and falling pendants, or which have to be moved in any way or which are not hanging vertically downwards, hardly exceed a life of 600 hours. In no case should a tungsten lamp be taken from its socket before it has cooled down, as a contracting filament is so fragile that it breaks almost every time the lamp is handled. Otherwise a hot filament is less fragile than a cold one.

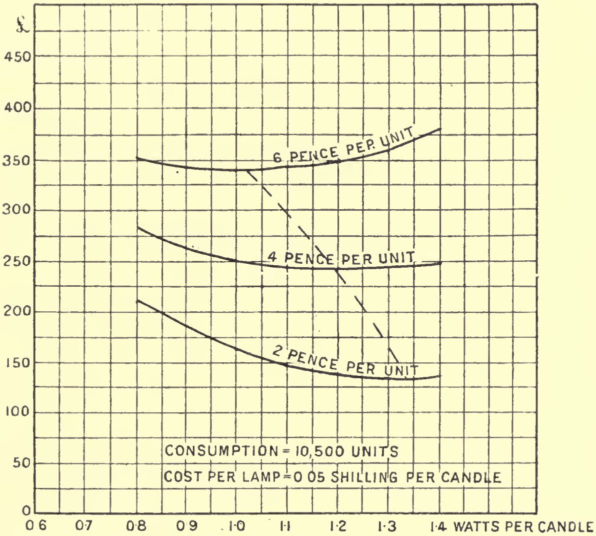

FIG. 5·24.—Cost of a 1050-candle Tungsten Lamp Installation during 10,000 Hours as Function of the Specific Consumption.

Speaking generally, we should replace carbon and tantalum lamps when they become dim and tungsten lamps when they break.

88. **INITIAL RATING.**—After the lamps have been finished in the factory they are brought into the test-room, where they are rated for

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* The Deutsche Gasglühlicht Aktiengesellschaft, Berlin, manufactures now Osram lamps which use only 1 watt per candle (British) with a reputed life of 1000 hours and over. The lamps are made for intensities above 100 candles. Four lamps tested by the Reichanstalt were still burning after 1000 hours, when the candle-power had been reduced by about 10 per cent.

candle-power and consumption. Work of this nature is usually performed by girls, of whom one manipulates the photometer, another notes the consumption, and a third inserts the lamps. The lamps are tested for mean horizontal candle-power, the determination taking place either by means of the method illustrated in fig. 5·02, or by revolving the lamp in a holder such as is shown in fig. 3·32. With a direct reading scale, a large number of lamps can be dealt with in a short time, as the testing of a lamp does not exceed half a minute. All lamps, the consumption and candle-power of which at a constant normal voltage lie outside prescribed limits, are placed separately. If the values of the candle-power-watts are plotted according to fig. 5·25, we get the so-called target or shot-gun diagram. Fig. 5·25 holds for a normal 16 candle-power 3·25 watt per candle carbon lamp. All the lamps outside the rectangle or target are unsuitable for the given voltage and should be re-sorted for other voltages so as to bring them within the target. A target diagram for tungsten lamps is shown in fig. 5·26.

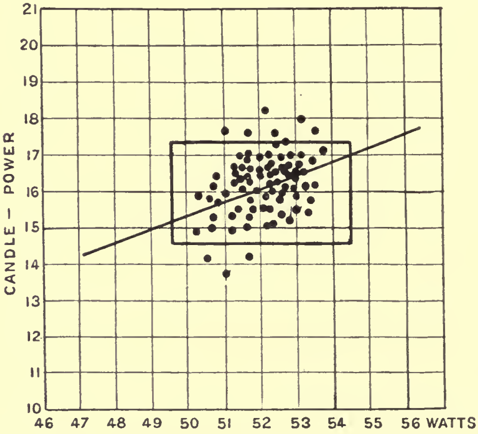

FIG. 5·25.—Target Diagram for a 16 Candle-Power Carbon Lamp.

A more accurate sorting of lamps is as follows:—We plot the candle-power-volts, and specific consumption-volt curves as shown for a tungsten lamp in fig. 5·27. This may be facilitated with the aid of Table XI., from which we get

$$\eta = \frac{C}{V^{2 \cdot 26}}.$$

The exponents in these equations do not vary with the size of the lamps (or very little), so that the constants may be found by a single test.

In the example the value of the constant C is 245,000. Suppose then that we are given a batch of lamps to sort, the lamps being nominally for thirty candles at 220 volts and absorbing 1·25 watts per candle. We know that the correct voltage will be somewhere between 200 and 240, hence we test all lamps for 220 volts. The standard lamp should be conveniently of the same voltage and type, so that both lamps may be regulated simultaneously. Assume now that in the test one lamp absorbs 42 watts at 220 volts and gives 39 candles, thus 1·08 watts per candle. We require however a lamp using 1·25 watts per candle, *i.e.* we must find an ordinate which is $\frac{1\cdot25}{1\cdot08}$ or 1·158 times larger than the correct ordinate in the figure. This ordinate is indicated by point P; the corresponding abscissa gives the correct voltage equal to 203. To find the candle-power of the lamp, we divide the candle-power ordinate corresponding to 203 volts by the ordinate for 220 volts and multiply the ratio by 39. We have $I = \frac{21}{30} \times 39 = 27\cdot4$ candles. The method is both accurate and rapid when the experimentalist has become used to it.

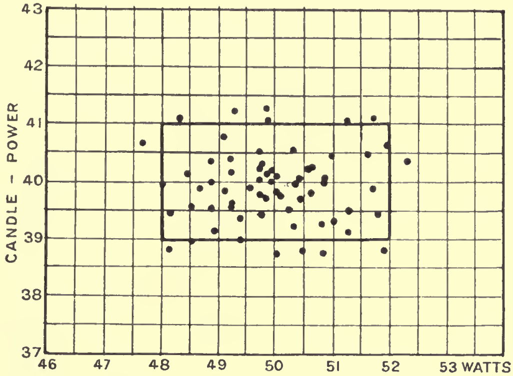

FIG. 5·26.—Target Diagram for a 50-watt Tungsten Lamp.

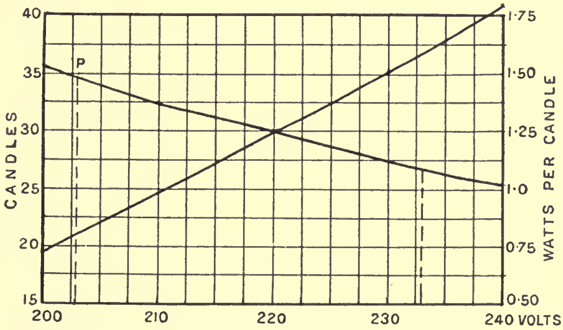

FIG. 5·27.—Sorting Incandescent Lamps.

89. **MECHANICAL LAMP TESTER.**—When lamps are employed for the lighting of railway trains or trams, they are subjected to frequent jerks and shocks. To get an idea of how lamps will last under these conditions, special mechanical testers are used with which the working

conditions are imitated as nearly as possible. Such a lamp tester is shown in fig. 5·28 together with the connections employed in the tests.* The arrangement needs little explanation. A cam is revolved, and once in each revolution the lamp drops a small distance, thereby receiving a definite shock. The cam, which is driven by a small motor, carries at one end a counter on which the number of revolutions is read.

For testing the filament when glowing, the arrangement on the right in fig. 5·28 is employed (hot test). By means of an automatic switch the motor driving the cam is stopped as soon as the filament fails. To test the lamp when cold, the arrangement in the lower part of the figure is used. The current passes through the lamp only for an instant in each revolution, the time being too short to heat the filament to incandescence. Should the lamp fail, the current through the automatic switch is for an instant interrupted and the circuit is broken. We see that the apparatus needs no attention whatsoever.

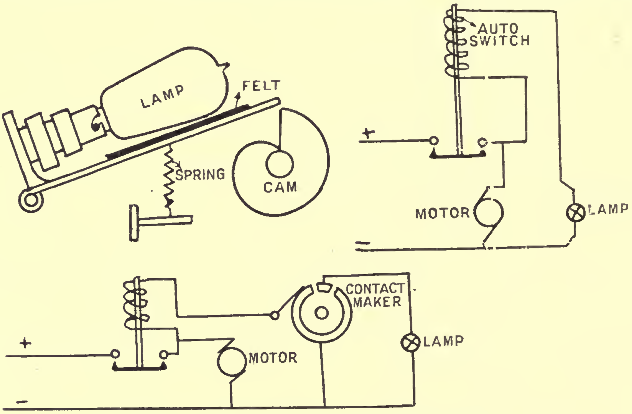

FIG. 5·28.—Mechanical Lamp Tester.

90. **EFFECT OF FREQUENCY ON THE VARIATION OF CANDLE-POWER OF INCANDESCENT LAMPS.**†—In order to determine the variation of candle-power of a lamp during the cycle of an alternate current, Messrs Kiely and Wasserboehr measured the intensity of light in a single horizontal direction at successive and regular electrical time-intervals throughout the cycle. A small single-phase synchronous motor was arranged to rotate a sectored disc in front of the lamp. This occluding disc had slots equal in number to that of the poles of the motor, and each slot had an opening of eight degrees. The disc was adjustable about the motor shaft to provide for admitting light to a Lummer-Brodhun photometer at any desired point of the cycle. The field of light was reduced by a second fixed screen having a ¼-inch slot. Owing to a difference in ratio of energy input and output at any instant, a lag is introduced

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* See *Electrician*, 22nd September 1911.

† See Kiely and Wasserboehr, *Electrical World*, 1911, p. 430.

into the candle-power curve. To investigate this, to determine the zero current point, and to provide a means of detecting any angular oscillations in the synchronous motor (hunting), the oscillograph had to be employed. The vibrator of the latter was connected in the lamp circuit and a direct-current carbon lamp was placed before the revolving disc. The intense beam of light from the arc was reflected by means of a train of mirrors and totally reflecting prisms to the vibrating mirror, and thence to the ground-glass screen. When the cylindrical mirrors were at rest, by observing the two images on the screen—because of the two slots per pair of

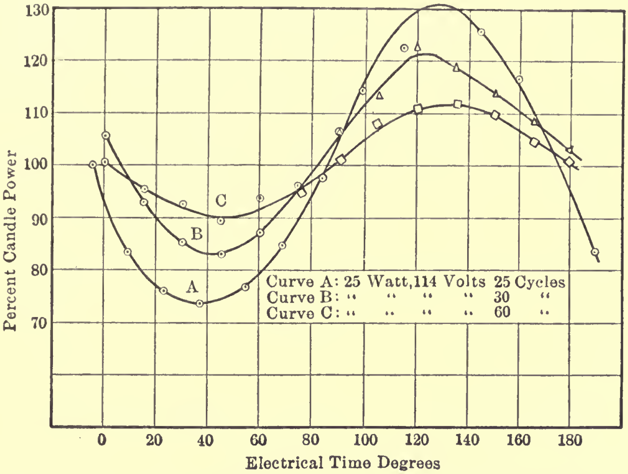

FIG. 5·29.—Curves showing Per Cent. Cyclic Variation in Candle-Power for Tungsten Lamps.

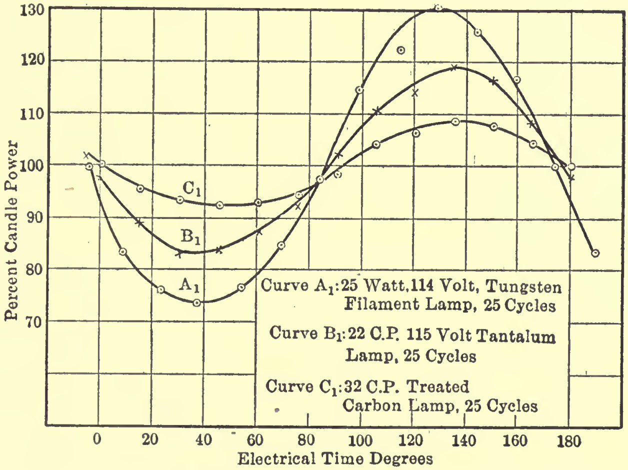

FIG. 5·30.—Curves showing Per Cent. Cyclic Variation in Candle-Power.

poles—the angular position of the occluding disc was easily adjusted for the zero point. Any hunting of the motor was seen by the surging of the images.

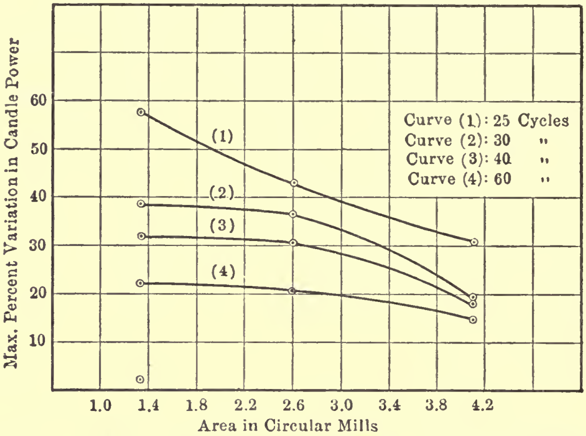

FIG. 5·31.—Maximum Per Cent. Candle-Power Variation for Different Cross Sections of Tungsten Filaments.

The results of the tests are shown in the accompanying figs. 5·29 to 5·32. We see that the variation increases with a decrease in the frequency

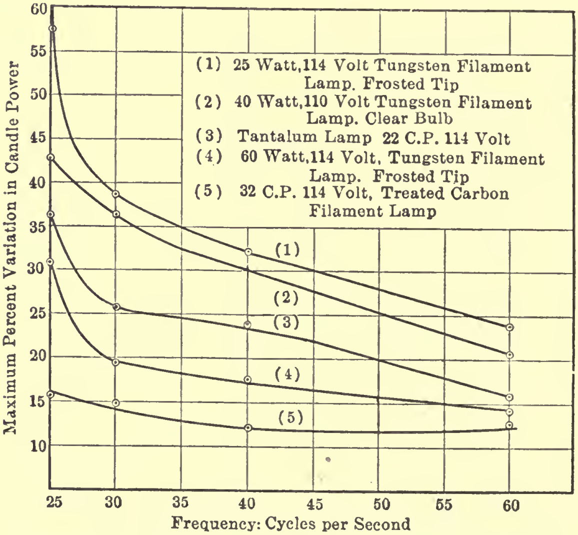

FIG. 5·32.—Curves showing Maximum Per Cent. Variation in Candle-Power with Frequency.

of the alternate current and in the thickness of the filament, as one would expect, since on a low frequency the filament is given more time to cool down than on a high one, and since a thin filament has a smaller heat capacity than a thick one. The voltage wave applied in the test had a sine shape. The curves of the candle-power variation are approximately also sine curves.

91. **RELATIVE EFFICIENCY OF LIGHT PRODUCTION BY CONSTANT TEMPERATURE AND VARIABLE TEMPERATURE INCANDESCENT LAMP FILAMENTS.***—A lamp filament may be considered as a receiver, a holder, and a deliverer of energy. When operated at constant temperature it receives energy at a certain rate, depending on the current applied, *i.e.* on the P.D. and the resistance; the energy which it holds depends on the temperature, dimensions of the filament, and the specific heat; and the rate at which energy is delivered (chiefly by radiation) depends on the temperature and is equal to the rate at which it receives.

When a filament is worked on alternating current, it receives energy at a certain rate at any instant of time depending on the P.D. applied and the resistance of the filament at that instant; it holds a certain amount of energy which depends on the difference between the total input and output of energy up to that time; it delivers energy at a rate which depends upon the temperature at that instant. The amount delivered during a cycle is exactly equal to the amount received during that time.

Assume now, in order to compare the efficiency of light production under conditions of variable temperature with that obtained under conditions of constant temperature, that the same average luminous intensity (taken as unity for simplicity) is to be obtained with the same lamp in each of the two ways. Let the power required in the case of constant temperature be unity (output and input). Then the power output at any instant for variable conditions is

$$\mathrm{P}_i = \mathrm{I}_i^n,$$

where I_i is the candle-power (see fig. 5·29) and n a constant. Hence the total mean output (or input) per cycle is expressed by

$$\mathrm{P} = \frac{1}{2\pi}\int_0^{2\pi} \mathrm{I}_i^n d\theta$$

(assuming the candle-power curve to be a sine curve), so that—since for constant temperature conditions the output is assumed to be equal to unity —the ratio

$$\frac{\text{Variable power}}{\text{Constant power}} = \frac{1}{2\pi}\int_0^{2\pi} \mathrm{I}_i^n d\theta \quad . \quad . \quad . \quad 5{\cdot}09$$

The exponent n is not entirely constant and increases a little with the candle-power. From 0·7 to 1·3 of normal candle-power (the maximum experienced in practice) it decreases 1·6 per cent. for tungsten, 2·16 per cent. for tantalum lamps. In Table XI. we had found for an Osram lamp I proportional to $\mathrm{P}^{2\cdot32}$, whence P is proportional to $\mathrm{I}^{0\cdot432}$.

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* From an article by E. J. Edwards, *Electrical World*, 1911, p. 421.

If then we insert for n the value 0·432 and integrate equation 5·09 for a maximum variation in the candle-power (above or below the average) of 30 per cent., we get,

$$\frac{\text{Variable power}}{\text{Constant power}}=\frac{1}{2\pi}\int_0^{2\pi}(1+0{\cdot}3\sin\theta)^{0{\cdot}432}d\theta$$
$$=0{\cdot}9943.$$

We see that for all practical purposes this ratio is unity, since observation errors in a test may easily account for more than the difference between this value and unity.

92. **ARC LAMPS.**—The tests consist of the determination of the mean spherical and mean hemispherical candle-powers and of the behaviour of the lamps. As regards the candle-power of the lamp we proceed in the way shown under incandescent lamps, *i.e.*, we plot polar curves and determine from the latter the mean spherical or mean hemispherical intensities either as the mean ordinate of the Rousseau curve or by one of the other methods explained. In the case of symmetrical lights we may facilitate the work by testing the lamp under certain angles.

93. **RUSSELL'S METHOD FOR DETERMINING THE SPHERICAL CANDLE-POWER OF SYMMETRICAL ARC LAMPS.**—Russell recommends * the following procedure:—The vertical diameter of a circle is divided into ten equal parts, and from the middle point of each part horizontal lines are drawn until they intersect at the circle. The points of intersection are then joined to the centre of the circle, and under the angles of these lines we determine the intensities of the lamps. The mean spherical candle-power is given by the mean result of all ten determinations, the mean hemispherical candle-power by the mean of the lower five determinations only.

94. **DR BLOCH'S METHOD.**—When the lamp is unsymmetrical we must rotate the lamp and plot the polar curve and the resulting Rousseau curve, as Drysdale has suggested. When this cannot be done we must either make a large number of determinations in all directions, or employ Dr Bloch's method, which is as follows:—Plot first the polar curve along any meridian and then make three additional measurements under the angles of 90, 180, and 270 degrees against the meridian in each of two latitudes, one of which coincides with the equator or lies 10 degrees below it, and one of which lies 45 degrees lower down. Next divide the mean value of these four intensities as found on each latitude by the mean value along the meridian, which gives us two factors of which we again take the mean, and with this we multiply the mean value along the meridian, the result being the M.H.S.C.P.

All these methods are however still laborious and consequently expensive, especially where lamps have to be tested in large numbers. Moreover, the accuracy attainable is by no means great, since the light of an arc is

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* *J.I.E.E.*, vol. xxxii. p. 631.

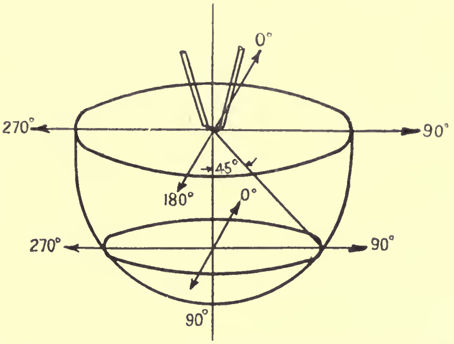

FIG. 5·33.—Dr Bloch's Method for determining the M.H.S.C.P. of Unsymmetrical Arc Lamps. (Inclined Carbons.)

never steady on account of the burning away of the carbon and the consequent feeding of the lamp and the travelling of the arc from one side to another. Ulbricht's globe photometer is therefore to be preferred, and when lamps of similar type and size are to be tested, a simple calibration suffices. The calibration, which has already been indicated under photometrical apparatus, may be summarised as follows:—Insert the lamp to be tested with its source anywhere between the centre and opening of the sphere, also the glow lamp with known spherical candle-power I_o and screens as shown in fig. 3·45. Compare the intensity of the light emitted through the window from the glow lamp with a standard lamp; for equality this intensity is given

$$I = \frac{L_1^2}{L_2^2} \times \text{standard},$$

in which L_1 and L_2 are the distances of the standard and window from the photometer respectively. The constant of the apparatus is then expressed by

$$c = \frac{I_o}{I}.$$

Next switch off the glow lamp and switch in the arc lamp and obtain again equality of the optical fields, when the intensity at the window is given by

$$I_1 = \frac{L'^2_1}{L'^2_2} \times \text{standard},$$

and the M.S.C.P. I'_o of the arc lamp by

$$I'_o = cI_1 = c\frac{L'^2_1}{L'^2_2} \times \text{standard}.$$

The calibration for hemispherical determinations is similar.

For each different type and size of arc lamp, the sphere should be recalibrated.

95. **TESTS FOR ARC LAMP CARBONS.**—The proper working of an arc lamp depends chiefly upon the quality of the carbons used. The manufacture of the carbons is usually as follows:—Gas-retort carbon is broken into pieces, ground and mixed with coal tar and soot, to provide a plastic paste. This paste is densely packed into a cylinder to exclude as much air as possible and then forced through dies by means of hydraulic

pressure. If the carbon is to be cored, a needle is placed in the centre of the die, over which the paste is forced, leaving a central space in the rod for the core. The carbons are now placed into ovens, surrounded by coal dust, and thoroughly baked. The softer core, which consists of a mixture of carbon and potassium silicate or sodium, is often inserted by means of a hand press, after which the carbons are again baked. In front of the die is very often a small wheel which impresses upon the carbons the name of the firm.

Ordinary open arc lamps have a cored positive and a solid negative carbon when used on direct current; on alternating current both electrodes should be cored. For enclosed lamps we mostly use solid carbons, but in some cases it is of advantage to core the positive carbon.

The test on arc lamp carbons includes the *range*, the *resistance*, and the *life*. The range is determined by supplying the lamp with the carbons to be tested, burning them until the tips are properly shaped and the lamp is thoroughly heated (half an hour). We then connect a voltmeter to the carbons and very carefully depress the upper electrode until the lamp commences to "hiss." The voltmeter will then show a sudden drop. We call this voltage the "hissing"-point; it varies with the quality of the carbons. For an ordinary arc lamp it lies somewhat near 40 to 45 volts. The test is then repeated, but this time the carbons are more and more separated until the arc commences to "jump," and may even leave the crater. The voltmeter then indicates the jumping-point, which should lie over 60 volts. If the length of the arc be further increased, the arc will commence to flame, and the voltmeter indicates the flaming-point, which should not lie below 65 volts.

Generally speaking, the hissing-point should be at least 5 volts below the normal voltage of the lamp, where steadiness of light is required. Hissing, jumping, and flaming points are entirely dependent on the quality of the carbon, and slight impurities greatly reduce the steadiness of burning. Soft carbons contain a great deal of soot, while harder ones contain more retort carbon. The softer the carbon, the greater the amount of dust which is deposited by the carbons, but the greater the quantity of the light usually emitted. The quantity of dust should be less than 4 per cent. of the weight of the upper carbon. A smaller amount will show a long life, but will probably also indicate a poor light. The deposit of dust may be almost entirely eliminated by coating the carbon with copper. This also reduces the resistance of the electrodes. The latter is measured best by a Kelvin double bridge. A carbon 11 millimetres in diameter (seven-sixteenths of an inch), about 30 centimetres long (1 foot), has usually a resistance of 0·16 to 0·23 ohm, and carbons 12·5 millimetres (or $\frac{1}{2}$ inch) thick a resistance from 0·14 to 0·18 ohm. This resistance is reduced for 11-millimetre carbons to about 0·05 ohm if for 1000 30-centimetre carbons we employ about 1·23 kilograms (3 lbs.) of copper.

The life of the carbon is best tested by consuming it completely in the lamp at the normal voltage. The time of the test may be reduced by burning the lamp, say, for half an hour, so that the tips have assumed the proper shape, then weighing the carbons, and burning them again for an hour, after which the weighing is repeated. The amount consumed shows the rate of consumption. A rough idea of the life of the lamp would also be obtained by measuring the length of the carbons before and after the test. The one-hour test is best carried out at the average point of burning, so that a 30-centimetre carbon (12-inch) should be broken off to a length of about 16 centimetres. The carbons are, of course, not completely consumed, *i.e.* they must be renewed before the carbon-holders are brought into contact; stops have therefore to be provided, which prevent further feeding of the carbons when the length of 30-centimetre carbon has been reduced to about 5 centimetres. The weight of carbon 30 centimetres long consumed in a complete life test is about 63 per cent. for the ordinary open arc, so that, if we divide 63 per cent. of the weight of both carbons when new by the rate as determined in the one-hour test, we also get the life approximately.

96. **ABSORPTION OF LIGHT BY ARC LAMP GLOBES.**—It would appear that the easiest method for determining the absorption of a globe would consist in finding the M.S.C.P. of the lamp (*a*) without the globe, (*b*) with the globe. This procedure possesses however serious objections. When a lamp burns without a globe the consumption of carbon is usually materially increased, since the supply of oxygen is unlimited, whereas most globes partly limit the passage of air. Again, for enclosed lamps such tests would be completely unreliable, as at least one globe is essential for such lamps. It will also be found that a lamp may flicker badly if burnt without a globe. Tests which are otherwise entirely satisfactory become in these circumstances almost impossible, since the absorption depends also somewhat upon the nature of the light and its distribution. It has been seen in Chapter II. that the absorption of light depends largely upon the wave-length, so that it would be obvious that if we carry out the absorption test with, say, a standard glow lamp, the results obtained in this way might be altogether wrong, when directly applied to arc lamps.

In all cases we obtain a higher mean spherical candle-power when testing without a globe, on account of the unlimited supply of oxygen, than would be the case if we could test the lamp without the globe, but limit the supply of oxygen to that of a lamp when burning with a globe. As arc lamps are always employed with globes, and mostly with reflectors, the results of a test should be stated for the lamp under working conditions.

Although absorption tests do not yield very reliable results, it is still possible to carry out tests in such a manner as to obtain some idea of how much the light is obscured by the globe. For this purpose we employ a large metal filament incandescent lamp, which, since the lamp burns in a vacuum, is independent of the supply of oxygen, and test the arc lamp first without the globe and then when placed centrally within it. The results obtained in this way will not be so very far out, since the light of a metal filament lamp does not differ very much from that of an ordinary arc lamp, although it differs materially from that of a flame arc. Some error will probably also be introduced by the fact that the distribution of the light of the incandescent lamp differs from that of an arc lamp. Tests carried out in this way by Professor J. T. Morris * are illustrated in the accompanying Table XIII.

The first column shows the name and the size of the lamp; the second column, the dates of the tests on which they were carried out; the third column, the angle below the horizontal under which the maximum candle-power occurred; the next two columns show the mean spherical and hemispherical candle-powers; column seven represents the mean volt × amperes; column eight, the mean watts; columns nine and ten, the mean spherical and hemispherical candle-powers per watt respectively. In column eleven is given the percentage of the light emitted; and in column twelve, the corrected M.S.C.P. per watt, which takes into account the absorption of light by the globes.

We see from this table that the absorption of light for the different lamps varies considerably. It should also be pointed out that the values hold for perfectly clean globes, and that the slightest deposit on the inside from the carbons materially reduces the light emitted. In fact, in some cases the light obscured might amount to 80 or 90 per cent. of the total amount.

From this it will be obvious that the efficiency of even a flame lamp will not be much greater than that of an incandescent metal filament lamp unless the globes are kept perfectly clean. On the whole, we may reckon that the following amount of light is absorbed :—

	Per cent.
Clear glass	10
Alabaster glass	15
Opalescent glass	20 to 40
Ground glass	25 to 30
Opal glass	25 to 60
Milky glass	30 to 60

Globes usually alter the distribution of the light, especially if the lamp is provided with a reflector. In some cases, especially for flame arcs with inclined carbons, we place a special prismatic reflector near the bottom of the globe; the effect of this is to direct the light, which is chiefly emitted in a downward direction, towards the horizontal, whereby a great uniformity in the illumination is obtained. (For further information, see the article on the Design of Reflectors.)

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* See *Illuminating Engineer*, 1908, p. 719.

TABLE XIII.—EFFICIENCIES AND CONSUMPTIONS OF ARC LAMPS (MORRIS).

Name of Lamp.	Date.	Maximum C.P.	Angle of Maximum.	M.S.C.P.	M.H.S.C.P.	Mean. V. A.	Mean Watts.	M.S.C.P. per Watt.	M.H.S.C.P. per Watt.	Light Emitted.	Corrected M.S.C.P. per Watt.
New Century D.C. open, 15 amp.	9/6/08	930	Degrees. 43	600	810	51 × 15	765	0·78 } 0·75	1·06 } 1·0	75%	1·0
	6/7/08	1100	50	570	790	54 × 15	810	0·71	0·98		
Jandus enclosed ordinary, 5 amp.	25/5/08	570	42	250	340	80 × 5·8	465	0·54 } 0·55	0·73 } 0·75	91%	0·6
	27/5/08	560	39	230	350	80 × 5·7	455	0·55	0·77		
Crompton - Blondel, 10 amp.	29/5/08	1080	10	720	910	40 × 10	400	1·80 } 1·95	2·27 } 2·5	60%	3·25
	10/7/08	1380	14	845	1110	40 × 10	400	2·11	2·77		
Excello, 10 amp.	1/6/08	1720	60	900	1400	47 × 10	470	1·92 } 2·25	2·98 } 3·55	74%	3·05
	6/7/08	2550	70	1130	1830	44 × 10	440	2·57	4·16		
Gilbert D.C., 10 amp.	16/6/08	2450	60	1240	2000	48 × 10	480	2·58 } 2·25	4·17 } 3·65	78%	2·9
	10/7/08	2140	61	915	1490	47 × 10	470	1·95	3·17		
Oriflamme D.C., 9 amp.	12/6/08	1020	47	495	825	38 × 10	380	1·30 } 1·55	2·17 } 2·55	67%	2·3
	6/7/08	1140	52	540	880	34 × 9	306	1·77	2·89		
Westinghouse, 9 amp.	13/6/08	960	36	550	790	54 × 9	486	1·13 } 0·9	1·63 } 1·4	58%	1·55
	10/7/08	750	59	340	585	55 × 9	495	0·69	1·18		
Gilbert A.C., 12 amp.	19/6/08	1520	56	695	1130	55 × 11·5	630	1·10 } 1·05	1·79 } 1·65	73%	1·45
	15/7/08	1500	60	640	1000	55 × 11·8	650	0·98	1·54		
Oriflamme	13/7/08	820	45 }	430	690	44·2 × 10	440	0·98 1·0	1·57 1·55	65%	1·55
		880	90 }								
Jandus enclosed flame, 5½ amp.	24/6/08	1700	15–30	885	1425	58 × 6·1	355	2·49 } 2·65	4·01 } 3·9	84%	3·15
	26/6/08	1820	0–10	1045	1400	59 × 6·3	370	2·82	3·78		

Taking arc lamps as a whole, we may accept the results given in the accompanying Tables XIV. and XV., which are self-explanatory.

Table XIV.—Efficiencies of Arc Lamps (Morris).

	M.S.C.P. per Watt.
High-grade flame carbons	2·9 to 3·3
Lower-grade ,, ...	1·5 to 2·5
Ordinary carbons, open	about 1
,, ,, enclosed	about 0·6

Table XV.—Efficiencies of Arc Lamps (Morris).

	M.H.S.C.P. per Watt.
Lamp with high-grade flame carbons, enclosed	3·9
,, ,, ,, open .	3·5 to 3·7
,, Auer carbons	2·5
,, lower-grade flame carbons . .	1·4 to 2·5
,, ordinary carbons, open . .	about 1
,, ,, enclosed . .	about 0·75

97. **MOORE TUBE LIGHTING.***—In order to determine the light emitted by the Moore tube system, it is necessary to screen off the whole tube except a narrow strip, the intensity of which is to be determined. In the tests carried out by Professor Wedding, the tube was 44 millimetres in diameter, with a glass thickness of 2 millimetres. The whole tube was covered with black paper, leaving free only a strip of 1 square centimetre, which on testing gave an intensity of 0·202 candle. Increasing this area to 1 × 2; 1 × 3; 1 × 4 square centimetres, in the direction of the axis of the tube, it was found that proportionality existed, *i.e.* the light increased directly with the length of the tube exposed.

The same thing applied to cylindrical exposed surfaces, the intensity of a ring surface of 1 centimetre length being 0·47 candle. On testing the tube for absorption of light by the gas enclosed, by placing two tubes side by side so that one screened off the other as far as the photometer screen was concerned, it was found that for all practical purposes the absorption was negligible. We may therefore judge the system by the amount of light emitted by a ring surface of 1 centimetre length.

The connections for the test are shown in the accompanying fig. 5·34, in which A_1 and A_2 represent ammeters, V_1 and V_2 voltmeters, T the transformer, C the choker, S the solenoid for operating the valve, P_1 and P_2 wattmeters, and F the frequency indicator. The voltmeter V_2 is joined to a special volt transformer, which reduces the P.D. in the ratio 15,000 to 110. One pole of the high potential secondary circuit is joined to earth.

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* See also "Das Moore Licht," by W. Wedding, *E.T.Z.*, 1910, p. 501.

The results of the tests are shown in the accompanying Table XVI. The average value of candle-power is 0·485 for a surface of 1 centimetre width. As the length of the tube was $37\frac{1}{2}$ metres, and the primary power 3333 watts, we have per metre length of tube 89 watts and 48·5 candles measured perpendicularly to the axis of the tube. Hence for one candle we must expend 1·87 watts.

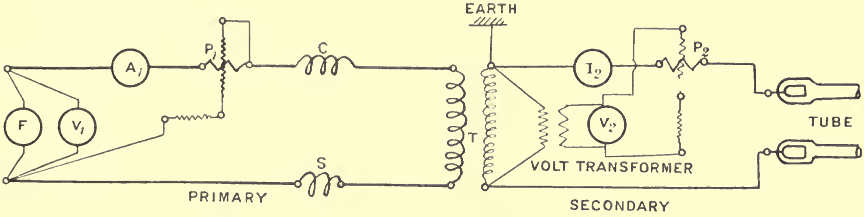


FIG. 5·34.—Connections for testing Moore's Tube System.

TABLE XVI.—BEHAVIOUR OF THE MOORE TUBE SYSTEM UNDER NORMAL CONDITIONS (WEDDING).

Frequency. f.	Primary Volts. E_1.	Primary Current. I_{c1}.	Primary Power. P_1.	Power Factor. $\cos\phi_1$.	Secondary Volts. E_2.	Secondary Current. I_{c2}.	Secondary Power. P_2.	Efficiency. η.	Candles per Centimetre Length of Tube. i.
50	220·6	23·1	3348	0·658	12,800	0·279	2850	0·853	0·551
50	221·3	23·0	3356	0·658	12,860	0·279	2850	0·85	0·444
50	221·5	23·2	3356	0·658	12,870	0·279	2870	0·856	0·435
50·4	220·1	23·0	3272	0·645	12,780	0·273	2880	0·882	0·508
50·1	220·9	23·075	3333	0·655	12,827	0·277	2862	0·86	0·485

98. **INFLUENCE OF THE PERIODICITY.**—The behaviour of the system on different frequencies is represented in the accompanying Table XVII. During the test it was impossible to maintain the secondary P.D.

TABLE XVII.—BEHAVIOUR OF THE MOORE TUBE SYSTEM FOR DIFFERENT FREQUENCIES (WEDDING).

f.	E_1.	I_{c1}.	P_1.	$\cos\phi_1$.	E_2.	I_{c2}.	P_2.	η.	i.
36	153·0	23·0	2272	0·645	8680	0·272	1655	0·729	0·218
40	153·0	22·8	2272	0·652	8500	0·273	1655	0·729	0·23
43	153·7	23·1	2236	0·630	7860	0·275	1655	0·742	0·228
46	153·5	22·9	2184	0·622	7760	0·276	1655	0·757	0·216
49	153·0	22·9	2052	0·586	7180	0·271	1615	0·788	0·20
50	153·2	22·9	2024	0·578	6935	0·279	1665	0·848	0·189
53	153·7	22·9	1868	0·531	6320	0·279	1512	0·811	0·111
56	153·9	22·9	1684	0·478	5660	0·279	1258	0·748	0·072
60	156·0	22·7	1552	0·438	5160	0·274	1165	0·752	0·047

constant, as will be seen from the table. It will also be seen that, with increasing periodicity, constant primary P.D., and constant current, the secondary pressure drops on account of increasing losses in the circuits. Moreover, when the secondary P.D. falls too much, the light commences to flicker. It was also noticed that the luminous gas possessed considerable inertia, which prevented rapid variations in the light due to rapid changes in the supply P.D.

99. **INFLUENCE OF INDUCTANCE IN THE CIRCUIT ON THE LIGHT.**—The steadying resistance of arc lamps is replaced in the Moore system by a choking coil. The choker was provided with five tappings, allowing a fair variation in the number of the turns. The next table, XVIII., shows the results. When the choking effect is small, the secondary current and E.M.F. are very irregular, whereas, with an increase in the number of turns on the choker, the light decreases, due to a decrease in the secondary P.D. and power.

TABLE XVIII.—EFFECT OF INDUCTANCE ON MOORE'S TUBE SYSTEM (WEDDING).

Tapping of Choker.	E_1.	I_{c1}.	P_1.	$\cos \phi_1$.	E_2.	I_{c2}.	P_2.	η.	i.
1	200·0	22·8	3220	0·706	14,150	0·261	2665	0·828	0·504
2	200·5	23·6	3152	0·677	12,295	0·278	2645	0·845	0·455
3	200·1	23·0	3068	0·666	11,325	0·277	2560	0·840	0·421
4	200·5	22·9	2902	0·632	10,360	0·277	2080	0·718	0·424
5	200·7	22·8	2592	0·567	9,020	0·279	2190	0·844	0·277
2	220·3	23·0	3400	0·670	13,800	0·274	3045	0·897	0·596
3	220·1	23·0	3272	0·645	12,780	0·273	2880	0·882	0·515
4	219·5	23·0	3176	0·628	11,900	0·272	2780	0·878	0·520
5	220·1	23·0	3024	0·598	10,840	0·278	2640	0·874	0·420

Again, when the number of turns in the choker is small, the light flickers considerably, and when the choker was short-circuited, the light was too irregular for testing; moreover, the valve commenced to pump and the equilibrium of the tube was destroyed. The choking effect should be such that the light is steady and the decrease in the intensity a minimum. The energy absorbed by the choker is represented in Table XIX.

TABLE XIX.—POWER LOST IN THE CHOKER (WEDDING).

Frequency.	Current.	Tappings.	Volts.	Power.
50·5	22·9	1	39·5	77
50·5	23·1	2	86·8	120
50·5	23·1	3	111·0	140
50·	23·0	4	128·7	156
49·75	23·0	5	147·5	167·5

For normal working, when tapping 3 was employed, the loss was 140 watts, or about 4 per cent. of the input.

100. **POTENTIAL AND CURRENT CURVES.**—The behaviour of Moore's tube system is best studied by means of oscillograms. The connections for such a test are shown in the accompanying fig. 5·35, which is self-explanatory. Results of such tests are illustrated in figs. 5·36 to 5·38.

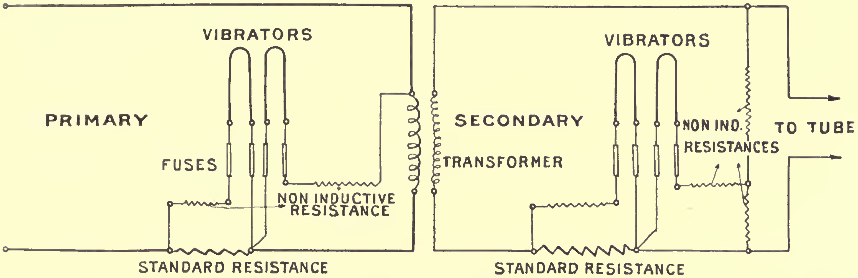
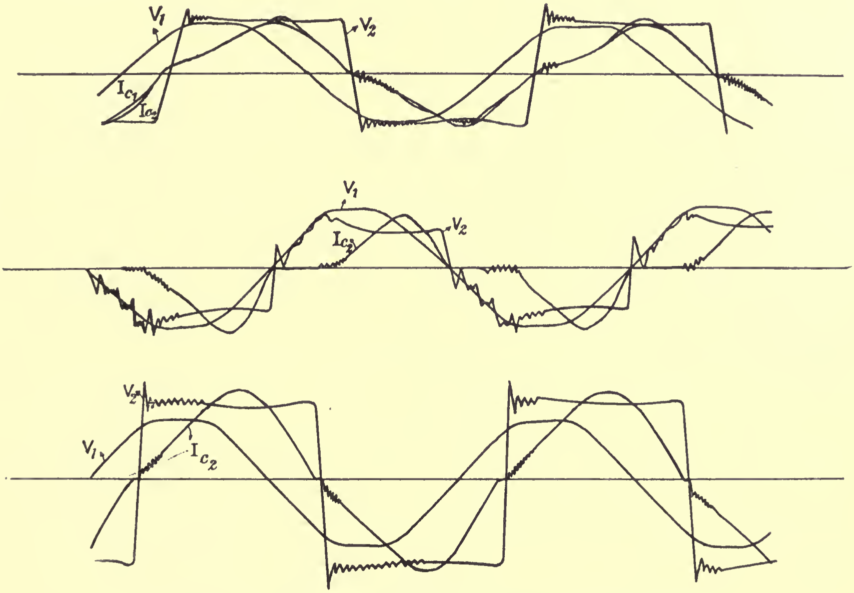


Fig. 5·35.—Connections for Moore's Tube Test.

It will be seen from these figures that secondary P.D. and secondary current are in phase; but, if we look at Table XVIII., we find that there is an apparent phase displacement—*i.e.*, if we divide the secondary true power by the secondary volt-amperes the ratio is not unity, but lies between 0·7 and 0·8. This is due to the peculiar shape of the secondary P.D. curve.



Figs. 5·36 to 5·38.—Oscillograms from Moore's Tube Tests.

As secondary volts and currents are in phase, it follows that the gas column offers no capacity or inductive effects to the current, but acts as a pure resistance. The figures also illustrate the behaviour of the tube for different inductances in the primary circuit. When the choker is joined to the first tapping, the secondary current takes considerable time before it commences to change its direction (see fig. 5·37), whereas in fig. 5·38, which was plotted with the choker joined to tapping 5, the change of the current takes place almost instantaneously. The experiments show that the gas column itself chooses the most favourable conditions irrespective of the shape of the volt-curve which is impressed upon the transformer. The following table, XX., shows in a convenient form the behaviour of the tube for different inductances, as obtained for the various contacts of the choker. The apparent power-factor of the secondary circuit is included therein. The actual phase displacement is of course unity.

TABLE XX.—BEHAVIOUR OF MOORE'S TUBE SYSTEM FOR DIFFERENT INDUCTANCES (WEDDING).

Tapping of Choker.	Ratio of Wave-Length to Length of Zero Current (see figs. 5·37 and 5·38).	Cos ϕ_1.	Cos ϕ_2 (Apparent).
1	1 : 3		
2	1 : 6	0·670	0·806
3	1 : 11	0·645	0·826
4	1 : 14	0·628	0·859
5	1 : 18	0·598	0·876

CHAPTER VI.

THE DESIGN OF REFLECTORS AND SHADES.

101. **GENERAL CONSIDERATIONS.**—When lamps are employed for local lighting—for instance, incandescent lamps for the lighting of a table—the polar distribution must usually be modified in order that the maximum possible flux is made available in the region where the light is wanted. A glow lamp hanging vertically downwards gives its maximum candle-power in a horizontal direction, where the light is not required (except in the case of street lighting); hence a shade should be used to direct the light downwards. On the other hand, flame arc lamps should give a maximum intensity about 10 degrees below the horizontal, whereas without reflectors they produce this intensity vertically downwards. By means of a reflector underneath the lamp the distribution may be altered as desired.

By means of a few examples the method of designing reflectors is illustrated below.

Example 1.—It is required to illuminate a table, having a diameter of 3 metres, uniformly near its circumference, to a width of 0·5 metre, for which purpose a 100 candle-power tungsten lamp is available, with a distribution according to figure 6·01. Let the lamp be fixed 1·5 metres above the table.

Plot the luminous flux curve for the whole spherical polar curve, according to the method explained for fig. 5·11, and a flux of 873 lumens is obtained. Insert the height of the lamp above the table and the radius of the table, and indicate by a thick line the part of the table which has to be illuminated. We see that the flux is required in a region lying between angles of 34 and 45 degrees, the mean angle being 39·5 degrees. The flux below 34 degrees cannot be utilised conveniently, and may be employed for the general illumination of the centre of the table. The flux within the principal region is $220 - 175 = 45$ lumens, which alone would give an illumination of only $\frac{45}{3 \cdot 93} = 11 \cdot 4$ candle-metres, where 3·93 is the area in square metres of that part of the table which we have to illuminate. We may use however the flux radiated above 45 degrees. This flux is equal to $873 - 220 = 653$ lumens. If we assume that 30 per cent. is absorbed by the reflector, we have still 457 lumens which, when added to the 45, give us a total of, say, 500 lumens. The resulting illumination will then be equal to $\frac{500}{3\cdot93}=127$ candle-metres. The actual design is indicated in fig. 6·01. If we employ a metal shade with a diffusing coating, it is sufficient to design it for reflecting the light principally to the centre line of the ring surface of the table. By the diffusing nature of the reflecting surface the light will be sufficiently scattered to procure uniformity of illumination. If we make use of regular reflection, we must see that the reflector is so designed that the whole ring surface receives the light flux uniformly, otherwise streakiness results. This may even happen with a diffusing shade. It can be prevented by making the reflector fluted or corrugated.

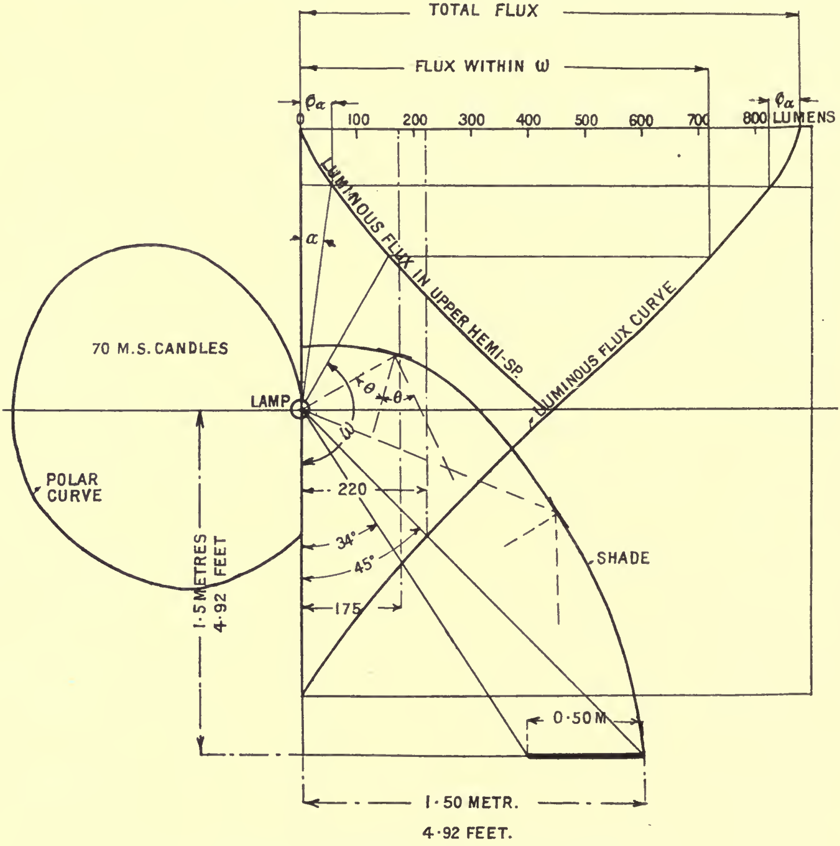


FIG. 6·01.—Designing a Reflector for a Table.

The reader will notice that the reflector increases the illumination of the table considerably.

Example 2.—It is required to illuminate a town square as uniformly as possible by means of arc lamps with polar curves according to fig. 4·11. The area has a length of 230 metres, and a breadth of 175 metres, containing therefore 40,000 square-metres. The illumination must not be less than 5 candle-metres.

The flux from each lamp is 20,000 lumens (from 1600 M.S.C.P.), so that, since we require a flux of 5 × 40,000 = 200,000 lumens, ten lamps are wanted, assuming that the whole flux is utilised. As the flux into the upper hemisphere is already small, we shall be safe if we assume a total loss of 20 per cent., which means that we must employ twelve instead of ten lamps.

Divide therefore the area into twelve squares of 57·5 metres a side, and place one lamp in the centre of each square, according to fig. 6·02. The distance between the lamps is then 57·5 metres. We may proceed in two ways.

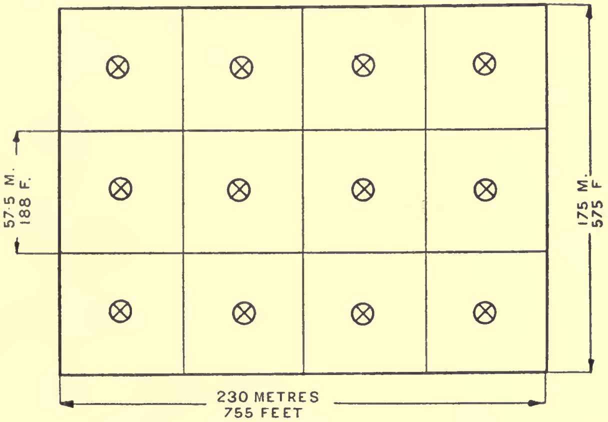


Fig. 6·02.—Arrangement of Arc Lamps.

(*a*) Provide each lamp with a reflector which limits the flux approximately to its particular square. This method is physiologically poor, because the shadows thrown by objects will be very dark and appear like obstructions, as no other lamp is able to illuminate the shadow and enable us to see objects in it.

(*b*) Use the natural distribution of the light of the lamp as far as possible, and only where the light is insufficient allow the reflector to add to the illumination. The method, indicating the design of the reflector, is clearly shown in figure 6·03. Let the light of each lamp be able to reach as far as the post of the next lamp. Above the angle θ corresponding to this distance, the shade cuts off the light. Curve 3 gives the illumination when the lamps are without reflectors. The illumination is already uniform. The degree of uniformity is further improved by utilising the light flux above the angle θ and by directing it chiefly to areas half-way between the lamps. The value of this flux is 5600 lumens. Suppose 30 per cent. of it is absorbed by the reflector, *i.e.* 1680 lumens, then 3920 lumens from each lamp are available for raising the illumination between the lamps.

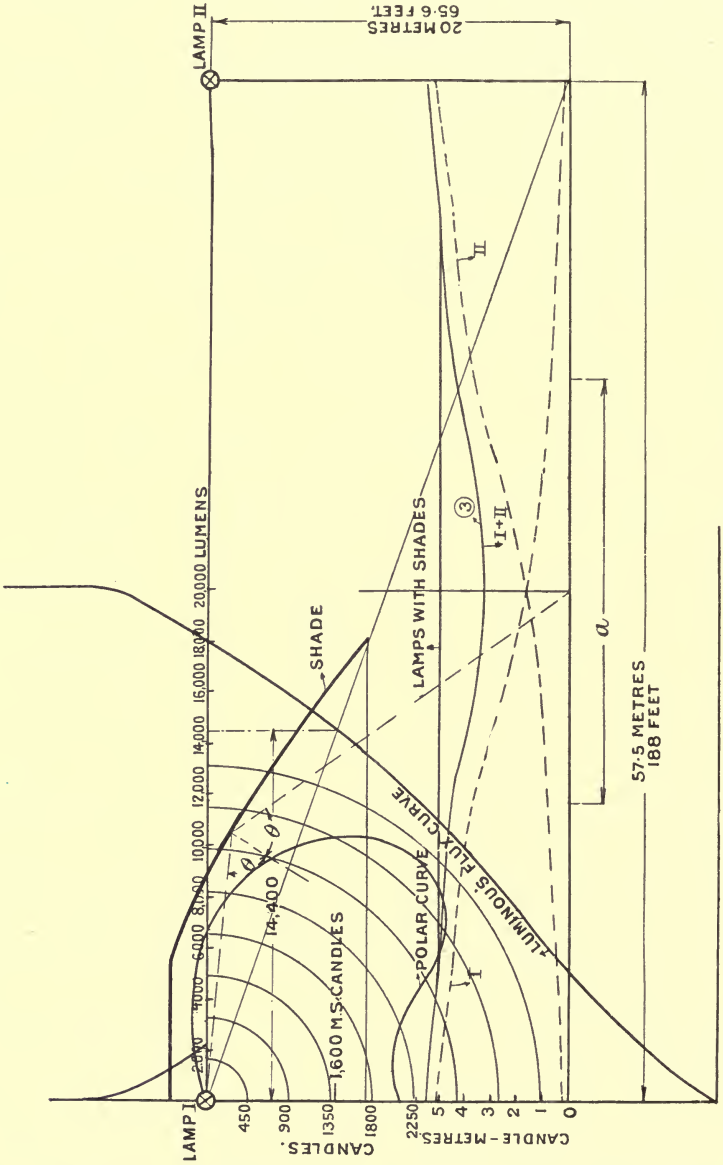


FIG. 6·03.—Design of Reflector for Arc Lamps.

The area of the ring surface, indicated by the letter *a* in fig. 6·03, which requires an increase in the illumination, is about 3600 square-metres, so that the average increase is about $\frac{2 \times 3920}{3600} = 2{\cdot}17$ candle-metres. The illumination without reflector right under the lamp is 5·6 candle-metres; half-way between it is 3·3. By adding 2·17 to the latter, we get 5·47. We must however direct somewhat more light towards the area of minimum illumination and less where the curve 3 rises, by shaping the reflector accordingly, and the illumination can be made as uniform as one may wish.

102. **DIFFUSION AND DIFFRACTION.** — When the intrinsic brilliancy of a radiator is too high from the physiological standpoint and the flux concentrated too much over a narrow angle, we must employ diffusing or diffracting globes or shades. There is a distinct difference between diffusion and diffraction. A diffusing globe is given by opal glass; and if we look at such a globe, which contains, say, an incandescent filament, the latter will usually be just faintly visible, but the principal effect consists in turning the shade into a secondary radiator, emitting light approximately uniformly in all directions. The light distribution is thus entirely changed. On the other hand, if the radiator be placed in a diffracting globe, either edged or sand-blasted, the radiator itself is invisible, but the globe does not appear uniformly illuminated. The light seems to be concentrated in the centre of the globe. If the illuminant be a metal filament lamp, we see an apparently cylindrical radiator only slightly larger than the cylinder formed by the filament. The difference between the two types of radiator is illustrated in fig. 6·04. The shading represents the intensity of illumination as it appears to the onlooker. The diffusing globe scatters the light with a maximum intensity perpendicular to the plane of the glass, whereas the diffracting shade passes the light chiefly in the direction of the impinging ray. It follows from this that the shape of a diffusing globe is of importance for the distribution of the light, not so the shape of the diffracting globe.

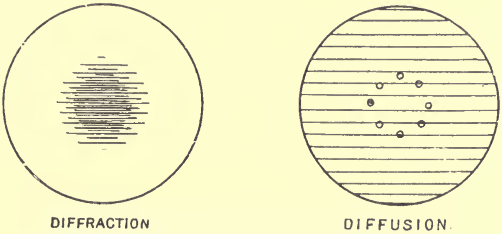


FIG. 6·04.—Diffraction and Diffusion.

It must be remarked that pure diffusion and diffraction does not occur with either of these globes, and that there is always a mixture of both, with one or the other predominating.

103. **REFRACTION.**—Opal and frosted globes absorb a considerable amount of light. Better results are obtained by the employment of prismatic shades and reflectors. These shades, which are known under the name "Holophane" (all light), are due to Blondel and Psaroudaki of Paris.

When light falls on a denser medium, it is refracted; when it strikes a less dense material, it is either refracted or reflected. Reflection takes place when the angle of incidence is greater than the critical angle. If the refractive indices of two contiguous media be a and b, a greater than b, then the critical angle for any incident ray in the denser medium is the angle whose sine is $\frac{a}{b}$. Assuming that the refractive index of air is unity, that of glass 1·6, we know at once for which angle refraction and for which reflection will take place. In our case the critical angle is about 39 degrees.

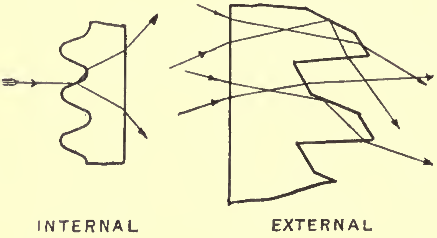


FIG. 6·05.—Prisms of Holophane Shades.

In the holophane shades and reflectors these principles have been applied. There are two principal types of shade made. If the light is to be diffused, the shade is provided with internal and external prisms according to fig. 6·05. The internal prisms diffuse the light. Each ray is broken into two or more rays, and as the eye in following up the ray is

FIG. 6·06.—Light as it appears through a Holophane Shade.*

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* Type of shade used by Siemens.

unable to see the source of light, the whole globe appears more or less illuminated. This is excellently illustrated in fig. 6·06, which represents a prismatic reflector with a clear glass globe as used for arc lamps.

The external prisms of diffusing shades have mostly four faces, of which one or more pass the light after simple refraction, while others reflect it completely. The reflected ray is then refracted by another surface. In designing such reflectors, care must be taken that the light is not reflected back into the shade, as this would mean a loss of light.

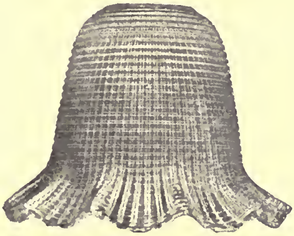

Fig. 6·07.—Holophane Pendant.

The polar curve for the holophane pendant, shown in fig. 6·07 and carrying a 50-watt tantalum lamp, is reproduced in fig. 6·08. Other holophane diffusing shades are illustrated in figs. 6·09 and 6·10, while a complete installation is given in fig. 7·22.

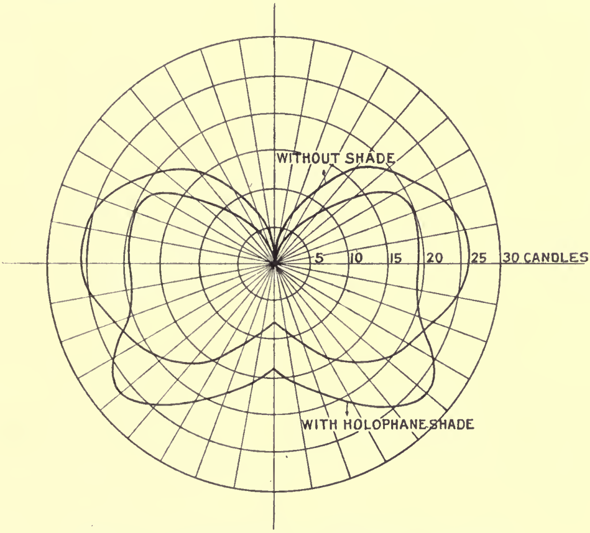

Fig. 6·08.—Polar Curve for Holophane Pendant.

If the shade is to act as the reflector for directing the light in any particular way, the prisms must be arranged accordingly. Reflectors of this type are smooth inside, except near the top, where they are grooved vertically. The outside is formed of rectangular, totally reflecting vertical prisms, on which the light falls at angles which are greater than the critical angle. The prisms act in a manner that the light is reflected downwards. Near the top are placed a few circumferential prisms; these, the tops, and bottoms of the vertical prisms allow sufficient light to pass for general illumination, thus avoiding sharp contrasts.

FIG. 6·09.—Holophane Shade.

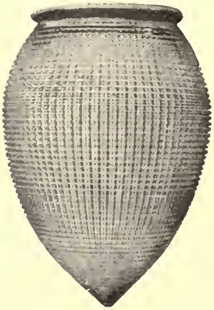

FIG. 6·10.—Holophane Shade.

104. **HOLOPHANE REFLECTORS.**—A holophane reflector is shown in fig. 6·11, and its polar curve when used in connection with a 50-watt tantalum lamp in fig. 6·12. It will be seen from the latter that the intensity in a downward direction has increased from 8 to 64 candles.

Although the area of the new polar curve is much larger than that of the original curve, it must not be assumed that the flux is now greater. As a matter of fact the flux is a little smaller than that of the naked lamp on account of some absorption of light by the reflector. This can easily be tested by finding the mean spherical candle-power for each curve.

FIG. 6·11.—Holophane Reflector.

Other types of reflectors are shown in figs. 6·13 and 6·14.

The reflectors shown so far are symmetrical, *i.e.* they show the same kind of prisms all round. For street lighting purposes we may conveniently combine totally reflecting and diffusing shades. Such a type is illustrated in fig. 6·15.* It has two portions—a face and a back. The former faces the street proper and possesses a smooth exterior surface with vertical, totally reflecting and refracting prisms on the inside. The back, which faces the houses, has a series of totally reflecting prisms on the exterior and a smooth interior.

The distribution of the light for such a shade from a 40 candle-power

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* See *Illuminating Engineer*, 1908, p. 424.

metallised carbon filament (gem) lamp is given by figs. 6·16 and 6·17. The first figure represents the polar distribution in a horizontal plane 10 degrees below the horizontal through the centre of the lamp. The vertical

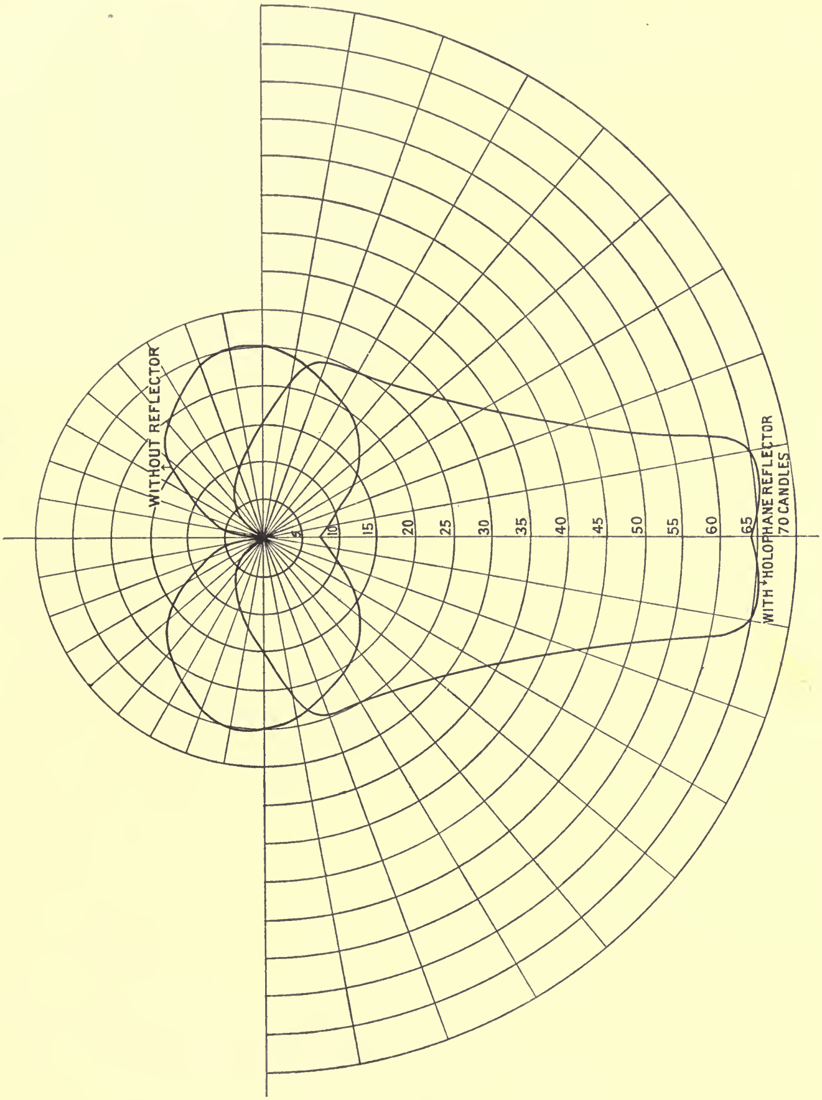

Fig. 6·12.—Polar Curve for a 50-watt Tantalum Lamp under a Holophane Reflector.

line indicates a plane at right angles to the direction of the road. We see that the maximum light is not thrown along the footpath, where it would cause glare, but into the road at an angle of about 65 degrees. The second figure shows the distribution in a vertical plane through the 65 degrees ordinate of maximum candle-power illustrated in the previous figure.

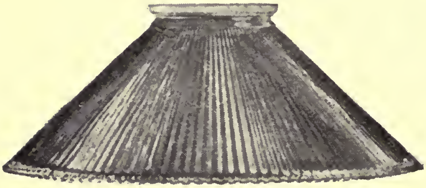

Fig. 6·13.—Holophane Reflector.

Fig. 6·14.—Holophane Reflector.

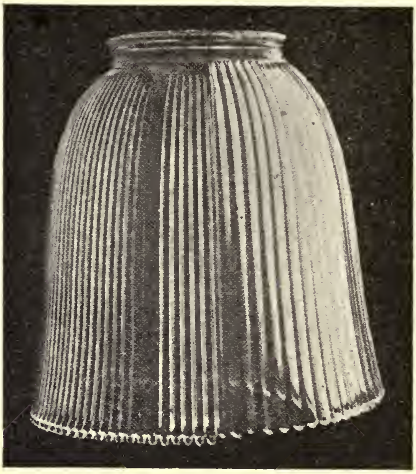

Fig. 6·15.—Holophane Shade for Street Lamps.

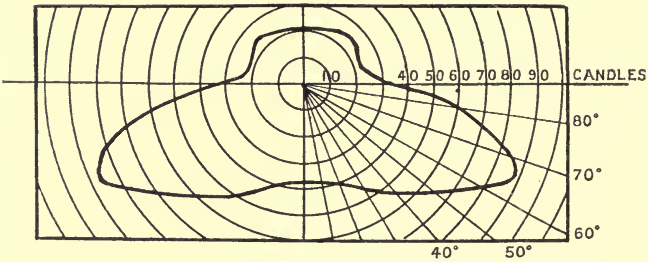

Fig. 6·16.—Distribution of Light for a Street Lamp with a Special Holophane Shade in a Plane 10 Degrees below the Horizontal.

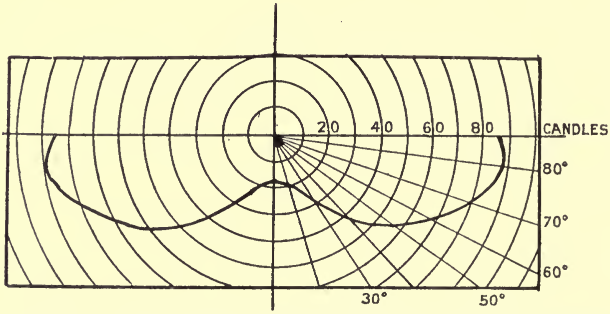

Fig. 6·17.—Distribution of Light for a Street Lamp with a Special Holophane Shade (in a Vertical Plane).

If prismatic reflectors are to be effective, they must be kept scrupulously clean. This means that they should be frequently wiped, especially shades with external circumferential prisms, which easily collect dirt and dust. Reflectors with vertical ridges are better in this respect, and where they are used for outdoor lighting, falling rain will clean them to a large extent.

Holophane shades are much more expensive than metal shades. Where a uniform illumination is required, it is in most cases sufficient to fix the lamps close to the ceiling and to provide them with ordinary conical shades, which have an aperture of about 90 degrees. The ceiling must however be fairly high, in any case not less than 3 metres (10 feet), as otherwise the radiators will be in the line of vision. In large rooms even this height is not enough. Where it is impossible to fix the lamps so high, the totally enclosing shades of fig. 6·09 are preferable to ordinary diffusing or diffracting globes, which absorb a considerable amount of light, and the increase in the price of the holophane globe is more than counterbalanced by the greater amount of light obtained.

105. **SHADES AND GLOBES FOR ARC LAMPS.**—We shall confine our remarks to flame arcs, since the ordinary type of lamp with pure carbons is but rarely installed to-day.

Flame lamps mostly have inclined carbons, so that the maximum intensity is directed vertically downwards. This means that the illumination of the street will be high under the lamp and very low half-way between the posts. By means of prismatic reflectors we may refract the light in such a manner that the maximum intensity is shifted from the vertical to a direction lying between 10 and 30 degrees below the horizontal. The type of globe employed for arc lamps is illustrated in fig. 6·06. Where the prismatic globe is used it is no longer necessary to provide the lamp with an opal or diffracting globe, since the light is sufficiently diffused by the prisms, which prevent glare, and a small clear external glass globe only need be added. The amount of absorbed light is much smaller for such a system than for opal or frosted globes, for which the absorption is frequently 50 per cent. or more. The manner in which the light is refracted by the prism glass is illustrated in fig. 6·18. The external globe

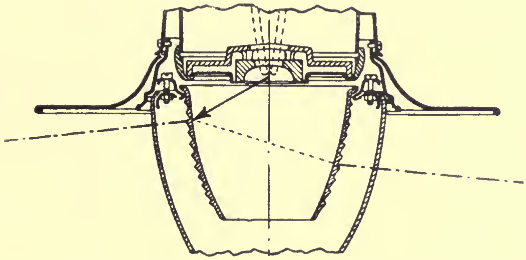

FIG. 6·18.—Refraction of Light from a Flame Arc Lamp by a Prismatic Globe.

should pass the light without much refraction. To prevent the gases produced by the arc from frosting the globe, since they contain fluoric acid, the ventilation of the lamp must be very efficient. The difference between badly and well ventilated globes is shown in figs. 6·19 and 6·20. The extent to which the degree of uniformity of the illumination is improved by the prism glass is well seen by comparing the accompanying figs. 6·21 and 6·22; they are self-explanatory.

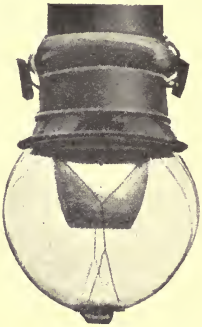

Fig. 6·19.—A Badly-Ventilated Globe for Arc Lamps.

Fig. 6·20.—A Well-Ventilated Globe for Arc Lamps.

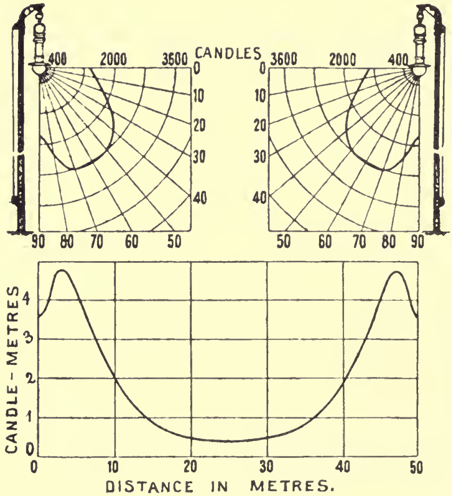

Fig. 6·21.—Illumination by Flame Arc Lamps without Prismatic Globes.

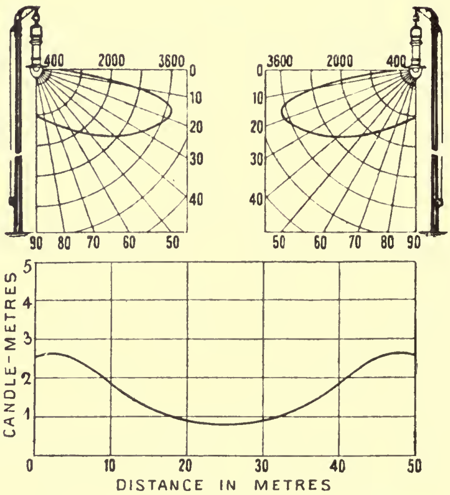

Fig. 6·22.—Illumination by Flame Arc Lamps with Prismatic Globes.

106. **HRABOWSKI'S TOTAL REFLECTOR FOR ARC LAMPS WITH INCLINED CARBONS.***—This reflector is illustrated in the accompanying figure 6·23. It consists of two parts, a large diffusing shade of enamelled sheet iron and a ring-shaped reflector of prism glass. The

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* Made by Siemens-Schuckert Werke, Berlin; see also *E.T.Z.*, 1910, pp. 11–13.

latter possesses three accurately ground spherical surfaces, of which two are totally reflecting. Between 0 and 45 degrees the light is allowed to pass through the clear glass globe directly. Light under these angles does not cause glare to the eye in its ordinary position, unless it is fixed very low down. The metal shade acts diffusingly, while the crystal reflector distributes the light by total reflection practically uniformly without loss over the whole area to be illuminated. The action of these prisms is clearly indicated in the figure.

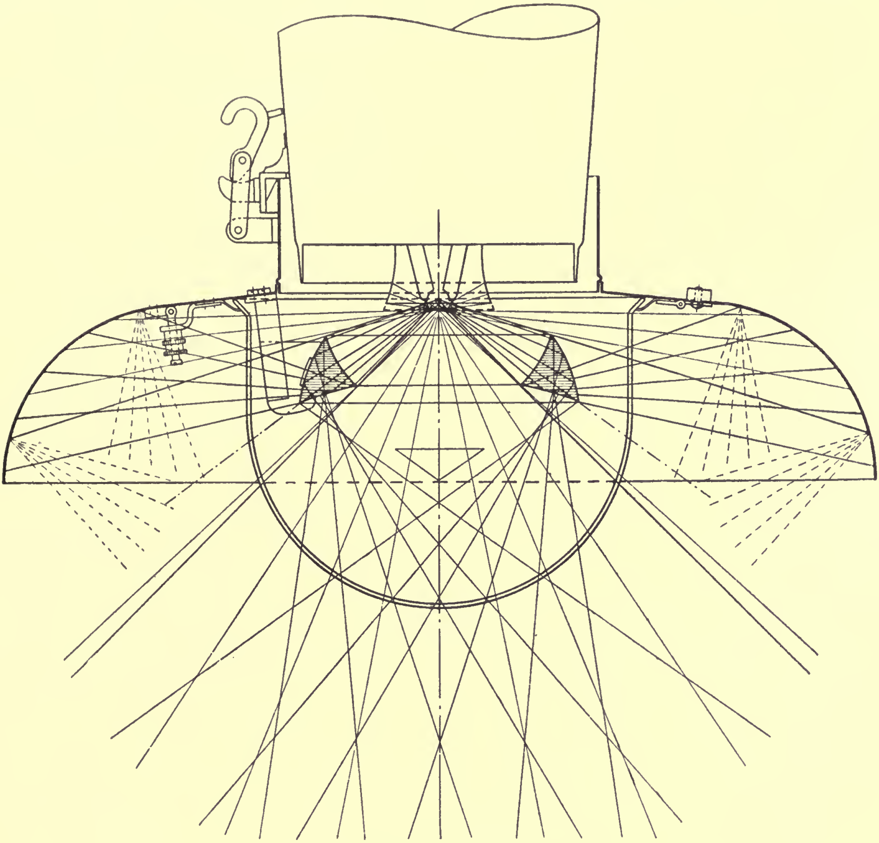

Fig. 6·23.—Hrabowski's Total Reflector.

The chief advantage of this type of reflector lies in the small loss of light by absorption, since a clear glass globe may be employed, and the avoidance of glare, as the rays are mainly directed downwards and therefore do not enter the eye. The system is especially suitable for the lighting of high shop windows and for planes of a limited area which require a high illumination.

Flame arcs may also be used with this system, since the glass prisms become sufficiently hot to prevent the gases from depositing on them.

CHAPTER VII.

ILLUMINATING ENGINEERING.

107. **QUANTITY OF LIGHT REQUIRED.**—Of great importance for proper illumination is a knowledge of the amount of light required. The light should be such that the eye is able to recognise fine details. This quality of the eye is called *visual acuity*, which is determined by experiment. According to a large number of tests carried out by the author, the following table represents the minimum amount of light required for reading ordinary text-book type in rooms of different colours.

TABLE XXI.—MINIMUM AMOUNT OF LIGHT REQUIRED FOR ROOMS OF DIFFERENT COLOURS.

Colour of Room.	Illumination.	
	Candle-metres.	Candle-feet.
Black	35	3·28
Deep red	32	3·00
Dark green	30	2·80
Pale blue	28	2·62
Light yellow	25	2·34
Cream silvery	23	2·15
White	20	1·87
White (indirect light)	15	1·40

The table aims at equal comfort in all cases; that is, it is as easy to read the print in a room with a white ceiling and white walls having an illumination of 20 metre-candles as it is in a room with black walls with 35 metre-candles. This implies however that in the rooms of darker colours the eye roams as little as possible from the print.

The divergency of the table may be explained as follows:—In a dark room the eye feels the surrounding blackness instinctively and the slightest roaming causes the eye to expand as it encounters the surrounding blackness, but looking at the brilliantly illuminated paper again, a glare is experienced, causing the eye to contract. This contraction makes the illumination now appear insufficient, and the eye has to expand again. This repeated expansion and contraction seems to make the higher illumination necessary. There is no doubt that the eye is affected more by contrast than by actual illumination.

On the whole it is useless to install for the purpose mentioned a greater illumination than given in the table, as light would simply be wasted, since the eye is already in full action, and only in the case of extreme requirements should the illumination be greater.

108. **CONTRACTION OF THE PUPIL AND FATIGUE.**—The illuminating engineer has to satisfy two requirements simultaneously: viz. those of physics and physiology. He must therefore be careful that he does not neglect one at the expense of the other. Very often a lighting installation may be perfect from the physical standpoint—*i.e.* when we measure the intensity of the illumination and the uniformity with physical instruments, the results leave nothing to be desired,—whereas from the physiological standpoint the installation is defective. It is, of course, in the first place essential that the quantity of light should be sufficient, and the above table will usually give results ensuring comfort. It must not however be assumed that by doubling the quantity of light, we also increase the comfort. As a matter of fact an increase in the intensity not only often reduces the comfort but even the quantity of light which enters the eye. A high uniform intensity causes fatigue to the eye and makes it contract. This is especially the case with direct light, and it is therefore essential that such light be averted from the eyes, either by placing it out of the line of vision, or by surrounding it with proper globes. The contraction of the eye takes place when a sudden excess amount of light enters the eye, whereas fatigue is caused by continued absorption of large quantities of light fluxes. This would mean that—in order to be able to rest the eye—we should supply two illuminations: a fairly high one for working purposes, as is indicated in Table XXI. and which is usually called local illumination; and a considerably lower one which allows the eye to rest from the high intensity and to recover increased sensitiveness. We may compare this system with walking alternately on a hard road and a softer grass-covered footpath, which is far less tiring than walking continually on one type of road. The general illumination should however not be too low, as then the eye would experience glare when returning to the highly illuminated surface. (It is comparable to replacing the grassy footpath by deep loose sand or snow, which would greatly add to the tiring process.)

109. **COLOUR OF LIGHT.**—We have seen in Chapter II. that the colour of the light has an important bearing on the comfort attainable. When the illumination is low, as is the case in street lighting, the sensitiveness moves towards the greenish-blue part of the spectrum; hence we should install light which is rich in these rays, such as the mercury vapour

lamp. Unfortunately, the almost total absence of red rays makes everything look of a ghastly colour. The next best thing from the physiological standpoint would be to use a vapour lamp combined with a number of incandescent lamps rich in red rays, somewhat after the type of lamp shown in fig. 2·06; or to employ the ordinary enclosed arc lamp also rich in greenish-blue rays without being deficient in red ones.

In rooms with light colours these lamps are less desirable. Dirt has mostly a brownish colour, and when the light of a mercury vapour lamp falls upon it, it appears almost black. A room with a red wall-paper would look like a dark room when studied in the light of a vapour lamp. To avoid stains appearing abnormally dirty, and red and brown papers from appearing too sombre, we should use lamps rich in red rays, such as the carbon filament lamp, or in any case incandescent lamps. For indoor lighting the yellow flame arc is not to be recommended unless it can be placed in positions where it does not pollute the atmosphere. For outdoor illumination it is also not altogether suitable, since such illumination is usually low and consequently a whitish light is preferable, except for advertising purposes. Flame lamps with white light are now available, and for colour-distinguishing purposes they are beaten only by the pure arc with inclined carbons.

110. **UNIFORMITY OF ILLUMINATION: SHADOWS.**—The proper distribution of the light is of great importance from the physiological standpoint. Sharp shadows should be avoided; at the same time they must not be prevented altogether, as then it becomes difficult to distinguish fine details. To see is to distinguish fine details, and for this different shades are essential. Shadows are always sharply marked when a single illuminant is employed without a diffusing globe. One often notices this in street lighting, when the lamps are fixed on low posts without proper diffusing shades. It is then difficult to distinguish the object from the shadow which it casts, and the latter appears like an obstruction. There is too little light in the shadow. This applies also to the lighting of a room by a single lamp. Where this is done—as is possible when the room is not too large—it is advisable to employ a well-diffusing globe, such as the holophane type, and highly reflecting walls. With a large metal filament lamp we still get sufficient local light upon the table below and at the same time a general illumination which allows the eye to rest and recover its sensitiveness without experiencing a glare when returning to the paper. Sharp shadows cause irritation, as the eye has to be strained to distinguish the shadow from the object. Hence the illumination must be sufficiently diffused to make the edge of the shadow look blurred.

The best diffusion is usually obtained with indirect lighting. At the same time, this type of lighting is not always to be recommended, even if we neglect the matter of cost. We notice articles by distinguishing different shades. Suppose we employ a hollow sphere with diffusing white walls, such as Ulbricht's globe. It will be obvious that if we insert another white sphere and a white flat disc of similar diameter, the two can only with difficulty be distinguished. If we could produce perfect diffusion, it would be impossible to see the articles at all. In rooms with white ceilings and white walls, the diffusion is a good deal less perfect than in a hollow sphere; hence shadows will be formed. This is excellently illustrated in figs. 7·01 and 7·01A (reproduced by permission of the Union Electric Company Ltd.), which represent an artist's studio lighted by Union Special "OI" inverted arc lamps,* fig. 7·01 showing the point of view from which photo of 7·01A was taken. At the same time we can obtain satisfactory results very often without indirect illumination if we take care that the proportion of directed and diffused light is correct. We see that *shadows* form an important point in illuminating engineering. The sharpness of the shadow depends not only upon the type of illuminant, the distribution and the reflecting powers of the surroundings, but also upon the distance of the shadow-casting body away from, and its relative position to, the radiator.

FIG. 7·01.—Studio lighted with Union "OI" Inverted Arc Lamp.

If we hold a stick parallel to a Moore tube it casts a sharp shadow; if placed at right angles, hardly any. A stick placed under a street lamp with a high candle-power on a low post in a manner that the light falls under an angle of, say, 30 degrees upon the stick causes a black shadow, whereas at considerable distance the shadow is less distinct. In the latter

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* J. Eck, *Electrician*, 1911, 23rd June; *Illuminating Engineer*, 1911.

case the next lamp takes some part in the illumination, causing it to be more diffused. Even in a room with a uniform illumination we may find that from a physiological standpoint the illumination is satisfactory only in a few places, as can easily be tested by casting shadows. Where a number of lamps cast the shadow of, say, a rod, in different directions, the illumination of the shadows is sufficient to see in the shadows; but near a corner of the room this might not be the case, since here this illumination may be chiefly due to one lamp, and the shadow thrown in consequence

FIG. 7·01A.—Studio lighted with Union "OI" Inverted Arc Lamp.

very dark. It will be obvious from these remarks that the quality of an illumination must almost entirely be judged by the ability with which we recognise fine details; the illumination should in consequence be neither too little nor too much diffused. As we have to deal with two sciences it follows that a judgment cannot be so easily formed. Testing the illumination with photometers may satisfy the physical science, but it gives no indication as regards the physiological quality. It is in the latter direction in which investigations are largely wanted. An attempt has been made by Dr Konrad Norden * to bring the physiological quality of an illumination within the range of mathematics. He expresses diffusion as the extent to which shadows are illuminated. The more we illuminate the shadows cast by a single radiator by means of other illuminants the more perfect is the resulting diffusion. When the illumination is by a single point source, the diffusion D is nil, and when no shadows are cast it is perfect and has the value unity. All other cases lie between these two values. We have—

$$1 \geqq D \geqq 0.$$

Although it is possible to express the diffusion, or rather the shadow power $S_p = 1 - D$ by some formulæ for very simple cases, as has been done by Dr Norden, their practical value will be small until further experiments are carried out which tell us exactly what the diffusion ought to be for recognising fine details, and also instruments are devised by means of which we are able to determine the shadow power of the installation and to express it physiologically. It appears to the author that the lumeter described in Chapter III., and represented in fig. 3·41, would probably be suitable for the purpose. In the meantime some indications will be given in the succeeding paragraphs which will help the reader when installing lighting plants.

111. **PRIVATE HOUSES.**—We require local lighting according to Table XXI. in regions where work has to be carried out, usually on tables, and a low general illumination of about 10 candle-metres (one candle-foot) for the eye to rest and to recover its sensitiveness. In a small room of about 4 metres square (13 feet square), with light walls, this may be obtained with a single 50-watt tungsten lamp fixed about 2·5 metres above the floor in the centre of the room and provided with a prismatic globe. The light is then sufficiently out of the line of vision to prevent glare and yet yields sufficient local illumination to give comfort at work and satisfactory general illumination. This is, on the whole, preferable to a table lamp. Where the latter is used, the shade must completely hide the lamp. Opal glass shades are mostly used. The general illumination is now however poor.

Larger rooms require more lamps. With the size of the rooms the height of the lamps should increase, as otherwise the radiators will be in

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* See *E.T.Z.*, 1911, p. 607.

the line of vision. A chandelier in the middle of a large room gives a physiologically defective illumination for most parts of the room. At the same time there is no necessity for distributing the light too much by using very small units, unless the surroundings are of a very dark colour. The dining-room in the author's residence, 20 by 15 feet (28 square metres) is pleasingly lighted up with two 50-watt tungsten lamps placed $1\frac{1}{2}$ metres (5 feet) above the table within frosted globes which completely hide the lamps. The ceiling is painted a very light green mixed with yellow ornamentations, while the principal colour of the wall-paper is a golden yellow. The lamps are 1·2 metres (4 feet) apart. If the same room were given a dark red wall-paper, the general illumination would appear too low. In no case should we install illuminants which are deficient in rays similar in colour to that of the surroundings. Entrance halls and corridors are mostly given a general illumination only varying from 10 to 20 candle-metres (1 to 2 candle-feet).

112. **DRAWING OFFICES.**—In this case we require a high general well-diffused illumination which is preferable to mixed local and general lighting. It is best obtained with very light walls and ceilings and distributed direct or indirect ceiling lighting. Shadows must be avoided as much as possible ; hence indirect illumination with distributed lamps will yield the best results.

113. **WORKSHOPS.**—A general illumination of at least 1 candle-foot (10 candle-metres) should be installed in addition to local lighting. The general custom is to provide one incandescent lamp for each machine tool or counter of smaller sizes, and two or more for larger ones. The lamps should be of sufficient candle-power to allow them to be hung high up out of the line of vision. The general lighting is obtained with distributed large candle-power incandescent (or smaller arc) lamps. The distribution depends upon the colour of the surroundings and the size of the shop.

114. **SCHOOLS.**—What has been said under "Drawing Offices" holds also here, with the addition that special light is required for the blackboard. The reflector for this purpose should preferably extend along the whole length of the board, and hide the lamps completely. It should not be fixed too close to the board, in order that the intensity of the illumination on the latter varies comparatively little from the top to the bottom. Walls and ceilings are best painted white or yellow, down to a height of about 4 feet (1·2 metres) above the floor. This lower portion should be painted a dark colour (dark green). Also the tables should be dark, so as to reflect as little light as possible. The radiators must be well distributed so as to make the illumination uniform, and reduce the shadows to a minimum for all parts of the room. The illumination of the blackboard should be high (not less than 35 candle-metres—about 3·5 candle-feet), especially where infants are taught, who are unfamiliar with the characters and hence have to exercise great diligence. The total candle-power must be great enough for allowing the lamps to be placed close to the ceiling and out of the

line of vision. Where the ceiling is white and provided with a frieze extending down the walls, reflectors are unnecessary. Indirect illumination gives the best results. Table XXI. is in most cases applicable.

115. **LIBRARIES.**—Mixed lighting gives the most comfortable results. By distributing a number of lamps over the ceiling, close to it, we provide a general illumination of 1 to 1½ candle-feet (10 to 15 candle-metres). In addition, we should place a fairly large lamp over each reading-table and newspaper stand, but high enough so as to keep it out of the line of vision. Deep conical shades of opal glass or metal have been found to give good results. In this way we distribute the light sufficiently and yet provide enough contrast for allowing the eye to rest periodically. If the local light hangs too closely over the table, readers at other tables may easily look into the radiators; it is also more than likely that light is reflected from the radiator by the paper into the reader's eyes. An alteration in the position of the reader or of the paper will however overcome this (see fig. 7·15).

116. **HOSPITALS.**—The lighting of sick-rooms is always local and low. The radiator should be placed in a position that the patient cannot look into it. The intensity of the illumination should however be high enough *when wanted* to enable the patient to read in comfort.

For operating tables highly concentrated illumination is essential, and the values given in Table XXI. should at least be doubled.

117. **HALLS FOR ENTERTAINMENTS.**—The illumination is usually made high and brilliant for advertising purposes. The lamps should however be fixed in such positions that glare is avoided. The colour of the light is in this case of considerable importance. Arc lamps are not always suitable, especially those which are rich in blue rays. Articles which look red in daylight or with glow lamps appear then with a bluish tint or even violet (see Table II.), and this does not add to the beauty of the articles or of the faces of the people. In some cases lighting with incandescent lamps is either too costly or requires a number which detracts from the appearance of the hall. (Since the advent of the metal filament lamp this probably holds good no longer.) We may then mix arc and incandescent lighting, but it must be done in a manner that sharply defined shadows are prevented and that both sets of rays mix properly. In the White Hall of the German Emperor's Palace at Berlin this result was achieved by enclosing both arc and incandescent lamps in a double completely closed prismatic globe.

118. **DRAPERS' SHOPS.**—The remarks made under "Workshops" hold also here. Of great importance is the colour of the light, which should be white and approach daylight as nearly as possible. Arc lamps with white light (see Table III.) are best, but also incandescent lamps yield satisfactory results as far as the physiological standpoint is concerned, if the lamps are distributed so as to provide the proper mixture of directed and diffused light.

119. **MUSEUMS AND PICTURE GALLERIES.**—They might be included under "Halls for Entertainments," except that the light is wanted as much on the walls as in a horizontal plane. The colour of the light should be such that the daylight colours are also seen with artificial light, *i.e.*, it should be white. Indirect lighting can be made to yield satisfactory results if the diffusion is such that fine details can be distinguished. Where direct lighting is employed care must be taken that the image of the radiators is not seen in the pictures. As these places are for show purposes, the values of Table XXI. should be doubled or trebled.

120. **STREET LIGHTING.**—The lighting of streets in most towns still leaves much to be desired. Except for a few principal thoroughfares, one chiefly finds a lamp at corners where other streets branch off, but few in addition unless the distance between streets is abnormally large. The illumination is consequently very low.

The ideal lighting would have to be high enough to allow vehicles to move about at night without carrying lamps themselves. An illumination of about 1 candle-foot (10 candle-metres) average would be required for such a purpose. Unfortunately, on account of the enormous area to be illuminated, such lighting would be very expensive. Even in main streets one does not find an illumination exceeding half a candle-foot, and in side streets it is rarely more than 0·01 candle-foot. To make such a low illumination satisfactory, it should be as uniform as possible – a result obtained by employing lamps with polar curves which show the maximum intensity about 10 degrees below the horizontal, and which are fixed on high posts. If the radiator is on a low post and of great intensity, with the maximum light in a direction nearly vertically downwards, we obtain a high illumination and sharp shadows under the lamp and semi-darkness half-way between the lamps. As lamps are largely fixed near the edge of the pavement, light thrown in a direction at right angles to the road in the direction of the houses is largely wasted. Shades should then be so constructed that they redirect the light radiated in this direction, a result obtained by employing shades according to fig. 6·15. No light should be directed upwards as it is wasted, *i.e.*, each lamp should be provided with a reflector. To prevent glare, the shade should direct the light outwards, for which a conical shade turned upside down will do. The more we can see of the reflecting surface of the shade, the better is the light distributed. Lamp-posts, which were originally erected for low candle-power glow lamps, are far too low for high candle-power tungsten lamps and should be replaced.

Naked arc lamps should in no case be employed unless they are placed in towers at extreme heights. By using opal globes the distribution is unfortunately altered, *i.e.* the diffusing globe has the tendency to make the light uniform in all directions. In modern flame arc lamps this difficulty has been overcome (see figs. 6·06 and 6·18) by placing underneath the arc a prismatic reflector and using a clear globe. The colour of the light is also important. For low illuminations a greenish blue light is physiologically preferable to a yellow light (see fig. 2·07). The absence of red rays makes however everything appear ghastly in such light. A white light is the next best, whereas yellow flame arcs are suitable for decorative illumination.

121. **SQUARES.**—A limited number of arc lamps with white lights and great intensities fixed on high poles give satisfactory results. Where the area is not too large a single large lamp in the centre fixed on a tower might be used.

122. **RAILWAY STATIONS.**—The general illumination should be fairly high, about 10 candle-metres (1 candle-foot). With the advent of the metal filament lamps, arc lamps have largely been replaced with economical results.* Shunting yards should have an illumination of not less than 3 candle-metres (0·3 candle-foot), and the colour of the light should not interfere with that of signals. Glow lamps are mostly unsuitable, since too many posts are required, which are so many obstructions, unless we employ very large lamps. (They are now available up to 2000 candles—mean horizontal.) The flame arc is on the whole very suitable for railway yards. The colour of its light makes it quite distinct from that of red and green signal lamps, and as lamps up to over 3000 M.H.S.C.P. can be obtained, the number of obstructing poles may be small.

123. **EXAMPLES IN ILLUMINATING ENGINEERING. Indoor Lighting. Amount of Light Required per unit Area of Floor Space.**—The subject shall be considered for general illumination only. In local lighting, the illumination of a particular area is practically caused by a single radiator, whose size depends upon the area to be lighted. (See also "Design of Reflectors" in Chapter VI.)

It has already been explained that the distribution of lights depends largely on the colour of the surroundings and that it is difficult to give a rule holding in all cases. For white walls we obtain pleasing results if we reckon about one lamp for every 10 square metre floor space (107 square feet). If the surroundings are very dark, this should be *reduced*, approximately corresponding to the *increase* in the illumination required. The mixing of direct and diffused light is then correct for recognising fine details.

The lamps are best placed parallel to the sides of the walls, or at the corners of equilateral triangles according to figs. 7·02 and 7·03 respectively. In the former case we divide the room into a number of squares according to the number of lamps used and then place a lamp into the centre of each square.

The illumination obtained in a spherical chamber is expressed by

$$E=\frac{\phi}{S}\left(\frac{1}{1-K}\right).$$

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* See H. Remané, *Electrician*, 1911, p. 829.

Thus for light yellow wall-paper we find

$$E = \frac{\phi}{S \times 0{\cdot}51},$$

which shows that the illumination is nearly twice as large as it would be in a room with dead-black surroundings. Few rooms are spherical or possess a hemispherical ceiling, so that the reflection follows other laws than those expressed by the above equation. The increase in the illumination depends then also upon the size of the room, its height, and the position of the lamps.

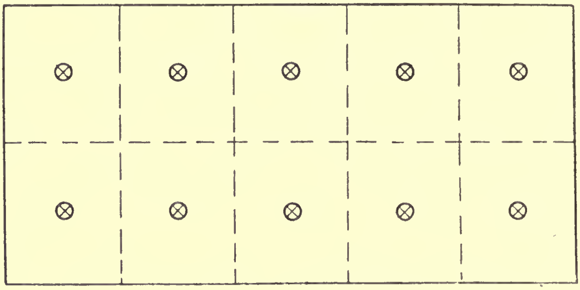

FIG. 7·02.—Distribution of Incandescent Lamps.

If ceiling, walls, and floor take part in the reflection, and if the size of the room is not too large, we should have to use for K the average value, expressed by

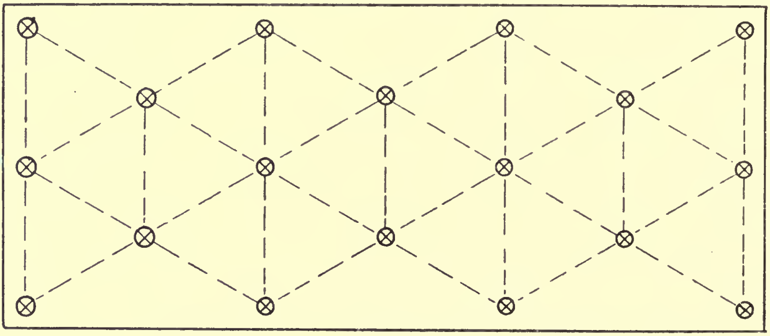

FIG. 7·03.—Distribution of Incandescent Lamps.

$$K = \frac{S_1K_1 + S_2K_2 + S_3K_3}{S_1 + S_2 + S_3} \quad . \quad . \quad . \quad . \quad 7{\cdot}01$$

in which S_1, S_2, S_3 are the areas and K_1, K_2, and K_3 the reflection coefficients of ceiling, walls, and floor respectively. In many cases the reflection from the floor is negligible, especially as the test plane is 1 metre above it. Moreover, furniture, tables, etc, should reflect light as little as possible, to prevent glare.

For practical purposes, not too much reliance should be placed on the value of the reflection coefficient as calculated from formula 7·01, as this value will vary with the shape of the room. Better results are obtained by experiments, and although they cannot be accepted as standards in all cases, they give us very often sufficient information for providing the best illumination for given conditions.

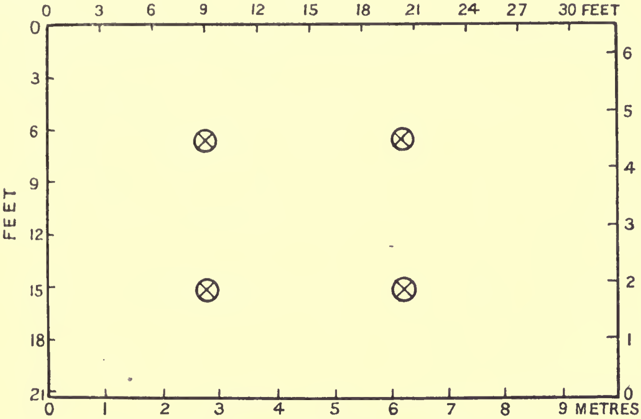

FIG. 7·04.—Arrangement of Lamps in Test Room.

The following tests were carried out in a room 10 × 6·5 square metres (700 square feet) with four 220-volt 100-watt drawn tungsten lamps arranged according to fig. 7·04 and having the flux distributions of fig. 7·05. The left-hand side of this figure holds for spherical distribution of the lamp, the right-hand side for hemispherical as caused by metal cone reflectors with an aperture of 90 degrees and a maximum diameter of 30·5

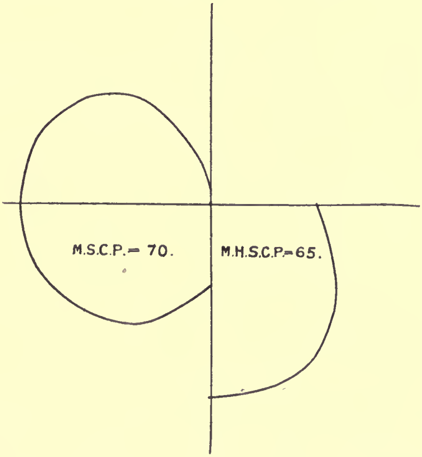

FIG. 7·05.—Polar Curves of Lamps employed in the Tests.

centimetres (12 inches). The ceiling of the room was white, having a reflection coefficient of about 0·65 (the whitewash was old, but in good condition). The walls were a very light yellow with an absorption of about 50 per cent. They were 5·5 metres high (18 feet), and painted a dark green to a height of 1·2 metres (nearly 4 feet). As however the tests were carried out in a horizontal plane one metre high (3·28 feet), this had little influence on the illumination of the test plane. The furniture consisted of black tables and chairs, a bookcase and a blackboard.

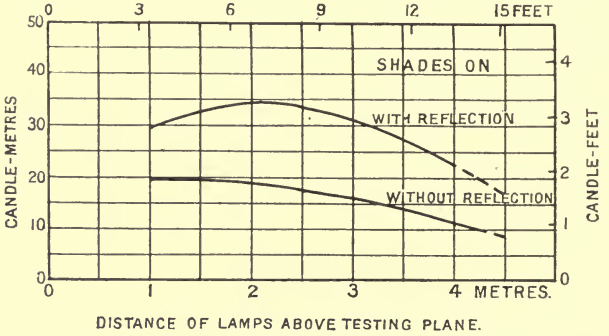

FIG. 7·06.—Illumination of a Room with and without Reflection. (Shades on.)

From the polar curves of the lamp (see fig. 7·05) the illumination was first calculated for different heights of the lamps, neglecting reflection, and the average values taken. It was then tested with a Wingen photometer and the average value thus found compared with the calculated values. The results of the tests are shown in figs. 7·06 and 7·07, from which follow directly figs. 7·08 and 7·09 respectively.

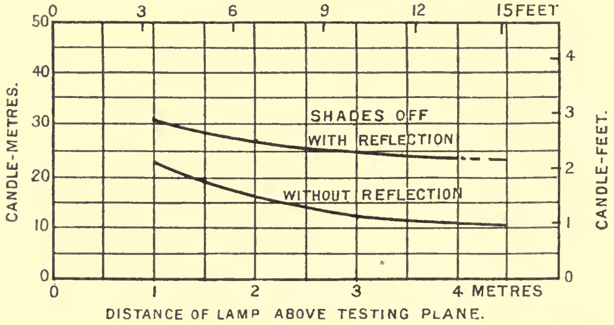

FIG. 7·07.—Illumination of a Room with and without Reflection. (Shades off.)

With the lamps lower down and carrying shades, the reflection is chiefly from the walls, but the reflecting area is small. As the lamps are raised more and more, the reflecting surface increases, and also the ceiling becomes somewhat illuminated, thus reflecting light, especially as the lamp bulbs extended a little beyond the shades. The maximum increase in the illumination is 98 per cent., thus the factor of increase 1·98. For a spherical chamber with light yellow walls its value would have been 2·0.

The value for the room is surprisingly high, but this is partly due to the ceiling, which had a higher reflection coefficient than the walls. In reality a rectangular chamber is less favourable for reflection than a spherical one.

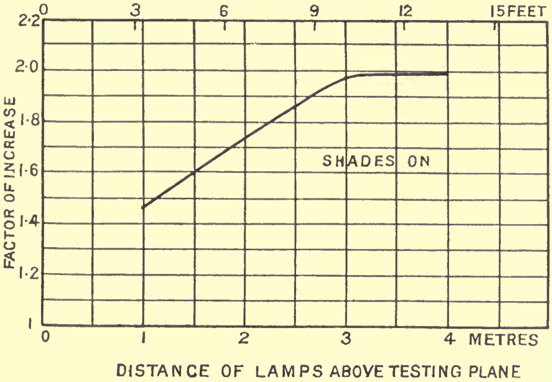

FIG. 7·08.—Factor of Increase in Illumination. (Shades on.)

When the shades were taken off, the ceiling became the principal reflecting surface, and the amount of the maximum increase was further augmented, the increase factor being 2·14.

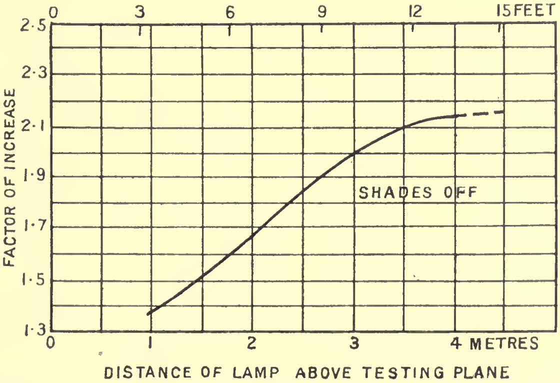

FIG. 7·09.—Factor of Increase in Illumination. (Shades off.)

Although the tests were carried out as carefully as possible, the results cannot be relied upon within less than 10 per cent., but this is usually sufficient for practical purposes.

As the lamps are raised more and more the uniformity improves. This is especially the case for lamps with shades. In rooms with very light colours and bare lamps the uniformity does not improve to any extent as the lamps rise, but where the colours are dark and little reflection takes place, the uniformity improves with the increase in the height. This is strikingly illustrated in figs. 7·10 and 7·11.

With the aid of the previous figures and a knowledge of the size of the room and its colours, we are now able to determine approximately the candle-power required per unit area floor space for any given illumination and heights of the lamps. The results are plotted in figs. 7·12 and 7·13 for illuminations as given in Table XXI. In addition to the values given for light yellow walls and a white ceiling, values have been added for various other colours of the walls.

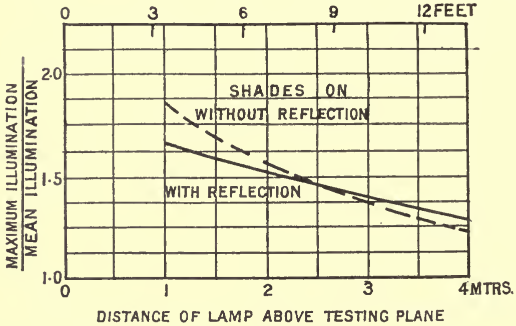

Fig. 7·10.—Degree of Uniformity of Illumination. (Shades on.)

Example 1.—We are asked to light a room 11·3 × 5·5 = 62 square metres (37 × 18 = 666 square feet) (see fig. 7·02), and having very light walls and ceilings (the room is the student's common room in the Hiddingh Hall of the South African College), so as to produce an average illumination of about 23 candle-metres (2·15 candle-feet). If we take the curve for cream-silver (the whitewash was not perfectly white) and place the lamps close to the ceiling, which is 5·6 metres (18·4 feet) high, or 4·6 metres (15 feet) above table height, we require per square metre floor

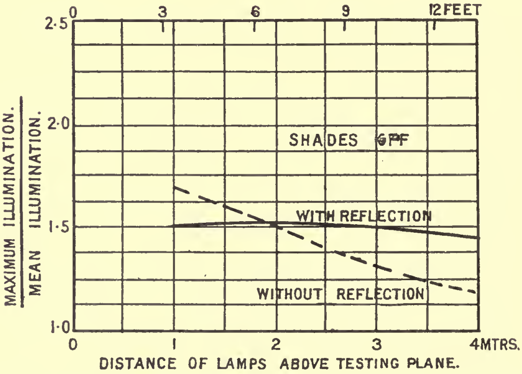

Fig. 7·11.—Degree of Uniformity of Illumination. (Shades off.)

about 4·5 candles (see fig. 7·13) (0·42 candle per square foot) or a total of 280 candles (mean spherical). The actual number of lamps installed is 10, of the 50-watt tungsten type, with a mean spherical intensity of 35 candles (42·7 mean horizontal candles), so that the illumination is somewhat larger than is required, to allow for a reduction caused by ageing, in the ratio $\frac{350}{280} = 1{\cdot}25$. The illumination should therefore be $1{\cdot}25 \times 23 = 28{\cdot}7$. On testing, the average illumination was found to be 28 candle-metres,

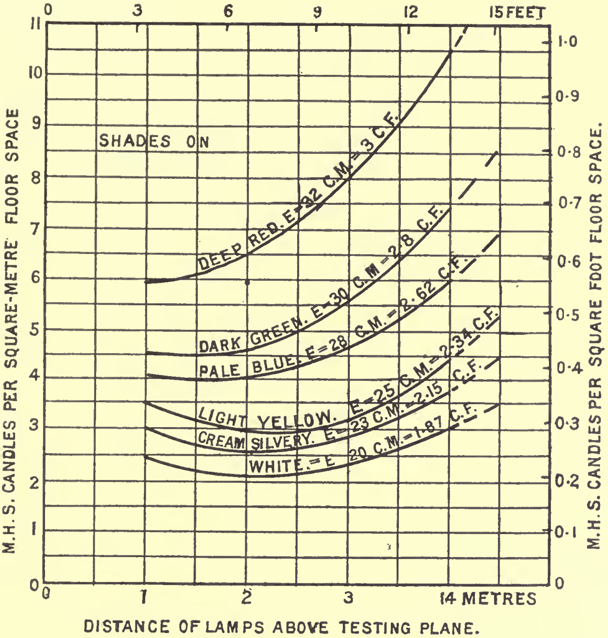

FIG. 7·12.—Illumination required per Unit Area. (Shades on.)

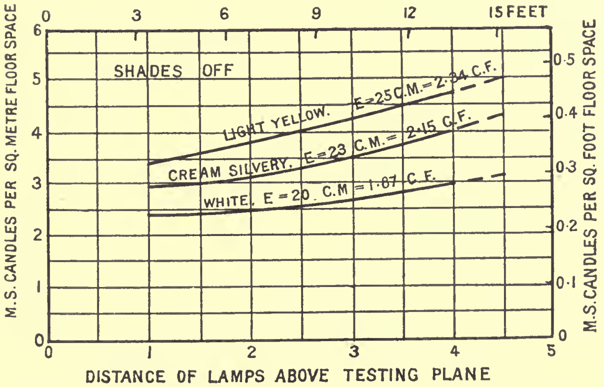

FIG. 7·13.—Illumination required per Unit Area. (Shades off.)

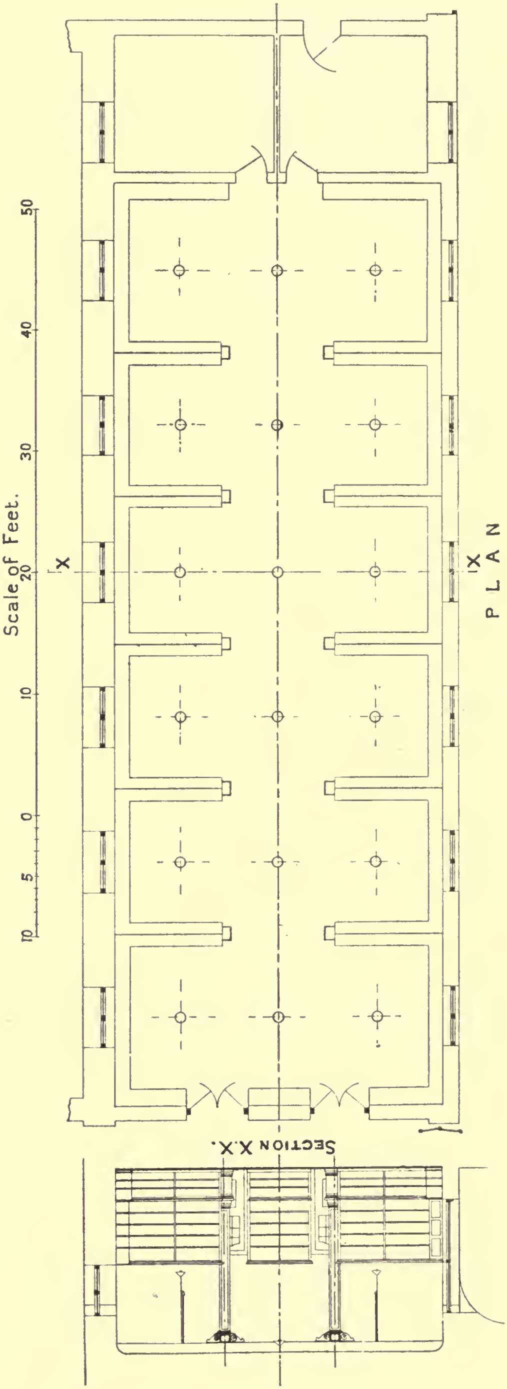

Fig. 7·14.—Lighting of a Library.

which shows a very fair agreement with the figures given in the curves. With ten lamps distributed uniformly over the ceiling according to fig. 7·02, the degree of uniformity is very high, the value $\frac{\text{maximum illumination}}{\text{minimum illumination}}$ being 1·2.

Example 2.—It deals with the library in the Hiddingh Hall of the South African College. The size is 76 feet × 27 feet 9 inches, giving a total area of 2109 square feet (196 square metres). The room is divided by means of bookshelves into 12 alcoves, each about 11 feet 6 inches by 8 feet 6 inches, leaving free a central space of 10 feet 9 inches. The height of the room is 15 feet (4·56 metres). The general illumination consists of six tungsten lamps giving about 35 M.S.C.P. fixed close to the ceiling with conical opal shades. The illumination of each alcove is brought to the required amount by the addition of a similar lamp fixed to a rising and falling pendant. The illumination is perfectly satisfactory when the lamp is level with the top of the bookshelf, which is about 8 feet high. There is also sufficient light for reading the names of titles of books even at the bottom of the shelves. A lamp plug is however added for a portable lamp. The shades on this local lamp are conical, but deep enough to hide the lamp bulb. The arrangement is shown in the accompanying fig. 7·14. The total candle-power available is 630, which gives 3·2 candles per square metre floor space. Walls and ceilings are white, but the greater part of the former is covered with teak bookcases.

If the lamps are too close to the tables it may happen that the reader experiences a glare, since there is always regular reflection mixed with diffused reflection, as is indicated by the male person in the accompanying fig. 7·15.* By altering the position of the book this may be overcome, but by fixing the lamps sufficiently high above the table this is prevented without the reader endeavouring to find the best position. This also applies to newspaper stands, for which the light should be arranged that reflection as indicated in fig. 7·16 is avoided. The lighting of bookshelves is indicated in figs. 7·17 and 7·18.†

Example 3.—The Assembly Room of the Hiddingh Hall of the South African College. The arrangement of the lamps is shown in fig. 7·19. The illumination consists of seven chandeliers of five lamps each, and of twelve brackets with two lamps each. The ceiling is white, and the walls are teak-panelled up to a height of 12 feet. The lamps are of 35 M.S.C.P. This gives per square metre floor space about 6·3 candles. It would have been better to have arranged the brackets over the windows, on the *white* part of the walls, instead of on the dark teak panelling. The latter was however not decided upon until the wiring was complete. The illumination is fairly uniform, varying from 25 to 35 candle-metres, giving a pleasing appearance.

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* From the *Illuminating Engineer.*

† *Ibid.*

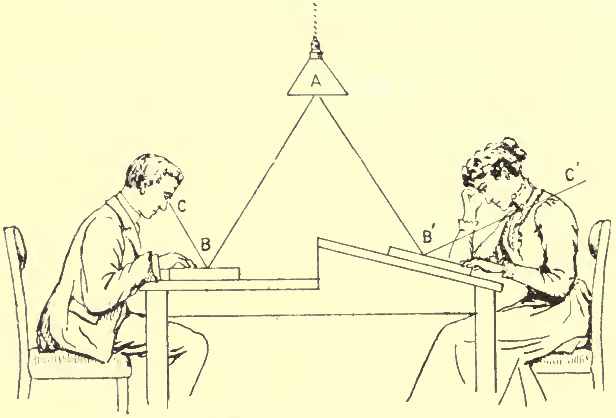


Fig. 7·15.—Effect of Mixed, Diffused, and Regular Reflection.

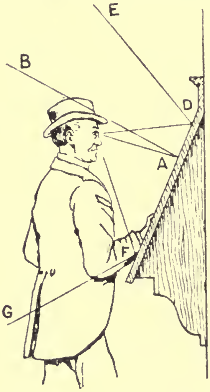
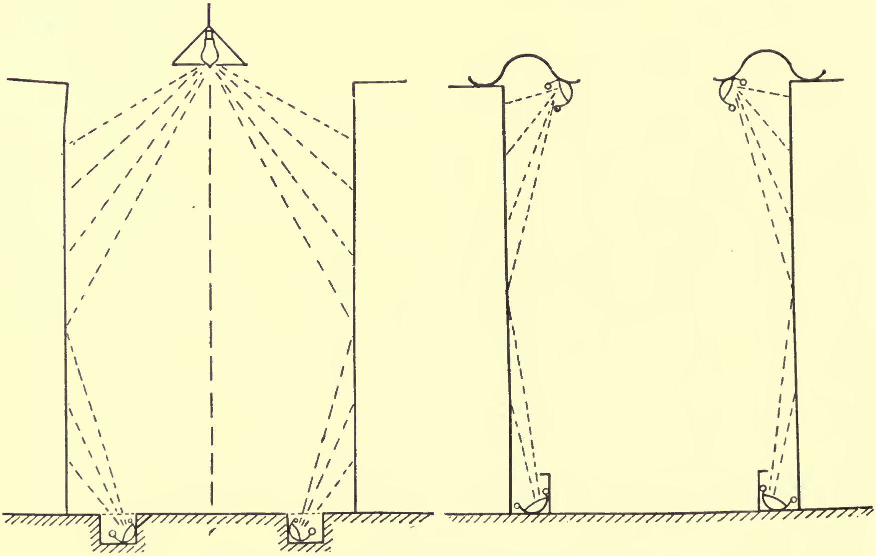


Fig. 7·16.—Lighting of Newspaper Stands.



Figs. 7·17 and 7·18.—Lighting of Bookshelves.

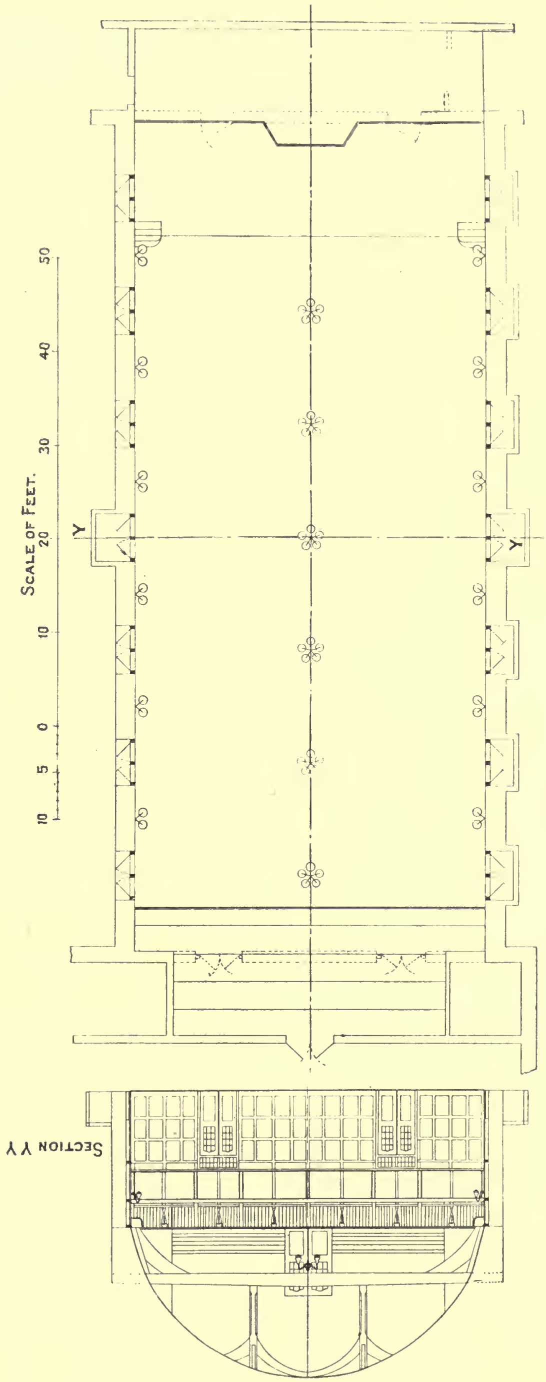


Fig. 7·19.—Lighting of a Hall for Entertainments.

124. **MISCELLANEOUS EXAMPLES.**—In the following photographs are represented a number of installations with incandescent lamps. Fig. 7·20 * represents the dining-room of a wine restaurant, illuminated with tantalum lamps distributed over the whole ceiling. Fig. 7·21 shows the Court Theatre at Cassel, in which a number of tantalum lamps are enclosed in prismatic globes at the ceiling, providing a very uniform illumination. Fig. 7·22 illustrates the concert room of Bad Neuenahr, also illuminated with metal filament lamps within prismatic glass globes.

A large number of incandescent lamps carried by a single elaborate fitting gives sometimes rise to difficulties when lamps burn out and have to be exchanged. Lowering gears for heavy chandeliers must be exceptionally strong to avoid accidents. Moreover, a large number of fittings is apt to obstruct the free outlook. For these reasons it might be advisable sometimes to install arc lamps which can easily be fixed to a lowering gear. The Mozart Hall of the new Opera House in Berlin-Schöneberg is illuminated in this manner, as is indicated in fig. 7·23. The ventilation of this theatre being excellent, flame arcs are employed. The latter can always be used where the hall is illuminated by sky-light. We then place the lamps above the glass ceiling, as is indicated in fig. 7·24, providing an illumination as shown in fig. 7·25, which represents the installation of the Musik Hall at Hamburg. The recarboning is done by means of a little trolley.

Fig. 7·20.—Lighting Installation of a Wine Restaurant.

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* Figs. 7·20 to 7·25 represent installations by Siemens-Schukert Werke, Berlin.

FIG. 7·21.—Lighting Installation of the Court Theatre at Cassel.

FIG. 7·22.—Lighting Installation of the Concert Room at Bad Neuenahr.

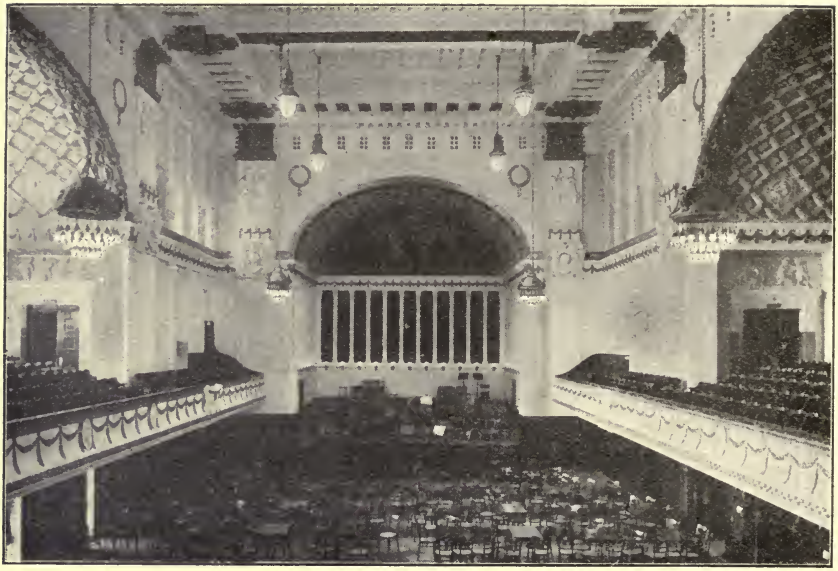

FIG. 7·23.—Lighting Installation of the Mozart Hall in the Opera House at Berlin-Schöneberg. (Flame arc lamps.)

FIG. 7·24.—Arc Lamps above a Glass Ceiling.

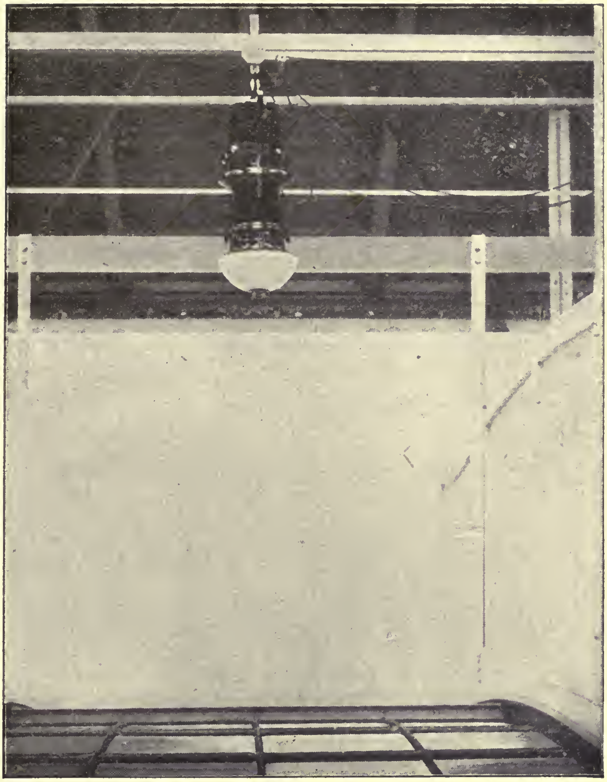

FIG. 7·25.—Illumination by Means of Arc Lamps above a Glass Ceiling.

125. **ILLUMINATION OF CHURCHES.**—The illumination of a church depends somewhat upon the character of the building. The Roman Catholic service is largely carried on by the priests and choristers, while the people take comparatively little active part. A high general illumination in such churches is therefore not required. In dissenting chapels the congregations take a more active part in the singing and reading, and consequently the illumination should be of high general character. If the installation is put in when the church is being built, it is a comparatively simple matter to arrange the lighting in the best manner, but where candles or oil lamps have to be replaced it is more difficult to fit in the lights so that the general appearance is in no way spoiled.

Where the congregation takes an active part, the illumination should be approximately as high as given in Table XXI. Glare should in all cases be avoided, so that lamps must be out of the line of vision and carry diffusing globes.

In fig. 7·26 is represented the lighting of the Holy Name Church, Manchester, by metallic filament lamps fixed to chandeliers, and in

FIG. 7·26.—Lighting Installation of the Holy Name Church, Manchester.

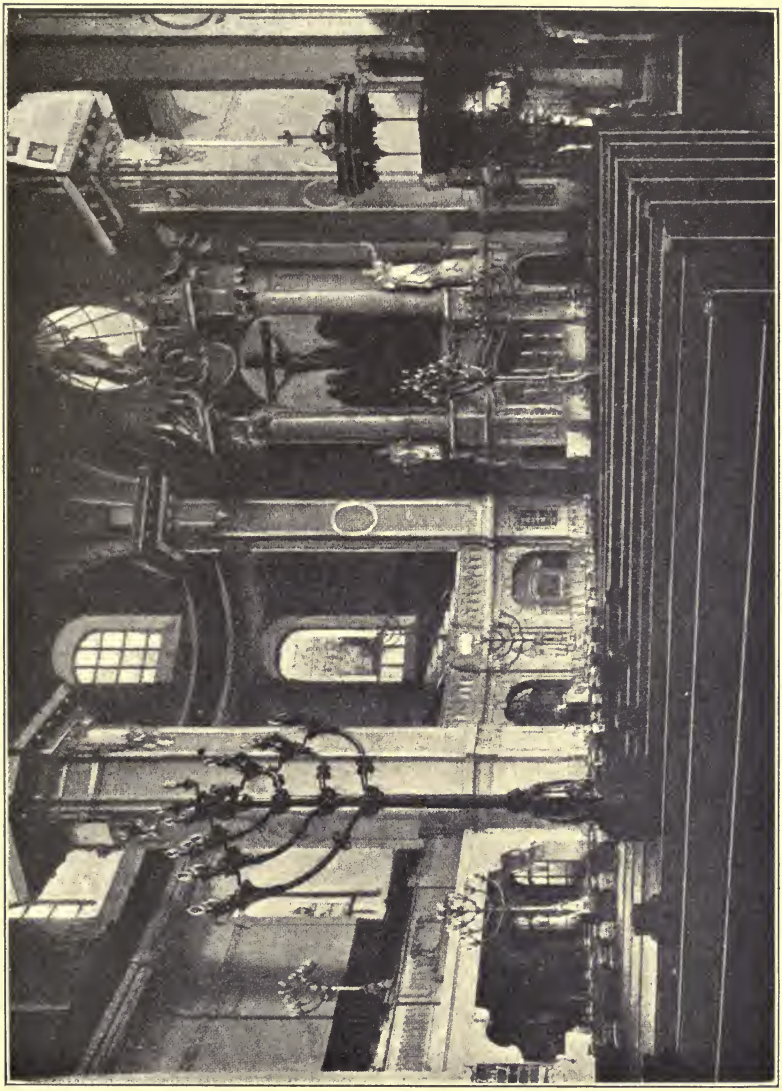

Fig. 7·27.—Lighting Installation of the Kreuzkirche, Dresden.

fig. 7·27 the interior of the Kreuzkirche of Dresden,* in which the lamps are fixed in standards at the ends of the pews.

126. **INDIRECT ILLUMINATION.**—Where a well-diffused general illumination is required, as, for instance, in drawing offices and schools, indirect lighting yields undoubtedly the best results. In these places it is not necessary to distinguish fine details which are recognised by differences in light and shade, but to see various colours, *i.e.* the marks made

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* *Illuminating Engineer*, **1909, p. 37.**

by the pencil on the drawing-paper or by the chalk on the blackboard. With a well-diffused illumination, shadows, which are irritating, are practically avoided.

For a given illumination inverted light has to be stronger than direct light, since part of it is absorbed by the reflector. In low rooms the ceiling acts as reflector, whereas for very high ceilings (over 6 metres) it is more economical to use a special reflector above each lamp. The direct light is prevented from reaching the area to be illuminated by means of a reflector placed underneath the lamp. This reflector directs the flux of the lower hemisphere upwards. If it is semi-transparent, we speak of semi-indirect illumination. Where the semi-indirect method is applied, direct light would usually give equally good results, besides being cheaper.

Speaking generally, indirect light should not be installed in rooms with dark walls and ceilings. Even if we place efficient reflectors above the lamp, the result is not pleasing. If the lighting of a drawing office is to be indirect, the walls and ceiling should be constructed accordingly, the ceiling preferably with a frieze extending down the walls, and the colour of both should be white, or at least a very light yellow. Even then 30 to 50 per cent. of the light is absorbed by the reflecting surfaces.

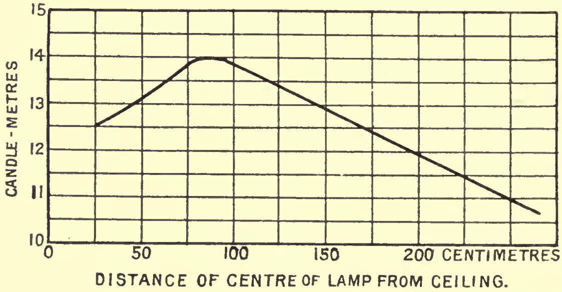

FIG. 7·28.—Best Distance of Radiator from the Reflecting Ceiling.

Of importance is the distance of the lamp from the reflecting surface, as is seen from fig. 7·28. We notice that the illumination is a maximum when the centre of the radiator is about 750 millimetres (27·5 inches) from the ceiling. Dr Monasch obtained similar results; the most favourable distance in his case was however only 450 millimetres (16·5 inches). The actual best distance depends upon the types of lower reflector and lamps used, and should in each case be determined by an experiment.

Where, on account of the great height of the ceiling, a special reflector has to be employed above the lamp, the size should be very large and the lower reflector must be so constructed that no light is reflected past the upper shade, since it would be largely wasted. The actual design of the reflectors follows the lines laid down in Chapter VI.

The average amount of light required for indirect illumination may be seen from the accompanying Tables XXII. and XXIII. Both hold for reflecting surfaces about 5 metres (16·4 feet) high. Table XXII. has been plotted for rooms not exceeding one hundred square metres (1070 square feet) in area, in which the reflection from the walls is considerable, whereas Table XXIII. stands for rooms in which the reflection from the walls is negligible on account of the large size of the rooms. It will be readily understood that less light is required in the latter case, since there is no absorption by the walls, the light being able to fall directly on the illuminated area after reflection from the ceiling. The tables are further meant for well-distributed lights, *i.e.*, the number of square metres floor space allotted to each lamp should not exceed thirty (about 300 square feet). If we use large units, the uniformity of the illumination is greatly reduced, and we might as well employ the direct method. The *average illumination* is little affected by the size of the radiators and the distribution. In both tables the reflectors below the lamp have a reflection coefficient of 0·7. The reflection coefficients of the walls and ceilings considered are 0·7, 0·57, and 0·50 for white, cream, silvery, and light yellow respectively.

TABLE XXII.—INTENSITY OF LIGHT REQUIRED PER UNIT AREA OF FLOOR SPACE (WALLS AND CEILING REFLECTING).

Colour of Walls and Ceiling.	Illumination.		M.S. Candles per Unit Area.	
	Candle-metres.	Candle-feet.	Square Metres.	Square Feet.
White . . .	15	1·4	3·8	0·35
Cream silvery .	18	1·68	5·5	0·52
Light yellow .	20	1·87	7·0	0·65

TABLE XXIII.—INTENSITY OF LIGHT REQUIRED PER UNIT AREA OF FLOOR SPACE (CEILING ALONE REFLECTING).

Colour of Ceilings.	Illumination.		M.S. Candles per Unit Area.	
	Candle-metres.	Candle-feet.	Square Metres.	Square Feet.
White . . .	15	1·4	3·1	0·29
Cream silvery .	18	1·68	5·0	0·47
Light yellow .	20	1·87	6·4	0·60

Example 4.—We are asked to light a room 10 metres long and 10 metres wide to the extent of 15 candle-metres in a horizontal plane 1 metre above the floor. The room is 5 metres high; ceiling and walls are white.

TABLE XXIV.—SUMMARISING VIEWS OF AMERICAN AND CONTINENTAL

N.B.—The letters *a*, *b*, *c*, and *d* inserted in the column beneath the name
(in the first column) which

Re Framing Standard Specification for Street Lighting.	Bell.	Bloch *	Bunte and Drehschmidt.
1. Ought the specification to contain a statement of: (*a*) The electrical energy or gas to be consumed; or (*b*) the amount of light provided; or (*c*) both energy or gas consumed and amount of light?	(*c*) Yes	(*c*) Yes	(*c*) Yes
2. Should the amount of light supplied be specified in terms of: (*a*) the provision of a certain actual minimum illumination in the street; or (*b*) the provision of lamps of a certified candle-power?	(*a*) No (*b*) Yes	(*a*) or (*b*)	(*a*) Yes (*b*) No
3. If illumination is to be measured, should this measurement be carried out: (*a*) in a horizontal plane at a stated height above the ground; or (*b*) in a vertical plane; or (*c*) in some other inclined plane such as 45 degrees? (*d*) Should both the mean and the minimum street illumination be measured and specified?	(*a*) Yes †	(*a*) Yes (*d*) Yes, also max.	(*a*) Yes (*b*) Yes ‡
4. If candle-power is to be tested in the street: should (*a*) the mean spherical or mean hemispherical c.-p.; or (*b*) the c.-p. in several specified directions, be tested?	(*b*) Yes, 25° to horl.	—	(*a*) No (*b*) Yes
5. Should the contract demand: (*a*) actual measurements in the streets; or (*b*) only laboratory tests of the competing lamps previous to the acceptance of a tender; or (*c*) preliminary laboratory tests supplemented by periodical tests of the actual lighting conditions when the lamp is in position?	(*c*) Yes	(*c*) Yes	(*c*) Yes
6. Should any test of the constancy of the candle-power of the lamps be prescribed?	Yes	Not at present	
7. Do you advocate the introduction of any stipulation regarding the efficient shading of lamps, height above ground, etc., with a view to the avoidance of glare, such as is recognised to be dangerous and inconvenient to traffic and pedestrians?	Yes	,,	
8. Should any specific colour of the light be prescribed? If so, how should this be tested?	No	,,	
9. What other clauses would you suggest being inserted?	See p. 412, *Ill.Eng.*, 1911.	,,	

* Favours specification of *Verband Deutscher Elektrotechniker*, to which

† In Europe. ‡ In experimental not routine work.

‖ Stated type of lamp with specified consumption preferred.

AUTHORITIES ON STANDARD SPECIFICATIONS FOR STREET LIGHTING.

of each authority indicate the corresponding suggestions in the list of queries meet with his approval.

Herzog.§	Millar.	Monasch.*	Rumi.	Sartori.*	Scholz.	Voege.*
—	(*a*) Yes (*b*) No (*c*) No‖	(*a*) No (*b*) No (*c*) Yes	(*c*) Yes	—	(*c*) Yes	(*a*) No (*b*) No (*c*) Yes
—	(*a*) No (*b*) No	(*a*) Yes (*b*) No	(*b*) Yes	(*a*) Yes	(*a*) No	(*a*) Yes (*b*) No
(*a*) Yes (*d*) Yes	(*a*) Yes (*b*) Yes	(*a*) Yes (*b*) No (*c*) No (*d*) Yes	(*a*) (*b*) (*c*) (*d*) No.	(*a*) Yes	(*a*) Yes (*b*) Yes	(*a*) Yes (*b*) No (*c*) No (*d*) Yes
—	(*a*) No (*b*) Yes	(*a*) M. Hem. C.-P. (*b*) No	—	Neither	(*a*) M. Hem. C.-P.	(*a*) M. Hem. C.-P.
(*c*) Yes	(*c*) Yes	(*a*) No (*b*) Yes (*c*) No	(*b*) Yes	(*a*) Yes	(*a*) No (*b*) Yes (*c*) No	(*c*) Yes
—	Yes	No	—	—	No	No
—	No	No	Yes	—	No	Yes
—	No	No	—	Yes	No	No
—	See p. 415, *Ill. Eng.*, 1911.	—	—	—	—	—

Prof. Teichmüller (see p. 417) also gives assent.

§ Approves method adopted in Budapest. See Jehl, *Elec. World*, 1909, p. 986.

We divide the space into four squares, each of which has an area of 25 square metres, and place a lamp in the centre of each square. Per square metre floor space we require about 3·8 mean spherical candles or, in all, 380 candles. Each lamp must therefore give 95 M.S.C.P., or about 120 mean horizontal candles.

127. **OUTDOOR ILLUMINATION.**—Streets and squares are illuminated so as to enable people to recognise one another, to distinguish objects on the ground, and to read an address in at least some parts of the illuminated area. From this it might appear that a vertical plane would be best for testing the illumination. Against this stands the fact that a vertical plane may have different positions with regard to the incident rays, in some of which the plane would appear quite dark. Moreover, one could test in this manner only the illumination caused by a single lamp, whereas the region may have light from a number of sources. These disadvantages are possessed also by inclined planes, so that the horizontal alone remains as the plane in which street lighting can be properly tested and in which it should be judged. In the May 1911 number of the *Illuminating Engineer*, the questions in Table XXIV. were asked as regards the framing of standard specifications for street lighting, with the tabulated answers from a number of prominent engineers.

From this table it appears that all are unanimous as regards the *position* of the test plane, which in Germany is fixed 1 metre above the ground (about 40 inches). (A few inches more or less matters very little.) Testing the illumination at this height is more convenient than measuring it on the ground, as one would have to kneel down when taking measurements.

Until the Commission which has been appointed has framed specifications for street lighting it is advisable to accept the following recommendations:—

(*a*) The illumination should be judged in a horizontal plane 1 metre (or 40 inches) above the ground. (Some engineers prefer 3 feet, but this difference is of no account.)

(*b*) The illumination of a street or square is usually judged by that of the darkest part—that is, by its minimum.

This appears to be hardly correct for avenues which contain rows of trees, etc., and would hardly be fair to the contractor. At the same time, to judge by the maximum would be unfair to the public, as with a satisfactory maximum illumination, parts of the illuminated area may still be in comparative darkness. To be fair to both parties, the illumination should be judged by the average value. At the same time we should express the uniformity of the lighting by $\frac{\text{maximum illumination}}{\text{minimum illumination}}$. The more this ratio approaches unity, the more evenly is the light distributed. These values should however not be freaks, but rather represent average maximum and minimum values respectively. The average illumination represents the mean of the whole illumination, and not the mean of maximum and minimum or the mean ordinate of the illumination curve unless the area be circular.

The consumption should be expressed in watts on the basis of 1 candle-foot (or of 1 candle-metre) per square foot (or square metre).

As regards the candle-power, it is the custom to state the maximum candle-power and the angle of its ray with the vertical (or horizontal). This gives however very little information of the light flux, so that in addition, the mean hemispherical, and preferably also the mean spherical, intensities should be stated.

Large squares and wide streets are best illuminated with flame arc lamps, fixed some 10 to 20 metres high. The lamps in squares are suitably arranged at the corners of equilateral triangles, those for streets on poles erected in the middle of the road where the streets are sufficiently wide to allow for an island round each post.

The determination of the average illumination may be accomplished by plotting illumination curves in various directions and taking the mean of all the plotted values. Such a method is however extremely laborious. It may be simplified by making several assumptions. We may take for granted that the lights are symmetrical. Since most arc lamps possess diffusing globes, and glow lamps diffusing shades, the error introduced by this assumption is not formidable, especially as in any case we can obtain approximate results only.

Further simplifications are introduced by dividing the square or street into rectangles or squares * (from 20 to 30 in number), and by determining for the centre of each the illumination. We must know for this purpose the distances of these centres from those lamps which take part in the illumination of these points, and by means of the polar curves determine the illumination of the centres from each lamp. By adding all the calculated values and dividing the sum by the total number of squares, we get the average illumination.

The method looks laborious, but if the lamps are equally spaced and the lights symmetrical and fixed at equal heights above the road surface the number of squares considered need not be so very large. The method is at least useful in cases where the illumination is already installed. The division into squares of places and streets is indicated in figure 7·29.

For a precalculation of street lighting, Dr Bloch advocates a further simplification.† The street is divided into such a number of rectangles or squares that for each one we have one lamp, which is placed in the centre. This area is then changed into an equal circular one, and it is assumed that no other lamp takes part in the illumination. This introduces two errors. By changing the rectangle into a circle and calculating the illumination for the latter, we obtain a value which is too large. On the

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* Dr Bloch, *E.T.Z.*, 1906, p. 493.

† See *E.T.Z.*, 1906, p. 493.

other hand, by neglecting the light from other sources, we obtain an average value which is too small. These errors partly neutralise one another; the remainder may be expressed by a factor K_1, with which the calculated average illumination has to be multiplied in order to obtain a more correct value. Dr Bloch gives this factor for street lighting as $K_1 = 1 - 0{\cdot}1\gamma$, where γ is the ratio $\dfrac{\text{distance between lamps}}{\text{width of street}}$.

The distance between the lamps is measured in the direction of the street, even if the lamps are staggered. The average illumination is found from equation 5·07*a*, viz.,

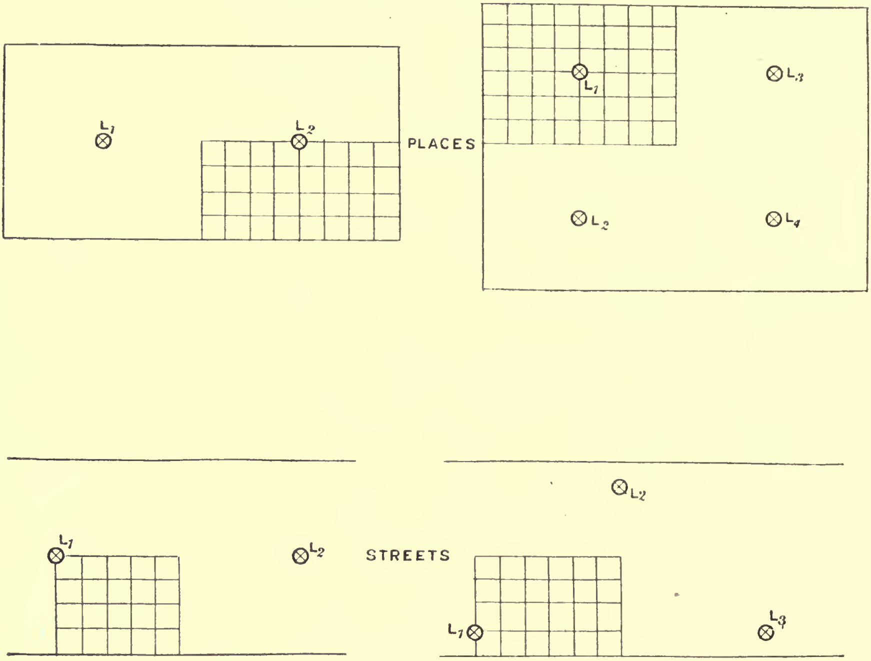

FIG. 7·29—Dividing an Area into Small Squares.

$$\bar{E} = \frac{\phi^{\theta}}{S}.$$

(See also fig. 5·11.)

The method shown in figure 5·11 possesses the advantage that the luminous flux has to be derived once only from the luminous intensity or polar curve, and that we can obtain from it the value of the flux for any lamp height and any radius a_1 of the circular area to be illuminated. It may even be applied for lamps of different intensities, as long as their light distribution is similar; the values of ϕ^{θ} taken from the curve have then simply to be multiplied by a known ratio.

It is advisable to plot for different types of lamps normal luminous intensity (polar) and luminous flux curves always ready for use, for a round number of mean spherical or mean hemispherical candles—for instance, for 3000 candles (see figure 5·11).

When the mean horizontal illumination and the area are specified, we find

$$\phi^{\theta} = \mathrm{S}\bar{\mathrm{E}}.$$

For the radius corresponding to the area S and a given or assumed height h we find the angular region θ_1, and from the luminous flux curve the corresponding value ϕ^{θ_1} at 3000 M.H.S.C.P. From the ratio of the calculated value ϕ^{θ} to the value ϕ^{θ_1} for 3000 candles we then obtain the required intensity of the lamp.

In the formula

$$\bar{\mathrm{E}} = \frac{2\pi}{\mathrm{S}}\int_0^{\theta} \overline{\mathrm{I}d(\cos\theta)} = \frac{\phi^{\theta}}{\mathrm{S}}$$

the height h is contained indirectly. For if for a constant area S the lamp is raised more and more, the angular region, and thus the flux, becomes smaller and smaller. The degree of uniformity is however improved thereby.

Example 5.—A street 60 metres wide is to be illuminated by arc lamps 100 metres apart. The polar distribution of the lamp used is shown in figure 5·11. The lamps are fixed on poles 16 metres high or 15 metres above the standard plane. We are asked to find the average illumination.

The area to be illuminated is $60 \times 100 = 6000$ square metres. To this area corresponds a circular one with a radius of 43·7 metres. We plot now the angle θ_1 given by the height of 15 and the radius of 43·7 metres and find the flux inside this angle from the luminous flux curve. We get $\phi^{\theta_1} = 12{,}700$ lumens. The factor K_1 is expressed by

$$\mathrm{K}_1 = 1{\cdot}2 - 0{\cdot}1\gamma = 1{\cdot}2 - 0{\cdot}1 \times \frac{100}{60} = 1{\cdot}033,$$

whence

$$\bar{\mathrm{E}} = 1{\cdot}033 \times \frac{12700}{6000} = 2{\cdot}18 \text{ candle-metres.}$$

Example 6.— A street 150 feet wide shall be given an average illumination of 0·25 candle-foot. The lamps are to be of the type shown in figure 5·11, fixed on poles 45 feet high (or 42 feet above the testing plane) and 300 feet apart. Find the mean spherical candle-power required.

We have

$$\bar{\mathrm{E}} = \mathrm{K}\frac{\phi^{\theta}}{\mathrm{S}},$$

$$\mathrm{K} = 1{\cdot}2 - 0{\cdot}1 \times \frac{300}{150} = 1{\cdot}0,$$

whence

$$\phi^{\theta} = \frac{150 \times 300 \times 0{\cdot}25}{1} = 11{,}250 \text{ lumens.}$$

We plot again the angle θ_2 corresponding to a height of 42 feet and a radius of

$$\sqrt{\frac{150 \times 300}{\pi}} = 119{\cdot}5 \text{ feet,}$$

and find $$\phi^{\theta_2} = 12{,}000.$$

The ratio $$\frac{11{,}250}{12{,}000} = 0{\cdot}937\ ;$$

hence the mean hemispherical candle-power of the lamp must be $0{\cdot}937 \times 3000 = 2800$ candles approximately.

In a similar manner we can find for given areas, illumination, and M.H.S.C.P., the height at which the lamps must be fixed, or for standard poles, illumination, and lamps, the distances between the lamps.

Reflection has been entirely neglected in these examples. In manufacturing towns it will be negligible, but in countries such as South Africa, where the buildings are white, the illumination is considerably increased and improved in uniformity by the reflection from the houses.

When the polar curves of lamps are not as favourable for uniform illumination as that employed in the examples, the radiators should be placed on poles which are higher than those used in our examples. In fact lamp-posts are in most cases too low, which is probably due to the one-time small candle-power of the illuminants in use. By fixing the lamps very high up we not only improve the uniformity of the illumination but also make the lighting better from a physiological standpoint, since sharp shadows and glare are avoided.

128. DETERMINATION OF THE RATIO K_u.—In order to be able to judge the quality of an illumination we should know the ratio

$$K_u = \frac{\text{maximum illumination}}{\text{minimum illumination}}.$$

This ratio is easily obtained if we possess the illumination curve for each lamp. It has already been pointed out in Chapter IV. (see fig. 4·25) that the degree of uniformity of an illumination is not altered if we vary the distance between the lamps as long as the height of the radiator above the illuminated area is changed proportionally, *i.e.*, as long as $\frac{2a_1}{h}$ remains constant. Neither do we alter the factor K_u if we replace a set of lamps by another set of characteristically the same distribution. For every particular type of lamp we may therefore plot the ratio K_u for various values of $\frac{2a_1}{h}$ always ready for use, as

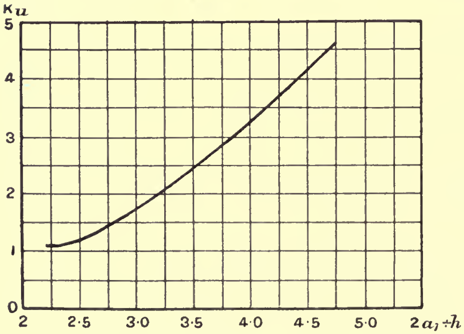

FIG. 7·30.—The Ratio K_u for various Values of $\frac{2a_1}{h}$ for a Siemens T. B. Lamp.

has been done for the Siemens T.B. lamp, illustrated by its polar curve in fig. 4·11, in the accompanying fig. 7·30.

To illustrate the method, let us take the example of fig. 6·03. The lamps are fixed in the centre of a road 30 metres wide. The illumination will be a minimum half-way between the lamps near the edge of the road and not on the line joining the lamps (see fig. 7·31). The distance from L_1 to L_2 through P is 64·8 metres, so that $\frac{2a_1}{h} = 3·24$. For this ratio we get from fig. 7·30 for K_u a value of 2·06, while for the middle of the road $\frac{2a_1'}{h} = 2·87$ and $K_u = 1·625$.

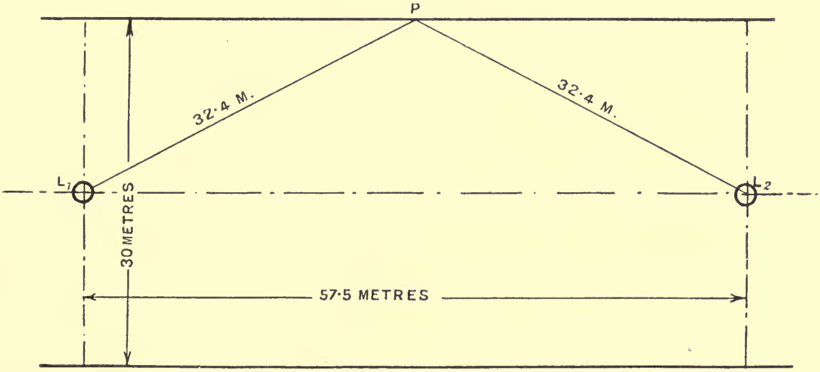

Fig. 7·31.—Arrangement of Lamps.

129. P. HÖGNER'S METHOD FOR DETERMINING THE MEAN HORIZONTAL ILLUMINATIONS OF STREETS AND SQUARES.*—

As streets and squares are usually rectangular, they may easily be subdivided into a number of squares, according to fig. 7·32. The determination of the illumination is then reduced to the evaluation of the illumination of these squares. The method is indicated in fig. 7·33. We draw two arcs as shown and divide each one into 9 parts, differing by 10 degrees. By placing planes at right angles to each other through the points of intersection of the rays from L with the x and y axis we divide each quadrant of the area surrounding the lamp into 81 sections, and if we join the corners of each section with the source L, we obtain 81 pyramids with the spherical angle ω. The latter is approximately given by

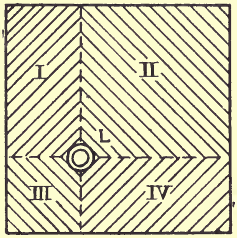

Fig. 7·32.—Subdivision of Area (Högner).

$$\omega = \frac{[\tan(\alpha + 5°) - \tan(\alpha - 5°)] \times [\tan(\beta + 5°) - \tan(\beta - 5°)]}{\sqrt{(1 + \tan^2\alpha + \tan^2\beta)^3}} \quad . \qquad 7·02$$

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* See *E.T.Z.*, 1910, p. 234.

The angle θ, formed by the vertical and the ray from the source to the centre of each section, is expressed by

$$\tan\theta = \sqrt{\tan^2\alpha + \tan^2\beta} \quad . \quad . \quad . \quad . \quad 7{\cdot}03$$

Table XXV. shows the evaluation of these equations. With its aid we are able to find for any given angle θ (represented by its tangent in the table), and the corresponding intensity as shown by the polar curve, the flux within the considered pyramid, simply by multiplying the intensity by the spherical angle ω (see also equation 4·28, in which, if we replace i by I, we obtain ϕ instead of E). These fluxes are now arranged in tabular form according to Table XXVI. and added up from the zero point L outwardly. The upper values represent the fluxes of the different pyramids, the lower ones the sums of the various fluxes counted from L. For instance, the flux striking the field *a b c d* is 189 lumens; for *a e f g* it is 458 lumens. The area *a b c d* reaches up to two sections of 10 degrees

TABLE XXV.—VALUES FOR ω AND TAN θ (HÖGNER).

L. ⊕	10°	20°	30°	40°	50°	60°	70°	80°	90°
10°	$\tan\theta=0{\cdot}1235$ $\omega=0{\cdot}0292$	0·282 0·0283	0·457 0·0265	0·702 0·0241	1·002 0·0210	1·430 0·0172	2·150 0·0128	3·733 0·0086	... 0·005
20°	$\tan\theta=0{\cdot}282$ $\omega=0{\cdot}0283$	0·379 0·0275	0·5385 0·0261	0·750 0·0239	1·035 0·0211	1·453 0·0180	2·160 0·0135	3·740 0·0090	... 0·0055
30°	$\tan\theta=0{\cdot}475$ $\omega=0{\cdot}0265$	0·5385 0·0261	0·660 0·0255	0·842 0·0240	1·102 0·0217	1·502 0·0188	2·195 0·0148	3·760 0·0100	... 0·006
40°	$\tan\theta=0{\cdot}702$ $\omega=0{\cdot}0241$	0·750 0·0239	0·842 0·0240	0·990 0·0235	1·220 0·0225	1·590 0·0205	2·255 0·0170	3·795 0·0123	... 0·0065
50°	$\tan\theta=1{\cdot}002$ $\omega=0{\cdot}0210$	1·035 0·0211	1·102 0·0217	1·220 0·0225	1·414 0·0230	1·740 0·0226	2·365 0·0211	3·860 0·0156	... 0·0075
60°	$\tan\theta=1{\cdot}430$ $\omega=0{\cdot}0172$	1·453 0·0180	1·502 0·0188	1·590 0·0205	1·740 0·0226	2·020 0·0244	2·580 0·0247	4·000 0·0217	... 0·0080
70°	$\tan\theta=2{\cdot}150$ $\omega=0{\cdot}0128$	2·160 0·0135	2·195 0·0148	2·255 0·0170	2·365 0·0211	2·580 0·0247	3·035 0·0301	4·300 0·033	... 0·0085
80°	$\tan\theta=3{\cdot}733$ $\omega=0{\cdot}0086$	3·740 0·0090	3·760 0·0100	3·795 0·0123	3·860 0·0156	4·000 0·0217	4·300 0·0330	5·28 0·0526	... 0·0120
90°	$\tan\theta=\infty$ $\omega=0{\cdot}005$	... 0·0055	... 0·006	... 0·0065	... 0·0075	... 0·0080	... 0·0085	... 0·0120	... 0·1163

TABLE XXVI.—VALUES FOR ϕ (SEE POLAR CURVE OF FIG. 7·35) (HÖGNER).

		Direction $y\rightarrow$up to 90°.					
	L.	a 10°	20°	30°	b 40°	50°	e
up to 90°←Direction x	10°	24 24	32 56	34 90	30 120	26 146	
	20°	32 56 d	34 122	33 189	31 250 c	26 302	
	30°	34 90 g	33 189	33 289	30 380	26 458	f

each on the vertical plane x and to three sections of 10 degrees each on the horizontal plane y.

It is sufficient to tabulate these values once only for lamps of similar type but different intensities, since the light fluxes are proportional to the mean hemispherical candle-powers. Thus, if we plot the table for 1000 M.H.S.C.P., we obtain the results for 500 candles by multiplying the values of the table by 0·5.

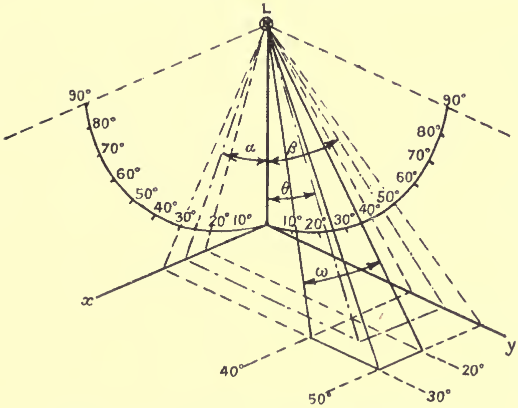

FIG. 7·33.—Principle of Högner's Method for the Determination of the Average Illumination.

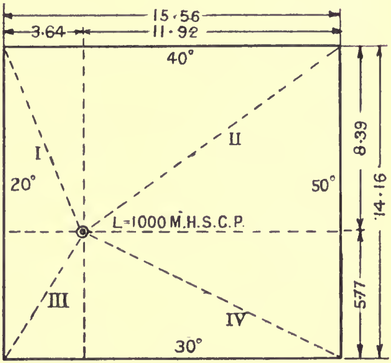

FIG. 7·34.—Position of Lamp in Example 7.

Example 7.—A place 15·56 metres long and 14·16 metres wide is to be illuminated with an arc lamp fixed 10 metres high. The position of the lamp is shown in the accompanying fig. 7·34. We divide the area into four rectangles I, II, III, IV. Rectangle I reaches up to 20 degrees in the x axis and to 40 degrees in the y axis and receives, according to Table XXVII., from a lamp with a polar distribution according to fig. 7·35, 250 lumens. (In this table only the sums have been inserted.) For the other rectangles we have 603, 189, and 453 lumens. The total flux is thus 1500 lumens. The average illumination is therefore $\bar{E} = \frac{1500}{15{\cdot}56 \times 14{\cdot}16} = 6{\cdot}8$ candle-metres. The flux diagram for one quadrant is also shown in fig. 7·35; this diagram will be found useful when the rectangles do not end at 20, 30, etc., degrees.

Table XXVII.—Values of ϕ for Example (Högner).

L. ⊕	10°	20°	30°	40°	50°	60°	70°	80°	90°
10°	24	56	90	120	146	165	177	185	188
20°	56	122	189	250	302	340	365	380	387
30°	90	189	289	380	458	515	558	578	590
40°	120	250	380	500	603	685	740	770	788
50°	146	302	458	603	732	840	910	955	975
60°	165	340	515	685	840	970	1060	1120	1140
70°	177	365	558	740	910	1060	1190	1265	1300
80°	185	380	578	770	955	1120	1265	1390	1425
90°	188	387	590	788	975	1140	1300	1425	1570

Example 8.—A street 25 metres wide is to be illuminated with Excello lamps having polar curves as shown in fig. 7·36. The lamps are fixed in the middle of the road 10 metres above the ground. The arrangement is illustrated in fig. 7·37. We plot Table XXVIII., from which we see that part I of the street receives 798 lumens from lamp L_1 (inclination is 51 and 80 degrees). The total street surface receives therefore from both lamps L_1 and L_2 $4 \times 795 = 3180$ lumens, and as the area is $60 \times 25 = 1500$ square metres, the average illumination is $\bar{E} = \frac{3180}{1500} = 2{\cdot}12$ candle-metres. The lamp employed has an intensity of 1000 M.H.S.C.P. For 2000 M.H.S.C.P. the illumination would have been 4·24 candle-metres.

Table XXVIII.—Values of ϕ for Example (Högner).

L. ⊕	10°	20°	30°	40°	50°	60°	70°	80°	90°
10°	19	38	57	75	94	112	130	141	144
20°	38	76	114	143	190	226	263	285	295
30°	57	114	172	229	286	345	400	436	455
40°	75	143	229	307	387	467	548	600	620
50°	94	190	286	387	490	598	705	778	816
60°	112	226	345	467	598	735	880	975	1000
70°	130	263	400	548	705	880	1075	1210	1240
80°	141	285	436	600	778	975	1210	1390	1440
90°	144	295	455	620	810	1000	1240	1440	1570

Example 9.—The same lamps are arranged according to fig. 7·38. From Table XXVIII., or from the flux diagram of fig. 7·36, we obtain for area

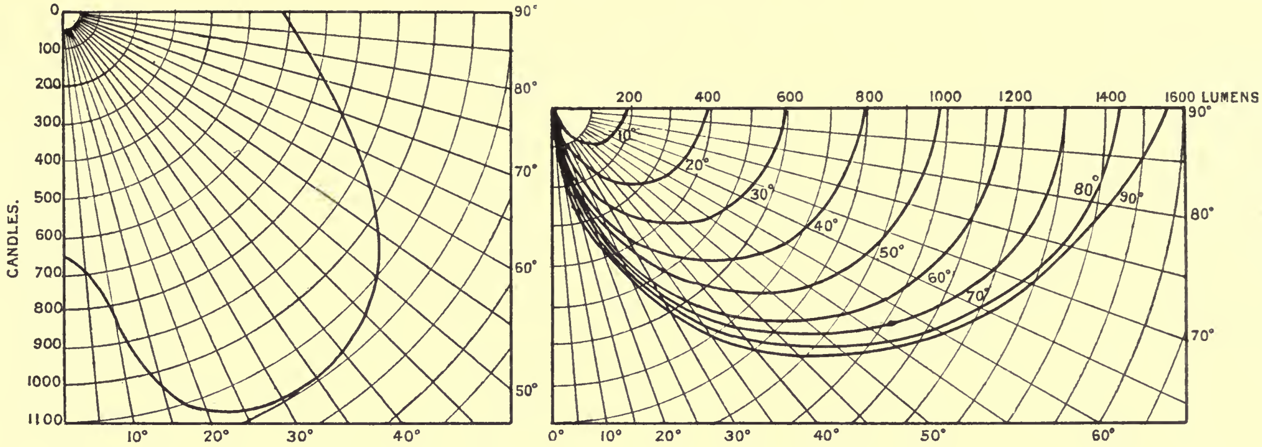

FIG. 7·35.—Polar Curve and Light Flux Diagram used in Example 7.

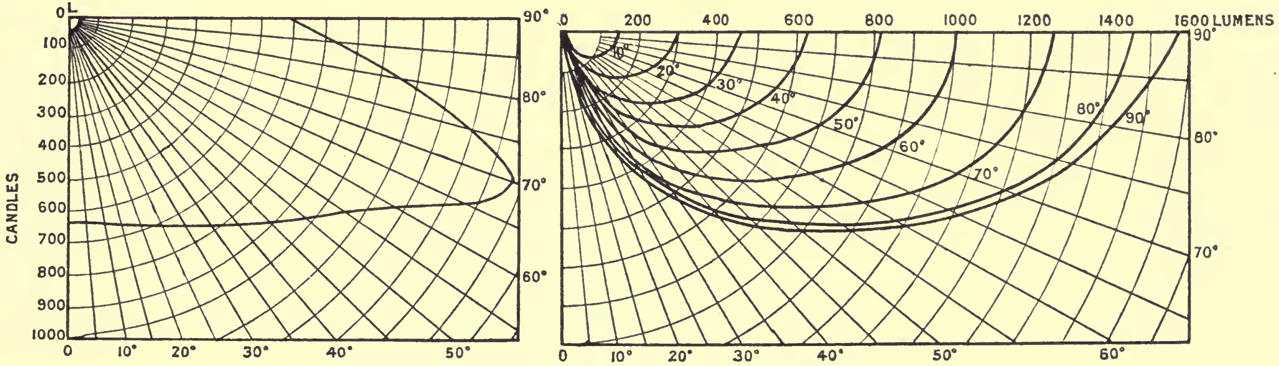

FIG. 7·36.—Polar Curve and Light Flux Diagram for Example 8.

I a flux of 278 lumens and for area II, 1092 lumens. From both lamps the flux is thus $2 \times (278 + 1092) = 2740$ lumens, and the average illumination is $\bar{E} = \frac{2740}{1500} = 1{\cdot}82$ candle-metres. We see that, if we stagger the lamps, the illumination is less than when the lamps are fixed above the middle of the road.

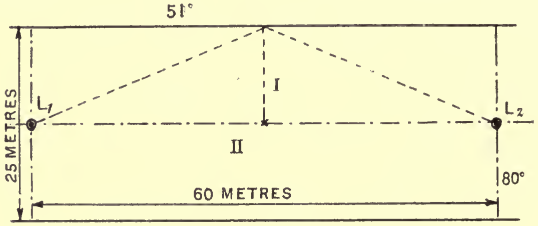

Fig. 7·37.—Arrangement of Lamps in Example 8.

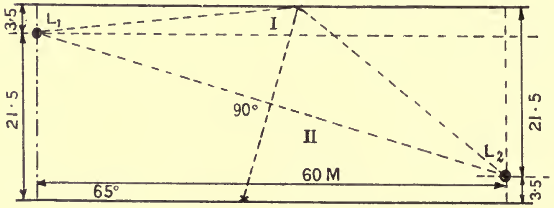

Fig. 7·38.—Arrangement of Lamps in Example 9.

In a similar manner we may determine the mean illumination of vertical planes.

130. **COST OF ELECTRIC LIGHTING.**—Every illumination should be satisfactory from the physiological standpoint, and the radiators which procure this result with the minimum amount of cost are the best. At the present day the tungsten filament incandescent and the flame arc lamps are principally installed. Local conditions decide where one or the other type is preferable. After the type of radiator has been settled, we should see that all available light flux is utilised, and this is possible only with properly designed shades and reflectors. Naked lamps should be avoided, except in places where they can be fixed high up out of the line of vision, and where the ceiling has been constructed with a view of providing an efficient reflector.

In street lighting, all the light emitted above the horizontal through the centre of the arc is wasted, but a shade above the lamp prevents this and limits the waste to the absorption by the reflecting surface. Uniformity of illumination is of great importance, and a high degree of uniformity should be aimed at by every illuminating engineer. He cannot easily go too far in this direction.

After the illumination has been designed, the cost depends upon the price of the radiator, the fittings, the price for energy, and the expenses for maintenance. As an example we shall consider a hall for entertainments for which the electric lighting installation cost £350 and which consisted of 150 50-watt tungsten lamps. Assume the life of the lamps to be 1000 hours and that the lamps burn for 1000 hours every year, so that they must be renewed annually. The average illumination produced over an area of 900 square metres is 22 candle-metres. The cost bill works out as follows:—

150 lamps at 2s. 6d. each cost £18, 15s. 150 lamps of 50-watt each consume in 1000 hours 7500 units, which at sixpence per unit amounts to £187, 10s. Interest at 5 per cent. on £350 accounts for £17, 10s. Adding 5 per cent. for depreciation, we get a total sum of £241, 5s. The illumination of each square-metre floor space per year costs therefore 5·36 shillings, or 2·92 pence per candle-metre (the figure per candle--foot per square foot is the same).

The total power expended is 7500 watts, or 8·33 watts per square-metre floor space, or 0·38 watt per candle-metre per unit area.

This figure is comparatively high. We must however take into consideration the fact that the hall includes a large number of small rooms, of which the walls are as well illuminated as the floors, because the lamps are all fixed near the ceilings. The area actually illuminated is therefore far greater than 900 square metres.

By expressing the quality of an illumination in this manner, we do not take into account the physiological quality. Unfortunately we have up to the present no apparatus with which we can test this, and we have to rely on the judgment of our eyes. The depth of existing shadows, the ability for recognising fine details, the absence of glare apart from the sufficiency of the illumination, should all be taken into account when judging an illumination. Only when these points have been satisfactorily settled can we compare cost figures obtained in the manner described above.

As regards street lighting, we may proceed in a similar manner. Consider the installation illustrated in fig. 7·37. The average illumination is 2·12 candle-metres for a street 25 metres wide. Suppose the road is 600 metres long, thus requiring ten arc lamps. Each lamp absorbs 550 watts, necessitating a total power of 5500 watts. Let the number of burning hours per year be 3000, then the consumption of energy is 16,500 units annually. At one penny per unit the expenditure for current is £68, 15s. For an installation costing £750 without the lamps and reckoning 5 per cent. interest and depreciation, the annual outlay is £37, 10s. The price of the ten lamps is £50. Allowing 5 per cent. for interest and 10 per cent. for depreciation, the annual expenses from this source amount to £7, 10s. The carbons are consumed at the rate of 40 millimetres per hour each, so that for 3000 burning hours and allowing for waste we require about 3000 metres of carbon per year, which cost £75. Wages for cleaning and recarboning amount to £4 per lamp per year, or £40 in all. The total expenses thus sum up to £228, 15s. or to £22, 15s. 8d. per lamp per year. The area illuminated is 15,000 square metres; hence we expend per candle-metre per square metre 1·71 pence per annum. As the power absorbed is 5500 watts, the power per unit area is 0·367 watt, or 0·173 watt per candle-metre per square metre.

It will be interesting to compare this installation with one of tungsten lamps. In our previous example the total flux from each lamp was about 8000 lumens, of which 3180 were utilised. Assuming a similar state of affairs for the tungsten lamps, we require lamps of 635 M.S.C.P. each, or of 800 mean horizontal candles. If we reckon 1·25 watts per mean horizontal candle, the power absorbed per lamp is 1000 watts, or 10,000 in all. At one penny per unit of energy, this entails an annual expenditure of £125. Having to pay £1 per lamp,* the cost for renewals amounts to £30 per year. Wages for cleaning need not be paid. If otherwise the installation costs the same as that for the arc lamps, the total annual expense sums up to £125 + £37, 10s. + £30 = £192, 10s. We see that there is a difference in favour of the tungsten lamp.

Arc lamps bigger than those used in the example have a higher efficiency, especially if prismatic globes are used. Where wages are low, it is certainly cheaper to install arc lamps of the flame type instead of tungsten filament lamps, as long as sufficient care is taken that the globes remain always clean. If this is not done, it will be found that the light-giving efficiency of the arc lamp soon drops below that of the tungsten filament lamp. Where wages are high, preference must be given to the incandescent radiator.

With the aid of these examples the reader should be able to work out the costs for any particular installation. General tables are useless, because the working costs depend so much on local conditions. At the end of the book will be found a list of papers on the subject, which the student should consult.

131. **COMPARISON BETWEEN THE COST OF ELECTRIC AND INCANDESCENT GAS LIGHTING.**—From a series of tests carried out by the author the following results were obtained:—

TABLE XXIX.—COST OF ELECTRIC AND GAS LIGHTING.

Electric Lighting.		Gas Lighting.	
Price per Unit of Energy.	Cost for 100 M.S.C.P.	Price for 1000 Cubic Feet.	Cost for 100 M.S.C.P.
9 pence	1·35 pence.	10 shillings	1·30 pence
8 ,,	1·20 ,,	9 ,,	1·18 ,,
7 ,,	1·05 ,,	8 ,,	1·03 ,,
6 ,,	0·90 penny	7 ,,	0·90 penny
5 ,,	0·75 ,,	6 ,,	0·78 ,,
4 ,,	0·60 ,,	5 ,,	0·65 ,,
3 ,,	0·45 ,,	4 ,,	0·52 ,,
2 ,,	0·30 ,,	3 ,,	0·39 ,,
1 penny	0·15 ,,	2 ,,	0·26 ,,

The gas mantles used were partly of the ordinary, partly of the inverted, types. The electric lamps were of tungsten, with a mean consumption of

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* This price has been considerably reduced since the above was written.

1·52 watts per M.S.C.P. The table does not include the expenditure for renewals, which depends so much upon the manner in which the lamps are handled. On the whole, there is not much to choose between the two illuminants in this direction. Which method may prove the cheaper of the two depends to a large extent upon the prices for gas and electrical energy. It must however be remembered that electric lamps can be obtained in much smaller units than incandescent gas lamps, and that people switch off electric light when they leave a room for a short time, but not the gas light, as they object to the trouble of relighting.

132. **THE HYGIENIC ASPECT OF ELECTRIC LIGHTING.**—Of all the different systems of artificial lighting the electrical system is the best from the hygienic standpoint. As long as proper precautions are taken to guard the eyes against ultra-violet light, and the right type of lamp is installed in the right way, perfect comfort is attainable physiologically and hygienically. From the very nature of electric light this seems self-evident, yet statements to the contrary are not infrequently made. These statements rest however mostly on the basis of ignorance, and cannot be substantiated by actual tests.

The purity of the atmosphere is usually judged by the quantity of carbon dioxide. This is, however, hardly the right way of judging the atmosphere, since even an amount of 5 per cent. of CO_2 causes no ill-effects as long as the air is otherwise pure. Only an amount of 10 per cent. of CO_2 causes choking, and such quantities are never found in even the worst places. Of course, an increase in the carbon dioxide means usually a reduction in the available amount of oxygen, but then electric incandescent lamps do not consume oxygen, and consequently produce no carbon dioxide, so that from this standpoint electric incandescent lighting is superior to all other installations. It is however not so much the carbon dioxide which pollutes the air as the transpirations from the skins of the people assembled, which cause the inconvenience and have a nauseating effect. The production of this poisonous toxin is not proportional to the amount of CO_2 produced by a given number of people, because where the people assembled are physically clean the air keeps pure far longer than in rooms filled with a dirty mob. The rate of the production of this poisonous toxin depends largely upon the temperature, whereas the rate of production of CO_2 is independent of it.

The accompanying Table XXX. shows the amount of heat and of CO_2 produced by different illuminants, and illustrates the striking superiority of electric light over all other radiators. To this must be added the heat produced by the people assembled, which may be expressed approximately by the following equations:—

$$\left.\begin{array}{l} H = 6(37 - t) \text{ for adults} \\ H = 3(37 - t) \text{ for children} \end{array}\right\} \quad . \quad . \quad . \quad . \quad 7{\cdot}04$$

in which t is the temperature in centigrades.

TABLE XXX.—HEAT AND CARBON DIOXIDE GIVEN OFF BY VARIOUS ILLUMINANTS.

Type of Illuminant.	Kilogr. Calories per Candle per Hour.	Litres of CO_2 per Candle per Hour.	Litres of Air required per Candle per Hour.
Ordinary paraffin oil lamp	45	10	75
Paraffin oil incandescent light	9·7	2·2	15·5
Air gas ,, ,,	5·5	0·83	5·8
Acetylene ,, ,,	6·1	0·55	3·2
Coal gas ,, ,,	8·4	0·95	6·1
,, inverted light	5·55	0·63	6·1
,, press light	4·35	0·50	5·0
Carbon filament electric light	2·85	...	...
Metal ,, ,,	1·33	...	...
Ordinary arc lamp	1·06	0·03	0·16
Flame ,,	0·22	0·011	0·17

Electric lighting is however even more favourable than this table indicates. As an electric lamp gives off so little heat, it can be brought much closer to the area which requires local lighting; consequently, smaller units may be employed, and for this reason it is often possible to replace a 70-candle gas light by a 30-candle incandescent electric lamp.

To the production of heat by gas and other flame lights we must add that of moisture. Moisture facilitates the production of the poisonous toxin due to transpirations. Electric lamps do not increase the moisture in the atmosphere, since they glow in a vacuum, and even if arc lamps are used it will be found that the percentage of moisture usually decreases instead of increases, which is to be explained by the increase in temperature without the formation of H_2O.* The increase in the temperature is therefore practically counterbalanced by the reduction in moisture.

All flame lamps which burn gases, and especially coal gas, produce sulphuric and nitric acid. If we enter a room whose atmosphere has been lowered in quality by gas burners, we feel oppressed, and there is little doubt that throat troubles are largely caused by the products of combustion. Extensive experiments further indicate † that the increased ventilation caused by the hot gases from gas burners is largely imaginary. If we add to this the danger of poisoning by gas (New York alone has 2000 cases per year), the trouble of gas leakage (no pipes are perfectly sound, so that some gas always escapes before it is consumed by combustion), the inconvenience of lighting and cleaning—all of which are non-existing for electric lighting—the unbiased should have no hesitation in deciding which method of artificial lighting is the better one from the hygienic standpoint.

* See K. Schlesinger, *E.T.Z.*, 1911, p. 944.

† *E.T.Z.*, 1911, pp. 981–982.

APPENDICES.

I.

The want of an absolute standard of light is very much felt, and various proposals for supplying this want are made from time to time. Dr Strache * suggests that, if the total radiation from a black body be received on a thermo-couple joined to a galvanometer, a deflection proportional to the entire radiation is received. This radiation should now be cut down, so that only visible radiation remains, and the latter should be resolved in a spectrum; by means of diaphragms the light at each point of the spectrum should be cut off to such an extent that the remaining intensities coincide with the Lummer curve. The latter represents the relative sensitiveness of the eye to light as a function of the wave-lengths (see also paragraph 30). The spectrum should next be reassembled by means of a cylindrical lens. In this way the illuminating value may be expressed in terms of the visible radiated energy. The Lummer curve varies however for different individuals, so that an average value would have to be taken.

Dr Houston † proposes the following definition :—

The unit of light intensity is that source the total intensity of radiation from which at an optical distance of 1 metre after passing through an ideal filter would be x ergs/cm. sec.; the ideal filter to be one possessing the light-absorbing properties of a 3 per cent. thick aqueous solution of $CuSO_4 . 5H_2O$, of strength 0·200 gramme-molecule per litre, and a 1 centimetre thick aqueous solution of potassium bichromate ($K_2Cr_2O_7$) of strength 0·0025 gramme-molecule per litre, but neither to reflect nor to absorb any light in any other way.

These solutions have the property of stopping the infra-red and ultra-violet radiations and of cutting down the energy of the visible spectrum in the inverse ratio of the light-producing effect.

The value of x is about 0·8 in the units specified.

II.

a. An interesting paper on colour discrimination was read by Th. E. Ritchie before the Illuminating Engineering Society on 16th January 1912. The results are embodied in the Table XXXI., which should be compared with Table II. in paragraph 15.

b. The relationship between the temperature and consumption of incandescent lamps has been investigated by Drs M. von Pirani and A. R. Meyer. ‡ The results,

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* *Illuminating Engineer*, 1911, p. 513.

† *Ibid.*, 1911, p. 618.

‡ *E.T.Z.*, 1912, p. 456.

as far as they concern the efficiency under which glow lamps are run in practice, are given in the Tables XXXII.–XXXV.

These tables confirm what has been said in Chapter II., viz., that tungsten and tantalum lamps are run at much higher temperatures than carbon lamps, also that for the same temperatures the carbon lamp is less efficient than either of the other two. From Table XXXV. we see that a black-body radiator is more efficient than one which reflects light. The value of the absorption a has been inserted in the tables.

Table XXXI.—Changes in the Appearance of Coloured Objects under Different Lights (Ritchie).

Description of Light Used.	Appearance.	Colour.					
		Brown.	Red.	Green.	Mauve	Blue.	Orange and Yellow.
Bright diffused daylight.	Bluish white or pure white	Normal	Normal	Normal	Normal	Normal	Normal
Inverted O.I. arc lamp	Bluish white or pure white	Normal	Slightly brighter than normal	Normal	Slightly darker than normal	Normal	Normal
Enclosed arc lamp	Bluish white	Darkened	Lightened several shades	Darkened considerably	Darkened slightly	Darkened slightly	Darkened slightly
Metallic filament incandescent lamps	Yellow-white	Lightened and changed to reddish tint	Lightened many shades	Darkened and changed to a yellower tint	Changed to redder tint	Darkened and changed to purplish colour	Brightened and changed to a more orange shade
Inverted incandescent gas	Greenish yellow	Darkened	Lightened many shades	Darkened and changed to a yellower tint	Darkened and changed to a redder tint	Darkened and changed to a more navy blue	Brightened many shades
Carbon filament incandescent lamps	Orange-yellow	Reddened in tint	Lightened many shades	Darkened and changed to a yellower tint	Darkened and changed to a pinker tint	Darkened and changed to a much more purple colour	Brightened and changed to a deep orange
Ordinary gas light	Yellow	Reddened in tint	Lightened considerably	Changed to a yellower green	Changed to a pink rose-coloured tint	Darkened and changed to a more navy blue	Brightened and changed to orange
White flame arc lamp	Bluish white	Slightly reddened in tint	Lightened many shades	Changed to a yellower tint and lightened slightly	Changed to a bluer and darker shade	Brightened and changed to a more intense blue	Changed to a deeper and more orange colour
Yellow flame arc lamp	Deep yellow	Darkened slightly	Changed to a brick red	Deadened and changed to a yellower colour	Darkened considerably and changed to a purple	Darkened and changed to a more navy blue	Changed to a deeper and more orange colour
Mercury vapour lamp	Pale blue-green	Changed to a greenish colour	Changed to almost black	Lightened considerably	Changed to a slate-blue grey	Deadened	Changed to a greenish yellow

TABLE XXXII.—TEMPERATURES OF TUNGSTEN LAMPS (VON PIRANI-MEYER).

Watts per Candle.	Black-body Temperature in °C.	Actual Temperature in °C. ($a=0·51$).
4·4	1692	1816
3·3	1767	1901
2·2	1887	2035
1·65	1978	2140
1·54	1998	2166
1·43	2023	2194
1·32	2051	2226
1·21	2082	2262
1·10	2115	2301
1·045	2136	2323
0·99	2155	2346
0·935	2176	2371
0·88	2200	2399
0·825	2226	2430

TABLE XXXIII.—TEMPERATURES OF TANTALUM LAMPS (VON PIRANI-MEYER).

Watts per Candle.	Black-body Temperature in °C.	Actual Temperature in °C. ($a=0·56$).
4·4	1697	1805
3·3	1774	1889
2·0	1892	2021
1·65	1984	2125
1·54	2007	2151
1·43	2031	2179
1·32	2058	2210
1·21	2089	2244
1·1	2124	2283
1·045	2142	2303
0·99	2162	2327

TABLE XXXIV.—TEMPERATURES OF CARBON LAMPS (VON PIRANI-MEYER).

Watts per Candle.	Black-body Temperature in °C.	Actual Temperature in °C. ($a=0·7$).
5·5	1841	1915
4·4	1903	1981
3·3	1991	2076
2·2	2116	2211
1·65	2218	2321
1·54	2243	2347
1·43	2270	2377
1·32	2300	2411
1·21	2334	2448
1·10	2373	2489

TABLE XXXV.—RELATIONSHIPS BETWEEN ACTUAL AND BLACK-BODY TEMPERATURES IN TUNGSTEN AND TANTALUM LAMPS (VON PIRANI-MEYER).

Candles per Square Millimetre.	Temperatures in °C. for Tungsten and Tantalum Lamps.	Temperatures for Black Bodies.
9	2666	2459
5·4	2513	2309
3·6	2397	2199
1·8	2220	2035
0·9	2065	1889
0·54	1964	1796
0·36	1887	1727

c. A patent has recently been granted to Dr C. P. Steinmetz for a method dealing with the introduction of red rays in mercury vapour lamps. It was mentioned in paragraph 21 that metals, included in the mercury for giving red rays, collect on one pole and that the mixed spectrum soon makes room again for a pure mercury one. Moreover, if sodium, potassium, lithium, rubidium, or thallium are added, the glass tube is attacked and gradually becomes black. This may be obviated by the use of an iodide or other salt of these metals. Well adapted is lithic meta-silicate, which sets off a transparent deposit. The vessel is evacuated, but slightly filled with hydrogen. The substances to produce the red rays are given an excess of pure iodine or mercury iodide.*

d. The manufacture of drawn tungsten filaments is as follows :—

The pure tungsten is obtained, according to the method explained in paragraph 26, in a brittle mass, but in fairly large pieces instead of filaments. A cautious mechanical treatment commences now, consisting of rolling, hammering, and drawing, the temperature of the filament being that of a light red heat. In this way the metal is gradually formed into a wire, which is no longer brittle, the mechanical treatment having reduced the brittle mass into a fibrous one. The final drawing may be cold or hot, a hot wire being preferred.

Another method consists of subjecting tungsten powder to a very high pressure in order to form it into bars, which are then heated in dishes containing silicon and placed in iron tubes, being subjected at the same time to a current of hydrogen at 1200 degrees C. The bars are next heated by means of a powerful electric current for ten minutes and then gradually cooled by reducing the current. The metal may now be rolled, hammered and drawn into wires. The drawing is done by means of steel or diamond dies, the wire being heated by circularly arranged gas burners.

The tensile strength of tungsten is supposed to exceed that of steel.

III.

Equation 5·02, paragraph 80, viz., $I = cV^x$, holds correctly only as long as the variations of the voltage are very small and the lamp is worked near its normal

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* In the latest type of mercury vapour lamps, the steadying resistances are replaced by tungsten lamps, and a better colour of the light obtained in this way. See also Dr J. Pole, *E.T.Z.*, 1912, p. 484.

efficiency. F. E. Cady* has carried out further extensive experiments, from which he deduced the following equation, which holds for voltages 30 per cent. above or below the normal P.D. :—

$$\frac{I}{I_1}=\left(\frac{V}{V_1}\right)^{x_1}\left[1+B\frac{V-V_1}{V_1}+C\left(\frac{V-V_1}{V_1}\right)^2\right],$$

where I_1 is the candle-power at the normal voltage V_1, and x_1 is the value of x at this voltage, as given in the table in paragraph 80. $B=0{\cdot}05$ for treated carbon, 0·024 for tantalum, and 0·02 for tungsten. $C=1{\cdot}2$ for carbon, 0·65 for tantalum, and 0·5 for tungsten.

IV.

Considerable prominence has been given lately to the methods of lighting shops, printing works, private houses, and the readers who wish to pursue the subject further should consult the papers which appeared in the March, April, and May 1912 numbers of the *Illuminating Engineer.*

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[*] *Electrical Review and Western Electrician*, Nov. 25, 1911.

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ABBREVIATIONS.

Am. Inst. Electr. Proc.	Proceedings of the American Institute of Electrical Engineers.
Atti dell' Assoc. Elettr. Ital.	Atti della Associazone Elettrotecnica Italiana.
Bureau of Standard, Bull.	Bulletin of the Bureau of Standards.
Electr. Review, N.Y.	Electrical Review (New York), which is now Electrical Review and Western Electrician.
Electr. World.	Electrical World.
E.T.Z.	Elektrotechnische Zeitschrift.
Frank. Inst. Journal.	Journal of the Franklin Institute.
Inst. Electr. Engin. Journ.	Journal of the Institution of Electrical Engineer.
Soc. Int. Electr. Bull.	Bulletin de la Société Internationale des Electriciens.
Z.f.B.	Zeitschrift für Beleuchtungswesen.

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