No. 123

THE INSTITUTION OF
POST OFFICE ELECTRICAL ENGINEERS

Modern Electrical Illumination

BY

J. J. EDWARDS, B.Sc.(Eng.), A.C.G.I., D.I.C.

A PAPER

Read before the North Eastern Centre of the Institution on the 13th November, 1928.

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MODERN ELECTRICAL ILLUMINATION.

I.—THE NEED FOR SCIENTIFICALLY DESIGNED INSTALLATIONS.

It is a coincidence, and not inappropriate perhaps, that what I have to say to-day should relate to a subject which is rec iving much attention in connection with a campaign for the scientific utilisation of electrical energy conducted by the leading electrical engineers and manufacturers of the country. I refer to the Electrical Development Association campaign. The fact that good lighting involves more than the provision of light, is one that has been little realised until recent years, and judging by the number of obsolete installations which one sees still in commission, particularly in private and public, as distinct from commercial, premises, there are still many who do not, or will not, realise it. At the beginning of the electric light era, the advantages of the new illuminant were so obvious that it was used indiscriminately. A lamp was considered merely as a source of light without reference to the production of glare and shadows, or the control of its energy.

> " Often when an electrician was sent to put a light in, say, a factory, the first question he asked of an operator was ' Where do you want this light? ' The operator indicated what he considered was the most suitable position, and so an extension to the system came into being.
>
> " In the majority of cases where a light had been fitted under these conditions, it was subsequently found pulled over with string to another position or a piece of paper had been fastened to the reflector to keep the glare from the eyes. In fact, where bare lamps had been installed, it was not uncommon to find the lamp completely enveloped in a paper bag! "*

Without further comment on this state of affairs, it is evident that while such installations are permitted to persist

* " Modern Electrical Illumination," by Sylvester and Ritchie.

there is a wide field for the conduct of the campaign to which I have referred.

Much progress has been made of recent years in the direction of eliminating poor lighting installations, and the benefits accruing from a well designed installation have been emphasised from time to time by the special committees and conferences called to consider the question of artificial lighting. As a result of their researches, chiefly into industrial conditions, it has been established that good lighting is essential,

(1) as a hygienic necessity;

(2) as a means of preventing accidents;

(3) on purely economic grounds.

The first two considerations do not require stressing; but with regard to the third item, an experience related by a well known Illuminating Engineer* will perhaps be of interest.

It had been observed that a precision grinder when at work on a certain machine produced large quantities of scrap, and the operator complained that something was wrong with his machine. The machine was examined and found to be in good order; and the man was, therefore, watched carefully. It was found as a result, that he produced large quantities of scrap only when a certain near-by machine, a turret lathe for turning crank shafts, was working, and that a beam of light was reflected from a certain crank on to the man's eyes, causing a flash of light and impairing his visual judgment. The elimination of this reflected ray caused the production of excessive scrap to cease.

Further examples of a similar nature might be quoted where economy has suffered due to poor lighting, and where increased output has resulted from the installation of a scientifically designed system. Increases of output as high as 40% have been claimed as a result of better lighting where the cost of the improvement has been covered by probably not more than 5% of the output.

The rapid advance of electricity, as an illuminant, has been due more than anything else to the development of the tungsten filament lamp, vacuum and gas-filled, and particularly to the latter. Up to the time that the tungsten

* "Modern Electrical Illumination," by Sylvester and Ritchie.

filament lamp was put on the market about 1907, various forms of carbon and metal filaments, including osmium, zirconium and tantalum, had already been tried without any real success in producing a lamp which would yield a fair luminous output per watt and have a reasonable life. There had been no difficulty in securing a consumption as low as 1.2 or even 1.0 watt per M.H.C.P. (mean hemispherical candle power); but the life had always suffered and there had been a marked diminution of candle power at its end. The discovery of the suitability of tungsten for lamp filaments resulted, however, in the production of the modern type of vacuum lamp, with a consumption of about 1.4 watts per mean spherical candle power, *i.e.*, about 8.5 lumens per watt, and a life of about 1000 hours; and experience with this type of lamp has enabled a step further to be made and a lamp produced filled with inert gas, which gives a much improved efficiency without detracting from its economical life.

The maximum efficiency at which a lamp can be run is limited by the temperature at which the filament can be maintained; the higher the temperature, the greater is the efficiency. The temperature to which the filament can be heated depends, in its turn, on the filament evaporation. Evaporation eventually causes the filament to break and, also, the evaporated substance is deposited on the bulb and obscures light. The function of the gas in a gas-filled lamp is, therefore, to prevent the evaporation of the filament and make possible the use of higher temperatures without blackening the bulb or shortening its life. The gas, however, cools the filament by conducting heat from it to the bulb: this is, of course, a waste of energy, and, in order that the gas-filled lamp shall be more efficient than the vacuum type, the gain in efficiency due to increasing the working temperature, must be greater than the loss due to cooling. To fulfil this condition, the filament must be comparatively thick—much thicker than would be practicable for lamps for ordinary purposes; and as, for a given wattage and candle power, the length and diameter of a filament are fixed, the difficulty has to be overcome in another way. The filament is made as a close spiral of very fine wire, so that, in respect of heat loss and light emission, it behaves almost as if it were a short wire of the same thickness as the external diameter of the spiral, while still having the resistance of a long thin wire.

A further effect of introducing the gas is to convey the evaporated particles to the top of the bulb. For this reason, the bulb is so shaped as to offer a large cooling surface to the hot gas arising from the filament, whilst the small amount of evaporated tungsten is deposited where the slight blackening does not obscure the light. For lamps of this type, the output of light varies from about 10 lumens per watt in the 40 watt lamp to about 21 lumens per watt in the 1500 watt lamp, in both cases on 200 volts.

These lamps can be produced in such a range of sizes that one can be found to suit almost every purpose, with the result that they are now being used in spheres where previously other types have held undisputed sway. For example, in street lighting they are displacing the high pressure gas system and the arc lamp; for use in projectors they have largely displaced arc lamps and acetylene burners. In spheres where electricity has already been recognised as the most suitable form of illuminant, such as industrial, shop window, and theatre lighting, the introduction of the gas-filled lamp has brought about new methods and revolutionised our ideas of electricity as an illuminant. It will, perhaps, be of interest, therefore, to examine the principles involved in designing a modern lighting installation.

II.—UNITS AND NOMENCLATURE.

1. *Units.*

(*a*) As in all other branches of scientific investigation the basis of our analysis must be observation and experiment, and in order that we shall be able to compare the relative magnitudes of the effects we observe, it is essential to have some language in which to record them; that is, we must have some units by which to measure the magnitudes of these effects.

(*b*) *Light* may be defined as radiant energy in a form capable of exciting the sensation of vision. A light source emits luminous energy continually in all directions, and the rate of emission of energy is termed the amount of flux emitted by a source. The following definition has been adopted internationally*: "Luminous flux is the rate of passage of radiant energy evaluated by reference to the luminous sensation produced thereby." The flux emanating from a source whose dimensions are negligible compared

* British Standard Specification No. 233/1925.

with the distance from which it is observed, may be considered as coming from a point.

(*c*) *The luminous intensity* of a point source in any direction is the luminous flux per unit solid angle emitted by the source in that direction.* For practical reasons, the fundamental unit chosen for purposes of photometric measurement is the unit of luminous intensity, *i.e.*, the candle,† and this unit is now maintained in this country by means of a certain group of electric incandescent filament lamps kept at the National Physical Laboratory.

(*d*) With this unit defined, it is now possible to say what we shall take as our unit of *luminous flux*, and that is the flux emitted in unit solid angle by a uniform point source of one International Candle, and is called the *Lumen*.*

It will be noticed that the definition of luminous intensity taken above refers to the intensity in a single direction. The average value in all directions in space is termed the Mean Spherical Intensity and its magnitude is termed the Mean Spherical Candle Power (M.S.C.P.). Since the total solid angle at a point is 4π, the total flux emitted by a source of mean spherical candle power I is $4\pi I$, *i.e.*, 12.57 I lumens.

(*e*) *Illumination.* When luminous flux reaches a surface, that surface is said to be illuminated, and the *illumination* of a surface may be defined* as the luminous flux reaching a surface per unit area.

It will now be easy to determine the relation between illumination and luminous intensity. Consider a point source placed at a distance d from an element of surface of area S:

If the surface is perpendicular to the rays and the C.P. in that direction = I, then

Flux received by the surface is $I \times S/d^2$ since the surface subtends a solid angle S/d^2 at the source.

Now the illumination of the surface we defined as Flux/S

$$\therefore \text{E (Illumination)} = \frac{I \times \frac{S}{d^2}}{S} = \frac{I}{d^2}$$

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* British Standard Specification No. 233/1925.

† International Candle Definition, B.S.S., No. 161/1928.

∴ The Illumination of a surface is inversely proportional to the square of the distance of the surface from the source illuminating it.

The unit of illumination must, therefore, be the illumination of a surface one foot distance from a source of one candle in the direction of the surface, and is called a foot-candle. (The French unit is 1 metre-candle = 1 lux).

Consider now a surface the normal to which makes an angle θ with the light ray. Since the light travels in straight lines, it is clear that the flux reaching the surface is distributed over a larger area the more the surface is tilted away from the normal to the ray, and the illumination is accordingly decreased in a ratio depending on the angle θ—in fact in the ratio cos θ, and the general expression for the illumination becomes $\frac{I \cos \theta}{d^2}$ – (where θ is again the angle between the ray and the normal to the surface).

There is one more term to be defined and that is

(*f*) *Brightness*. The brightness of a surface results from the flux which it emits either by virtue of its self-luminosity or by reflection of light received from luminous sources. Thus (Fig. 1) the brightness of the surface S in the

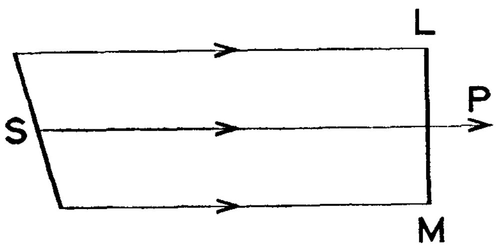

FIG. 1.

direction SP is equal to the luminous intensity (candles) in the direction SP divided by the projected area LM (sq. ft.) and is measured in candles per square foot.* As an example of the order of magnitude of this unit, the brightness of the blue sky at the zenith on a bright day is round about

* British Standard Specification No. 233/1925

three candles per square inch while the brightness of a piece of paper having an illumination of three foot candles is $\frac{1}{144}$ candles per sq. inch.

NOTE.—The flux emitted per sq. ft. by a perfect diffuser of brightness B = πB lumens.

1 Lambert = 1 lumen per sq. cm.

1 foot-Lambert = 1 lumen per sq. ft.

(See Appendix 1).

(*g*) Before proceeding further, it will be convenient to summarise what we may call our terms of reference:

Term	*Unit.*	
1. Luminous flux.	Lumen.	Flux per unit solid angle from 1 candle.
2. Luminous intensity.	Candle.	Mean spherical intensity 1 candle emits 4π lumens.
3 Illumination.	Foot-Candle.	1 lumen per square foot.
4. Brightness.	Lambert.	1 lumen per sq. cm.
	Foot-Lambert.	1 lumen per sq. ft.
	Candles per sq. ft.	—

2. *Mean Spherical Intensity.*

Definition from Illumination Research Paper No. 5 —" Until recently, it has been customary to rate light sources either in terms of their candle-powers in a certain convenient direction, such as the direction of maximum candle-power, or in terms of the average value of the candle-power in a specified plane. In the case of the vacuum lamp, having the ordinary squirrel cage filament, or an upright gas mantle, the figure ordinarily taken has been the average value of the candle-power measured in all directions in a plane at right angles to the axis of symmetry, *i.e.*, measured in a horizontal plane, since the axis of symmetry is normally vertical under ordinary working conditions. This figure has been called the Mean Horizontal Candle-Power (M.H.C.P.)."

Although the mean horizontal candle-power has been a convenient figure for describing the output of those sources of light which have been most used in the past, there have always been important classes of work for which this rating is unsuitable—for example, in the case of arc lamps or gas installations for street lighting, the sources must be so designed as to emit the greatest possible proportion of their light below the horizontal plane. It follows that an M.H.C.P. rating is useless in this case, and such sources have frequently been rated in terms of the average value of their candle-power measured in all directions below the horizontal. This value is termed the Mean Lower Hemispherical C.P.

Owing to modern developments in lamp manufacture it is now possible to utilise sources having a larger variety of candle-power distribution: in addition, the rapid increase of the intrinsic brightness of light sources has resulted in the employment of reflectors and shades for the purpose of redistributing the light. In consequence of these developments a revision of the method of describing the output of light sources was necessary and it has now been realised that for most purposes the most practical rating is in terms of the total output of the source, rather than its C.P. in any particular direction. This realisation has led to the adoption, in the electric lamp Specification of the B.E.S.A., of a candle-power figure which is a measure of the total output of the lamp instead of the M.H.C.P. previously used. There are two methods of expressing this figure:

(1) The average of the candle-power in all directions in space—this we have already called the Mean Spherical Candle-Power.*

(2) In terms of the lumens emitted by the source—this we have already shown to be $4\pi \times$ M.S.C.P.

3. *Polar Curves.*

It is frequently necessary to know the luminous intensity of a light source in various directions. The distribution of light from most of the common sources of to-day can be regarded as symmetrical about the axis of symmetry of the source, and, for such sources, it is possible to show the candle-power distribution in a single plane passing through this axis of symmetry by means of a diagram. This is called the polar diagram of the source, and it indicates, in convenient graphical form, the candle-powers measured at various angles to the vertical in any one plane. The radial lines indicate the directions, and the distance of the curve from the

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* See Appendix 1.

centre of the diagram to the point where it cuts a radial line represents to scale the candle-power in that direction. This curve furnishes an invaluable guide to the character of any source or unit and shows, at a glance, whether the fitting will be the correct one for a given purpose.

Fig. 2 shows the polar diagrams of two lamps (A) vacuum, with the ordinary type of squirrel cage filament; (B) gas-filled, with the common type of ring filament.

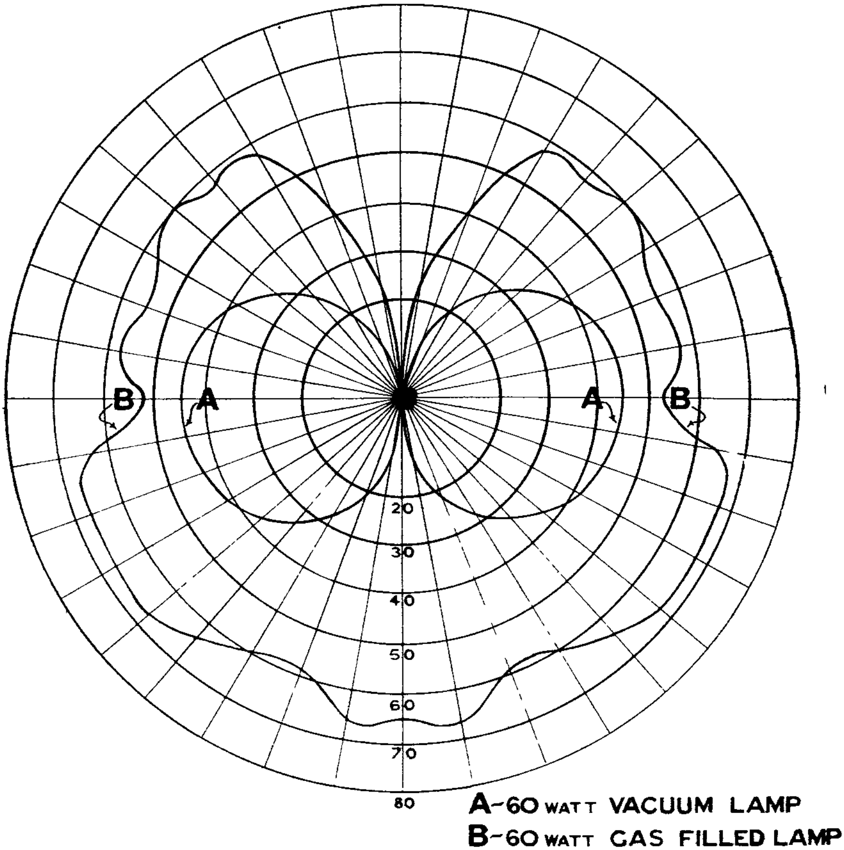


FIG. 2.

A bare light source alone is not suitable for any purpose because, apart from the glare which is injurious to the eyes, a large percentage of the light is wasted in horizontal and upward directions. The function of the reflector is to intercept and control this light, which would otherwise not be utilised in the most efficient manner. Fig. 3 illustrates the

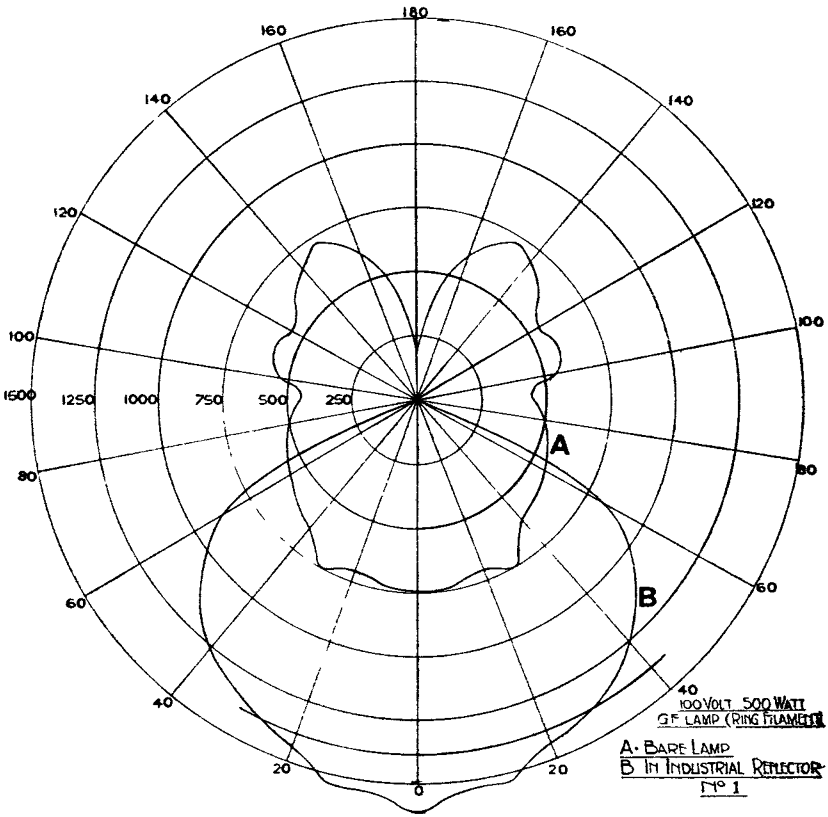


FIG. 3.

effect of putting a reflector (No. 1) over a high powered lamp (500 watt G.F.). It will be observed that the effect of the reflector is

(1) to cut off the light going upwards and reflect it to the working plane;

(2) to increase the "apparent" maximum C.P. from 700 to 1700, approximately;

(3) to widen the polar curve, *i.e.*, disperse the light (1000 C.P. at 60° and about 1500 C.P. at 30°).

III.—DIRECT LIGHTING REFLECTORS.

1. *Various types of Reflector.*

Figs. 3 and 4 show the polar curves of various types of direct lighting units; and the purpose for which each fitting i- intended will be obvious from the shape of the curve.

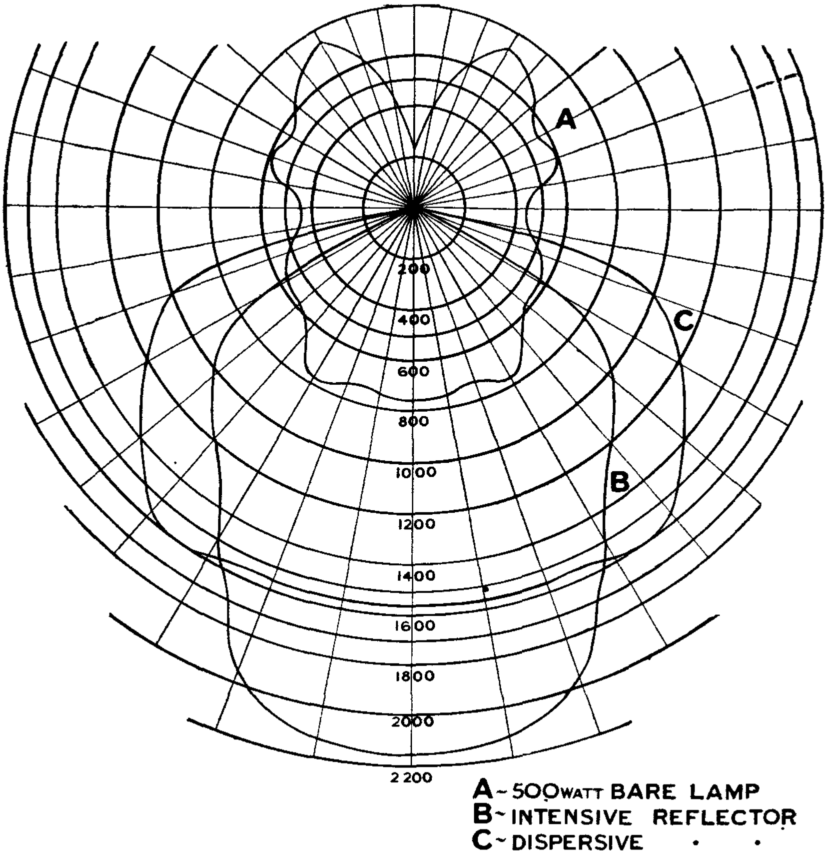


FIG. 4.

Fig. 5 shows what is known as Industrial Reflector Fitting No. 1. A good deal of research and experiment has been carried out with this fitting, and the results have been published by the Department of Scientific and Industrial Research in Illumination Research Report No. 3. Questions which they have examined include the effect on the distribution and luminous efficiency of the diameter of the fitting, the height of the lamp filament above the bottom of the reflector, *i.e.*, the angle of cut-off, and the type of filament; and, as a result, this type of fitting is now manufactured to standard dimensions for a given size of lamp. (B.E.S.A., No. 232—1926).

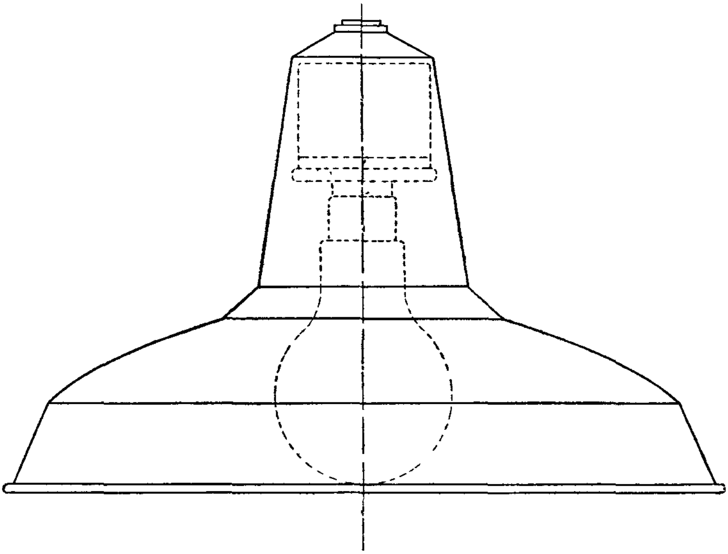


FIG. 5.

As will be seen from the polar curve in Fig. 2 the distribution is fairly dispersive and the fitting is intended for general illumination. It will be noted, too, that the eye is well shielded from the filament.

The reflector illustrated in Fig. 6 is of the distributing type and re-directs only the light which would normally go upwards. It will be observed from Fig. 4 that the candle-power values at angles 50° and 60° from the vertical are larger than with the previous type.

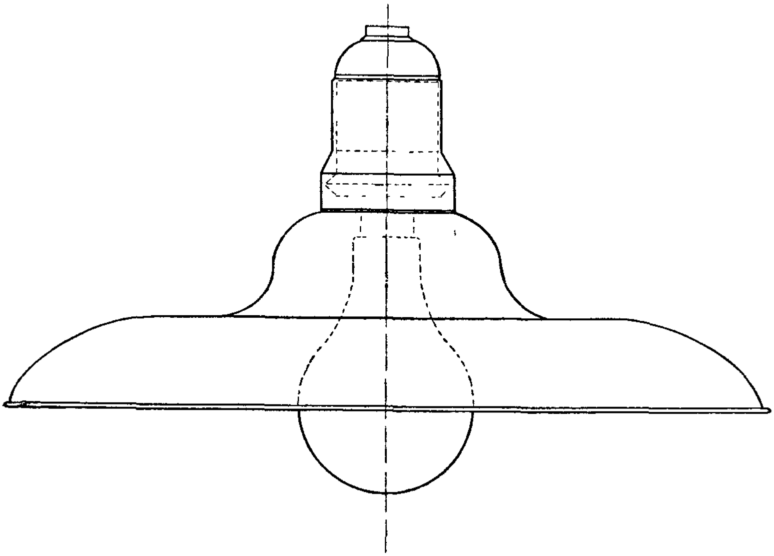


FIG. 6.

Where a very dispersive type of reflector is required and a shallow reflector is used, the eye is protected from the glare of the filament by the use of an opal glass which does not, however, interfere with the wide distribution (Fig. 7).

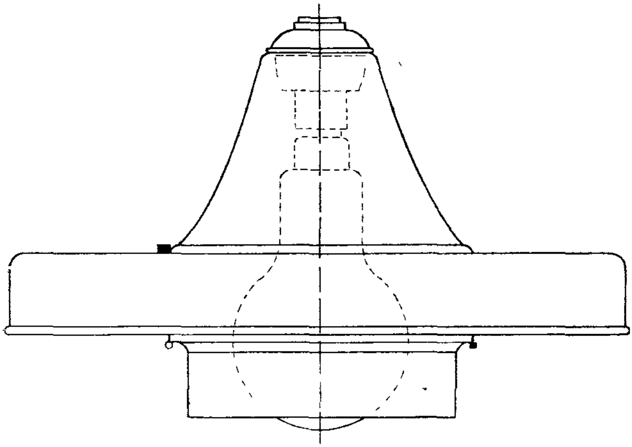


FIG. 7.

The next reflector shown (Fig. 8) is of the concentrating type, and is of smaller diameter than the other types for the same size of lamp. It completely envelopes the light source.

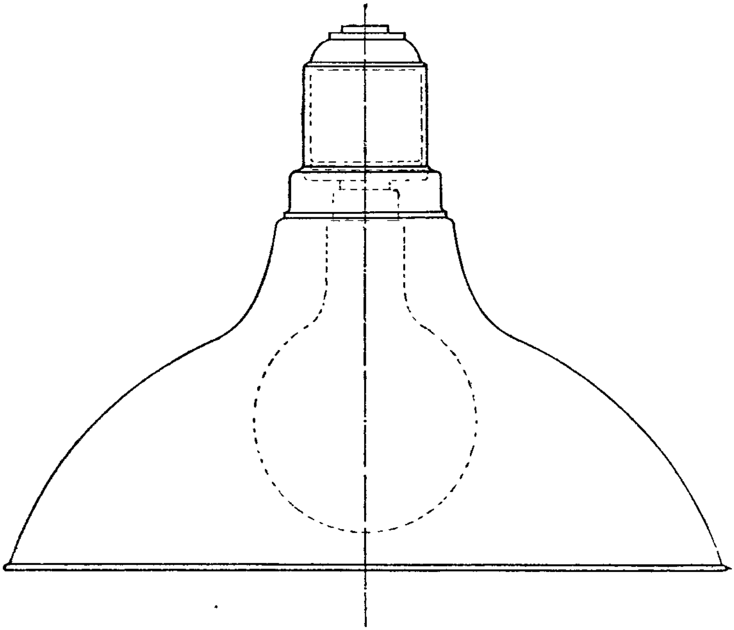


FIG. 8.

The parabolic angle reflector (Fig. 9) is designed for illuminating both horizontal and vertical areas from a side position. It not only illuminates the area in front, but distributes light to each side in such a manner as to build up very effectively the illumination between units. It is useful, therefore, for illuminating such interiors as inside tennis courts.

The elliptical angle reflector (Fig. 10) has its chief use where drop fittings cannot be installed owing to the main floor area being occupied or, for example, to overhead space being occupied by a crane. They can then be fitted on columns or girders.

Fig. 11 shows curves for the type of reflector now used by the Post Office with a 60-watt lamp—(*a*) vacuum, (*b*) gas-filled (tip-frosted)—and two things will immediately be noticed:

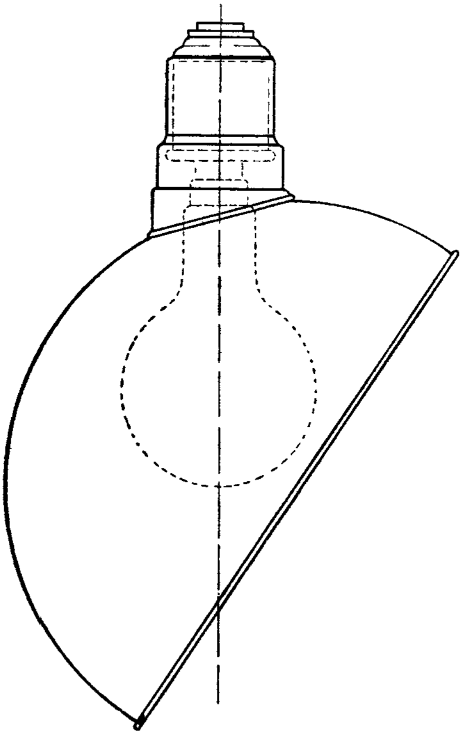


FIG. 9.

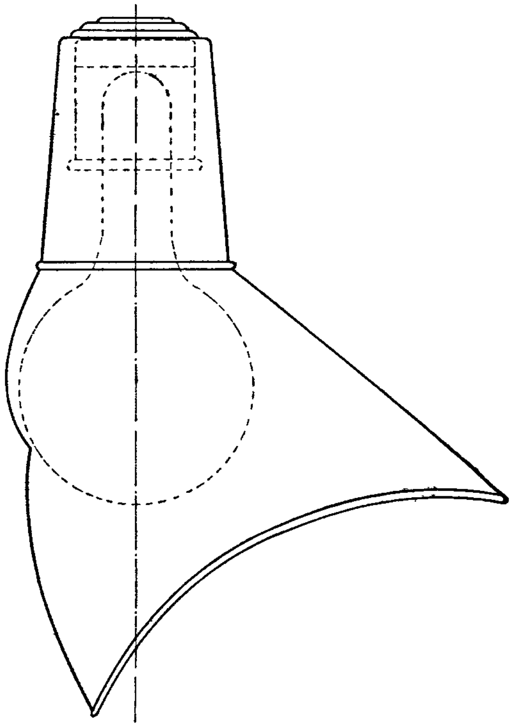


FIG. 10.

(1) That the maximum C.P. of a vacuum lamp is not vertically beneath it as it is with the gas-filled lamp.

(2) That the maximum C.P. of a gas-filled lamp, apart from that in the vertical direction, occurs at a greater angle from the vertical than with the vacuum lamp, *i.e.*, the dispersive effect is greater.

A type of fitting suitable for office interiors, etc., which was very popular some years ago, and is still so to a large extent, is the Holophane reflector. The glass shade is made up of a series of right-angled prisms giving a fluted effect. Now, a ray of light at certain angles incident on the hypoteneuse of a prism suffers what is known as total internal reflection, and it is reflected back towards the source. Thus, by judiciously shaping the contour of the reflector into which these prisms are built, the rays can be re-directed downwards instead of being transmitted through the glass. Some of the rays, of course, reach the prism surfaces at such angles as to permit of their escape by transmission through the reflector which actually, therefore, makes use of both refraction and total internal reflection. The Holophane shade is produced in various shapes to give dispersive, concentrating and intensive effects, as in the case of the vitreous enamel reflector. The concentrating type has a distribution very similar to the Post Office opal shades, and has a somewhat higher efficiency : it is, however, not altogether free from the charge of glare.

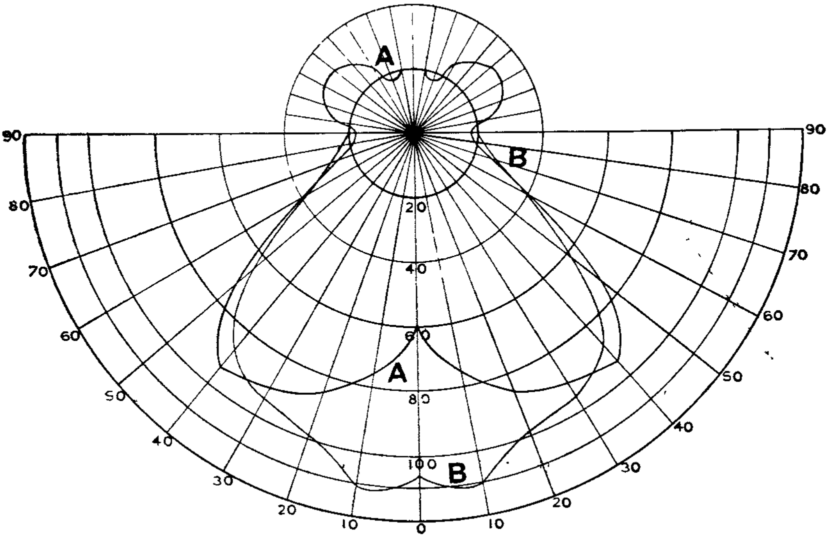


FIG. 11.

2. *Illumination on the horizontal plane.*

It has been shown that the illumination from a source varies inversely as the square of the distance from the source and is in fact equal to $\frac{I \cos \theta}{d^2}$. Now let us take that a step further, and consider the illumination of a point on the working plane, between two of the lamps in a row as in Fig. 12. Consider, first, the illumination at a point X due to lamp A, and let θ be the angle that the line joining point X to the

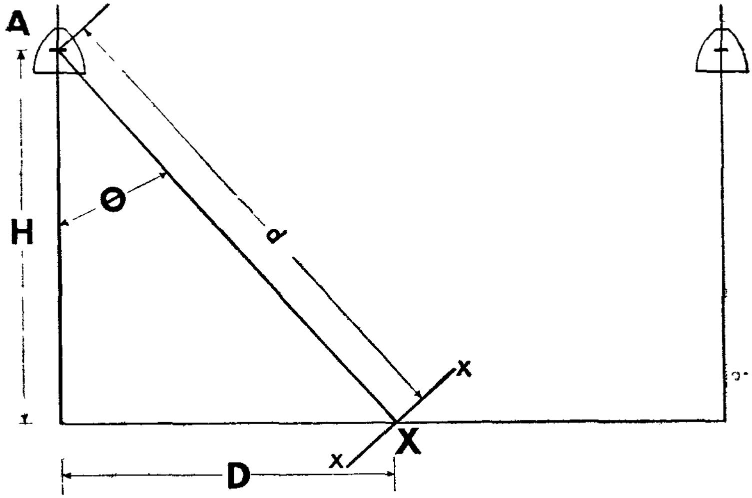


FIG. 12.

centre of the filament makes with the vertical. Then, if the candle-power in the direction AX (found from the polar curve) is I_θ, the illumination at X due to A is $\frac{I_\theta}{d^2}$, that is, the illumination normal to AX. The illumination on the horizontal plane is $\frac{I_\theta \cos\theta}{d^2}$

$$\text{Now } d^2 = H^2 + D^2 \text{ or } \frac{H^2}{\cos^2\theta}$$

$$\therefore \text{ Illumination} = \frac{I_\theta \cos\theta}{H^2 + D^2} \text{ or } \frac{I_\theta \cos^3\theta}{H^2}$$

It can be seen more clearly what this means if a curve showing the relation between Illumination and D is plotted. This has been done in Fig. 13 and curve E_A shows at a glance the illumination on the working plane at any point distance D from the lamp A. Point X, however, is also receiving some light from lamp B, and if its distance is reckoned from

B, it will be seen that its illumination is given by the same expression as above. That is, if a base line is measured off to represent the distance between two lamps, the illumination due to one lamp can be plotted from one end, and that due to the other lamp from the other end, and obviously the

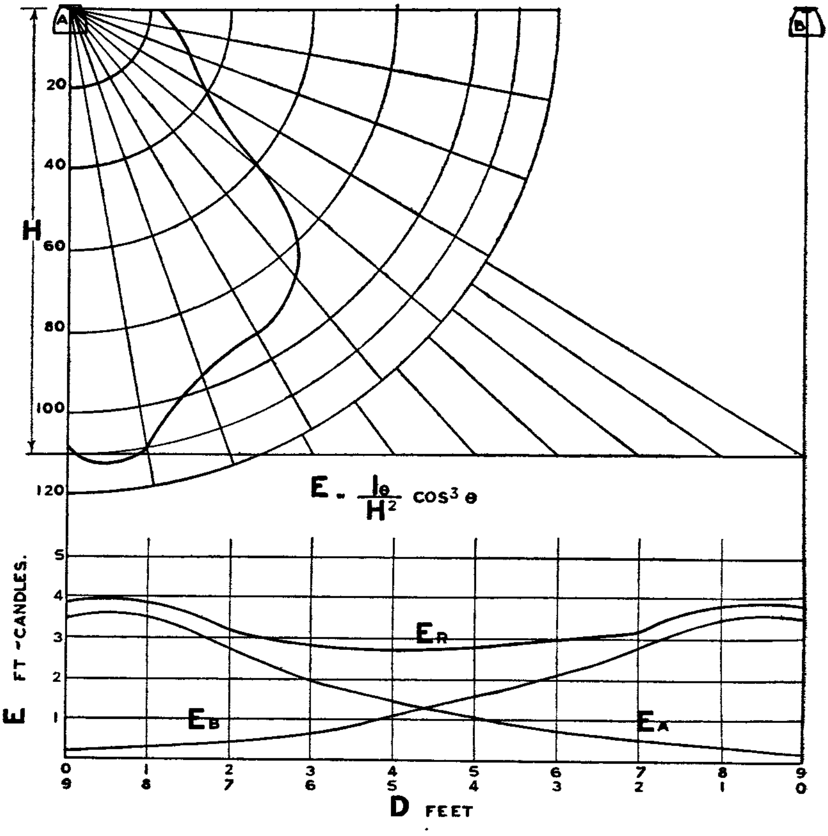


FIG. 13.

resultant illumination at any point due to the two lamps is the sum of the heights of the individual curves at that point. This resultant curve shows, therefore, the illumination of the working plane between two lamps in a row, and it can be seen immediately how far the lamps may be placed apart and still retain uniform illumination. It is useful, therefore, in showing the performance to be expected from any type of fitting.

Having said something of the performance to be expected from direct lighting units, attention may now be turned for a few moments to the question of choice of units. There are no hard and fast rules that can be laid down to govern all cases, and the choice of the type of fitting to be used must, in every case, be governed entirely by the conditions to be met. In an office interior some form of opal or prismatic glass shade will be used, because the effect of dust and dirt will not be so marked as in the case of a workshop or garage where vitreous enamel reflectors would be used. Whether a dispersive biflector or a concentrating type of fitting will be used will again depend on whether the scheme of lighting projected provides for general lighting or individual lighting. It must be assumed, therefore, that this particular choice has been made, and that it has fallen for sound reasons on, say, some particular type of enamelled steel reflector to give general illumination. Three questions then arise—What size of lamp shall be used? How many will be required? How high shall they be fitted? In deciding it must be remembered that the direction of maximum candle-power of a lamp in a given fitting is ascertainable from the polar diagram, and that in order that the resultant illumination from two of them shall be uniform over the area between them, these two directions should meet on the working plane as shown at point O on the diagram (Fig. 14). If they meet above the working plane, the intensity on that plane is not so high as it should be, and if they meet below the working plane, the area between, such as MN, will be dark. Thus, assuming AO and BO to be the directions of maximum intensity, the light centres should be located somewhere along these lines.

If the fittings are moved to a distance Y apart, they should be raised to height H in order to comply with our condition; but the lamp and reflector must also be increased in size to maintain the intensity on the working plane. It follows from this, of course, that where a system of general lighting has been installed, a broken fitting or lamp should not be replaced by one different in size or shape as the direction of maximum intensity is changed, and the uniformity of the illumination is destroyed. Even the difference caused by variation of the height of the light centre in the fitting

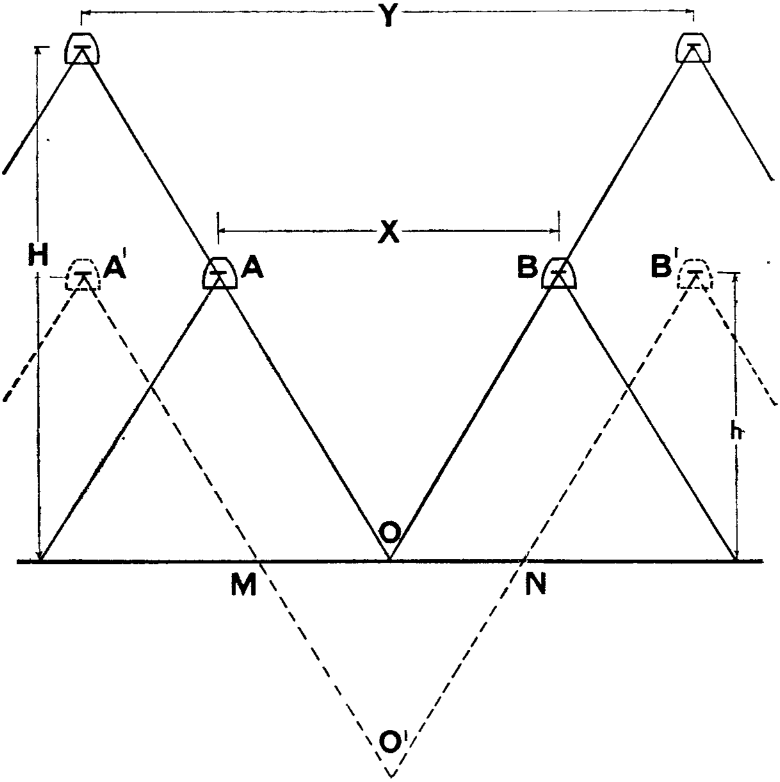


FIG. 14.

can be sufficient to alter materially the distribution of light from the unit and, therefore, its luminous efficiency.

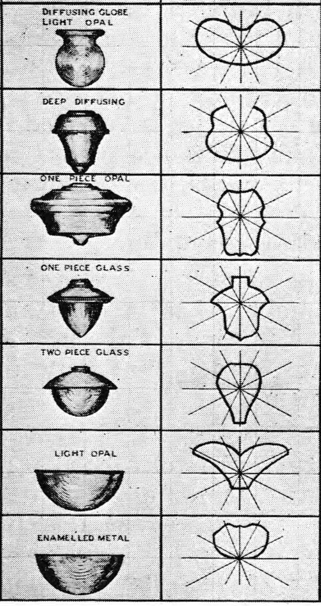
IV.—OTHER FITTINGS—SEMI-INDIRECT AND INDIRECT.

So far only the direct lighting type of fitting has been dealt with; and, before we proceed to illustrate the general method of calculation, it will be as well to say a few words about other important types.

The design of lighting equipment has been so progressive that there is, at the present time, a large variety of fittings on the market. The chief factors which govern the selection of any particular unit are its efficiency, appearance and cost. Efficiency in this case is the suitability of the unit to meet certain requirements: that is, the unit may be efficient for one interior and very inefficient for another. The various types have been divided by two prominent authorities (M.E.I., Sylvester and Ritchie, 1927) into five classes, according to the way in which the units control and diffuse the light. The five classes are:—

1. Enclosing-Diffusing.
2. Enclosing-Directional.
3. Semi-Enclosing.
4. Semi-Indirect.
5. Totally Indirect.

and their characteristics are shown in comparative form in Fig. 15.



ITEM	TYPE	POLAR CURVE	EFFICIENCY BASED ON:— ILLUMN ON VERTICL	ILLUMN ON HORIZL	FAVOURABLE APPEARANCE OF ROOM	DIRECT GLARE	REFLECTOR GLARE	SHADOWS	MAINTENANCE
1A	DIFFUSING GLOBE LIGHT OPAL		B-	B-	A	B-	B	B+	B+
1B	DEEP DIFFUSING		B-	A	A	A	B+	A-	A-
2A	ONE PIECE OPAL		B	B	A	B	B+	A-	A-
2B	ONE PIECE GLASS		B	A	A	B+	B+	A-	A-
3	TWO PIECE GLASS		C+	B-	A	B+	B+	A-	B-
4	LIGHT OPAL		B-	C+	A	B+	B+	A-	C
5	ENAMELLED METAL		C	C	B+	A+	A	A+	C

FIG. 15.

1. *The Enclosing-Diffusing* type of unit is shown at 1A and 1B. With this unit the light is distributed through-

out the interior in all directions and not specially in a downward direction. Such fittings make an interior bright and attractive and provide adequate illumination for high shelves and wall cases in shops.

2. *Enclosing-Directional.* (Nos. 2A and 2B). The light is directed chiefly downwards so that, compared with the enclosing-diffusing units, there is less illumination upon the upper portions of an interior and more upon the floor. Maintenance, with this type of unit, must be close, especially in interiors with a fairly high reflection factor, as otherwise the dust which would settle on the top of the units would absorb a certain proportion of the light.

3. *Semi-Enclosing.* This type of unit is shown as No. 5. It is suitable for fitting in a fairly high room where it can be suspended at some distance from the ceiling. When fitted at a suitable height and spacing distance, the illumination is abundant and well diffused.

4. *Semi-Indirect.* This type of fitting is very suitable for rooms where the upper portions of the walls and ceilings are finished in light colours which have a good reflection factor. A portion of the light is directed downwards through the opal glass or alabaster and the remainder is reflected in an upward direction towards the ceiling, whence part is reflected downwards and part on to the walls, thus ensuring that the light is well diffused. It is a type of fitting much used in Sorting Offices and large offices generally.

5. *Totally Indirect.* This type of unit is designed to meet special requirements; it is suitable where a quiet and subdued atmosphere is necessary. The whole of the light is reflected from the walls and ceilings, and is thus perfectly diffused and soft and free from shadows.

There is another fitting with which we are all familiar as a standard Departmental fitting. It consists of a bowl very similar to that used with the ordinary semi-indirect fitting, known officially as "No. 1," and has an enamel reflector fitted over the top, so that it may be used in locations where no ceiling or a ceiling unsuitable for an open bowl is available, as in rooms with V roofs or with the ceilings cut up by girders. The light is collected and projected downwards by the reflector, *i.e.*, none escapes upward and is lost. Comparing its characteristics with those of the other types, we may say

Efficiency: horizontal	B –
do. vertical	B
Favourable appearance of lighted room	B
Direct glare	B +
Reflected glare	B +
Shadows	A –
Maintenance	B –

V.—GENERAL METHOD OF DESIGN.

1. *Standards of Illumination.*

It is essential that we should first of all establish some form of standard for the amount of illumination required by the eye in daily life. Experience shows that some kinds of work require more light than others, and a rough guide as to the illumination necessary may be obtained from the recorded investigations of physiologists on the variation of acuteness of vision with increasing illumination.

Our ability to see things seems to depend on two distinct factors:—

(i) Perception of form.
(ii) Perception of light and shade.

(i) *Perception of form.* The sharpness of printed letters will depend, of course, on the perfection of the optical system of the observer's eye, and no amount of light will enable a person to see an object clearly if the eye lens cannot be so adjusted as to bring it into focus. An extremely short-sighted person, for example, cannot usually be helped by brightly illuminating the object to be examined. On the other hand, the average person requires, under normal conditions, a certain amount of light to read type clearly and, once this value is obtained, further increase of illumination is of little service.

(ii) *Perception of light and shade.* If an object were of exactly the same colour and brightness as its surroundings, it would be indistinguishable from them. The percentage change in tone which can be detected by the human eye varies according to the individual and the order of illumination. Under favourable conditions a variation of less than 0.5 per cent. is perceptible.

There is in addition to these two factors—the complicated question of perception of colour. In this respect individuals differ greatly. Also, the explanation of the curious changes in colour vision which occur with diminishing illumination is still a matter of controversy among authorities. (See "Modern Illuminating Engineering"—Gaster and Dow). It may be mentioned, however, that, in a fading light, the blue or short wave end of the spectrum appears to persist longer than the red or long wave end; and, in a feeble illumination, the blues and greens still appear luminous, when the reds appear black. In a very weak light, the eye is incapable of perceiving colours.

The curves shown in Fig. 16 depict the results of Laporte and Broca's researches on the relation between illumination and acuteness of vision. Various standard sizes of type were

CURVES SHOWING HOW ACUTENESS OF VISION IN VARIOUS INDIVIDUALS IS AFFECTED BY INCREASED ILLUMINATION.

LAPORTE & BROCA

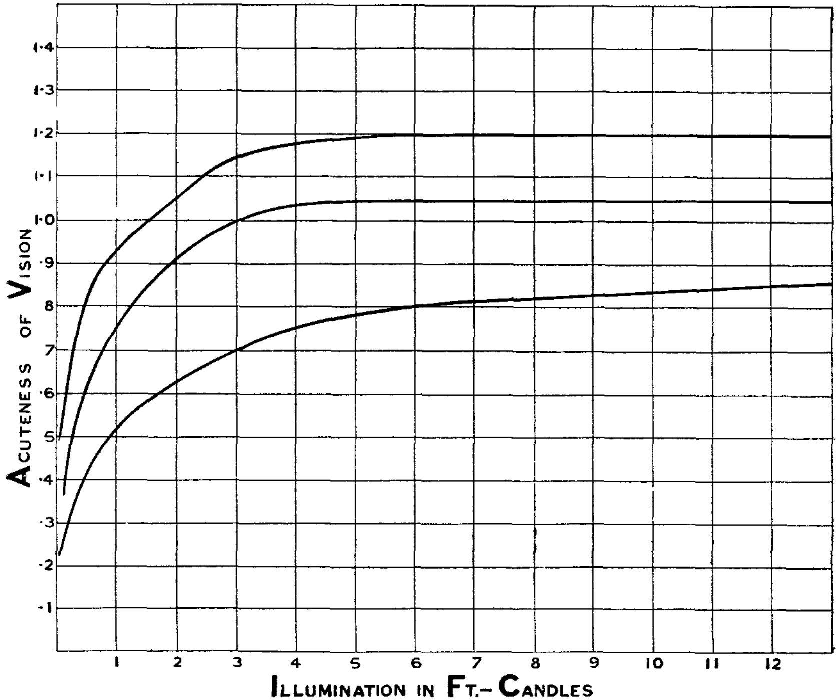


FIG. 16.

illuminated by various illuminants and the type that could just be read at a specified illumination was determined. It will be seen that up to 3-4 foot-candles, the acuteness of vision increases rapidly with illumination, but beyond that figure the increase of acuteness of vision for an increase of illumination is comparatively small.

The influence of the intensity of illumination on the perception of light and shade is illustrated by Fig. 17, which shows the percentage change of brightness detectable by the eye at various intensities, and it is at once evident that the curve is broadly similar to those in Fig. 16.

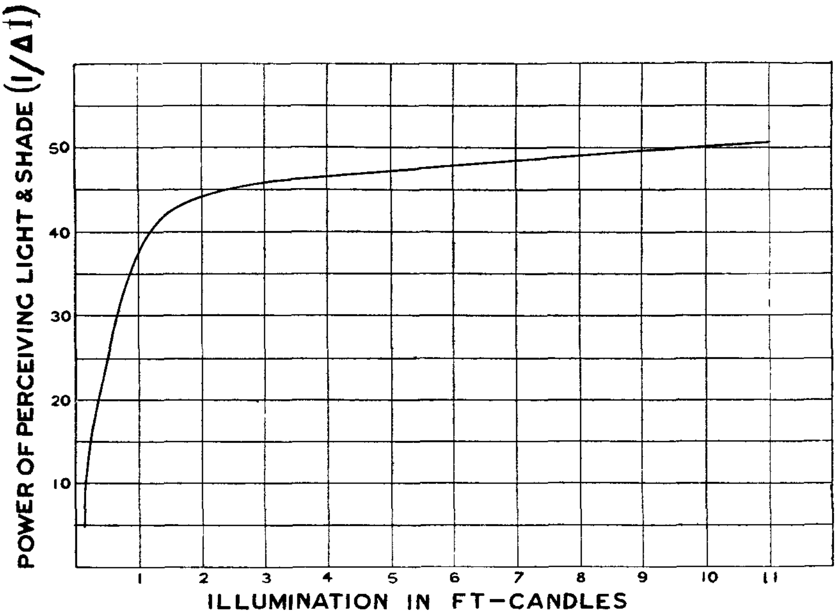


FIG. 17.

From these and many other researches, the conclusion has been drawn and generally accepted that, so far as ordinary vision is concerned, the eye has arrived at a fairly stable condition when illumination of 3 foot-candles has been reached. For close work and complicated workshop operations higher intensities are of course required, and these may be of the order of 5-10 foot-candles. For special commercial purposes, such as shop window lighting and floodlighting, even greater intensities are required (up to 150 foot-candles in some cases). On the other hand, the minimum illumination required to enable people to see their way about in corridors, passages, etc., is of the low order of 0.25 to 0.5 foot-candles.

The Post Office standards are based on the recommendations of the National Physical Laboratory Committee on the Lighting of Public Buildings, and until recently they agreed fairly closely with standards laid down by outside and independent authorities; now there is a tendency in general practice outside the Post Office to use somewhat higher intensities. The figures are probably familiar to many and I will not reproduce them; but I should like to draw attention to certain others of the recommendations of the N.P.L. Committee, namely:—

(1) That, in the absence of special circumstances, the semi-indirect method of lighting, in conjunction with light ceilings and upper parts of walls, be generally recognised as best for ordinary office employment.

(2) That the direct light be screened from the eye.

(3) That the brightness of the visible light-giving surfaces does not exceed three candles per square inch.

(4) That for general office work, an average illumination of 3 foot-candles be provided at the mid-period between successive re-decorations.

(5) That the average illumination should not fall below 2.5 foot-candles.

(6) That the illumination at any point of work should not fall to less than 2 foot-candles.

(7) That for corridors and staircases, a minimum illumination of 0.25 foot-candles at floor level should be provided.

The clauses to which I wish to draw particular attention at the moment are (2) and (3). They are a direct effort to avoid the extremely harmful effects of "glare," which may best be defined, perhaps, as "conditions of excessive brilliancy that are trying to the eye." The eye is marvellously adapted to accommodate itself to changes of brightness, but such transitions must be gradual and not abrupt. If the changes are too rapid, the nerves controlling the pupil aperture are constantly endeavouring to respond to the changing conditions; but they fail to do so and extreme discomfort to the eye results. Everyone is aware that it is injudicious to give more than a glance at the sun; yet, in lighting rooms artificially, people frequently place unscreened brilliant sources of light in such positions that it is difficult for the eye to escape them. In this connection, it will be of interest to note the brilliancy of the various sources in common use. ("Modern Illuminating Engineering," Gaster and Dow). (Fig. 18).

INTRINSIC BRILLIANCY OF VARIOUS ILLUMINANTS

SOURCE	CANDLES	SUPER-FICIAL AREA	INTRINSIC BRILLIAN-CY
		SQUARE INCHES	CANDLES SQ.INS.
CANDLE	1·0	0·4	2·5
ACETYLENE	25·0	1-2	10-25
GAS FLAT FLAME	5·25	2-5	2-5
INCANDESCENT			
LOW PRESSURE	10-80	1-3	10-30
HIGH ..	100-1500	2-5	50-300
ELECTRIC INCANDESCENT.			
CARBON FILAMENT	16	0·04	400
METAL .. VAC.	32	0·04	800
.. .. G.F.	350	0·07	5000
POINTOLITE	100	0·008	13000
ELECTRIC ARC	-	-	100000 APPROX
HOLOPHANE GLOBE ROUND VACUUM LAMP.	-	-	0·5 – 1·0
DENSE OPAL ROUND VACUUM LAMP.	-	-	0·01 – 0·05
AV: BRIGHTNESS OF SKY	-	-	2·5

FIG. 18.

It will be seen at once, how vastly the intrinsic brilliancy of modern illuminants exceeds that of older sources, such as the candle and flat-flame gas-burner. It is agreed by many authorities that the candle has about the highest brilliancy that can comfortably be observed at close quarters, and this degree of brilliancy, *i.e.*, 2.5-3.0 candles/sq. in., is frequently set as a limit. It is curious in this connection to note that the average brilliance of the sky is of the same order and this has been adduced as a further argument that the figure mentioned represents a natural limit.

2. *Calculations.*

In designing an installation, there are certain factors to be taken into consideration; and these are:—

(i) The intensity of illumination to be provided = E;
(ii) The dimensions of the room to be lighted;
(iii) The reflection factors of the walls and ceiling;
(iv) The type of fitting to be used and its efficiency;
(v) The size of lamp to be used: total lumens = L.

Now, an illumination of E foot-candles on the working plane is equivalent to E lumens per sq. foot on that surface.

Hence if A = total area of floor

Total effective lumens to be provided = A × E

Allowing a depreciation factor F for the lamp, this becomes F × A × E and, if conditions (ii) (iii) and (iv) are combined to give a co-efficient of utilisation C for that fitting in that room, total lumens to be provided $= \frac{F \times A \times E}{C}$

If then L = lumen output of lamp to be used

and N = number of lamps to be used

$$N.L. = \frac{F \times A \times E}{C}$$

and N being fixed

$$L = \frac{F \times A \times E}{C \times N}$$

The lamp necessary to give this lumen output may then be determined from the table in Appendix II.

3. *The Coefficient of Utilisation.*

The coefficient of utilisation depends on

(*i*) *the ratio of the* $\frac{\textit{room width}}{\textit{ceiling height}}$

It increases as this ratio increases, but not proportionately: also, for a given value of the ratio, the coefficient increases with the length of the room, because a smaller percentage of the total quantity of light is reflected from the walls and consequently less is lost by absorbtion;

(*ii*) *the reflection factor of the walls and ceiling*

this is obvious since, if a wall has a reflection factor of only 30%, it means that 70% of the total light incident on the wall is absorbed and ineffective for lighting. Usual values for the reflection factor are:—

	Very light.	*Fairly light.*	*Fairly dark.*
Ceiling ...	70%	50%	30%
	Fairly light.	*Fairly dark.*	*Very dark.*
Walls ...	50%	30%	10%

(*iii*) *the type of fitting*

Fig. 19 shows curves of coefficients of utilisation for one or two types of fitting and how they vary with the ratio, $\frac{\text{room width}}{\text{mounting height}}$. These are typical values that would obtain, say, near the re-decoration date in Post Office practice, and are taken from a recent work.* It will be noted that the coefficient increases fairly rapidly until the ratio $\frac{\text{room width}}{\text{mounting height}}$ reaches about 4.5 and then the increase is very gradual. Thus, in a wide room the fittings are utilised to much better advantage than in a narrow high room. Actually, as mentioned before, the length of the room affects the coefficient of utilisation somewhat and the curves in Fig. 19 have been plotted for a room with a length about twice the width.

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* "Mod. Elec. Illn.," by Sylvester and Ritchie.

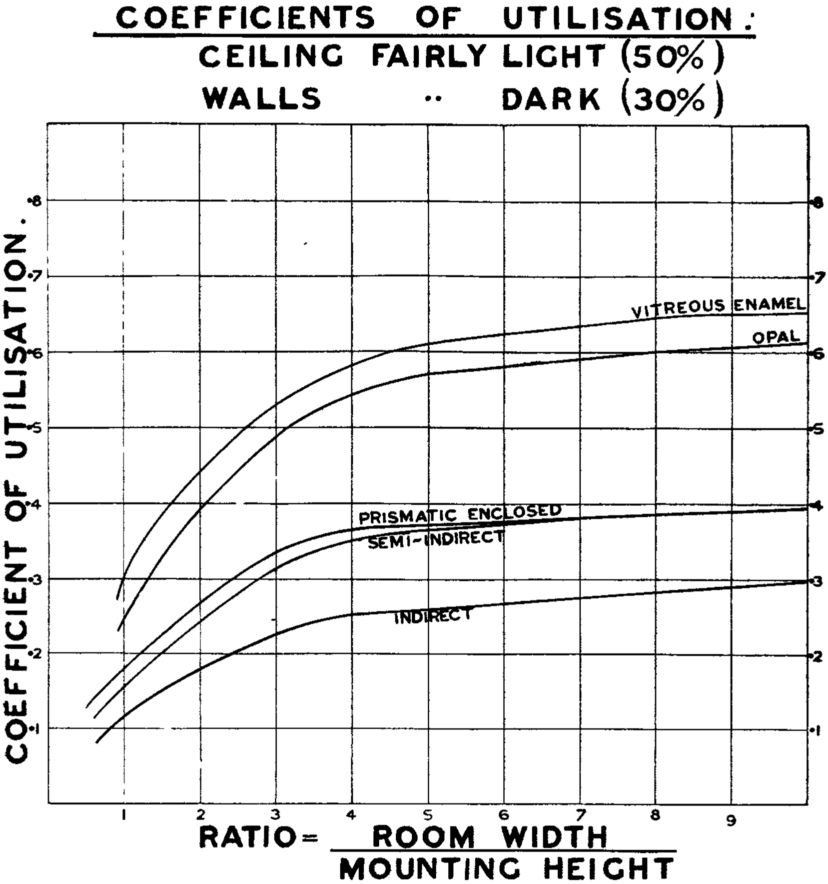


FIG. 19.

It is interesting to consider where the filament should be in relation to the reflecting portion of a semi-indirect or enclosed fitting, in order that the best results should be obtained. Some experiments have been carried out recently by the Department of Scientific and Industrial Research and published in Illumination Research Report No. 4 and briefly the method adopted and results obtained are as follows:—

When a lamp is surrounded by a diffusing glass bowl, the bowl becomes the effective source of light. If, therefore, the surface brightness of a bowl be measured, some idea will be obtained of the comparative value of that fitting as a source. This is what was done* and, when analysed, the results indicated that, for ordinary hemispherical bowls, the lamp filament should be on a level with the horizontal diameter of the bowl and, for the enclosing units, on a level, approximately, with its maximum diameter.

The writer has sought to convey some idea of the general methods adopted in the design of modern electric lighting installations rather than to delve too deeply into variations of detail encountered in the design of any particular class of work. The field is too wide to be covered in any but an extremely broad manner in a paper of this length. Many sources have been tapped for the diagrams, tables and extracts contained in the paper; and the writer wishes to acknowledge his indebtedness, apart from the footnote references, to the General Electric Co., Ltd., and in particular to Mr. T. E. Ritchie, Illuminating Engineer to the Company, through whose interest and courtesy the presentation of the paper has been rendered possible.

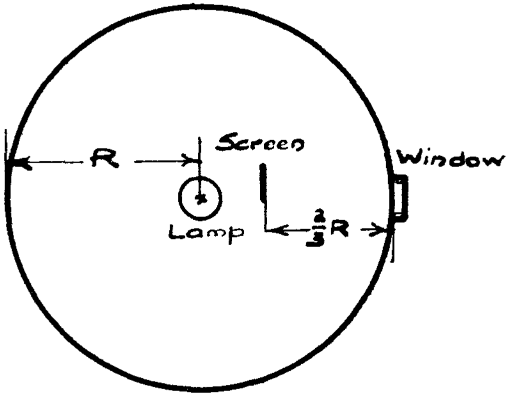
* See Ill. Research Report No. 4 (1926).

APPENDIX I.

Note on the Measurement of Mean Spherical Candle-Power.

The most obvious method of determination involves the making of a large number of measurements in all directions in space to obtain the necessary approximation to the true average value. It is possible, however, by the use of certain apparatus to determine this quantity from the result of a single measurement.

The simplest form of such apparatus consists of a hollow sphere, the internal surface of which is coated with powdered magnesia or sand-blasted white celluloid, so as to be as nearly perfectly diffusing as possible. Assuming the surface to be perfectly diffusing, it can readily be shown that the luminous flux received by any given area from any other given area is independent of the position of the areas. Thus, the illumination of the spherical surface due to reflected light is everywhere the same: it is only the direct light that is unevenly distributed.



A small translucent window is made, therefore, at one part of the sphere and screened from the direct rays of the source. The brightness of this window is measured by a photometer head in the usual way and, being dependent on a certain portion—the reflected portion—of the total flux, is a measure of the M.S.C.P. of the source. The measurement consists, therefore, in a comparison of the brightness of the window with the lamp under test as source and with a standard lamp as source.

Then $$\frac{I_t}{B_t} = \frac{I_s}{B_s}$$

where I denotes M.S.C.P. & B brightness, the sub-scripts *t* & *s* denoting the lamp under test and the standard lamp respectively.

The foregoing description is merely an outline of the theory and it will be seen that departures from the ideal conditions are inevitable owing to three considerations:

(i) the lack of a perfectly diffusing surface;

(ii) the necessity for a support and a supply for the light source and the fact that even the source itself must to a certain extent interfere with the distribution of the reflected flux;

(iii) the necessity for an aperture in the wall of the sphere for the purpose of making photometic measurements.

A full discussion of the effect of these and other considerations on the method of measurement is contained in Illumination Research Paper No. 5, Department of Scientific and Industrial Research and British Standard Specification No. 354, but it may be mentioned that the area of the sphere shoul l be about 100 times the area of the bulb; that is, a sphere about 1 metre in diameter may be used for lamps up to 200 watts.

APPENDIX 2.

Lumen Output of Metal Filament Lamps.
(B.S.S. 161/1928).

VACUUM LAMPS.

Voltage.	Wattage.	Rated Lumen Output.	M.S.C.P.
100 to 130	20	174	14
	30	273	22
	40	372	29
	60	570	45
200 to 250	20	152	12
	30	246	20
	40	348	28
	60	546	44

GAS FILLED LAMPS.

Voltage.	Wattage.	Rated Lumen Output.	M.S.C.P.
100-110	60	720	57
115-130	60	702	57
110 to 130	75	938	75
	100	1300	103
	150	2070	165
	200	2880	229
	300	4650	370
	500	8450	672
	1000	18700	1490
	1500	29400	2340
200-220	60	594	45
230	60	570	45
240-250	60	558	45
200-220	75	803	62
230	75	780	62
240-250	75	758	62
200-220	100	1160	90
230	100	1130	90
240-250	100	1110	90
200 to 250	150	1875	149
	200	2600	207
	300	4140	329
	500	7500	597
	1000	16900	1345
	1500	27000	2150

APPENDIX 3.

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