ELEMENTARY PRINCIPLES OF LIGHTING AND PHOTOMETRY

JOHN W. T. WALSH

METHUEN

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BY

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TO

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O.B.E., M.I.E.E., M.I.C.E., F.INST.P.,
DIRECTOR OF THE RESEARCH LABORATORIES
OF THE GENERAL ELECTRIC COMPANY

THIS BOOK IS DEDICATED
AS A MARK OF ADMIRATION FOR SERVICES
RENDERED TO THE SCIENCE
OF ILLUMINATION, AND OF GRATEFUL APPRECIATION
FOR AN INVALUABLE TRAINING
IN THE STUDY AND PRACTICE OF PHOTOMETRY

PREFACE

THE rapidly growing importance of the study and practice of illumination is too self-evident to need much demonstration. The formation of technical societies dealing with this subject alone in the United States of America, Great Britain, Germany, and Japan, as well as the existence of National Committees on Illumination in these and many other countries, is sufficient proof of the importance with which the subject is regarded by the scientific and technical interests of the most progressive nations. The first meeting since the war of the International Commission on Illumination, which took place in Paris this year, has also served to give a further impetus to the study of illumination problems, and by the efforts of this body international agreement has been arrived at concerning the fundamental basis of photometric measurements, viz. the international unit of candle-power.

Although in many cases illumination problems should be dealt with only by a specialist qualified by long experience to advise on lighting matters, in some form or other they come up for consideration by many whose principal concern is in quite another direction. Thus the electrical or gas engineer, the factory manager and, of course, the architect—to mention but a few—are all brought into intimate contact with lighting problems, while the ordinary householder is frequently far from immune from troubles arising solely from a lack of knowledge of illumination engineering principles.

It is the aim of this book to provide a brief and simple guide to the solution of the problems most commonly met with in lighting engineering, and to give both an explanation of the faults which past experience has shown it necessary to avoid, and of the means available for the attainment of a satisfactory result in any given case.

In order to provide a logical basis for the chapters dealing specifically with illumination matters, it has been thought necessary to devote the first part of the book to a very brief outline of the physiological phenomena underlying the process of vision, a short description of the principal illuminants in use at the present time, and a rather more detailed account of the means most commonly employed for the quantitative estimation of the candle-power of light sources and of the degree of illumination at any given position.

A knowledge of elementary science and engineering has been assumed, and no attempt has been made to avoid the use of elementary mathematics in the few places where it was needed, but I hope that even the most non-technical reader will nevertheless find the book quite easy reading, and I can only trust that the interest in the subject will serve to compensate for the many deficiencies in its treatment of which I am only too conscious.

I shall be most grateful for information concerning errors which may have crept in unawares, or for corrections to figures which may in some cases be not in accordance with the practice of to-day, although every effort has been made to bring the book up to date in all particulars until the very month of going to press.

In conclusion I wish to thank Sir Joseph Petavel, the Director of the National Physical Laboratory, for his kind interest in the work, and my colleagues in the Photometry Division for their advice and help always readily and ungrudgingly given. To Mr. Lewis my grateful thanks are also due for the very great trouble he has taken over the preparation of the diagrams, an all-important part of any book dealing with illumination.

JOHN W. T. WALSH

TEDDINGTON
March, 1922

FOREWORD

THERE can be no doubt as to the importance of the subject of illumination in connection with National Economics and Research. At the present time National Expenditure on artificial illumination runs into hundreds of millions per annum, and under present industrial and social conditions the well-being of every individual is, to some extent, dependent on adequate and efficient illumination. The fact that the advantages of improved methods are not immediately obvious, may partly account for the lack of interest, and consequent tardy development.

The corporate body to distribute electricity, gas or oil, trades, not in illumination, but in the means of producing it; and higher efficiency in the methods of lighting may imply in the first instance a reduction in the sale of their products. The user is content to neglect minor items on his yearly budget, and the adaptability of the eye to inadequate or excessive illumination masks the ultimately deleterious effect on eyesight and health.

In time, the methods now adopted by the skilled illuminating engineer will justly be regarded as matters of mere common sense, for common sense is the synthesis of the deduction drawn by the average man from the information available to the average man. The standard of sense which was common in the Middle Ages led to standards of living, cleanliness, and sanitation which made a woman old at thirty, and limited the life of the average population to two-thirds of our present expectation. Nature provides to some extent against such mistakes: it protects the individual from serious results by giving him organs widely adaptable; it protects the race by replacing rapidly individuals whose faculties have deteriorated. The race renews its youth and alters its characteristics: its numerical strength adjusts itself automatically to the limits fixed by natural resources and intelligence. This process of adjustment may, at the present time, be studied in operation in Russia.

The future of civilized nations depends on the adaptation of the progress of science to the requirements of daily life, and it is essential that as knowledge increases, science and common sense should advance hand-in-hand. The present book will, I hope, within its scope, contribute in some small measure to the attainment of this ideal.

J. E. PETAVEL

September 11, 1922

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THE ELEMENTARY PRINCIPLES OF LIGHTING AND PHOTOMETRY

CHAPTER I

LIGHT, VISION, AND THE EYE

ALTHOUGH lighting, either by natural or by artificial means, has necessarily received attention from the earliest ages, it is only comparatively recently that the means of artificial lighting at man's disposal have been of sufficient power and variety to exalt the practice of illumination to its present level as a branch of applied science, receiving at least equal attention with heating and ventilation from the architect or building engineer, and finding constantly more numerous applications as its æsthetic and industrial importance is more fully realized.

It seems the most obvious of truisms that the final judge of any scheme of illumination must be the human eye, and yet it is not at all infrequent to find a lighting system planned in complete disregard of the effect which it will have on the eyes of those who will live or work under its influence. Thus the first essential for the lighting engineer is an intelligent appreciation of the mechanism by which objects are perceived, and of the behaviour of the eye under different lighting conditions.

This introductory chapter will, therefore, deal with the method by which we see the objects which surround us, and will attempt to give a brief description of the different effects produced on the eye by various lighting conditions, particularly as regards intensity, colour, and distribution in the field of view.

The Characteristics of Light.—Light is generally regarded as a wave-motion in the ether. Like other wave-motions it has two principal characteristics, viz. intensity, and wave-length (or frequency). Although ether waves are known over an extremely wide range of wave-length, from the hundreds of metres used in wireless telegraphy, to the hundred-thousandth part of a millimetre used in X-rays, the eye can only appreciate as light a very small region, less than an octave, of these rays, viz. those lying between wave-lengths of about 750 and 400 millionths of a millimetre ($\mu\mu$). It is the wave-length of light which governs its hue or colour. Thus light of wave-length 700 $\mu\mu$ is deep red, while 450 $\mu\mu$ is the wave-length of violet-coloured light.

Most of the light of which we have experience is composite in character and is, in reality, a mixture of lights of every colour in the spectrum. The various colours are combined in very different proportions in the light emitted by different artificial light-sources, and all these, again, differ very markedly from the light given by the sun. Even daylight is not constant in its colour composition, the light from a blue north sky containing a considerably larger proportion of blue rays than that received from the sun direct, or from a white cloud. Nearly all the commonly used artificial illuminants are considerably poorer than daylight in the blue and violet rays, while a few are selective, i.e. they emit light of certain colours only, the rays corresponding to all other hues being entirely absent.

The Visibility of Objects.—The objects which we see are visible by reason of the light which they send to our eyes. In the case of a self-luminous body, such as a candle flame, or an electric lamp filament, this light is generated by the body itself. In the case of all other bodies, a portion of the light received by them from some self-luminous body is reflected by their surfaces to the eye of the observer, so that they appear to the latter to possess a certain degree of brightness and a certain colour.

The aim of any system of illumination is to provide the objects in a room, factory, etc., with sufficient light of a suitable colour and suitably distributed, so that they may be seen with the necessary degree of distinctness, truth of tint, and fineness of detail.

The brightness of a non-luminous body depends on the amount of light it receives per unit area (i.e. its illumination), and on the proportion of this light which it is capable of returning by reflection from its surface (i.e. its reflection ratio). The distinction between the illumination of a body, or the amount of light it receives per unit area, and its brightness, or the amount of light it emits, either by reason of its self-luminosity or by reflection, has to be carefully borne in mind when either of these terms is being used. For the amount of light received by a body does not in any way depend upon the nature of its surface. A sheet of white paper and a piece of black velvet lying side by side on a table may well be equally illuminated, i.e. they may receive the same amount of light per unit area, but their brightnesses will be very different, owing to the fact that the paper is capable of reflecting the light it receives to a much greater extent than is the velvet. The colour of the light, too, may be profoundly altered by the process of reflection. The light falling on the different parts of a Turkey carpet, for example, is of the same colour everywhere, but the form of the pattern seen is due to the fact that each part selects a certain component of the incident light, and reflects this to the eye, the remaining components being absorbed in the substance of the carpet.

It is clear that a substance can only reflect light of those colours which are present in the light it receives, and this explains why objects often appear different in colour when seen under different lighting conditions, notably by daylight and by ordinary artificial light. The latter being deficient in the blue and violet parts of the spectrum and correspondingly stronger in red and yellow rays, purples always appear much redder under artificial illumination than in daylight, while a dark blue is extremely hard to distinguish from a black when viewed by any of the yellower kinds of artificial light. When, therefore, it is necessary to distinguish between objects of slightly varying tints, as in matching coloured fabrics, it is essential that if artificial light be used this shall approach as closely as possible to daylight in its colour composition. Special means of attaining this result for such purposes will be described in Chapter X, under the heading of Artificial Daylight.

The colour of a light, then, is of the first importance where the colour values of objects are in question. For ordinary purposes, however, the intensity of the light is of more importance than its colour, provided the latter do not depart too much from that to which the eye is accustomed. The intensity of illumination required in many different types of problems met with by the lighting engineer will be dealt with in the chapters devoted to the discussion of those particular problems. Here, the general effect of change of illumination on visual acuity will alone be dealt with.

Intensity of Illumination and Visual Acuity.—It is a matter of common experience that insufficient illumination renders reading, or any other kind of work, far more difficult and more trying to the eyes than it would be under satisfactory lighting conditions. For any particular process there is some minimum illumination at which prolonged work is possible without serious discomfort, but a rather higher illumination is generally found to result in easier, more rapid, or more certain work. This effect may be illustrated by the easily reproducible case of reading black type of a given size printed on white paper. Experiments have been made on the effect of various illuminations on the ease of reading various sizes of type, and it has been found that when the illumination falls below a certain value (one foot-candle for ordinary sizes of type) the acuteness of vision falls very rapidly indeed, but that for illuminations of from 3 to 12 times this value, the acuteness of vision is practically unchanged. At the higher values of illumination, however, prolonged work soon produces fatigue and ultimately a diminution in the acuteness of vision.

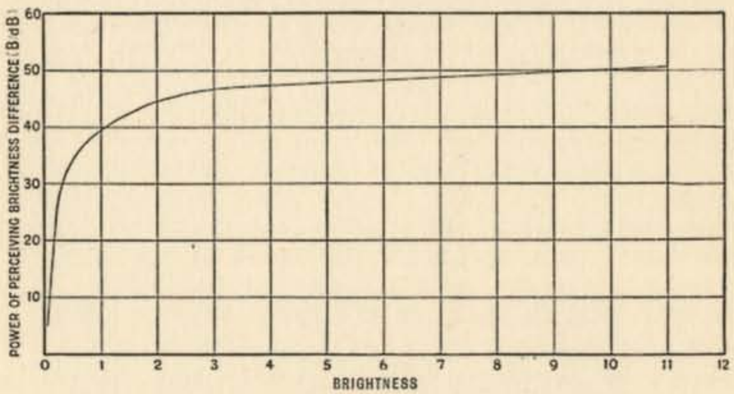


FIG. 1. Relation between Visual Acuity and Brightness
(Unit: the brightness of a white surface at 1 foot-candle illumination)

The same general result is found to hold for all kinds of work demanding visual activity, although, of course, the particular value of illumination below which a diminution in ease of working takes place will vary according to the particular kind of work under consideration. A great deal of work depends on the ability to distinguish readily between small differences of brightness (e.g. picking out the individual threads of a woven material). A curve connecting the average brightness of a surface with the percentage difference of brightness in its parts which the eye is capable of perceiving, is shown in Fig. 1. Under the most favourable conditions, the eye can just appreciate a difference of less than 1 in 50. Here again it will be seen that above a certain value of brightness very little increase in the power of perceiving detail results from further increase in the average brightness of the surface.

It will be noticed that the real criterion is not the *illumination*

of the object, but its *brightness*. Thus similar work on materials with different reflecting powers will require different illuminations. In fact actual experiment has shown that in order to distinguish the individual threads in a dark self-coloured material which reflects only 6 per cent. of the light it receives, seven times as high an illumination is required for equal visual acuity as in the case of a light material which reflects 40 per cent. of the incident light.

The Human Eye.—The structure and mode of action of the eye may be best explained by reference to Fig. 2. The eye may be compared, in some respects, with the photographic camera, although it differs from this instrument in many important particulars. The optical system of the eye consists of a lens L formed of a transparent horny mateiial, liquid or gelatinous

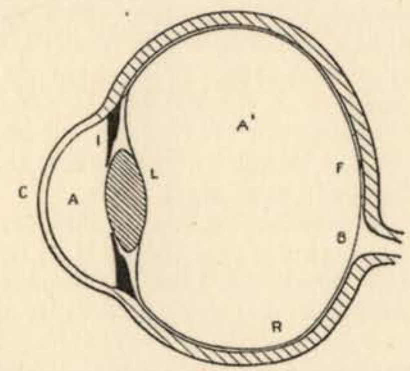


FIG. 2. Structure of the Eye

refractive media A and A′, and a sensitive surface R termed the retina. The whole is covered with a horny skin, transparent at the part C where the light enters, and in front of the lens there is a diaphragm I called the iris, which is subject to change of aperture by involuntary muscular action. One important difference between the camera and the eye is that, while in the former instrument objects at different distances are focussed by altering the distance of the negative from the lens, in the eye this result is attained by a muscular action which produces a change in the curvatures of the lens L. This action is termed " accommodation," and when the power of causing this change is lacking, or severely restricted in extent, the use of spectacles is necessary.

Another important difference between the eye and the camera is that, while the photographic plate is of approximately equal sensitivity all over its surface, the sensitivity of the retina has a marked maximum at a point called the fovea F which is in the centre of the yellow spot. Thus when an object is definitely "looked at," its image is brought upon this foveal region and consequently the images of all neighbouring objects fall upon the surrounding part of the retina, and are therefore seen comparatively indistinctly. There is one region on the retina, termed the blind spot B, which is quite insensitive to light.

The Power of Adaptation of the Eye.—After this brief outline of the structure of the eye, some of the chief phenomena of vision may be described. Perhaps the most important property of the eye is its extraordinary power of nearly unconscious adaptation to gradual variations of intensity in illumination. An important factor in this action is the iris diaphragm, but this is most useful in preventing damage from *sudden* exposure to increased illumination. This may be readily noticed if the eye be raised suddenly from the page of a book to look directly at the flame or filament of a lamp. An immediate contraction of the iris will be seen to take place and this helps to protect the eye by reducing, as far as possible, the brightness of the image on the retina, until adaptation proper has had time to take place there.

It is a matter of common experience that the eye which has become used to a high illumination such as that of sunlight, on being suddenly brought into a darkened room is unable for some few minutes to perceive anything at all. Gradually, however, adaptation to the new conditions takes place, and more and more detail becomes visible. Similarly on going from a comparatively dark room into sunshine, the eye is temporarily dazzled and unable to see clearly, until light adaptation has had time to take place.

This phenomenon of adaptation is one which has to receive careful consideration by the lighting engineer in many of the problems with which he has to deal. For example, it is not always realized that the illumination in the middle of an ordinary living room seldom exceeds 1 or 2 per cent. of that outside the building; for the eye of anyone inside is adapted to its surroundings and vision is perfectly comfortable, provided a necessary minimum of illumination be exceeded. Similarly, to a person in the open, the eye adapted to the much brighter prevailing illumination is perfectly at ease so long as a certain maximum be not exceeded. There are, of course, limits at both ends of the scale to this extensive region of comfortable illumination. As has already been mentioned, there is a lower limit of comfortable illumination for any given purpose. Similarly, when the upper limit is exceeded, as in

the case of a very bright sky or white objects seen in bright sunlight, or when the filament of an electric lamp is looked at directly, a sensation of discomfort is experienced, depending partly on the actual brightness of the object viewed and partly on that of the surrounding objects. This sensation is often termed "glare" or "dazzle," and will be dealt with in a later part of this chapter.

The Theory of Vision and Colour Perception.—The mechanism by which an image formed on the retina is conveyed as an actual sense impression to the brain has not yet been satisfactorily explained, but this does not really enter into the

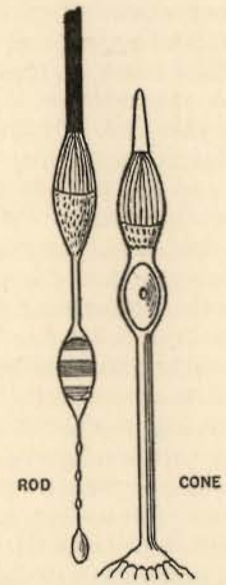


FIG. 2A. Retinal Elements

realm of lighting engineering. There have been several theories of vision which account more or less completely for the observed phenomena, and of these the one put forward by Dr. Edridge-Green will be briefly described here, mainly for the purpose of serving as a basis on which the peculiarities observed in the behaviour of the eye under various conditions of illumination may be correlated and remembered.

The surface of the retina has a peculiar dual construction, being composed of innumerable minute elements of two kinds, named respectively the "rods" and the "cones." The difference between these elements is shown diagrammatically in Fig. 2a. Surrounding these elements, more especially the rods which preponderate everywhere but at the yellow spot, is a fluid substance known as the visual purple, which on exposure to light undergoes a chemical change. The Edridge-Green theory of vision supposes that the function of the rods is to form the visual purple and to diffuse it over the whole of the retinal surface. When light falls upon this substance, the photo-chemical action which takes place so affects the cones that the sensation of vision is produced. Thus the *cones* are the sole percipient organs, but they have to be stimulated by some photo-chemical process in the visual purple which is formed by the *rods*. Hence it follows that for any part of the retina to be sensitive to light there must be both cones and visual purple present.

Now there are practically no rods at the fovea and hence no visual purple is formed there, so that vision at that place depends on the diffusion of visual purple from the surrounding regions where rods are plentiful. There is one further point to be remembered. Since the visual purple undergoes a chemical change when exposed to light, it becomes exhausted at a rate depending on the intensity of the illumination. When the illumination ceases, the visual purple is gradually restored.

It will now be seen how the theory accounts for the dazzling effect produced by looking fixedly at a very bright object. All the visual purple at the fovea has been exhausted, and until sufficient time has elapsed for more visual purple to diffuse in to the fovea from the other parts of the retina, temporary blindness exists at the fovea, and there results that familiar phenomenon of a dark image of the object previously looked at, when the eyes are turned quickly away from the object and towards some dull surface such as the ceiling or walls of a room. The effect of exhaustion of the visual purple is known as "fatigue" and its seriousness depends, of course, on the brightness of the object viewed, and the length of time during which it was looked at. Persistent fatigue always results in a decrease of visual efficiency, and frequently in headache. In extreme cases (as in direct unscreened vision of the sun's disc) it may cause a permanent defect in the vision (eclipse blindness).

The Edridge-Green theory of vision further supposes that the production of visual purple by the rods is stimulated by the action of light. This agrees with the fact that the ability of the eye to distinguish the form of a faintly illuminated object which is being looked at intently, is greatly assisted if the surroundings are of a lower, but still perceptible, degree of brightness. The general surface of the retina is then illuminated sufficiently to encourage the formation of visual purple, and this, by diffusion into the foveal region, assists direct vision.

Colour Vision: Purkinje Effect.—The theory of colour vision, i.e. the mechanism by which the eye distinguishes the hue of the light it receives at any part of the retinal image, is an extremely complicated subject which cannot be even touched upon here, except to say that, on the Edridge-Green theory, the *nature* of the stimulus communicated to the cones by the decomposition of the visual purple is in some way dependent on the wave-length of the light which causes that decomposition. All that can be done here is to mention some of the peculiarities of the eye as regards its power of colour perception and discrimination.

One such peculiarity is the behaviour of the eye towards light of different colours at low illuminations. If a piece of red and a piece of green matt glass be placed side by side and illuminated from behind by a single lamp, and if, when the lamp is close to the glasses, the red appear rather brighter than the green, it will be found that as the lamp is moved further and further away, so that the brightness of the glasses is gradually diminished in the same ratio, then at a certain stage, the green and red will appear approximately equal in brightness, while if the lamp be moved still further off, the green will ultimately appear much brighter than the red. Thus the eye does not behave equally to all colours at very low illuminations, blue and green being much weighted with respect to red. This is known as the Purkinje effect.

If, now, the brightness of the glasses be still further diminished, it will be found that below a limit of about 0·02 candles per square metre (a brightness of the same order as that of objects seen by direct moonlight) all colour perception ceases, the red glass appears almost black, while the green, which is, of course, still of the same actual brightness, appears a ghostly grey. The same phenomenon may be observed when a red brick wall covered with a green creeper is seen by moonlight. In the daytime the wall may be considerably brighter than the creeper, but at night the wall appears almost black, while the creeper is grey of a distinctly brighter tone. Under such conditions, then, objects are perceived not by differences of colour, but by differences of brightness only.

Another peculiarity of the eye at low illuminations is the fact that for faint green light the part of the retina surrounding the fovea is more sensitive than the fovea itself. From this it results that a very faint green light, such as a signal light almost on the limit of visibility, is seen most readily when the eye is caused to "look at" a point slightly to one side of it. Frequently a faint green light picked up in this way is lost again when looked at directly, only to reappear when the eye is turned slightly so as to cause the image to fall on a part of the retina away from the yellow spot. This effect does not take place in the case of red light. It is of importance in connexion with the visibility of signal lights.

Many eyes are defective as regards colour vision, i.e. they are incapable of distinguishing light of different colours to a greater or less extent. Often this affects only certain colours, most frequently red which becomes indistinguishable from green, but it may sometimes affect other colours, so that the power of distinguishing objects by colour differences of a certain kind is completely absent. Clearly the presence of this defect to any considerable extent may be very disadvantageous for the carrying out of work, such as colour matching, or that involving the recognition of coloured light signals.

A portion of the retina may be very readily fatigued for light of a certain colour if a strongly coloured object is steadily gazed at for some minutes. To this is due the well-known effect observed when, after gazing fixedly at a bright red pattern, the eye is turned towards a white surface. The pattern is then seen in green on the white ground, showing that the particular part of the retina previously subjected to red light is no longer able to respond so readily as the remainder to light of this colour, and thus the colour of the light reaching the fatigued parts appears to be white with all the red rays removed, i.e. the "complementary" green.

Resolving Power of the Eye.—It is found that the eye is incapable of perceiving and distinguishing between two points which are separated by an angle of less than one minute of arc. For example, at a distance of a mile from the eye, two lights or two small objects less than half a yard apart will appear to the eye as if they formed a single unit. This minimum angle required for distinguishing objects or parts of objects is known as the limit of resolving power of the eye, and it may possess great importance in connexion with the arrangement of signal lights intended for observation at considerable distances.

Persistence of Vision.—Another peculiarity of the eye, the basic principle of the kinematograph, is the phenomenon known as persistence of vision. When the retina of the eye receives a visual impression of a very short duration, this impression does not disappear instantaneously with the removal of the source producing it, but it remains for a definite period and dies away comparatively gradually, lasting altogether for about one-thirtieth to one-tenth of a second,

depending on the brightness of the original impression. If then a series of impressions, similar but with small progressive changes, be received by the eye, the effect is that of a continuous picture of which certain parts are in motion. Use is made of this effect in a certain class of photometer, termed the flicker photometer, for comparing lights of different colours (see p. 174).

Glare.—The last subject for consideration in this chapter, and the one which requires the most careful attention from the lighting engineer, is that of glare. The term has been variously used in the past and it cannot be said that there is even now complete unanimity as to the meaning to be attached to it. Speaking generally, however, it is used to denote the state of the eye when it is unable to see clearly any object which is in the neighbourhood of another very much brighter object, or which is looked at immediately after the eye has been exposed to a very intense light. One of the most frequently noticed and most dangerous examples of this effect is the dazzle produced by an unscreened motor-car headlight, which renders the eye of anyone meeting it quite incapable of perceiving any object immediately in the neighbourhood of the beam. Although the effect is so noticeable in this particular instance, it is present to a less degree in a very large number of lighting systems met with to-day, and it is only recently that its bad effect on the efficiency of the eyes of those exposed to it has been fully realized. No doubt the introduction of the gas-filled lamp, with the greatly increased brightness of its filament, has contributed to this present-day appreciation of the deleterious effects of having very bright objects in the field of view, but it is still all too frequent to find this, one of the first requirements of a satisfactory lighting installation, completely ignored. For example, it is by no means infrequent to find the pulpit desk in a church lighted by means of an unshaded light source, so placed that it must inevitably come within the field of view of anyone looking at the speaker. In this case the persistent glare and consequent fatigue cannot fail to produce discomfort with, frequently, subsequent headache as the result.

It will be noticed that both fatigue and glare seriously interfere with the ability of the eye to do its work properly. They are, therefore, to be regarded as serious defects in any lighting system, and especially is this the case where the eye is required to be in the best condition for continuous work.

For the avoidance of fatigue it is desirable that, as far as possible, no object which is likely to come within the field of view shall have a greater brightness than three candles per square inch. This is approximately the brightness of a candle flame, and by the use of diffusing globes it is generally quite easy to reduce the brightness of any light source to this figure without undue loss of light. Means for doing this will be described in later chapters of this book.

To avoid glare it is not sufficient to set an upper limit to the absolute brightness permissible, but it is also necessary to determine what is the maximum brightness of an object which will seriously interfere with the vision of objects in its immediate neighbourhood, or those to be viewed *immediately* afterwards. Numerous experiments on this point have led to the conclusion that the presence in the field of view of an object whose brightness exceeds 100 times that of whatever is being looked at, interferes seriously with the visual acuity, so that it is generally recommended that the brightness of the light sources should not exceed 100 times that of the objects to be illuminated, unless these sources be so placed that there is little possibility of their coming within the field of view. The reason for this restriction, even when the eye cannot see both objects simultaneously, is that a very rapid transference of the gaze from one to the other does not give time for adaptation of the retina to take place, and thus the effect known as "successive glare" is produced.

Ultra-Violet Light.—The radiation from some sources of light, notably the mercury-vapour lamp, and the electric arc, includes a considerable proportion of rays of very short wave-length, the so-called ultra-violet light. Although radiation of this wave-length is not capable of producing the sensation of vision, it nevertheless produces a marked effect on the eye and in any appreciable quantity it causes a very painful inflammation known as "ultra-violet burn." Gazing for only a few seconds at a naked arc will produce this result and hence it is necessary always to shield the eyes from receiving ultra-violet light from any source which produces it in appreciable quantity. Fortunately most glass is opaque to ultra-violet light, so that the passage of the light through a glass bulb or globe is generally sufficient protection. It is, however, important to bear this matter in mind when dealing with unenclosed arcs or with the quartz mercury-vapour lamp, for quartz is transparent to the ultra-violet rays and so these lamps should invariably be used inside a glass globe. It has been shown that under certain conditions cataract may be caused by the action of ultra-violet light on the lens of the eye. Ultra-violet light is very efficient in producing photographic action, and it is this very power of stimulating chemical action that is the cause of its harmful effect on living organisms. A process of sterilization of water by the action upon it of the rays from a mercury-vapour lamp has been devised.

Defective Vision.—Needless to say, defects in the structure of the eye, such as excessive curvature of the crystalline lens so that the image of any except very near objects cannot be focussed on the retina (short sight), cause a strain on the mechanism by which clear vision is produced. Unless corrected by suitable lenses, these defects must necessarily cause strain and fatigue of the muscles of the eye, and accentuate the ill-effects of any defects in the lighting system such as those just described. On the other hand deficient illumination, by causing the object viewed to be brought habitually too close to the eye, may produce short-sight as a result of persistent effort to accommodate to this shortened distance.

Not least among the dangers attendant upon a bad lighting system is the fact that its effects on the eyes of those working by it may not be apparent until some time has elapsed, and the mischief is then usually too far advanced to admit of remedy. The eye is, of all the organs in the body, one of the most readily adaptable to extremes of working conditions, and unfortunately this very fact constitutes, perhaps, its greatest defect. It gives little warning, and when affected the damage is frequently permanent.

CHAPTER II

THE MEASUREMENT OF CANDLE-POWER

IT has already been said that surfaces which are not self-luminous are only visible by reason of the light which they reflect to the eye, and since the light reflected is, for the same surface, strictly proportional to the light received, i.e. to the illumination, it follows that the measurement of illumination is one of the most important operations which have to be carried out by the lighting engineer. It provides, in fact, the measure of the adequacy (as distinct from suitability) of the lighting. Now the illumination of bodies which are not self-luminous depends upon the presence in their vicinity of other bodies which possess the power of emitting light. Such bodies are termed " light sources " and the illumination of a surface, due to the light it receives from any light source, varies according to the power of that source, and to the distance of the surface from it.

Definitions of Photometric Quantities.—More precise definitions of such terms as the power of a light source or the illumination of a surface will be given in what follows. At the same time it will be necessary to consider briefly the two fundamental laws upon which the science of photometry, or light measurement, is based.

Light, like heat and X-rays, is a form of radiant energy, but it is distinguished from these and all other forms of radiant energy in that it alone is capable of affecting the retina of the normal eye in such a way as to produce the sensation of vision. LIGHT, then, may be defined as *radiant energy in a form capable of stimulating the retina of the normal eye. A light source is one which emits such radiant energy at a given rate.* Now the rate of passage of radiant energy is, for all practical photometric purposes, invariable, so that it necessarily follows that the rate of emission of luminous energy by a source is a measure of the capability of that source for producing radiant energy in the luminous form. It is, therefore, convenient to incorporate the idea of rate in a new term and to speak of the emission of " LUMINOUS FLUX " instead of the *rate of emission*

of luminous energy. A source which emits twice as much luminous energy as another in a given time is, therefore, said to emit twice as much luminous flux. The term luminous flux, then, involves in itself the idea of a rate and is thus exactly analogous to horse-power, which is the rate of doing work. The formal definition of these terms, and of some others will be found in the Appendix.

Standards of Candle-Power, or Luminous Intensity.—Now it is a matter of common observation that a source does emit luminous energy equally in all directions. An ordinary vacuum-type metal-filament lamp, for instance, gives more

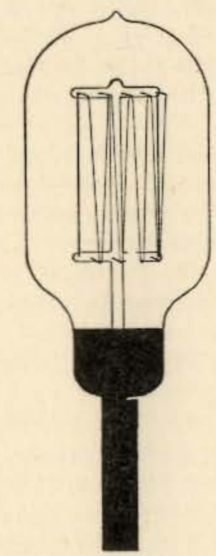


FIG. 3. Electric Glow Lamp Sub-standard

light in directions perpendicular to its axis than in the " tip-end " direction. Clearly, then, a strict definition of the light-giving power, i.e. the " CANDLE-POWER " of a source must refer to emission in a particular direction only. It has been found most convenient in practice to use as standards of reference certain electric glow-lamps, burning under specified conditions of voltage and current, and to express the light-giving power of all other sources in terms of that of any one of these lamps in a given direction. The lamps have, actually, a metal filament in the form of a grid, all the limbs of which lie as nearly as possible in one plane, as shown in Fig. 3. An imaginary light source which emits luminous energy in all directions, at a rate which is some definite fraction of that at which it is emitted by any one of these electric lamps in the direction perpendicular to the plane of its filament, is then defined as a uniform point source, having a candle-power of one CANDLE. Since it is impossible at present to manufacture electric lamps to any specification sufficiently rigorous to ensure exact uniformity of candle-power, the numerical fraction expressing the relation between the standard unit source and the electric lamp is different for each lamp; but this is immaterial, since all the electric sub-standards (as they are called) have been compared with one another so that a consistent value for the unit is obtained from each and every sub-standard. These sub-standards are kept at the National Physical Laboratory of Great Britain; the Bureau of Standards, at Washington; the Laboratoire Central d'Electricité, at Paris; and the Physikalisch-Technisches Reichsanstalt of Germany.

It is important to distinguish clearly between the terms "candle-power" and "candle," which are frequently confused in common speech. The former expresses the idea of light emission, just as the term "current" expresses the idea of passage of electricity. The "candle," on the other hand, is the unit of "candle-power" and corresponds with the ampere as the unit of electric current.

The Unit of Luminous Flux: The Lumen.—A uniform point source of unit candle-power is thus a source which emits luminous energy equally in all directions at a certain definite and constant rate. If such a source be placed inside a sphere of unit radius, then the rate at which luminous energy reaches unit area of the interior surface of the sphere is taken as the unit of luminous flux. This unit is called the LUMEN. Since the total area of the surface of a sphere of unit radius is 4π, it follows at once that a uniform point source of one candle-power gives luminous energy at the rate of 4π lumens. Of course, any practical source does not radiate equally in all directions. Its radiating power will be different in different directions, and hence the luminous flux which reaches the surface of the sphere from such a source will vary from point to point. If, however, the *average* candle-power of the source be unity, the total luminous flux emitted will still be 4π lumens.

The Units of Illumination: Foot-Candle and Metre-Candle.—So far the actual value of the unit used for the radius of the sphere has not been needed; but the value of the unit of illumination depends on this, and consequently two such units are in general use. The first of these is the illumination of

the interior surface of the sphere when its radius is one metre. This unit is called the METRE-CANDLE, or the LUX. The second unit is similarly that obtained by using a radius of one foot. This is called the FOOT-CANDLE. From the definition of the lumen given above, it will at once be seen that one lumen per square metre of surface results in an illumination of one metre-candle, while one lumen per square foot similarly gives an illumination of one foot-candle. The C.G.S. unit of illumination is, similarly, the centimetre-candle, or phot. The thousandth part of this, or milliphot, is sometimes employed.

The Inverse Square Law.—Since the area of the surface of a sphere varies as the square of its radius, it follows that if the radius (i.e. the distance of the surface from the source) be doubled, the luminous radiation originally reaching a given area of the sphere is now distributed over an area four times as great, so that the illumination must now be reduced in the ratio of 1 to 4. In other words the illumination varies inversely as the square of the distance of the surface from the source. This, the first fundamental law of illumination, is known as the inverse square law, and was enunciated by Bouguer in 1729. It follows from this law that 1 foot-candle is approximately equivalent to 10·76 metre-candles.

The Cosine Law of Illumination.—The other fundamental law of illumination, known as the cosine law, is due to Lambert, who first drew attention to it in 1760. To demonstrate this law it is only necessary to consider that the radiation which reaches unit area of a plane surface placed so as to be perpendicular to the light rays, would be distributed over a greater area in the case of a surface inclined to this direction. In fact, if the angle between the two surfaces be θ, the areas are in the ratio of 1 to sec θ respectively, and hence the illuminations are in the ratio of 1 to cos θ. This may be expressed more formally in the statement that the illumination of a surface varies as the cosine of the angle which its normal makes with the direction of the incident light.

The two laws just given may be expressed symbolically by the relationship

$$= \frac{J \cos \theta}{d^2}$$

or in words, the illumination is equal to the candle-power of the source, multiplied by the cosine of the angle of inclination of the surface, and divided by the square of the distance between the surface and the source. It will be observed that the distance d must be assumed constant for all parts of the surface, i.e. that the dimensions of the surface are negligible in comparison with *d*. Clearly, if the candle-power J be expressed in candles and *d* in metres, the illumination E will be in metre-candles.

The Brightness of a Surface: Reflection, Absorption, and Transmission.—The relation between the illumination of a surface and its brightness must now be considered. As stated in Chapter I, the brightness of a surface depends not only on its illumination, but also on its capability of reflecting the light which it receives. Light reaching the surface of a body may be either absorbed in the substance of the body, transmitted through it, or reflected from the surface at which the light is incident. In every practical case, both absorption and reflection take place, while sometimes there is transmission also. In the case of an opal glass shade, for example, the side of the glass nearest to the light is visible, by reason of the reflected light, the opposite side owes its brightness to transmitted light, while the difference between the amount of light incident on the surface of the shade, and the sum of the amounts reflected and transmitted, gives the amount of light absorbed in the opal material.

Most ordinary bodies which it is desired to illuminate are practically opaque, and thus all the light not reflected by the surface is absorbed in the body. In no known substance is all the incident light reflected. Every substance absorbs at least 1 or 2 per cent. of the incident light, most substances far more. The ratio of the amount absorbed to the amount incident is known as the ABSORPTION RATIO (or coefficient) of the body, and similarly the fraction transmitted is known as the TRANSMISSION RATIO. The REFLECTION RATIO, the fraction of the incident light reflected from the surface of a body, is the most important of the three ratios, as upon it must necessarily depend the illumination necessary to give the surface any desired degree of brightness. Clearly a surface of 50 per cent. reflection ratio will require twice as great an illumination as a surface of 100 per cent. ratio, in order that it may have the same brightness, and if ρ be the reflection ratio and E the illumination, the brightness will vary as the product ρE.

Specular and Diffuse Reflection.—It is a matter of common observation that the light reflected from a surface is differently distributed according to the state of polish of that surface. For instance it is obvious that a smooth surface, such as a polished table-top is not uniformly bright in all directions. There is a particular direction A, Fig. 4, depending upon the relative positions of the surface and the source,

at which the table appears considerably brighter than it does from other directions, such as B. This is due to the fact that a polished surface reflects most of its light in a direction which makes an angle with the surface equal to the angle of the incident light. In the case of an unpolished or matt surface, such as a sheet of blotting paper, no such concentration of the reflected light takes place. The light is distributed in all directions in such a manner that the blotting paper appears to have approximately the same brightness whatever be the direction from which it is viewed. Reflection from a polished

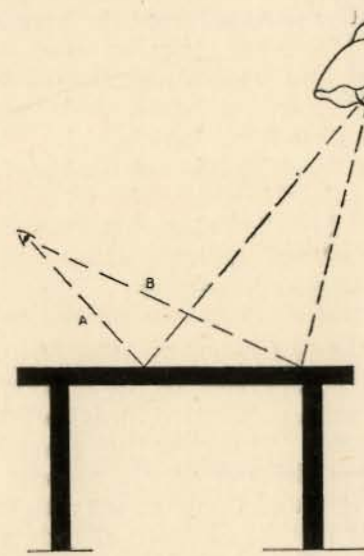


FIG. 4. Glare due to Specular Reflection

surface is said to be "specular," and that from a matt surface, "diffuse." In practice, no surface is perfectly polished (i.e. distributes the reflected light so as to appear equally bright in all directions). In some surfaces, such as a good mirror, the diffuse reflection may be neglected for all practical purposes, while in others, such as white blotting paper or etched enamel, the amount of specular reflection is negligible. In general, however, both specular and diffuse reflection are present or, to speak more correctly, the reflected light is concentrated to some extent (greater or less according to the nature of the surface) in directions which are near to the direction of specular reflection.

The following table gives some approximate values of reflection ratios for surfaces commonly met with in lighting engineering :—

TABLE I

Surface.	Reflection Ratio (per cent.)
Pure magnesium carbonate	98
White blotting-paper	82
Silvered glass mirror[1]	80
White enamel	75
Light grey paint	50—70
Medium grey paint	30—50
Dark grey paint	15—30
Light buff paint	50—60
Sage green paint	40—50
Sky blue paint	30—40
Scarlet paint	30
Brown paint	20
Deal wood	40
Polished nickel-plate	64

[1] Specular reflection.

Perfect Diffuser.—A surface which, when evenly illuminated, appears equally bright whatever be the direction from which it is viewed, is termed a perfectly diffusing surface, or, sometimes, a perfect diffuser. If is clear that a small area of any illuminated surface reflects a certain amount of luminous flux in every direction, and therefore may be said to have a certain candle-power in that direction exactly as if it were a self-luminous source. For there is no difference in quality between the light reflected from a white surface and that emitted from the luminous source by which it is illuminated. Hence the brightness of a surface in any direction may be expressed as the candle-power of a given area of the surface in that direction. Clearly, if the direction be fixed, the candle-power is proportional to the area. Now, if the surface be flat, its apparent area varies according to the direction from which it is viewed : in fact, if the true area be a, and the line of sight make an angle θ with the normal to the surface, the apparent area is $a \cos \theta$. Hence, since a perfectly diffusing surface appears equally bright in all directions, it follows that the amount of luminous flux reflected by it in any direction is proportional to the cosine of the angle which that direction makes with the normal to the surface, for in this way the apparent area and the flux decrease in the same ratio

as θ is increased, so that the flux per unit apparent area remains the same.

Definition of Brightness : Table of Brightness.—The brightness of a surface, then, is the candle-power per unit projected area of the surface in the direction of vision, and the brightness of a perfectly diffusing surface is the same in all directions. The system of units which may be most conveniently employed to express a brightness depends upon whether the surface is self-luminous or not. For the high values of brightness met with in most modern light sources, the candle-power per square millimetre is generally used, while for surfaces illuminated by these sources a unit of one millionth of this magnitude, the candle-power per square metre, is often employed. The values of brightness of a number of modern light sources are given in the following Table :—

TABLE II

Nature of Source	Approximate Brightness (c.p. per sq. mm.)
Candle Flame	0·005
Paraffin Flame	0·01
Acetylene Flame	0·04 to 0·08
Incandescent Mantle (low-pressure)	0·02 to 0·05
Incandescent Mantle (high-pressure)	0·1 to 0·5
Carbon Filament	0·6 to 0·8
Tungsten Filament (vacuum)	1·5
Tungsten Filament (gas-filled)	7 (average)
Tungsten Arc	20
Electric Arc	170
Special High Intensity Arc	500
Mercury-vapour Lamp	0·02
Mercury-vapour Lamp (quartz)	1
Moore Tube	0·004 to 0·006
Sun apparent	1200
Moon apparent	0·004

The Unit of Brightness : The Lambert.—From what has been said above it will be clear that for any but a perfectly diffusing surface the brightness can only be specified in a given direction, and it will be found, as a matter of experience, that the brightness as viewed in any given direction varies also with the direction from which the light illuminating the surface is received.

A very usual method of specifying a brightness is to express it in terms of the brightness of a perfectly diffusing surface of 100 per cent. reflection ratio, illuminated to the extent of 1 foot-candle or of 10,000 metre-candles (i.e. 1 centimetre-candle). In the former case the brightness unit is referred to as the "equivalent foot-candle" while in the second case it has received a special name, the lambert. The latter unit is, of course, much too bright for ordinary purposes, and the thousandth part of it, the millilambert is generally employed. The equivalent foot-candle and the millilambert are of the same order of magnitude, the former being 1·077 of the latter. The use of this system of expressing brightness, though sometimes convenient, often leads to confusion as it might well be thought that a brightness of one equivalent foot-candle would be the same as a brightness of one candle per square foot. This, however, is not the case as, by means of a short investigation, it is quite easy to prove.

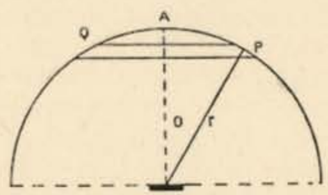


FIG. 5. Radiation from a Plane Surface

Relation between the Equivalent Foot-Candle and the Candle per Square Foot.—Each square foot of a surface illuminated to the extent of one foot-candle receives one lumen of luminous flux. If it be a perfect reflector (i.e. have a reflection ratio of 100 per cent.) it must, therefore, emit one lumen per square foot. If, further, it be a perfect diffuser the flux which it emits is distributed according to the cosine law of emission, and if we imagine the surface to be at the centre of a hemisphere as in Fig. 5, then the flux reaching the surface of the hemisphere at P will be equal to that reaching A, multiplied by the factor $\cos\theta$. If B be the brightness of the surface in candles per unit projected area, the flux reaching A is B/r^2 lumens per unit area so that at P it is $(B\cos\theta)/r^2$ lumens per unit area.

Considering an elementary zone of the hemisphere PQ, the illumination of the zone will be uniform all over, and the total flux it receives will be $\{(B\cos\theta)/r^2 \times 2\pi r^2\}\sin\theta\, d\theta$. Hence the total flux received by the surface of the hemisphere is

$$\int_0^{\frac{\pi}{2}} 2\pi B\cos\theta\sin\theta\, d\theta = \pi B.$$

But this total is equal to one lumen, so that $B = 1/\pi$ or in other words the brightness of a perfectly diffusing surface of 100 per cent. reflection ratio illuminated to the extent of one foot candle is $1/\pi$ candles per square foot. The relation is, of course, unaltered by changing the unit of length employed in both expressions, so that one equivalent metre-candle is the same as a brightness of $1/\pi$ candles per square metre. The brightness of a perfectly diffusing surface of reflection ratio ρ and illumination E metre-candles, is, therefore, $\rho E/\pi$ candles per square metre. Thus the following relations may be shown to hold:

1 equivalent foot-candle = 0·318 candle per square foot = 0·00214 candle per square inch = 1·076 millilamberts.

1 candle per square millimetre = 10^6 candles per square metre = 314159 millilamberts.

Photometry by Comparison of Brightnesses.—From what has been said above it will be clear that the only quantity which the eye is capable of appreciating is that of brightness. Neither candle-power nor illumination *per se* can affect the eye, so that if a measurement of either of these quantities is desired it becomes necessary to use a surface as intermediary, and to compare the brightnesses which they give to similar surfaces of known properties. The surfaces generally chosen for this purpose are as nearly perfect diffusers as it is possible to obtain, for then the definition of the directions from which the surfaces are to be viewed becomes of small importance. Further, a very slight experience will serve to show that the eye is at least as unreliable as the other organs of sense for actual quantitative measurement. All that it can do is to judge of equality of brightness, and this it is able, in the most favourable circumstances, to determine to an accuracy of about one-half of one per cent. By taking the mean of a large number of observations equality of brightness may be measured to an accuracy approaching two in a thousand.

Every photometer, then, is essentially an instrument for the ready comparison of brightness, but for the purposes of this book photometers will be divided into two classes according as they are primarily intended for the comparison of light sources, or for the measurement of illumination at a given position.

Measurement of Candle-power: The Bunsen Photometer—In the case of the former class, the two sources are generally placed one on either side of the photometer, and their respective distances from the comparison surfaces in the instrument are then adjusted until equality of brightness is obtained. Assuming the surfaces to have equal reflection ratios, and to be equally inclined to the incident light, this condition gives the distances at which the two sources produce equal illuminations, and hence the luminous powers of the sources (in the direction of the photometer) are in the same ratio as the squares of their respective distances from the photometer surfaces.

As a convenient example, the simple form of the Bunsen Grease-Spot photometer may be described. This consists of a sheet of opaque white paper rendered translucent over a small circular region in its centre by the application of paraffin-wax. This sheet S (Fig. 6) is mounted in a box which is blackened on the inside and provided with two mirrors M,M

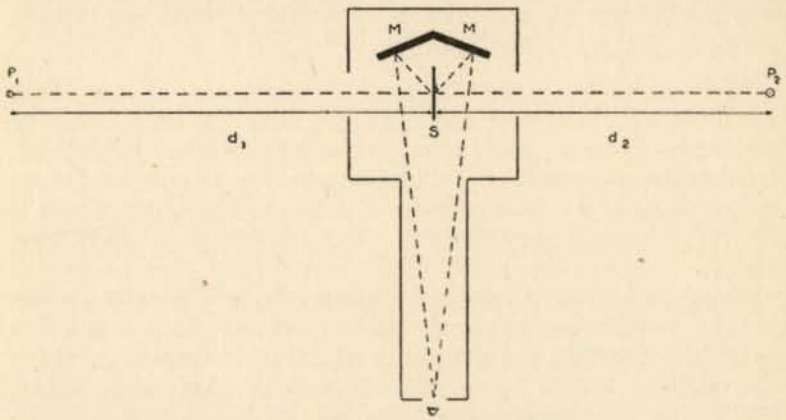


FIG. 6. The Bunsen Photometer

by means of which the two sides of the sheet can be simultaneously observed. The box is mounted between two sources of light, P_1, P_2, the sheet S being perpendicular to the line P_1, P_2. The box is then moved to and fro along this line until the observer obtains an identical appearance for the two sides of the paper as viewed in the mirrors. The candle-powers of the sources are then in the ratio of the squares of their distances, d_1, d_2, from the paper sheet in the photometer head, i.e. if J_1 and J_2 are the candle-powers of the sources in the direction of the photometer, then

$$\frac{J_1}{J_2}=\frac{d_1^2}{d_2^2}$$

The Lummer-Brodhun Contrast Photometer.—Modern photometry, as far as it is concerned with the comparison of light sources, and their measurement in a given direction by comparison with standard sources, depends on the use of a comparison photometer of the most sensitive type available, together with a photometer bench specially designed for the accurate determination of the distances involved.

The form of photometer head generally employed for work of the highest accuracy with lights of the same colour is the Lummer-Brodhun contrast type, the first form of which was described in 1889 though it has undergone several improvements since that date. The principle on which the instrument works will be best understood from Fig. 7, which shows a plan of the interior of the photometer head. S is a screen

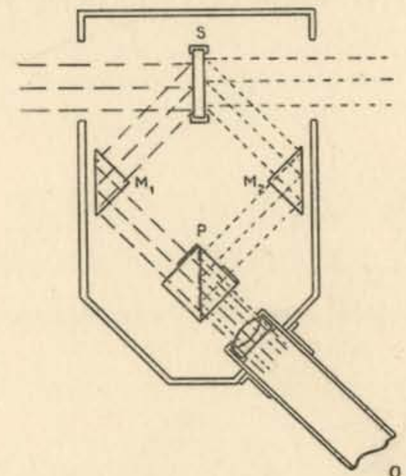
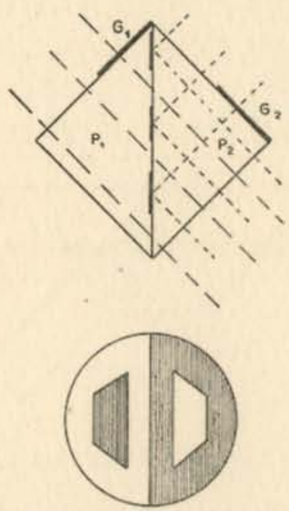


FIG. 7. The Lummer-Brodhun Photometer Head

(approximately 4 mm. thick) constructed of white plaster with as matt a surface as can be obtained. The two sides of this screen are respectively illuminated by light from the two lamps to be compared. M_1 and M_2 are total reflection prisms and by means of these the light from the two sides of the screen is brought to opposite faces of the prism system P.

This system, as may be more clearly seen from Fig. 7a, consists of two right-angled prisms placed with their hypotenuses in contact. The hypotenuse of the left-hand prism, however, is sandblasted with the pattern shown shaded in Fig. 7b, and thus the only parts of the two prisms which are in optical contact have the form of the white pattern in that figure. The result is that light passing into prism P_1 is transmitted without change to prism P_2 in the pattern shown white in Fig. 7b, while the pattern shown shaded in that figure is the pattern over which total reflection takes place in prism P_2, i.e. the pattern over which the light from M_2 is seen by the observer at O. In effect, therefore, the observer at O sees a pattern of this form in which the brightness of the shaded portion is due to light from the right-hand side of S, while the brightness of the white portion is due to light from the left-hand side of S. Clearly, when the two sides of S have the same brightness, the pattern will disappear.

Disappearance, however, is not the condition of which the eye is capable of judging most sensitively, and therefore sheets of glass G_1 and G_2 are inserted as shown in Fig. 7a, so that the



FIGS. 7A and 7B. The Lummer-Brodhun Cube, and Appearance of Field (Contrast Pattern)

light forming each of the rhomboidal patches is reduced by 8 per cent. and the condition to be arrived at is then equality of contrast between the patch and its background in both halves of the field in view. The observer is provided with a telescope at O, by means of which the pattern of the field is brought into accurate focus for his eye, as without sharpness of focus it is difficult to obtain accurate settings of the photometer.

The whole of the optical part of the apparatus is mounted rigidly in a brass box which is capable of rotation about a

horizontal axis. Further, the screen S can be removed for alignment of lamps on the bench, or for reversal of screen to eliminate differences due to difference in reflection ratio of the two plaster surfaces. The photometer windows are provided with brass shutters, and these should always be kept closed when the instrument is not in use as otherwise both the plaster screen and the glass surfaces of the prisms become dusty and the field of view becomes covered with specks so that the accuracy of the readings is much impaired. With experienced observers, lights of the same colour can be compared with this photometer to an accuracy of 0·2 per cent. by taking the mean of a number of observers working on several occasions and following the procedure described later in this chapter.

The Photometer Bench.—The photometer bench must next be described. The pattern designed and used at the National Physical Laboratory is shown in general view in Fig. 8. It

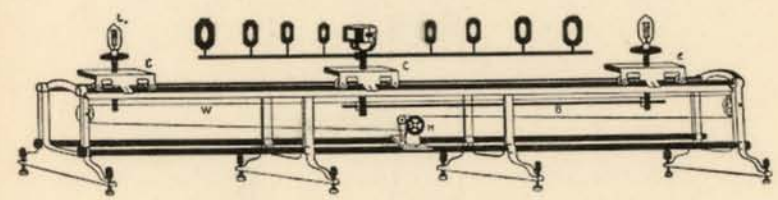


FIG. 8. The Photometer Bench

consists of two straight steel bars, 3,000 to 5,000 mm. long, supported rigidly at intervals, the distance between the bars being 180 mm. The lamps to be compared are set up on the carriages C,C, which consist of aluminium base-plates supported on three rollers with V-shaped grooves which run smoothly along the bars of the bench. The centre upright of each carriage has an adjustment for raising and lowering the lamp or photometer head. The upright of the carriage holding the lamps is also capable of rotation about its axis, so that the candle-power may be measured in any desired position. Different fittings are attached to the various carriages according to the particular apparatus which they are intended to bear, e.g. a rotator, apparatus for polar curve measurements, a photometer head and screening system, etc.

Sub-standards and comparison lamps are mounted in specially designed holders with tubular stems (as shown in Fig. 9) which fit snugly into the hollow uprights of the carriages, a slot S at the bottom engaging in a key at the base of the upright so that when a definite mark on the degree scale of the rotating table on the lamp carriage is opposite the pointer, the lamp filament is in a definite position with respect to the axis of the bench.

Test lamps are accommodated in special holders which have sockets designed to take lamps with ordinary standard caps. These holders terminate in tubular stems similar to those on the sub-standards, and they are provided with two pairs of

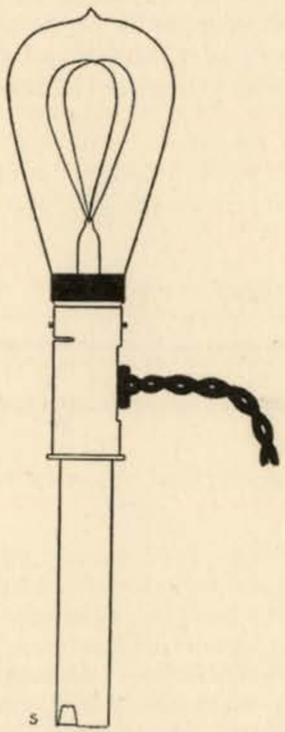


FIG. 9. Mounting for Sub-standard and Comparison Lamps

leads, both of which are soldered to those parts of the sockets which make contact with the lamp cap. One of these pairs of leads is used for supplying current to the lamp, while the second pair is used for voltage measurement. In this way the voltage is measured at points which are as near as possible to the actual lamp contacts, and no allowance has to be made for voltage drop in the supply leads (see p. 36).

Screening.—The carriage bearing the photometer head also carries a steel bar along which are placed at convenient intervals

a number of blackened aluminium screens with various sizes of aperture (Fig. 8). The relative sizes of the screens and their apertures, and the intervals at which they are placed along the bar, are so related that the screen of the photometer head is completely shielded from rays of light proceeding from anywhere but a narrow region surrounding the lamp to be measured (see Fig. 10). When the bench is in use black curtains are hung on either side of it throughout its length, and black velvet screens are placed behind the lamps being compared, so that as far as possible stray light is completely prevented from reaching the photometer. One source of stray light which is sometimes found to give trouble is the specular reflection of the light from the lamp by the polished surfaces of the steel rods of which the bench is composed.

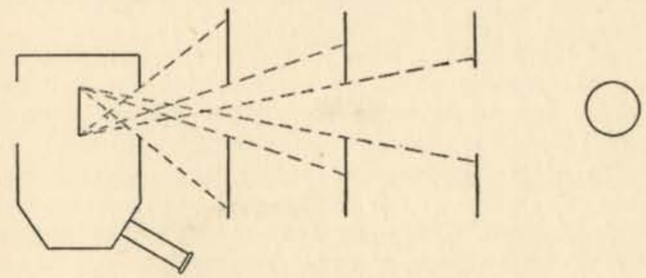


FIG. 10. Method of Screening the Photometer

This may be avoided by ebonizing the rods or by covering them temporarily at the half-way point with a piece of black velvet. The importance of adequate screening cannot be over-estimated in accurate photometric work.

The Substitution Method of Photometry.—The procedure followed in all accurate photometric measurement may be conveniently described by analogy with the double balance method of weighing. As in this method the object whose mass is required is first balanced by an unknown mass of sand, and is then removed from the scale pan and replaced by weights sufficient to balance the sand again, so in photometry by substitution, a lamp of unknown candle-power is used on the right-hand side of the photometer bench, and this is termed the " comparison lamp " (Fig. 8, p. 27). The carriage holding this lamp is clamped to the carriage holding the photometer head by means of a bar B of convenient length, so that the two carriages may be moved as one unit and the illumination on the right-hand side of the photometer head remains constant. The movement is effected by means of the endless wire W and handle H.

To adjust this illumination to 10 metre-candles, a glow-lamp sub-standard of accurately known candle-power L_1 is placed in a carriage at the zero mark on the left-hand end of the photometer bench. The distance of this lamp from the photometer head, which gives an illumination of 10 metre-candles on the screen, being accurately known, the corresponding distance for the comparison lamp (termed its "fixed distance") is found by photometric balance between the two. In actual practice this fixed distance is found as the mean of observations with four or five sub-standards and two or more observers, depending on the accuracy of the work to be undertaken. The distance between the photometer head and the comparison lamp is then fixed, by means of the bar, at the value thus obtained and the bench is then ready for the measurement of the test lamps.

A test lamp having been placed in the left-hand carriage of the photometer bench (in substitution for L_1), and the axis of its filament (or mean plane of the filament when dealing with grid filaments) having been carefully adjusted to be over the zero of the photometer bench, the observer makes a number of settings of the photometer head and an assistant notes these down. The square of the mean distance in metres multiplied by 10 gives at once the candle-power of the test lamp in the direction of the photometer. It is generally the case that two observers will obtain values for the fixed distance of the comparison lamp differing by several millimetres in 1,300 to 1,500 (the distance for a lamp giving about 20 candles). It is therefore customary to set the fixed distance at the value found by one observer and to correct the observations of the other observers so as to make these correspond with the fixed distances found by them.

It may be mentioned in passing that the observer at the photometer head never sees his own readings until they are all taken and entered up, so that he has no chance of being unconsciously biased in one direction or another. For really accurate work, such as the standardization of sub-standards where values are required to an accuracy of a quarter per cent., the procedure above outlined is gone through on three or four separate occasions as it is found that the relative values obtained by two or more observers will differ slightly from day to day, so that it is desirable to have the mean results of several days' observations.

It will be seen that this method of photometry avoids four of the errors to which a simple comparison of test lamp with

standard is liable. These errors are (i) photometer screen error, (ii) zero error of photometer head, (iii) unequal reflections from extraneous objects at the two ends of the bench, and (iv) observer's personal error. The first of these errors, due to lack of symmetry in the photometer head, can be compensated by reversing, but the same does not apply to the other errors, which still remain unless a substitution method be employed.

It will be clear that the bench, in addition to its millimetre scale, may bear a "square" scale so graduated that the position of the photometer head, when the illumination is equal to 10 metre-candles, gives the candle-power of the test lamp directly without calculation; for with a reading of n millimetres the candle-power is $\left(\frac{n}{1000}\right)^2 \times 10$ candles. It will be noticed that no allowance has been made above for the thickness of the plaster screen of the photometer head. If the distances of the two lamps from the photometer are approximately equal or even in the ratio of 2 to 1, with distances of 1,300 mm. or over, the error introduced by this neglect does not exceed 0·15 per cent. For work at short and unequal distances, however, the semi-thickness should be subtracted from the distance of the test lamp, assuming that the distance of the sub-standard has been given as that necessary to produce an illumination of 10 metre-candles on the actual surface of the photometer screen.

The Inverse Square Method.—It sometimes happens that the method of fixed distance described above is not practicable, either on account of the high candle-power of the test lamp and insufficient length of the bench, or when measuring a source in a number of positions in which the candle-power varies over a wide range. In this case it is necessary to fall back on actual candle-power measurements of the comparison lamp, and the use of the inverse square law, both lamps being held stationary, while the photometer head alone is moved. In this case if d be the distance between the two lamps, J the candle-power of the comparison lamp, and x the distance of the photometer head from the test lamp, the candle-power of the test lamp is given by the formula $J\left(\frac{x}{d-x}\right)^2$. This method, of course, involves much more calculation than the fixed distance method.

For the measurement of very high candle-power sources at the National Physical Laboratory, a 3 metre photometer bench is mounted on a table fitted with rollers which move along a rail track 30 metres in length.

Degree of Illumination Necessary for Accurate Photometry.—An important factor which has to receive consideration in accurate photometry is the degree of illumination desirable on the photometer screen. It seems to be generally agreed that an illumination of between 5 and 20 metre-candles is that at which the eye is capable of giving the best results with the Lummer-Brodhun photometer head. Outside these limits the accuracy of equality judgment begins to diminish.

In the case of very high candle-power sources of light it is sometimes inconvenient or impossible to place these sufficiently far from the photometer to give the desired value of illumination for comparison with a standard of normal candle-power, and various methods have been proposed for reducing the intensity in a determinable ratio. One such method, the

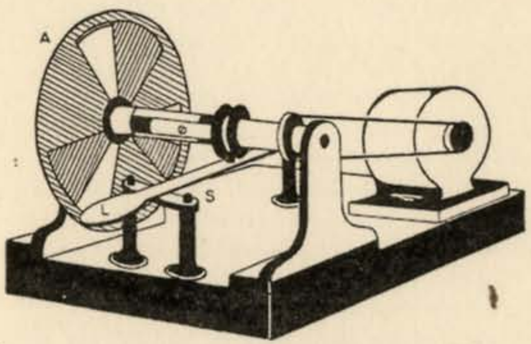


FIG. 11. The Sector Disc

use of a neutral-tinted glass plate (or double-wedge) placed in the path of the light has the disadvantage that truly neutral glass is unobtainable, so that in practice it is necessary to determine the transmission ratio of a given specimen of glass absorber by means of light of exactly the same colour as that with which it is intended to be used. An alternative is a combination of two glass plates ruled with fine opaque black lines exactly equal in breadth to the spaces between them. These two plates slide one behind the other, and so a variation in transmission of 50 per cent. to zero can be obtained.

The Sector Disc.—The most generally used apparatus for the purpose, however, is the sector disc in one of its many forms. The pattern devised and used by Abney is shown in Fig. 11, and possesses the advantage that the angle of the sector openings can be varied while the disc is in motion. The disc is placed so that its upper portion alternately intercepts and transmits the beam of light which it is proposed to

reduce. The shaft carries near one end a grooved pulley driven at any desired speed by an electric motor. At the other end is a disc A of which three equal sectors have been removed except at the shaft and the rim. A second, exactly similar, disc is placed behind this one and is rigidly attached to a flange fixed to a sleeve which slides on the shaft and has a pin engaging in a spiral groove cut in the shaft. Thus the longitudinal position of the sleeve along the axis of the shaft controls the relative positions of the two discs, and so the width of the sector openings is capable of control by means of a grooved wheel attached to the sleeve and acted upon by a pin in the lever L, which moves over a divided scale S.

It has been shown that the transmission ratio of a sector disc, if due precaution be taken to avoid stray light, is accurately the same as the ratio of the total angle of opening to 360 degrees. Of course, the smaller the opening the more the accuracy of the transmission ratio depends on the accuracy

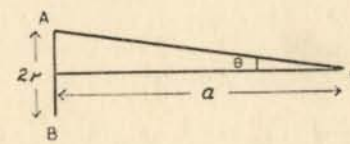


FIG. 12. Radiation from a Disc to a Point

with which the sectors are cut, and for this reason it is not generally advisable to use openings smaller than 10 degrees with a disc of ordinary construction. The speed of rotation has to be adjusted until all flicker of the field disappears and, therefore, needs to be higher the smaller the transmission ratio. For accurate work a disc with fixed openings is generally employed.

Effect of Dimensions of Light Source.—An important consideration in the photometry of sources of light of large dimensions, or where the candle-power is so small that the distance from the photometer has to be made comparable with the dimensions of the source, is the limit at which the inverse square law may be taken to apply with the necessary accuracy. This law is, of course, only strictly applicable to a point source of light, and in the practical case of a source of finite dimensions the illumination of the photometer screen is the sum of the partial illuminations due to all the elementary portions of which the source is composed, the inverse square and cosine laws being applied to each such elementary portion separately. Thus, in the case of a circular disc AB (Fig. 12), the illumination of an elementary surface at a point O along the axis of the disc, due to an element of the disc of area α situated at its centre is $\alpha B/a^2$ where B is the normal brightness of the disc. If the disc be a perfect diffuser the flux it emits in any direction is proportional to the cosine of the angle which that direction makes with the normal to the surface. The illumination produced by a similar element at A, therefore, is only $(\alpha B \cos^2\theta)/AO^2$, for the flux emitted by the disc per unit area in the direction of AO is $B \cos\theta$, and since this meets the surface at O at an angle θ with the normal to that surface, the illumination is again subject to the factor $\cos\theta$. Hence the illumination at O due to A is $(\alpha B \cos^4\theta)/a^2$. By integrating this expression over the whole disc it is found that the illumination at O due to the whole disc is $\frac{r^2 E}{a^2 + r^2}$ where r is the radius of the disc and E is the illumination calculated on the assumption that the size of the disc is negligible in comparison with its distance from O. Similarly it may be shown that for a single straight filament of length $2l$ the illumination at an elementary surface distant a from its centre is

$$\frac{E}{2}\left[\frac{a}{l}\tan^{-1}\frac{l}{a} + \frac{a^2}{a^2+l^2}\right]$$

where E has the same meaning as before. Clearly, in these two particular examples, if the error is not to exceed 0·2 per cent. then in the first case r/a must not exceed 4·5 per cent., and in the second case, l/a must not exceed 4 per cent. In Fig. 13 are given graphs of the percentage errors introduced by assuming discs or lines of various dimensions to behave as absolute point sources. These graphs give, therefore, the dimensions of the largest sources for which the inverse square law may be assumed to hold to any desired degree of accuracy. Recognition of this limitation to the use of the inverse square law is particularly important in the photometry of such sources as the mercury-vapour lamp, or a semi-indirect fitting treated as a single unit.

Accuracy required in Electrical Measurements.—As will be seen in Chapter IV, the candle-power of electric glow-lamps varies at a much more rapid rate than the voltage applied to the filament. Actually it has been found that for tungsten-filament vacuum lamps, a voltage change of 1 per cent. causes a 3·7 per cent. change of candle-power, while for carbon-filament lamps this change is as much as 5 to 6 per cent. For tungsten-filament gas-filled lamps the figure is

generally not much different from that for tungsten-filament vacuum lamps. In tungsten the change produced by a given current variation is approximately twice that produced by the same percentage change of voltage. From this it will be seen that to attain an accuracy of one-tenth per cent. in candle-power measurements it is necessary to ensure that the electrical measurements and regulation shall be accurate to at least 0·02 per cent. Either voltage or current regulation may be employed; the latter has the advantage that it is not necessary to ensure that the electrical measurements are made at the terminals of the lamp, but the former method has the advantage of greater sensitivity, and will be described here.

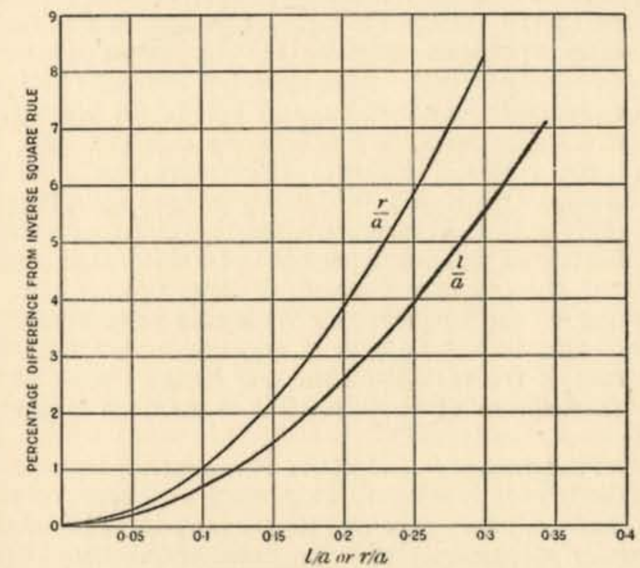


Fig. 13. Departure from Inverse Square Law for Sources of Appreciable Dimensions

For work where an accuracy of 1 per cent. in candle-power is the best aimed at, indicating instruments of a large-scale precision type are good enough if constantly checked against a standard cell and accurate potentiometer. For more accurate work, however, a potentiometer method of voltage measurement must be employed, and it is essential that the voltage of the supply shall be absolutely free from momentary fluctuations. In the most accurate work a storage battery, of reasonably high capacity for the loads to be taken, is essential. The leads from this supply are brought through adjusting resistances to the current terminals on the photometer bench.

From the voltage terminals, which are connected to the lamp contacts by a separate pair of conductors, leads are carried to the terminals of a potentiometer which is repeatedly checked during the course of a day against a standard Weston cell. If measurements of the current passing through the lamp are also desired, it is necessary to introduce into the main circuit of the lamp an accurately measured resistance capable of carrying the current without sufficient change of temperature to affect the value of the resistance. The voltage across the ends of this standard resistance can then be measured by means of the potentiometer and the value of current deduced.

Frequently, when using two electric lamps on the bench at the same time, it is convenient to be able to have a constant indication of the voltage on each lamp, and in this case an electrostatic voltmeter may be usefully employed on the comparison lamp circuit. This lamp has normally to be run for a considerable length of time at a constant voltage, and therefore a voltmeter with a sufficiently enlarged scale (that used at the National Physical Laboratory has a scale of 12 feet radius on which 1 volt is represented by a length of $2\frac{1}{2}$ inches) may be used for maintaining a watch on its voltage. The indication of this voltmeter has to be checked at intervals throughout the day on account of the slow upward creep due to the lag of the suspension. With this arrangement, the potentiometer is free to give a constant indication of the correctness of the voltage on the test lamp or sub-standard. A sketch diagram of the electrical connexions is given in Fig. 14.

Other Photometers.—The above is a general description of the methods usually adopted when using a comparison photometer of any ordinary type and for the purpose of illumination the Bunsen Grease-spot and the Lummer-Brodhun contrast photometers have been described. The method, however, is perfectly independent of the particular form of photometer head employed. The total number of types which have been devised is very large, and for a description of the others, a textbook on photometry, such as that of Liebenthal, *Praktische Photometrie*, or Trotter, *Illumination, Its Distribution and Measurement*, should be consulted. All of them depend, of course, on the comparison of brightness, but the arrangement of the surfaces to be compared and the form of the line of separation differ in the different instruments. Further, while the majority depend on the law of inverse squares for the variation of the illuminations, some use other means, such as polarization, for this purpose so that in these latter instruments the sources and the photometer are not

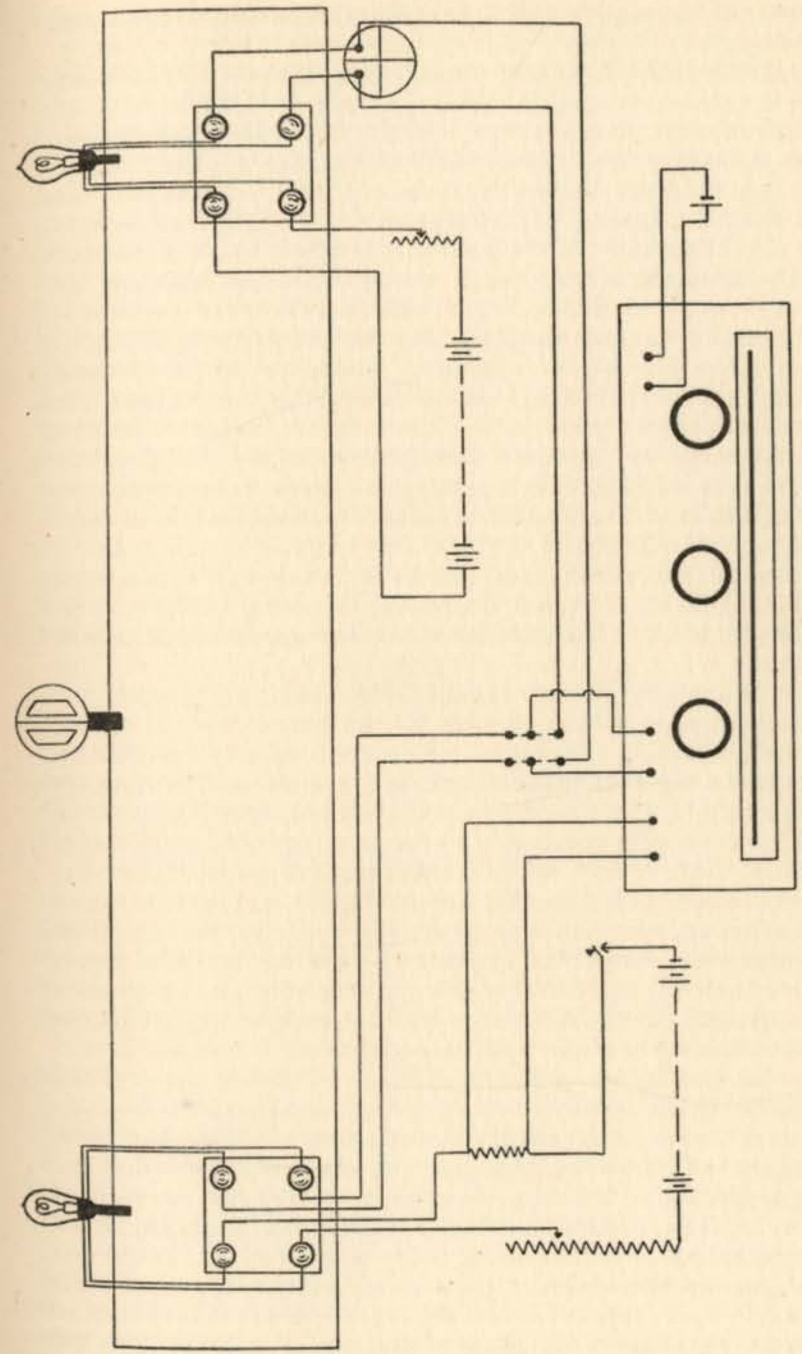


FIG. 14. The Wiring for a Photometer Bench

altered in relative position while the measurements are in progress.

The relative merits of the different patterns of photometer are difficult to decide. The accuracy obtainable in photometric work depends very largely upon the individual and each observer will obtain the best results with the particular instrument to which he is accustomed. Even the same observer differs in accuracy from day to day, and with the extent to which his eye has been fatigued by previous work. The time taken in making a reading differs with different observers, but if too long a time is taken, the precision of judgment tends to diminish after the first twenty seconds or so. The part of the apparatus which has to be moved to obtain a balance should be light enough to require very little manual effort on the part of the observer. It is often found convenient to approach the position of balance by overshooting on each side a number of times in succession, the amplitude of the overshoot being diminished each time. If the eye is allowed to see anything brighter than the field of view in the photometer, its power of accurate balance is destroyed for a period depending on the brightness of the object seen and the time for which the eye has been exposed to it.

All the photometers hitherto described have depended on the comparison of brightness by the human eye. It is self-evident that in the case of all measurements of light the eye must be the final judge of equality, but since individual eyes differ slightly from one another in their judgment it is inevitable that the results obtained by what may be called physiological photometry cannot be independent of the peculiar characteristics of the observer, and many proposals have been made to place photometry on a semi-physical basis, i.e. to design some instrument which will respond to light in the same way as the " normal eye " or the average of a very great number of individual eyes, none of which possesses any marked abnormality as regards light perception.

The Photometry of Flame Sources.—Although not explicitly stated, it will be obvious from the above description of photometric methods and apparatus that the procedure is practically the same whatever the nature of the source whose candle-power it is desired to measure. Mention may be made, however, of one or two details which call for special attention in the photometry of sources other than electric lamps. In the case of gas, acetylene, and similar flame sources, the pressure of supply needs to be carefully regulated while measurements are in progress, and a statement of this pressure should generally accompany any statement as to candle-power performance. Figures for the rate of consumption and data as to calorific value or purity are also generally included in any statement of candle-power of gaseous illuminants.

It should be noted, too, that the humidity and barometric pressure have a very marked effect on the candle-power of gas flames, and the amount of carbon dioxide present in the air also exerts an important influence so that if a gas flame be left burning in a small room, without special ventilation, the increase of carbon dioxide due to the combustion in the flame will cause a progressive diminution of candle-power.

Frequently such sources are tested against a Vernon-Harcourt Pentane lamp as sub-standard. This is a lamp depending for its light on a carefully regulated supply of vapour of a specially volatile hydrocarbon, pentane, and under standard conditions of atmospheric pressure and humidity it gives, if correctly constructed and operated, a candle-power of one or ten candles (according to pattern). In testing gas it is usual to assume that the departures from standard conditions of humidity and pressure affect both standard and flame in equal ratios. This assumption, while approximately true in the case of a gas flame, is not justified when testing an incandescent mantle or an acetylene flame.

There is the further difficulty in the case of the last-named sources, that the colour of the light which they give differs very greatly from that of the pentane flame. Even with an electric lamp as sub-standard, there is a considerable colour difference, and this is the cause of much difficulty in accurate photometry.

In all that has been said above it has been assumed that the two sources being compared give lights of sensibly the same colour, so that in making an intensity balance there is no difficulty due to difference in hue of the two sides of the photometer field. The problem of heterochromatic photometry, where this is not the case, will be dealt with in Chapter X.

Compensation for Voltage Fluctuation.—It may be mentioned that in the photometry of electric lamps when a storage battery is not available, it is quite usual to put the test lamp and sub-standard in parallel on the same source of supply. In this way the fluctuations of voltage affect both sources equally, and the consequent candle-powers are approximately equally affected. It should be noted, however, that if this arrangement be adopted, there should be no appreciable resistance in series with the two lamps, or accidental failure of the test lamp would cause a serious over-voltage on the sub-standard. This arrangement is clearly not applicable to the photometry of flame sources, or to the comparison of a carbon lamp with a tungsten standard or vice versa.

Another method which has been proposed for the automatic regulation of a fluctuating supply voltage is the following,[1] shown diagrammatically in Fig. 15. In the unbalanced Wheatstone Bridge ABCD, the resistances AC and DB are formed of tungsten-filament vacuum lamps in parallel, while CB and AD are ordinary resistances. Owing to the large tem-

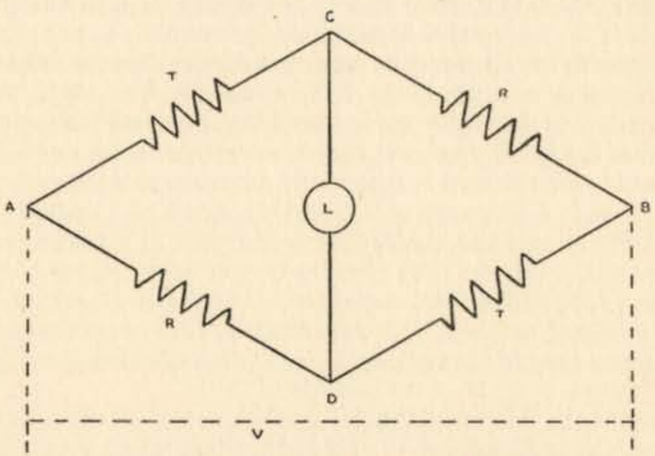


FIG. 15. The Automatic Voltage Regulator

perature coefficient of resistance of tungsten, rise of voltage across AB, with consequent increase in the current through the arms of the bridge, alters the ratio of AC to CB and of DB to AD, and if the values of these resistances be properly chosen it is possible to arrange that a change of voltage as great as 10 per cent. across AB will produce no appreciable change across CD, the photometric sub-standard. If the outside supply be 240 volts, and the voltage and current of the standard 50 and 0·3 respectively, the values of AC and DB are 75 ohms and of CB and AD 180 ohms approximately.

[1] F. G. H. Lewis. "An Automatic Voltage Regulator." *Phys. Soc., Proc.* 34, 1921-22, p. 17.

CHAPTER III

THE DISTRIBUTION OF CANDLE-POWER

Polar Curves of Light Distribution.—In the previous chapter a short description has been given of the principle and method of use of the photometer for the comparison of the candle-power of light sources. It has already been mentioned that

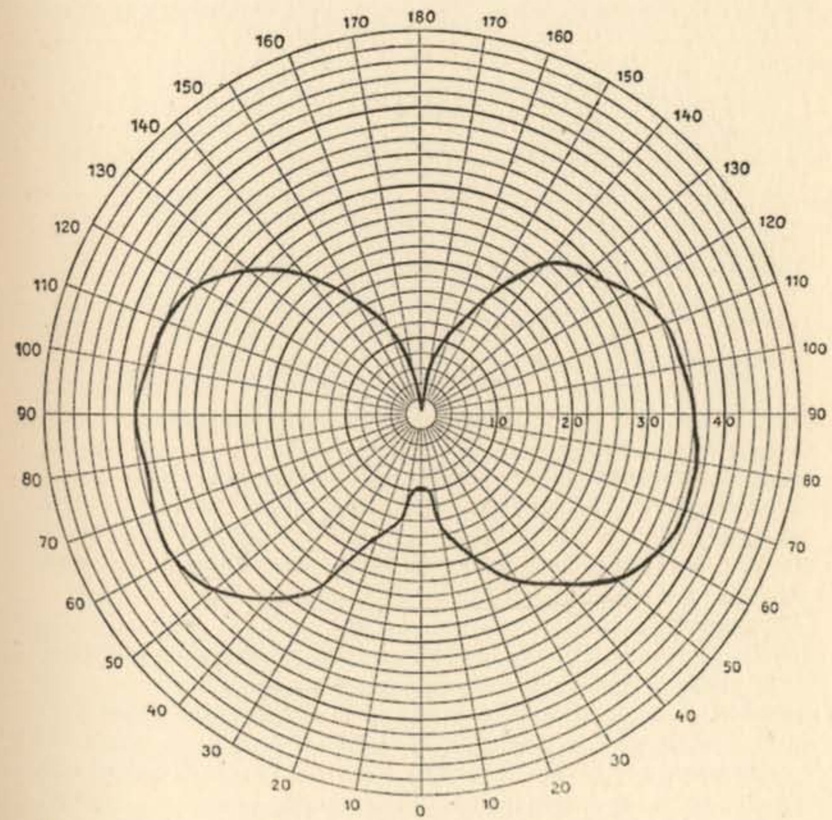


FIG. 16. Curve of Candle-power in a Vertical Plane (Tungsten Filament Vacuum Lamp)

the candle-power of a source is not the same in all directions, so that it is frequently of importance to know in what manner the candle-power varies with the direction. Particularly is this the case with lighting units in which the light is redirected by reflection or refraction at surfaces specially designed to produce a given distribution of the light from the source. It

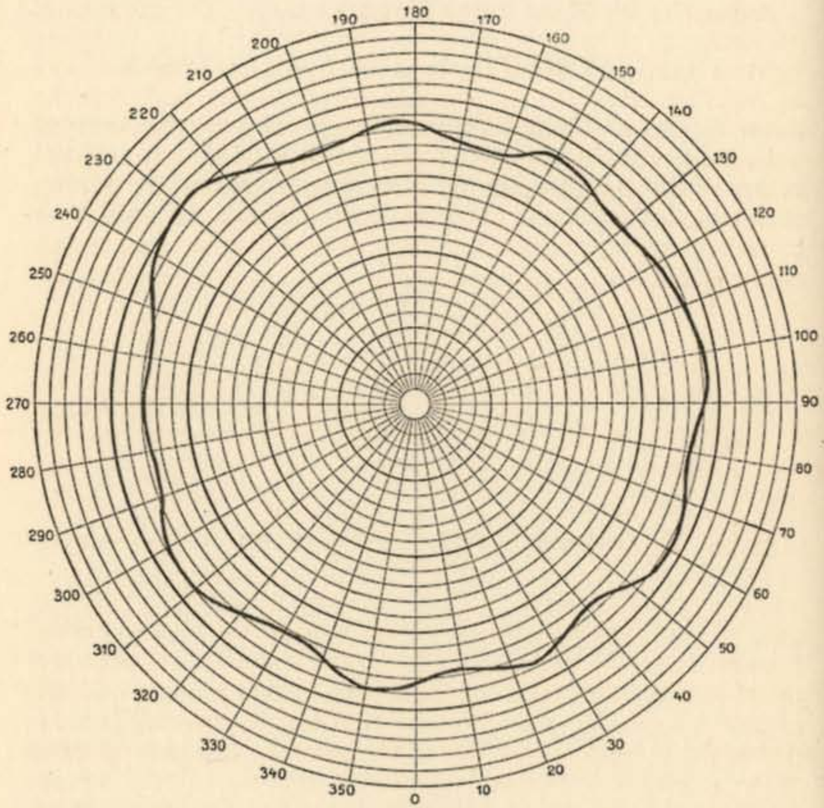


FIG. 17. Curve of Candle-power in a Horizontal Plane (Tungsten Filament Vacuum Lamp)

will be shown in the next chapter that, given a knowledge of the manner in which the candle-power of a unit varies with direction, it is possible to calculate the illumination produced by that unit at a given point, so that the determination of "polar curves" of light distribution, as they are called, is one of the most important of photometric processes. Such curves are shown for a vacuum electric glow-lamp in Figs. 16 and 17, the first being for a vertical plane, and the second for

a horizontal plane passing through the centre of the lamp. In these diagrams the length of the radius vector in any direction gives the candle-power in that direction, so that in Fig. 16, for example, the candle-power of the source in a direction at an angle of 50 degrees below the horizontal is 29 candles, while at 0 degrees (vertically downwards) it is 10 candles.

Apparatus for Polar Curve Measurements.—The method of obtaining a vertical polar curve for a source or a complete lighting unit will be understood from Fig. 18, which shows in diagrammatic form the apparatus generally used for the purpose. L is the lighting unit suspended in the vertical position so that its centre lies on the axis of the photometer bench (only the photometer head P is shown in the figure). M is a mirror, which must be large enough to exhibit a complete image of the unit when viewed from P, and which is firmly fixed to a framework capable of rotation about the

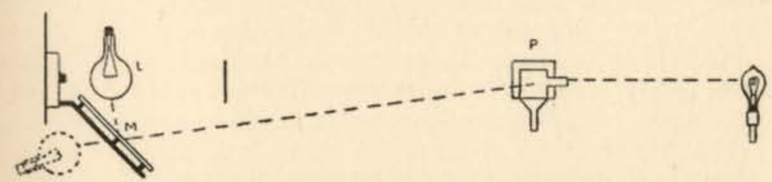


FIG. 18. Single-Mirror Apparatus for Measurement of Candle-power Distribution

axis of the photometer bench. M is tilted on its supporting framework until the rays of light from L, which are reflected by M to P, are at right angles to LP. Then for any position of the framework, the photometer readings give the candle-power of L in the direction of the mirror. Thus by placing M at different positions in a circle round L (with LP as axis) the distribution of candle-power of L in a vertical plane is found.

Of course, the distance to be used in computing the candle-power must be that of the photometer from the image of the source as seen in the mirror. The reflection ratio of the mirror must also be allowed for, so that, for example, if the mirror only reflects 80 per cent. of the incident light, the measured candle-powers must be multiplied by 1·25. The reflection ratio of the mirror may be readily determined by making a candle-power measurement with the centre line of the mirror M horizontal, and then rotating L through 90° until the part which was originally seen in the mirror from the photometer, now faces the photometer directly. The ratio of the candle-power in this position (the mirror being screened) to the candle-power previously obtained gives the factor by which the mirror measurements have to be multiplied in order to obtain true values of candle-power for the curves.

The tilting adjustment of the mirror described above is avoided by the use of three mirrors arranged at 45° as shown in Fig. 19. The principle of the method remains the same, but the light proceeds axially from the third mirror and the candle-powers measured, after allowing for the reflection ratio of the mirror system, are again those in a true plane through the source while the light reaches P normally.

With large sources the candle-power is often considerable, and to keep within the best illumination range for accurate photometry it is necessary to have the photometer head at a great distance from the source. This is further desirable when using a single mirror, or the light will reach P obliquely. It is, therefore, often convenient to mount the source and

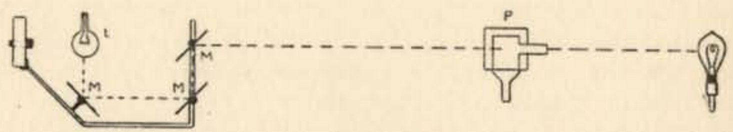


FIG. 19. Three-Mirror Apparatus for Measurement of Candle-power Distribution

mirror on the wall of the room in which measurements are to be made, and to have a photometer bench of ordinary length mounted on a table on castors so that its distance from the wall can be varied. At the National Physical Laboratory the bench is mounted on steel rollers which run in a track on the floor, and brass marks are fixed close to this track at intervals of a metre, so that, by means of a pointer on one leg of the photometer table, the bench can be moved an accurately known distance away from or towards the source.

In all that has been described above it has been assumed that the source is symmetrical about a vertical axis, so that a polar curve in one vertical plane should be the same for all such planes. This, however, is not the case in practice, and therefore it must be agreed to take the vertical distribution curve in some plane defined with respect to the source, or alternatively the source may be rotated about its vertical axis while the measurements are being made, so that the candle-power shown for any angle θ (measured from the vertical) represents the average value along all the lines forming a

cone with the source as apex and semi-vertical angle θ. When this is done, the speed at which the lamp has to be rotated may be reduced, or the flicker at any given speed may be lessened, by using two mirrors symmetrically placed with respect to the source instead of a single mirror. If this arrangement be adopted it is necessary to cut off the inner corner of each mirror so that both may be used at angles near the vertical. This method can only be applied to vacuum electric lamps, as a gas-filled lamp may change its candle-power by several per cent. if it be rotated, and rotation is clearly impossible in the case of flame illuminants.

For finding the polar curve in the horizontal plane, i.e. the plane perpendicular to the axis of the lamp, supposed upright or pendent, it is only necessary to move the lamp round in the holder and take candle-power measurements every 10 degrees or as often as may be desired.

Methods of Candle-power Rating.—The interpretation of the polar curve and its use in illumination calculations will be further explained in Chapter V, but from what has been said already, one important fact will be noticed at once. For expressing the relative performances of two sources of light, unless they be of the same pattern and therefore giving the same light distribution, a rating expressing the candle-power in a single direction is worse than useless for it may be very misleading. Vacuum electric lamps have generally in the past been rated in MEAN HORIZONTAL CANDLE-POWER (m.h.c.p.), i.e. the average of the candle-powers in all directions in a plane perpendicular to the axis of the lamp. This was generally obtained by a measurement of the lamp when rotating, and was fairly satisfactory owing to the uniform character of the lamps and of the arrangement of the filaments. The same may be said of upright incandescent gas mantles. With the advent of inverted mantles, and of the gas-filled lamp, however, no such uniformity of light distribution prevails, and, in fact, the mean horizontal candle-power of such sources by no means expresses their true performance—for it has been well pointed out that the candle-power in the downward direction is of more importance, in many cases, than the candle-power in the horizontal direction where the light has generally to be redirected by a reflector before it can be made use of. In the case of lighting fittings the over-all efficiency of a source can only be deduced from a knowledge of the candle-power in all directions. This is, in fact, the most satisfactory basis for the rating of all illuminants, and it is now being generally adopted. The AVERAGE CANDLE-POWER (a.c.p.) of a source (or lighting unit), often called its MEAN SPHERICAL CANDLE-

POWER (m.s.p.c.), is defined as the average value of the candle-power of the source or unit measured in all directions in space. For vacuum lamps and some other sources the ratio of the average candle-power to the mean horizontal candle-power is known as the REDUCTION FACTOR. Its value for a " squirrel-cage " filament lamp is 0·78, and for an upright incandescent mantle very close to the same value.

Calculation of Average Candle-power. Rousseau Diagram.—It might, perhaps, be thought that the relative performances of two lamps or lighting units of approximately symmetrical distribution could be seen at once from their respective polar curves, obtained by one of the methods described above ; but while it is true that this information can be deduced, after computation, from these curves, the appearance of the curves

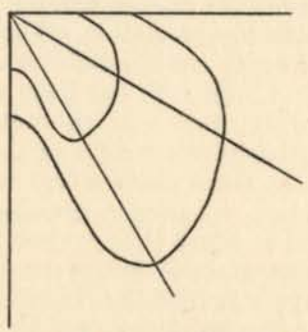
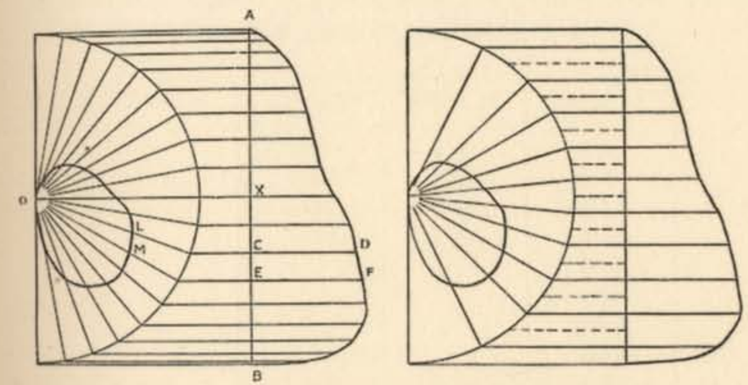


FIG. 20. Polar Curves of Two Sources of similar Distribution with Candle-powers in the Ratio of 2 : 1

themselves can be most misleading. This may be very well demonstrated by a consideration of the two curves shown in Fig. 20. All the radii vectores of the first curve are double the corresponding ones of the second, so that it is obvious that the total amounts of flux emitted by the two lamps must be in the ratio of two to one. Yet it is equally obvious that the areas of the curves are in the ratio of four to one, while the volumes of their solids of revolution about the vertical axis are in the ratio of eight to one. Clearly neither the area of the polar curve nor the volume of its solid of revolution about the vertical axis can give a mental conception of the relative amounts of flux emitted by the lamps. This can only be obtained by computation of the average candle-power of the lamp from the polar curve (in the case of a source whose candle-power performance is symmetrical about the axis of the polar curve). For, if J be the candle-power in a direction

making an angle θ with the vertical, then if we suppose a sphere of radius r to surround the source, the area of the zone of this sphere from which the source appears to have the candle-power J is clearly $2\pi r^2 \sin\theta \, d\theta$, so that the average candle-power is $\frac{1}{2}\int_0^\pi J \sin\theta \, d\theta$. The value of this expression may be obtained by a simple graphical method due to Rousseau, and termed the Rousseau diagram. Fig. 21 shows on the left the polar curve of a source of light. At the ends of the radii vectores, horizontal lines are drawn through a vertical line AB and from the point of intersection of any such horizontal a length is cut off equal to the length of the corresponding radius vector on the polar curve. Thus CD is



FIGS. 21 and 22. Rousseau Diagram and Russell Angle Method of Average Candle-power Calculation

equal to OL, EF to OM, and so on. A smooth curve is then drawn through all the points such as D, F. From the method of construction of the diagram it will be clear that the distance CX is equal to $r \cos\theta$ so that, in the limit, CE $= r \sin\theta \, d\theta$ and therefore half the area of the curve ADFB gives the average candle-power of the source. This area may be obtained either by means of a planimeter, or by erecting a series of equidistant ordinates on AB as base, and using one of the forms of Simpson's rule.

Russell Angles.—In the above method of obtaining the Rousseau diagram it will be seen that measurements of candle-power are made at regular intervals of 10 degrees (or whatever interval may be selected) and that these measurements are then spaced to give them their correct respective weights in determining the area of the curve. Russell's method consists in a predetermination of the angles at which measurements must be made to give equally spaced ordinates on the Rousseau diagram. The spacing of these angles is shown in Fig. 22 where it will be seen that the sphere is divided by the broken lines into 10 zones of equal area, and then candle-power measurements are made at the half-way points of these zones so that the area of the Rousseau diagram may be calculated at once by Simpson's rule without any need for the diagram to be drawn. The Russell angles to be used when the sphere is divided into 20, 10, 8, and 6 zones respectively, are as follow:

TABLE OF RUSSELL ANGLES FOR CALCULATION OF AVERAGE CANDLE-POWER

(Angles measured from the horizontal)

20 zones	10 zones	8 zones	6 zones
2·9	5·7	7·2	9·6
8·6	17·5	22·0	30·0
14·5	30·0	38·7	56·4
20·5	44·4	61·0	
26·7	64·2		
33·4			
40·5			
48·6			
58·2			
71·8			

The Integrating Sphere Photometer.—The above method of determining the average candle-power of a source necessitates the determination of the candle-powers in a certain number of fixed directions, and it has been necessary to assume that the polar curve is the same in all planes passing through the axis of the lamp, or else that this is sufficiently nearly the case for rotation of the lamp to give a true mean. In the apparatus now to be described this assumption is not made. The distribution of light from the source may be quite irregular and yet the correct value of average candle-power will be obtained by a single measurement provided the theoretical conditions of the apparatus be sufficiently closely fulfilled. Actually, as will be seen, the departures from these conditions rendered necessary by practical considerations make the values inexact for very unsymmetrical sources, and the cause of these

errors and their elimination will be the subject of the concluding paragraphs of this chapter.

If ABCD (Fig. 23) be a principal section of a globe, with a perfectly matt white interior surface, then the amount of flux reaching any point of the surface B from an element of the surface A is the same whatever be the relative positions of A and B. For if O be the centre of the sphere, and F the flux emitted from A in the direction AO, the flux emitted in the direction AB will be F cos OAB. Also this flux strikes the surface at B at an angle from the normal equal to OAB. The amount of flux reaching B is therefore proportional to $F \cos^2 \text{OAB}/\text{AB}^2$. But $\text{AB} = 2r \cos \text{OAB}$ and hence this expression becomes $F/4r^2$, which does not depend on the positions of A and B. Hence the flux received from A by all parts of the interior of the sphere is the same, since any two points of a sphere can be joined by a great circle.

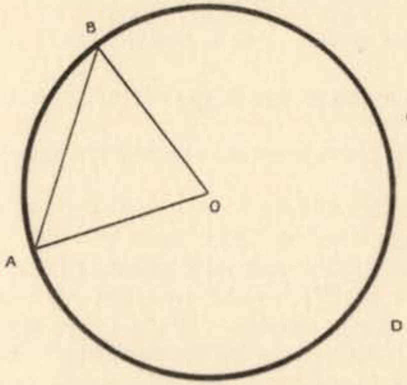


FIG. 23. Principle of the Whitened Sphere

If, then, a source of light be placed inside a whitened sphere, a certain amount of light from it reaches each part of the surface of that sphere. The amount diffusely reflected by that part to every other point of the sphere is the same and is proportional to the diffuse reflection ratio of the surface (for normally incident light if the source be placed at the centre of the sphere). Thus any particular spot on the sphere receives, in addition to its own share of the direct light from the source, a constant proportion of the light received by every other point of the sphere, and thus the illumination of a given point shielded from the direct light is proportional to the light received by all the other parts of the sphere, i.e. to the average candle-power of the source.

The exact mathematical investigation is as follows:—If F be the amount of flux per unit area which reaches the point A from the source, and if p be the reflection ratio of the surface of the sphere, then the amount of flux per unit area which reaches every other part of the sphere, due to reflection from A, is $p\frac{F}{\pi}\cdot\frac{1}{4r^2}$ since F, the flux reflected normally by a perfectly diffusing surface, is equal to the flux received by that surface divided by π (see p. 23). It is clear, therefore, that if F be the total flux emitted by the source, the amount of flux received, per unit area of the sphere, by a single reflection from each other part of the sphere is $p\frac{F}{\pi}\cdot\frac{1}{4r^2}$. Similarly the amount received by two reflections is $p^2\frac{F}{\pi}\cdot\frac{1}{4r^2}$ and so on. Hence the total flux received by reflection at any point of the sphere is

$$\frac{F}{4\pi r^2}\left\{p + p^2 + \ldots \text{ to infinity}\right\} = \frac{Fp}{4\pi r^2\,(1-p)}$$

But if J_o be the average candle-power of the source $F = 4\pi J_o$ (see p. 16), so that the above expression reduces to $\frac{J_o}{r^2}\left(\frac{p}{1-p}\right)$. But J_o/r^2 is the flux per unit area reaching the surface of the sphere, supposing all reflections absent and the source uniform in all directions. In the case of a sphere of one metre radius, a source of one candle would produce an illumination by direct light of 1 metre-candle. If the coefficient of reflection of the surface of the sphere be 80 per cent., the illumination by reflected light is $0{\cdot}8/(1 - 0{\cdot}8) = 4$ times as great as this, i.e. 4 metre-candles.

The first proposal to use this principle for the determination of average candle-power was made by Ulbricht in 1900, and many developments of the design and contributions to the theory of the sphere photometer have been made by him and others since that date. Recently a large photometer of this type has been constructed at the Bureau of Standards. This consists of a sphere of 88 inches internal diameter, built up of reinforced concrete on a steel network, and finished off inside to a truly spherical surface. There are two holes in the sphere as shown in the sectional diagram, Fig. 24. The top hole, T, is covered with a flat wooden disc which can be lowered from above in annular sections, so that a lamp can be suspended inside the sphere from above if desired. On one side of the sphere is a hinged door of segmental form, D, with

maximum dimensions, 37 × 16·5 inches. In the wall directly opposite the door, on the equator, is a milk-glass window, M, which can be removed at will, but which is perfectly flush with the inside surface of the wall when in place. By an ingenious arrangement of hinged rods carrying the lamp

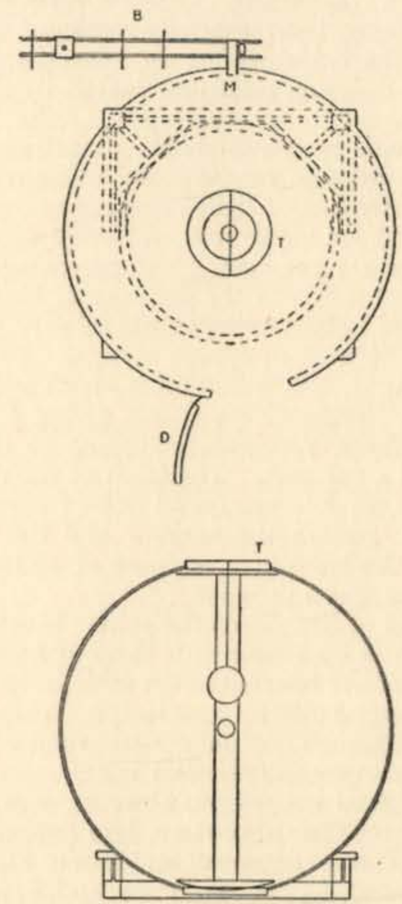


Fig. 24. Construction of the Integrating Sphere Photometer

socket, lamps can be brought to the door of the sphere for changing and then automatically returned to their correct position within the sphere. At a point about 27 inches in front of the window are two vertical rods which hold a runner for carrying the screens. These are of four sizes, viz. 11, 21, 30, and 38 cm. in diameter.

The inside coating of the sphere must, of course, be as non-selective as possible, owing to the number of reflections which much of the light has to suffer. In many cases a pure zinc white has been found satisfactory. In the Bureau sphere the inner coating is of Keene's cement, which was found to have a reflection ratio of 92 per cent.

The photometric apparatus consists of a 1·5 metre bench, B, with a photometer head specially designed for the direct comparison of the brightness of the sphere window with the brightness of a diffusing glass illuminated by the comparison lamp.

Tests were made to determine the magnitude of the errors introduced into average candle-power measurements by lack of uniform distribution of light from the source. The maximum error found for many sources having different types of distribution was 1·7 per cent. The percentage reduction of the measured value due to the presence of black discs in the sphere was found to be 10 times their relative area (i.e. ratio of area of disc to area of sphere surface). For white discs, such as the screens, this reduction is about one-third of that for black discs. Tests with a source giving a beam of light showed a maximum variation, according to the orientation of the beam, of 4 per cent. The effect of the distance of the source from the window was found to be 1 per cent. with the lamp half-way between the window and the centre of the sphere. With the lamp at a distance of 10 inches from the window the error was 2 per cent.

At the Bureau of Standards the sphere is calibrated before each period of use by means of a lamp of accurately known average candle-power inserted in the same lamp socket as that which subsequently holds the test lamps. This is the method also adopted with the cube photometer used at the National Physical Laboratory and described later.

Ulbricht's original suggestion, however, was to have both test lamp and sub-standard in the sphere during both calibration and test. This arrangement is shown in Fig. 25, where L_1 is the sub-standard, L_2 the test lamp and S_1 and S_2 screens shielding the window from these two sources respectively. A small screen S is also inserted to prevent specular reflection from one lamp when the other is alight. Calibration is effected by balancing the comparison lamp with L_1 on and L_2 off. The tests are then made with L_1 off and L_2 on.

If the window of the sphere does not form part of the photometer head, the two must be kept rigidly fixed in relation to each other. A useful adjunct is an iris diaphragm between the two, so that, when using the sphere for sources of very high candle-powers, the illumination on the photometer can be reduced. Of course the diaphragm must be at the same aperture for both calibration and test.

Correction for the Presence of Screens.—It will be seen from the theory outlined above that the illumination of the window is only truly proportional to the average candle-power of the source so long as the sphere is perfectly empty. The very presence in the sphere of a source of finite dimensions is a violation of this condition, and the fact that screens have to be introduced to shield the window from direct light at once introduces a further departure from the ideal conditions. The error caused by the presence of these bodies in the sphere is greater the larger their dimensions compared with those of the sphere. It has been laid down that the diameter of

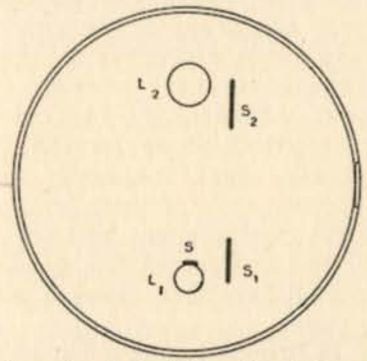


FIG. 25. Screening in the Integrating Sphere Photometer

the sphere should be not less than six times the diameter of the globe of the largest lamp to be measured in it. The screens, also, must be as small as possible and whitened on both sides. Where Ulbricht's arrangement is adopted the approximate error due to the screens, S and S_1, provided these do not exceed 5 per cent. of the area of a principal section of the sphere, has been given as $(80\,s - 100\,s_1)$ per cent. to be added to the measured value, where s and s_1 are the ratios of the areas of the screens S and S_1 to the cross-sectional area of the sphere. Where the screens are larger than this, more complicated formulæ must be employed. Where the substitution method of calibration is used, the error due to the screen may be taken as that found experimentally and given above under the description of the Bureau of Standards sphere.

The Integrating Cube.—Various modifications of the Ulbricht globe have been suggested. One of these consists of a whitened hemisphere, another takes the form of a whitened cube. The latter has been adopted for certain purposes at the National Physical Laboratory. Though theoretically less accurate, this form possesses the advantages of simple construction and greater ease of manipulation of the light sources inside it, and for the comparison of lamps of similar light distributions it has been found to give very accurate results. It has been shown that for sources as dissimilar in light distribution as a tungsten-filament vacuum lamp, unshaded, and a similar lamp of which the whole of the upper hemisphere has been covered by an opaque shade, the difference introduced into the values of average candle-power measured by the cube does not exceed 4 per cent.[1]

For certain purposes it is sometimes more important to measure the total amount of light given by a source in the lower hemisphere. This is expressed by taking the average of the candle-powers of the source measured in all directions below the horizontal plane, and is termed the average candle-power (lower hemisphere) or mean lower hemispherical candle-power. Its value may be obtained by obvious modifications of the methods described above for the determination of average candle-power. Less frequently used values are (i) the average candle-power (upper hemisphere) or mean upper hemispherical candle-power, and (ii) the mean zonal candle-power, i.e. the average of the candle-powers of the source measured in all directions within a given zone defined in any particular case.

There seems to be little doubt that the necessity for rating modern illuminants in average candle-power will cause the use of the Ulbricht globe—in comparatively small sizes for the measurement of lamps of the size generally employed in interior lighting—to become universal, very shortly, in photometric laboratories.

[1] H. Buckley. "The Whitened Cube as a Precision Integrating Photometer," *Inst. El. Eng. J.* 56, 1921, p. 143.

CHAPTER IV

MODERN LIGHT SOURCES

ALTHOUGH this book is mainly intended to give a description of the nature and amount of the illumination required for different purposes, and of the way in which the desired result may be attained and its attainment checked by photometric measurement, quite irrespective of the nature of the sources of light actually employed, it will, nevertheless, be useful at this stage to give a very brief account of the principal light sources in common use at the present time, together with an approximate figure for the amount of light which each may reasonably be expected to yield for a given rate of energy consumption.

The illuminants in use at the present time, then, may be conveniently classified as (1) those depending on combustion, and (2) those in which a solid body is heated to incandescence by some means other than chemical action. Although this classification is convenient at the present stage of the science, it would really be more fundamental to divide light sources into (1) those depending on the incandescence of a solid body, and (2) those which make use of the incandescence of a gas due to the passage of electricity through it. For both a paraffin flame and a carbon filament glow-lamp owe their light-giving properties to the incandescence of carbon, produced in the first case by chemical combustion between the hydrocarbons of the paraffin and the oxygen of the air, and in the second case by the heating action of an electric current passing through a fine thread of carbon termed the filament. Both these sources, therefore, depend on the brightness of a solid body heated to a high temperature. The incandescence of a conducting gas or vapour is a fundamentally different phenomenon, and although it appears that the path of progress in the efficient production of light lies in this direction, there are, at present, but few examples of the application of this principle in light sources used on a commercial scale. The most important are the mercury-vapour lamp and the Moore tube, and these will be described at the end of this chapter.

The Paraffin Oil and Paraffin Vapour Lamp.—Historically, the first artificial illuminant employed was some form of lamp differing very little in its fundamental principle from the paraffin lamp of to-day. The addition of a glass chimney to produce an upward draught, and therefore more complete combustion, is the chief improvement.

The chief technical uses of such a lamp to-day are in country house lighting, railway signal lights, navigation lights, vehicle lights, or as an emergency installation. This is due to the fact that such a lamp is self-contained. Other oils than ordinary paraffin are used in special cases, such as for ships carrying explosives, in miners' lamps, or for vehicle lamps subject to excessive vibration. The ordinary paraffin flame, either round with central draught, or duplex, may be taken to give about 1,000 to 1,200 candles (a.c.p.) per gallon of oil per hour. Compared with most modern illuminants the light is very yellow in colour.

It is not until we come to the paraffin-vapour lamp that a really important advance is noticeable. In this lamp the heat of the flame vaporizes the oil in a special chamber before combustion takes place. The vapour is then forced by its own pressure through a jet where it is ignited, and by its combustion it heats a mantle similar in action to that which will be described in connexion with sources depending on the burning of coal gas (see p. 58). The mantle is generally of the inverted form and, as far as distribution of light is concerned, no distinction need be drawn between this lamp and a gas-burner fitted with a mantle of the same size and shape. The colour of the light, being largely governed by the radiation from the mantle, is similar to that from a corresponding gas-mantle. Such a lamp will generally give an average candle-power in the neighbourhood of 6,000 candles per gallon of paraffin per hour.

Acetylene Lighting.—The use of acetylene gas for lighting purposes is mainly confined to country house installations, where no supply of gas or electricity is available, or to the flares used in night work on road construction or building operations, or to vehicle lighting.

The gas is generated by the action of water on calcium carbide, and very frequently this is done at the place where it is to be used, a special air-tight generator being employed to regulate the access of water to the carbide according to the pressure of the gas in the container and so to maintain a steady supply pressure at the burner. It is becoming increasingly popular, however, to use cylinders of the gas dissolved in acetone, a substance which can absorb over 200 times its own

volume of acetylene at a pressure of ten atmospheres. The danger attendant upon the use of compressed acetylene is thus avoided.

The gas is generally burnt from a steatite burner, frequently of the dual form in which two fine jets of flame impinge to give a "batswing" of high luminosity. For projector work a pastille of refractory material may be raised to a high state of incandescence by a flame of acetylene alone, or preferably by the intensely hot flame of a mixture of oxygen and acetylene.

The normal working pressure of an acetylene burner is about 4 inches of water, and from 30 to 35 candles (a.c.p.) per cubic foot of gas per hour may be obtained. A good quality of carbide will yield about 4·5 cubic feet of gas per pound.

Petrol-Air Gas.—Another system of lighting for country house work is that in which the illuminant is a mixture of petrol and air. The exact proportion of petrol varies from about 2 to 6 per cent. while the pressure of the mixture is usually maintained at a value of about 1½ inches of water. The mantles and burners used are generally of the inverted type, and the size of the nozzle is considerably larger than in the case of gas lighting. The consumption of a good type of burner giving about 20 to 30 candles (a.c.p.) is a gallon of petrol in about 130 hours.

Pintsch Gas.—For railway carriage lighting by gas the limited space available for storage renders it necessary to keep the gas under compression in a cylinder. It is found that coal gas rapidly loses its illuminating value when compressed, and it has, therefore, been largely substituted by the gas obtained by the destructive distillation of petroleum. This gas, known under the name of Pintsch gas or oil gas, is found not to deteriorate markedly when stored under pressure up to at least 12 atmospheres. The gas is used in conjunction with an inverted mantle and gives about 20 to 25 candles (a.c.p.) per cubic foot per hour.

The Gas Lamp (Low Pressure).—The gas flame in its many forms must now be considered. Originally the gas was burnt from a jet, generally in the form of a flat "batswing" flame. The illumination was derived from the incandescence of the various hydrocarbons in the gas as they united with the oxygen of the air. Modern science has devised more efficient methods of gas lighting, depending on the presence of a mantle of special solid substances which are heated by the flame, so that the self-incandescence of the gas has become of minor importance and attention is now almost entirely concentrated on its heating power, or calorific value.

The incandescent mantle, due originally to Auer von Welsbach, consists of a framework of ramie, artificial silk, or other suitable material, impregnated with a solution of thorium nitrate containing one per cent. of cerium nitrate, which is found, when heated, to emit a very intense and very white light. After impregnation, the fabric is burnt off and the resulting fragile framework of mineral oxides is dipped in collodion to give it strength sufficient for transport. When put in position on the burner this collodion is burnt off and the active framework left is raised to incandescence by the heat of the gas flame.

It has recently been found possible to manufacture "soft" mantles satisfactorily. In these the original fabric has not been burnt off during the course of manufacture, and no collodion treatment is therefore required. The use of artificial silk has been found very advantageous in the preparation of soft mantles, and this material has been stated to give better maintenance of candle-power.

The form of the mantle may be either upright or inverted. In the latter case the light is much more conveniently distributed for most purposes, the mantle, being smaller, is more robust, and the candle-power per cubic foot of gas per hour is increased, partly owing to the pre-heating of the gas before it reaches the burner. In Fig. 26 are given polar curves, showing the candle-power distribution from an upright and from an inverted mantle. The rate of deterioration of the candle-power given by a mantle is very variable according to the construction and mode of manufacture, but it has been found that for a modern mantle of the best quality this deterioration does not exceed 10 to 20 per cent. in the first 1,000 hours of burning. Such a mantle should, when new, give an average candle-power of about 12 candles per cubic foot of gas per hour, with gas having a calorific value of 500 British Thermal Units per cubic foot. With special devices designed to produce the highest efficiency in a low-pressure gas incandescent system, as much as 15 candles (a.c.p.) per cubic foot of 500 B.Th.U. gas per hour may be obtained.

The mantle is not, of course, the only factor upon which the efficiency of gas-lighting depends. It is necessary to produce an intimate mixture of air and gas in as nearly as possible the best proportions to secure complete combustion, so that the full effect of the calorific value of the gas may be made use of in heating the mantle. The exact proportion varies with the richness and pressure of the gas supplied, so that an adjustable air regulator is generally provided. An increase of

10 per cent. in the proportion of air to gas may mean an increase of about the same order of magnitude in candle-power. In the case of inverted burners it is necessary to avoid contamination of the air supply by the products of combustion, and hoods or deflecting wings are generally used to lead the waste gases away from the air intake. Sometimes use is made of these hot gases to pre-heat the gas-air mixture before combustion takes place.

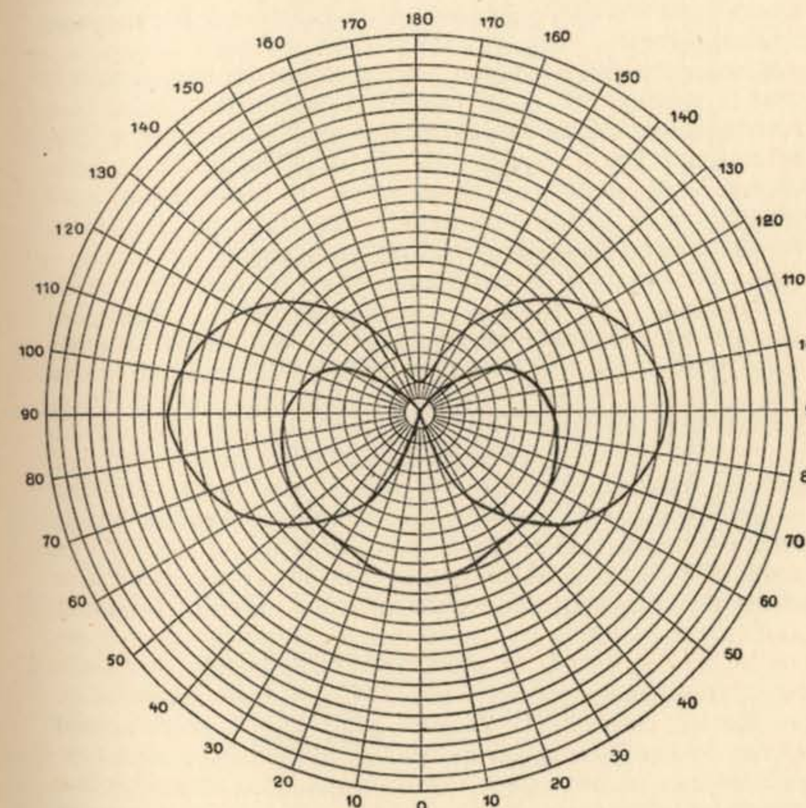


FIG. 26. Polar Curves for Incandescent Gas Mantle, Upright and Inverted

The effect of pressure of the gas supply on the actual candle-power given by a mantle, and on its efficiency, are shown by the following tables of which the first refers to a small upright incandescent mantle, the second to an inverted mantle, and the third to a high-pressure light (see next section). In the first two cases the candle-powers and consumptions have been expressed as fractions of their values at a pressure of 2·5 inches of water, and in the third case this "normal" pressure has been taken as 50 inches of water.

TABLE 1. (UPRIGHT MANTLE)

Pressure (ins. of water)	Average Candle-power (Candles)	Consumption (Cubic ft. per hour)	Candles per cubic ft. per hour
1·0	0·74	0·84	0·88
1·5	0·82	0·90	0·91
2·0	0·90	0·95	0·95
2·5	1·00	1·00	1·00
3·0	1·06	1·03	1·03
4·0	1·15	1·09	1·05
5·0	1·24	1·16	1·07

TABLE 2. (INVERTED MANTLE)

Pressure (ins. of water)	Average Candle-power (Candles)	Consumption (Cubic ft. per hour)	Candles per cubic ft. per hour
1·0	0·51	0·67	0·76
1·5	0·72	0·80	0·90
2·0	0·88	0·91	0·97
2·5	1·00	1·00	1·00
3·0	1·08	1·08	1·00
4·0	1·19	1·17	1·01
5·0	1·25	1·22	1·02

TABLE 3. (HIGH-PRESSURE GAS)

Pressure (ins. of water)	Average Candle-power (Candles)
45	0·93
50	1·00
55	1·06
60	1·12
65	1·16

It will, of course, be readily understood that the above figures can only be regarded as giving an approximate idea of the magnitude of the effect resulting from a given change of gas pressure. So much depends on the type of burner used, particularly as regards air regulation, that it is impossible to give any figures which will have anything approaching universal application.

High-pressure Gas.—The chief improvement which has been made in gas lighting since the introduction of the incandescent mantle is the use of high-pressure gas. Ordinary low-pressure systems work on a pressure of some 2 inches of water above atmospheric pressure. On high-pressure systems pressures from 50 to 100 inches have been employed. The pressure is used to force a very intimate mixture of gas and air through a pre-heater placed so as to utilize the heat from the burner. The secondary air supply to the burner is also heated before it comes into contact with the mantle, so that a flame of very high temperature, and consequently greatly increased efficiency, is produced. With such an arrangement a performance of about double that given by the most efficient low-pressure lamp may be obtained. Systems operating on a similar principle, but using either low-pressure gas and high-pressure air, or a mixture of compressed gas and air, have also been designed.

Naturally the use of a high-pressure supply puts a more severe strain on the strength of the mantle, and as long a life cannot be obtained as in the case of a low-pressure system; 300 to 400 hours is generally regarded as a satisfactory burning period for a mantle on high-pressure gas.

Methods have been devised for the control of gas lighting from a distance. These fall into three classes, according as they depend on (i) the use of a by-pass, the main outlets being opened or closed by a pressure wave sent along the pipe, (ii) electric ignition by spark or heated filament, or (iii) self-ignition by the spontaneous chemical action of a catalyst, such as platinum black.[1]

The Electric Glow-Lamp.—Of all the present-day light sources which do not depend upon combustion, the electric incandescent glow-lamp is undoubtedly the most extensively used. In this lamp, in its first practical form, a very thin filament of carbon, contained in an exhausted bulb, is brought to incandescence by the passage through it of an electric current. The highest temperature to which it is possible to raise such a filament is approximately 2100° C. absolute, and this results in the production of a light which, while whiter than that given by the paraffin flame, is not nearly so white as that given by the incandescent gas mantle.

The original form of carbon-filament lamp gave approximately 0·2 candles (a.c.p.) per watt of electrical power. By

[1] *Zeits. für Beleuchtungswesen*, 1909.

special treatment of the filament it was found possible to improve this performance by about 20 per cent., but the greatest step forward in the electric lamp was the introduction of a metal filament in place of the carbon, so that a higher filament temperature could be attained with a consequently much improved efficiency.

The Tungsten Filament Lamp.—The first metal used for this purpose was tantalum, but this has now been generally superseded by tungsten (wolfram). A tungsten filament possesses the advantage, already mentioned, that it can be raised to a higher temperature than carbon, but in addition it possesses to some extent the same property as the materials used for the gas mantle in that its radiation is selective in favour of the visible part of the spectrum, i.e. it gives more light than a carbon filament even supposing the latter raised to the same high temperature as the tungsten.

The light given by the tungsten filament lamp is, naturally, much whiter than that of the carbon filament lamp. Its efficiency is also much greater, a lamp of normal size and rating giving approximately 0·6 to 0·7 candles (a.c.p.) per watt. The life of such a lamp is generally 800 to 1,000 burning hours, a lamp being regarded as of no value when its candle-power has dropped to 80 per cent. of its initial value. The fall of candle-power is due partly to a thinning of the filament, and partly to blackening of the glass bulb with consequent absorption of light. The connexion between the efficiency of an electric lamp and the life which it will have, on the average, is very intimate, so that the voltage must be regulated as carefully as possible in order to avoid undue dimming of the light on the one hand, or too short a life of the lamp on the other. This point will be considered again later in this chapter.

It has been customary in the past to rate electric lamps in terms of the mean horizontal candle-power, i.e. the candle-power they will give in directions at right angles to the axis. The polar curve for a vacuum lamp of normal construction, in which the filament is arranged in a series of elongated loops, disposed about the glass stem in the form of a cylinder (the squirrel-cage type) is shown in Fig. 17, p. 42. From this it will be seen that the candle-power has its maximum value in a direction perpendicular to the axis, and, as a matter of fact, for all lamps of this type the average candle-power is very close to 78 per cent. of the mean horizontal candle-power. This figure, expressing the relation between the mean horizontal and the average candle-powers, is often referred to as the "reduction factor" of the lamp.

The candles per watt which can be obtained from an electric lamp with a 1,000 hour life vary slightly with the size and the voltage for which it is designed. The performances of typical sizes are shown in the Table below :—[1]

Size of Lamp	Average Candles per Watt.	
	Low Voltage (100–120)	High Voltage (200–240)
30 watt	0·67	0·61
60 watt	0·71	0·67
100 watt	0·74	0·71

For the same size, i.e. watt rating, the high-voltage lamps are more fragile than the low-voltage, since the filament must necessarily be finer and longer. The majority of metal filament lamps are now made with filaments of drawn wire, and these possess a much greater strength than the older squirted filaments. Most modern lamps will burn satisfactorily in any position, upright, pendent, or inclined. The most favourable position is still, however, pendent. Lamps required to withstand much vibration, such as those used for traction purposes, are made with the filament loops as short as possible.

The metal filament possesses one important feature which has to be remembered when arranging a local fuse to a bank of lamps. This is the fact that the resistance of a lamp filament when cold is only approximately one-tenth of its value when at working temperature. Consequently when such a lamp is first switched on there is a momentary rush of current which sinks down to normal in a fraction of a second, when the filament has attained its proper temperature. It has often been stated that this overshoot of current is harmful to the lamp filament, and that, therefore, repeated switching on and off is prejudicial to the life of a lamp. Experiment has failed to substantiate this statement in the case of vacuum lamps and, indeed, it seems hardly reasonable *a priori*. The chief factor determining the life of a filament is its temperature. As soon as the temperature rises the overshoot of current is checked, and in fact it has been shown that there is little, if any, overshoot of temperature. In these circumstances it is

[1] Adapted from the Specification for Tungsten Filament Vacuum Lamps issued by the British Engineering Standards Association.

difficult to see how the life can be materially affected. The same argument shows that there should be no difference in the life of a lamp whether it be run on alternating or on direct current. This does not hold, necessarily, for gas-filled lamps into the life of which other factors are found to enter.

The chief factor to be reckoned with in preserving electric lamps, whether metal or carbon filament, is over-voltage. The candle-power given by a metal filament lamp increases by 3·5 to 4 per cent. for every 1 per cent. increase in the voltage applied to it. For this reason the use of a lamp at too low a voltage is uneconomical. In fact, since the current through the lamp only increases at slightly more than half the rate of the voltage, it follows that a 1 per cent. increase in voltage means at least 2 per cent. increase in candles per watt. Now it may be taken as a rough approximation that a 1 per cent. increase in the efficiency of the lamp produces a 6 to 8 per cent. decrease in the life, so that 1 per cent. increase in voltage means something like 15 per cent. or more decrease in life. The importance of a life test to determine what is a reasonable voltage for any type of lamp will be at once appreciated, and claims of high efficiency should always be supported by a test for life and maintenance of candle-power.

Life-Testing of Electric Glow-Lamps.—It may be convenient here to give a brief outline of the methods used for determining the behaviour throughout life of electric glow-lamps. In general the candle-power of such lamps falls gradually as the lamp is run (after a short initial period of somewhat uncertain behaviour, generally including a preliminary rise), and this fall continues until the filament is fractured. It is clear that after the candle-power has decreased by a certain amount, the lamp becomes uneconomical in use and should be replaced. The life to this stage is termed the " useful life " of the lamp, and is frequently defined as the time which elapses before the candle-power falls to 80 per cent. of its initial value (the voltage being maintained constant throughout the run) or to previous failure, provided this does not take place by accidental means (i.e. when the lamp is not burning).

A life test may be made under several different sets of conditions, and these conditions must be carefully specified in order that the desired information may be afforded by the test. The simplest form of test is that in which the lamps are run throughout at constant (generally rated) voltage, all the photometric measurements being made at this voltage. Such a test does not, however, give the most reliable information as to the life performance of a set of lamps. Since life-testing must necessarily be by sample, it is essential that the conditions

under which the sample lamp is run shall be such as to give the nearest approximation to the average life of the lamps which it represents. This is best attained by a test at definite efficiency, i.e. the average working efficiency of the batch of lamps represented by the life-test lamps. This, of course, involves the adjustment of the voltages on each of these lamps to the values at which they give this definite efficiency. In general, therefore, each life-test lamp must run at a voltage peculiar to itself, and provision must be made for this arrangement in designing any equipment for the life-testing of electric lamps. A less satisfactory alternative, when this correct procedure is not possible, is to select as life-test lamps those whose efficiency at rated voltage happens to be nearest to the mean or rated value. These lamps are then tested for life at rated voltage.

The life of most modern electric lamps at normal working efficiency is from 500 to 2,000 hours, and many attempts have been made to avoid the long delay occasioned by tests such as those described above, and to substitute tests at a higher efficiency. By this means a shorter life is obtained, and then some form of correction factor is applied in order to calculate the life at normal efficiency. Such a test is termed a " forced " life test. The chief difficulty of this method lies in the fact that correction factors differ widely for lamps of different construction, and reliable factors can only be obtained as the result of life tests of large numbers of similar lamps under normal and " forced " conditions. Even with this information the correction factors can only be applied over a comparatively small range of efficiency, but nevertheless a considerable amount of time is saved by adopting this procedure where accuracy is of less importance than speed. The subject of the correction factors applied in forced life tests will be referred to again in the concluding paragraphs of this section.

From what has been said above it will be clear that in any life-test installation, two requirements of first importance are (1) a current supply of which the voltage is carefully regulated, and (2) arrangements for applying any desired voltage to each particular lamp on test. The apparatus used for this purpose at the large testing laboratories are generally similar, differing only in details of arrangement. The description here given is of the installation at the National Physical Laboratory, but that of the Bureau of Standards is not greatly different in general principle.

An alternating current supply of 55 cycles and 240 volts from a dynamo coupled with a Tirrill regulator feeds an autotransformer from which leads are taken to a number of racks supported in an iron framework. A diagram of the wiring of one of these racks is given in Fig. 27. The pick-off points of the transformer permit of any desired voltage in steps of 5 volts being applied to the leads of any rack. This voltage is further adjustable by means of a series resistance, so that if lamps are being run at specified voltage they can be put in the sockets on the rack, and the terminals T_1 T_1, T_2 T_2, etc., can be connected by short pieces of copper wire.

More frequently, however, the voltage at the terminals of each lamp on the rack is different, and then small resistances are inserted between the terminals T_1 T_1, T_2 T_2, etc. Each of these resistances is, to the nearest tenth of an ohm, that required to give, with the current taken by the lamp to which it applies, the necessary voltage drop between the rack leads and the lamp terminals. Before the lamp is put on life test,

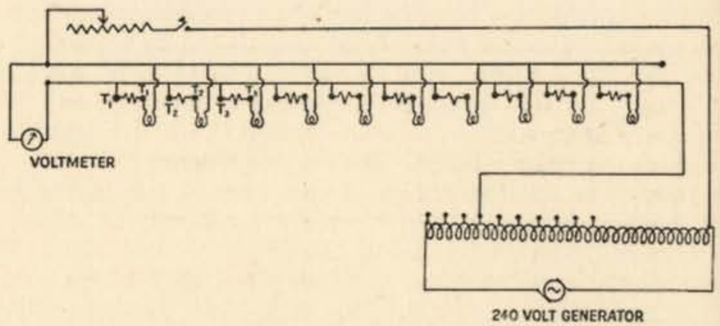


FIG. 27. Arrangement of Wiring for Life Test

measurements of candle-power and current at various voltages are made in the usual way (see p. 30), and the voltage at which the desired efficiency is obtained is then deduced. This voltage then becomes the life-test voltage of the lamp, and no attempt is made to alter this voltage as the efficiency of the lamp falls with lapse of time. Further, the candle-power measurements at stated intervals during the run are made either at this life-test voltage or, more frequently, at rated voltage. These measurements are often made at the expiration of 0, 50, 100, 200 and each subsequent 200 hours after the commencement of the test. In the case of a forced test the intervals at which candle-power measurements are made may be much shorter than this, as the total life is reduced in length.

The racks are so arranged on their framework that the lamps can be burnt upright or pendent, the latter being the more usual condition. The racks are inspected at frequent intervals and failures are noted, as far as possible to the nearest hour. It is the usual practice to regard any lamp,

the filament of which fractures when no current is passing through it, as having accidently broken. The results on such a lamp are then not included in determining the average life of the group to which it belongs. If the filament of a lamp should break, and fall across another portion, so as to complete the circuit through the lamp and cause it to burn, that lamp is nevertheless regarded as broken, and removed from the test.

Lamps are generally run until failure of the filament occurs, or until the candle-power, measured at one of the intervals mentioned above, shows more than 20 per cent. drop below the initial value. The interpretation of life-test results is a matter requiring very careful consideration. It is usual to draw the candle-power time curve for each individual lamp, and then to draw two curves showing respectively the mean candle-power and the mean value of watts per candle for

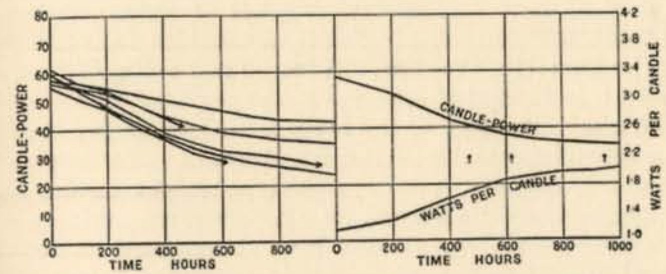


FIG. 28. Diagram of Results of Life Tests on Electric Lamps

the whole number of lamps burning at any time. Thus in drawing these latter curves, lamps removed from the test, either on account of breakage or candle-power fall, are not included in computing the averages for times subsequent to their removal. A set of such curves for a batch of six lamps is shown in Fig. 28, where the individual candle-power curves are shown on the left, and the mean candle-power and mean watts-per-candle curves are shown respectively above and below on the right. The removal of a lamp from the test is indicated by an arrow at the appropriate point on the time scale.

For specification purposes, however, it is desirable to have, in addition to the full information afforded by the curves, some figure of merit for the life-test lamps, by which it may be possible to judge of the probable performance of the lamps they represent. The figure adopted by the British Engineering Standards Association in this country is the "test life" defined as the average number of hours burnt by all the lamps in a group, throughout a specified running period. It is, therefore, the total number of hours burnt by all the lamps in a group, throughout each running period, divided by the number of lamps.

The advantages of speed and economy of power possessed by a forced life test were pointed out earlier in this chapter, as well as the difficulties attending the correct interpretation of such tests. These difficulties are diminished in proportion as the extent of the "forcing" is reduced. The extensive life tests carried out at the Bureau of Standards are made at efficiencies corresponding to about 0·9 to 0·95 watts per candle for tungsten lamps rated at from 1 to 1·15 watts per candle, and in many other cases the use of forced life tests is customary.

The determination of the conditions under which a forced test is to be run may be made in two different ways. The first method is to measure the voltage at some stated watts per candle, and to multiply this by a constant factor to determine the forced test voltage. A forced test voltage in common use with this method in America is 130 per cent. of the voltage at which the efficiency of the lamp is 1·23 watts per candle.

The second method is to run the lamps at the voltage which gives them, initially, some specified watts per candle higher in efficiency than the normal by a constant amount.

The life-test voltage having been determined as above, it is usual to make the photometric measurements at rated voltage for the sake of consistency and simplicity in records.

It is usual to reduce the life results of a forced life test to those of a test at normal efficiency by means of a relationship, such as the following :—

$$(\text{life}) = (\text{constant}) \times (\text{watts per candle})^n$$

for although n is not constant over a wide range of variation of the efficiency, yet within the limits of 15 per cent. in voltage above and below normal, the error in the computed life will not be serious if the departure of the efficiency from the normal value is not too great.

At the Bureau of Standards the value 7·4 is used for all sizes of tungsten lamps from 25 watts upwards, and the value 5·83 for carbon lamps. The same value of n cannot be applied to all interpretations of a forced life test. The figures given above refer to a "useful life" interpretation, i.e. life to 80 per cent. of initial candle-power, or earlier burn-out.

An important factor in the loss of candle-power during the life of a lamp is the blackening of the bulb, especially if this be small compared with the size of the filament. Some lamps

contain bulb-blackening preventives, which depend for their effective operation on the temperature of the bulb. It will be clear that if the variation of the action of this preventive with change of temperature is different in two classes of lamps, the life efficiency factor will be different also, and this effect requires consideration when forced life tests are being made.

It is also desirable that the number of life-test lamps should be a larger percentage of the total number of lamps represented than is the case with more normal tests. The standard specification of the British Engineering Standards Association calls for a life test on at least one half of one per cent. of the lamps in a batch, with a minimum of 5 lamps, in the case of ordinary tests, and this number should be doubled or trebled in the case of special, or of forced tests.

When setting up lamps on life test, it is, of course, necessary to ensure that failure of one lamp does not entail excess voltage on any of the others. Thus life-test lamps must not be set up in parallel on a circuit containing any appreciable external series resistance, otherwise the failure of one lamp will increase the effective resistance of the lamp portion of the circuit, with consequent rise of voltage to act adversely on the life performance of the remaining lamps. Constancy of voltage is, in fact, one of the chief requirements of a reliable life-test, and the B.E.S.A. Specification, referred to above, calls for a limit of variation which shall not exceed one per cent. as regards momentary fluctuations, or what is appreciable on an ordinary large-scale type indicating voltmeter as regards permanent error in the voltage at which the lamps are run. The reason for this requirement is readily understood from the high value of the life-efficiency characteristic when it is remembered that this means a life-voltage exponent of between 15 and 50 for a vacuum-type tungsten filament lamp. The degree of dependence of life upon efficiency for gas-filled lamps has not yet been determined, and it will probably prove to be extremely variable owing to the large number of independently variable conditions in this type of lamp.

The Gas-Filled Lamp.—The most important improvement effected in the electric lamp since the introduction of the tungsten filament, is the production of the gas-filled (sometimes misleadingly called "half watt") lamp. The limiting factor in the efficiency of the tungsten filament is the maximum temperature to which it can be raised without appreciable volatilization. It was found that this temperature could be greatly increased by surrounding the filament with an inert gas at pressures of the order of one atmosphere. The gas used is generally nitrogen in the larger lamps and argon in the smallest, mixtures of these two gases in various proportions being also employed. Another important difference is the disposal of the filament in the form of an exceedingly fine and close spiral. This tends to prevent too rapid a cooling of the filament by the convection currents in the gas filling the bulb. In spite of this coiling of the filament, however, a considerable amount of heat is lost by conduction and convection, and were it not for this fact the efficiency of the gas-filled lamp could be made appreciably greater than it is at present.

The coiled filament leads to a far greater concentration of the light source than is customary with the vacuum lamp, although coiled filaments are now being introduced into these lamps as well. The brightness of the filament of a gas-filled lamp greatly exceeds that of any other artificial illuminant in general use, except the arc crater. The importance of preventing such filaments from coming into the field of view cannot, therefore, be over-emphasized.

The performance of gas-filled lamps varies greatly with the size and voltage, and is undergoing continuous improvement at the present time. It may, however, be assumed as approximately 1·25 candles (a.c.p.) per watt for the larger sizes (i.e. 200 watt, 100 volt, or 400 watt, 200 volt, or over) and 0·8 candles per watt for the smallest sizes (60 watt). The life of gas-filled lamps is, at present, uncertain, but those of the larger sizes, at least, have about the same life as a vacuum lamp.

Fig. 29 shows the polar curves obtained for two of the most common forms in which the filaments of gas-filled lamps are disposed in the bulb; curve A refers to a filament in the form of a horizontal ring, curve B to a filament consisting of a series of V's arranged vertically about the axis of the lamps. The output of gas-filled lamps is nearly always expressed in "average candle-power."

Occasionally electric lamps are run in series on a high-voltage circuit. When this is the case it is important to ensure that each lamp in the series takes as nearly as possible the same current; otherwise the lamp of lower current will be seriously over-run. Generally, lamps to be used for burning in series are sold specially for this purpose, and are those whose filaments are made from the same reel of wire.

Gas-filled lamps are less liable to failure on alternating than on direct current, owing to the tendency for electrolysis to take place in the glass stem in the latter case.

The Electric Arc.—The other type of lamp depending upon the incandescence of a solid body heated by electric means is the arc lamp in its many forms. The simplest type of arc

lamp is that in which the electrodes are two rods of carbon with a small gap between them. When a current is once started in the circuit, either by momentary contact of the carbons, or by the ionization of the space between them by a smaller subsidiary arc, the current continues to bridge the gap and the end of the positive carbon (and also that of the

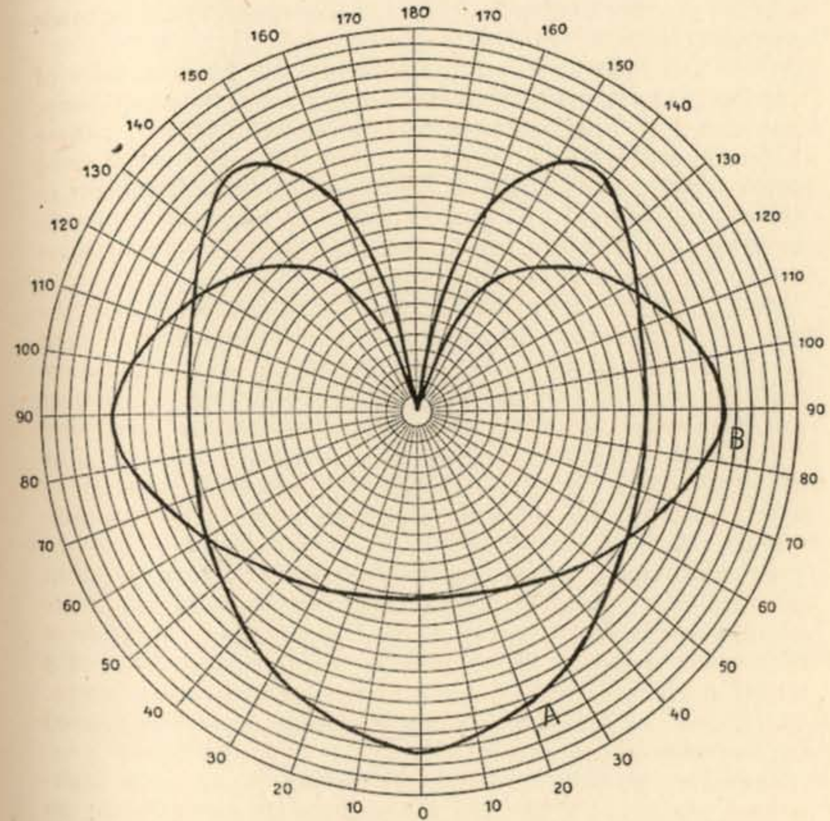


Fig. 29. Polar Curves of Gas-filled Electric Lamps
Curve A—Ring Filament
Curve B—Looped or Festoon Filament

negative carbon to a much smaller extent) becomes intensely brilliant. The flame between the carbons is also incandescent, but in the plain arc the light given by the flame is almost negligible in comparison with that due to the positive crater. The carbons are gradually consumed as the arc is kept burning, so that mechanism has to be provided for automatic feeding together as soon as the distance between the ends becomes too great. This is generally performed by a solenoid and ratchet arrangement which is brought into operation as soon as the potential difference across the arc becomes too great. This type of arc gives approximately 1·6 candles (a.c.p.) per watt, with a running period, without renewal of carbons, of 10 to 15 hours. This figure does not include the power

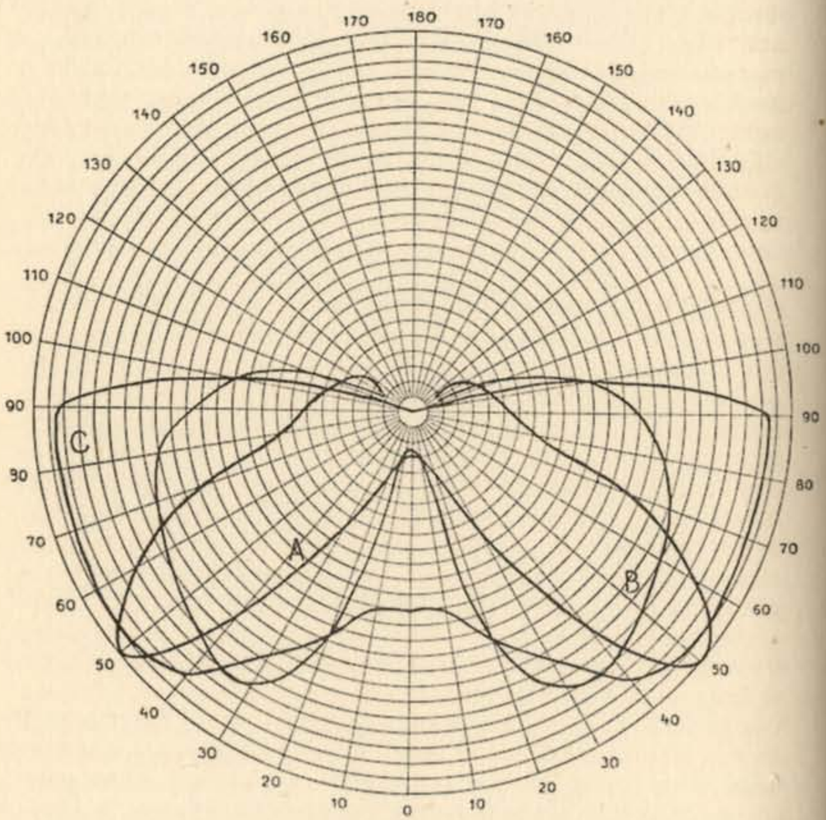


FIG. 30. Polar Curves of some Arc Lamps
Curve A—Plain Arc
Curve B—Jandus D.C. Enclosed Flame Arc
Curve C—Inclined Carbon Flame Arc

absorbed in the series resistance. In an "enclosed" type, where the carbons are burnt in an enclosed space to reduce oxidation, a renewal period of 100 hours or more may be obtained, but the performance is reduced to 50 or 70 per cent. of that of the open type. In these arcs, the end of the negative carbon obscures some of the light from the positive crater,

so that the polar curve of a plain arc is like that shown in curve A of Fig. 30. Arcs of this kind may be used on alternating current, but in this case a crater is formed on both carbons, and the polar curve is more symmetrical. The over-all performance, however, is not so good as with continuous current.

The most important improvement introduced into the design of the arc lamp was that of making the carbons hollow and filling them with a core composed of a special mixture of carbon and certain metallic salts. In these arcs the flame itself is intensely luminous and forms the principal source of light. Very frequently the carbons are placed so as to form the arms of a V with the arc flame bridging the gap at the bottom. For direct lighting this arrangement has the advantage of avoiding the obscuration by the negative carbon. One of the chief drawbacks of the flame arc lamp is the necessity for frequent renewal of the carbons and the various types of flame arc, such as the Excello, the Jandus regenerative arc, the Angold-Crompton, and the Oriflamme (to mention but a few), all possess certain special features designed to prevent too rapid a consumption of the carbons, or, alternatively, the arrangement of a magazine of carbons designed to come into operation in succession without attention. The deposition of fumes on the globe is a further drawback which has to be overcome by special design. The chief advantage of the flame arc is its relatively high efficiency, from 2 to 3 candles per watt being readily obtained. In the case of the performance of all arcs, however, there must be added to the consumption the power lost in the series resistance required for stabilizing the arc, or for the purpose of reducing the supply voltage to the 50 or 60 volts generally required across the arc. Occasionally arrangements are made for running a number of arcs in series so that the actual over-all performance is dependent upon the special circumstances of the case. The polar curves of some arcs are shown in Fig. 30.

An arc not employing carbon is the magnetite arc in which the positive electrode is of copper, while the negative consists of a mixture of the oxides of iron, chromium and titanium, enclosed in a thin tube of iron. Here again the light is derived from the flame which is intensely white. The arc gives about 1·5 candles per watt.

The Tungsten Arc.—The most recent form of lamp, the tungsten arc (or "pointolite" lamp) consists of a positive electrode in the form of a ball of tungsten raised to brilliant incandescence by the electronic stream from a negative tungsten plate. The arc is struck by the ionization of the intervening space due to electronic emission from a short tungsten filament covered with refractory oxides which is first switched on, and is then cut out of circuit when the arc has started. The efficiency is of the same order as that of a gas-filled lamp. The intense concentration of the source makes this lamp specially suitable for projection work.

Incandescent Vapour Lamps: The Mercury-Vapour Lamp.—Although the flame arcs have, for the sake of convenience, been described with the lamps depending for their light on the incandescence of some solid body, they really belong to the class of lamps now to be described, where the light is due to emission from a glowing vapour. These lamps, as a class, present the peculiarity that their light may differ widely in colour from that of other illuminants. In the case of a solid body, the light emitted depends mainly on its temperature; and as this temperature has been gradually raised from that of the paraffin flame to that of the positive crater of a plain carbon arc, so the light produced has gradually increased in whiteness, though it is still far from approaching daylight, the light given by a luminary whose temperature it is at present impossible to attain on the earth.

In the case of a glowing gas or vapour, however, matters are different. Every such gas gives light of a certain hue, or a mixture of different hues. Most of the flame arcs mentioned above give either a white or a distinctly yellow light, but in the case of the mercury-vapour lamp the predominating colour of the light is a greenish-violet which causes red objects to appear almost black, and shows up blues and violets to a remarkable degree.

This lamp consists of a horizontal exhausted tube containing two electrodes and a small quantity of mercury. The lamp is started by tipping the tube so that the mercury runs down to one end and makes contact with the electrode. As the tube is brought back to the horizontal and the mercury leaves this electrode it starts a long arc and the tube is then filled with glowing mercury vapour. Sometimes the starting is done automatically. The voltage depends on the length of the tube, an appreciable part being absorbed in series resistance. The lamp gives about 1 to 1·3 candles (a.c.p.) per watt absorbed in the tube itself. As has been already stated, the light from this lamp is of such a hue as to cause objects illuminated by it to appear in very unnatural colours. Attempts have been made to improve this by the addition of substances to the mercury, by the use of a combination with a tungsten-filament lamp, or by making use of the ultra-violet components to produce a pink fluorescence in

rhodamine or similar dyes. Recently an improvement in the efficiency of the lamp has been brought about by the use of a quartz tube instead of glass, thus enabling the lamp to operate at a higher temperature and pressure. With this arrangement a performance as good as 2 candles per watt used in the tube can be obtained. The candle-power given by a mercury-vapour lamp diminishes very rapidly to about 85 per cent. of its initial value in the first 200 hours, and then more gradually to 70 per cent. after about 3,000 hours burning.

The Moore Tube.—Another important lamp utilizing the luminescence of a gas is the Moore Tube, which consists of a glass tube containing nitrogen at a low pressure. This lamp works on the same principle as the Geissler tube, but a special device has to be employed to maintain the pressure of the gas inside the tube at a constant value. Very high voltages are needed, and a local transformer has to be employed. The tube may be of any length from 30 to 200 feet or more. The intrinsic brilliancy is low and the tube may be conveniently taken round the cornice of a room, no screening being necessary. The colour of the light is slightly pink, and the output approximates to half a candle per watt. If carbon dioxide be used instead of nitrogen, the light is very white but the lamp is not so efficient. The light, however, has been used where a close approximation to daylight is required (see Chapter X, p. 172). Neon gives a much higher efficiency, approximating to 2 candles per watt, with a deep red light. It has been suggested that a combination of neon tube with a mercury-vapour lamp might give a satisfactory approximation to daylight.

With regard to the relative advantages of the different systems of lighting, little can be said on general lines. Every problem must be considered on its own merits by the lighting engineer, and the above description of the different illuminants now available has been given only as a guide to the choice of that one—or it may well be that combination—which will give the best result when all the special circumstances of the case are taken into consideration.

CHAPTER V

THE MEASUREMENT AND DISTRIBUTION OF ILLUMINATION

In Chapters II and III of this book a description has been given of the measurement of the candle-power of a source of light, and of the manner in which the candle-power varies in different directions. In the present chapter, however, what is dealt with is the actual illumination at a surface, due, perhaps, to a number of sources of the same or of different kinds, and in the measurement of this illumination no attention whatever is paid to the source of the light.

The Illumination Photometer.—The illumination photometer, then, is an instrument for determining the illumination in any given position, and this is done by placing a matt white surface in that position and measuring its brightness by comparison with that of another surface contained in the instrument. The illumination of this latter surface is variable at will by the movement of some part of the instrument, so that, with a scale previously calibrated, the value of the illumination of the outside surface can be at once obtained. This will be better understood from a description of the first accurate illumination photometer designed.

The Weber Photometer.—This photometer is shown in vertical section in Fig. 31. L is a benzine lamp which acts as a source of standard candle-power, S is a translucent screen, the brightness of which is variable by moving it along the tube T_1, while its position is given by a pointer moving over a scale of illumination engraved on the outside of this tube. C is a Lummer-Brodhun cube and P is a total reflection prism for use when the tube T_2, which is capable of rotation about the axis of T_1, is used in the vertical position shown. The upper end of T_2 is closed by an opal glass disc and this forms the surface the illumination of which is to be measured. In later forms of the instrument a small electric glow lamp supplied by a portable battery is substituted for the benzine lamp.

The Sharp-Millar Photometer.—A more elaborate photometer on a somewhat similar principle is that of Sharp and Millar.

The plan of this instrument is seen in Fig. 32. L is the lamp, a 4-volt glow-lamp, which is capable of movement along the box by means of an endless wire moved by the handle H. The position of the lamp is indicated by the shadow of a pointer on a translucent celluloid scale at F. This lamp illuminates

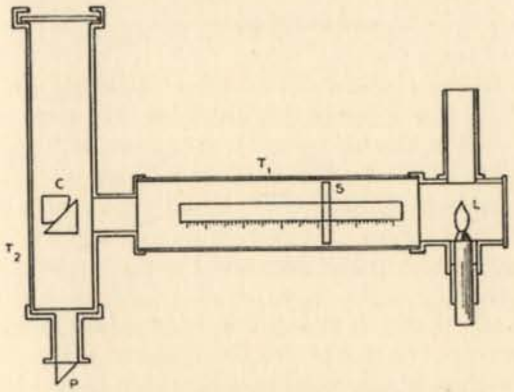


FIG. 31. Weber Illumination Photometer

an opal screen S_1, and the brightness of this is compared, by means of a Lummer-Brodhun cube viewed through the eyepiece E, with the brightness of a ground opal glass screen S_2 reflected in a 45 degree mirror, contained in an elbow tube of which T is the plan. The illumination to be measured is that at S_2 and the range of the instrument is increased by the insertion of neutral glasses, with known transmission ratios, between C and either S_1 or S_2.

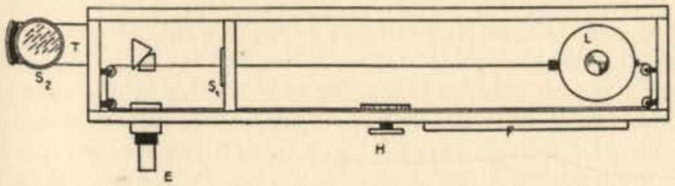


FIG. 32. Sharp-Millar Illumination Photometer

This photometer possesses the great advantage that the test-plate S_2 is viewed from below, so that its illumination is completely unobstructed by the person of the observer or any part of the apparatus. This is of considerable importance since, when the number of sources contributing to the illumination is large, it is often difficult for the observer to avoid shading one or more of them from the test-plate when this is viewed, as is usually the case in illumination photometers, from above.

It is also claimed for this photometer that the brightness of the comparison disc S_1 varies exactly as the inverse square of the distance from it of the lamp L. This is probably the case unless this distance is made too short, when the inevitable effect of interior reflections will be to cause departure from the exact inverse square scale.

The Trotter Photometer.—For street lighting and outdoor work generally the Trotter Illumination Photometer is very convenient. It is shown in vertical section in Fig. 33. L is a small 4-volt glow-lamp mounted in a screw socket, which is carried on a bracket sliding on a vertical bar B. By this means the distance of L from a mirror M can be varied to suit the candle-power of the particular lamp used in the photometer at any time. The light is reflected by M to a matt white celluloid screen C which is capable of rotation about an axis perpendicular to the plane of the paper. This rotation is effected by means of the snail cam A which moves a pin on C. This cam is so shaped that the angular motion of the celluloid surface is much slower than that of the cam at the positions where the light from M reaches C very obliquely. For at these positions it follows from the cosine law that the illumination will vary very rapidly with the inclination of C, so that unless a cam such as that shown is provided, the scale becomes very compressed at the lower values of illumination. A light leaf spring E gives just enough friction to hold the screen in any position while yet allowing a very free movement of the cam. The pin attached to C is held in close contact with the cam by means of a flat spiral spring. S is a knife-switch by means of which L can be lighted from a 2-cell accumulator connected to the terminals T_1 T_2 of the photometer. At the top of the box is a second matt white celluloid surface F, and the photometer is placed so that this surface is in the spot at which it is desired to measure the illumination. A plan view of F is shown in Fig. 33A and the measurement is made by viewing C through the slit in F and adjusting the brightness of the former by tilting it with the cam handle, until F and C appear equally bright. The illumination at F is then given by the position of a pointer attached to the handle by which A is turned. The scale is obtained by previous calibration with known illuminations provided by a standard lamp at different fixed distances.

To ensure that F is always viewed at a constant angle, C is provided with two small black pointers. These must be

just visible at the ends of the slot in F (as in Fig. 33A) when the measurement is being made. The direction actually used is 20 degrees from the vertical. Even with this precaution of constant angle of vision, if the sheet F be not perfectly matt and the light be incident upon it at an angle of about 20

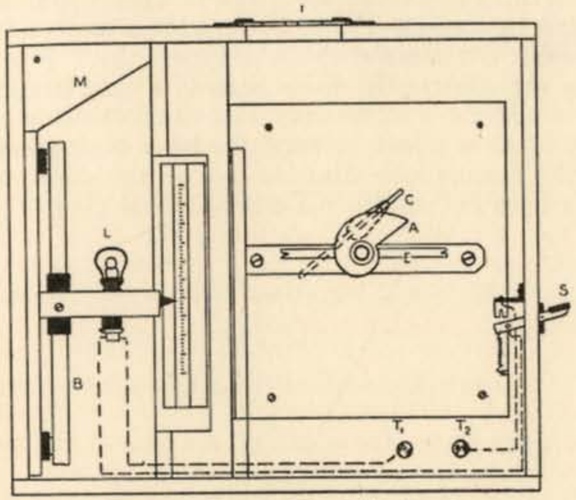


FIG. 33. Trotter Street Photometer

degrees there is danger that specular reflection may cause an appreciable error. It is best, therefore, to view the photometer in a plane perpendicular to that of the incident light, as shown in Fig. 34, which also gives a view of the complete instrument.

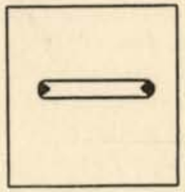


FIG. 33A. Field of Trotter Photometer

The Harrison Photometer.—In the Harrison photometer, the surface illuminated by the outside lights consists of a disc from which two diametrically opposite quadrants have been removed. This disc is set spinning pneumatically and thus the instrument acts on the flicker principle, and is adapted for use with lights of colours different from that of the comparison lamp contained in the photometer box (see p. 174).

The Foot-Candle Meter[1].—This instrument is more correctly described as an illumination gauge than as a photometer. It consists of a rectangular box, the top of which, as shown in Fig. 35, has at one side a strip of matt white paper with a row of translucent " Bunsen grease-spots." These are illuminated from below by a small electric battery lamp which is supplied by a dry cell contained within the instrument. The lamp is placed in a compartment at one end of a long trough which is directly under the white strip, and at the bottom of which is a strip of glass mirror. Since the lamp is situated at one end of the trough, the illumination of the strip decreases gradually from one end to the other and the rate of decrease

FIG. 34. Method of Use of Trotter Photometer

is controlled by the position of the mirror strip. Thus the translucent spots in the strip have brightnesses which decrease gradually from right to left. If, then, the instrument be placed in any position in a room, there will be one spot which has the same brightness as that of the white paper surrounding it under the prevailing illumination. This spot will be seen to disappear, while the spots on the left appear darker, and the spots on the right brighter than the paper surrounding them. Previous calibration gives a scale of illuminations which can be printed on the paper strip, so that to obtain a measurement of illumination at any point, it is only necessary to place the instrument at that point and read on the scale the illumination corresponding to the spot which appears indistinguishable

[1] C. H. Sharp. "Construction of a Simple Illumination Tester." *El. World*, 68, 1916, p. 599. See also H. T. Harrison. *Illum. Eng.*, 3, 1910, p. 373.

from its background. A resistance is placed in the lamp circuit and a voltmeter is provided, as shown at V, so that the voltage on the lamp can be set to the correct value when the instrument is being used. A second mark on the voltmeter gives the value to which the voltage on the lamp must be set in order that the lamp may have exactly one-tenth of its normal candle-power. The readings of the instrument have then to be divided by ten.

This instrument is very convenient and portable, but its readings are, of course, discontinuous, and the accuracy is

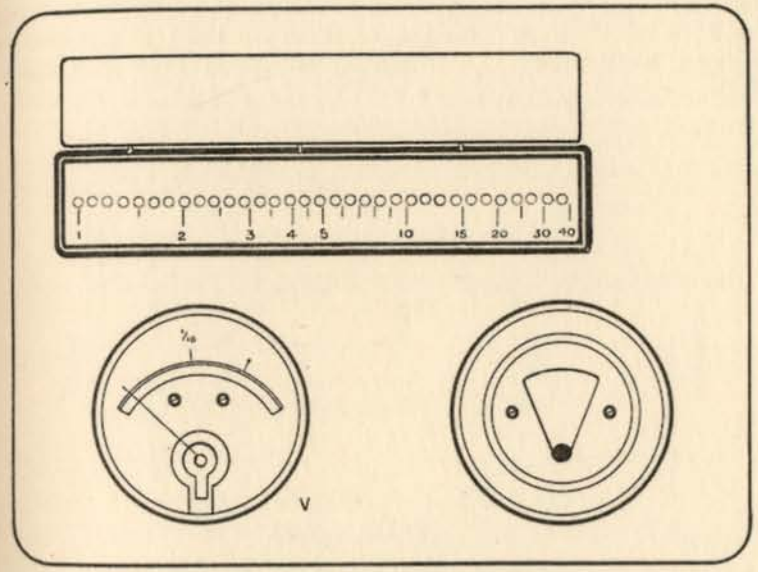


FIG. 35. The Foot-Candle Meter

not as great as that of portable photometers of more ordinary type. Two of these will now be briefly described.

The Luxometer.—This instrument is a portable form of the Trotter photometer (see above). It is shown in section in Fig. 36. L is a small 2-volt glow-lamp which illuminates the tilting screen S. The screen is reflected in the mirror M, and is seen in the plate C which is silvered over one half of its surface. The test-plate T is seen by direct vision through the unsilvered half of C, and the two halves of the field are brought to equality of brightness by tilting S. A pointer attached to the axis of the cam by which S is tilted moves over a scale which gives the illumination directly in foot-candles.

The Lumeter.—There are two slightly different forms of this instrument. The first form has now been reverted to by the makers, and this will be described here. The intermediate form is used in an exactly similar way and depends upon the same principle, so that there is no real difficulty in using either form from a description of the other. The instrument is shown in plan in Fig. 37. L is a small electric glow-lamp contained in a whitened enclosure provided with a diffusing glass window W. The light from this window illuminates a white screen S, which contains a central hole through which the exterior test-plate T is viewed. Screens L_1 and L_2 of the form shown in Fig. 37A are placed so that they can be moved, in turn, across the front of W. As L_1 is moved further and further across, the area of W from which S receives its light is gradually reduced, until when L_1 completely covers W only one-tenth of the original area (i.e. the area of the slot in L_1) remains.

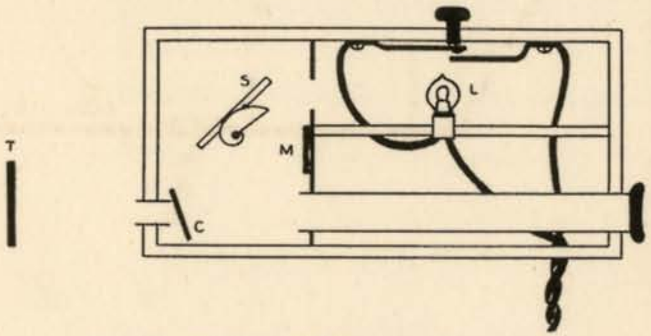


FIG. 36. The Everett-Edgecumbe Luxometer

As L_2 then passes across, the illumination at S is reduced still further from 0·1 of its original value to zero. L_1 and L_2 are moved by handles to which are attached pointers moving over scales. On one of these the graduation is from 1 to 0·1 foot-candles, and on the other 0·1 to 0 foot-candles. A measurement is made by moving the appropriate handle until a balance is obtained between the brightness of the outer ring at S and that of the test-plate T. It will, of course, be noticed that when L_1 is in use L_2 must be entirely out of action (i.e. its handle must be at maximum reading), while when L_2 is being used L_1 must be entirely in (i.e. its handle must be at minimum reading). Neutral glass screens are provided for insertion between T and S in both lumeter and luxometer so that the scale of the instruments may be increased. Generally the transmission ratios of these glasses are 10, 100, or 1,000, so that the reading of the scale has only to be multiplied by a

power of ten in order to obtain the correct value of the illumination.

The Test-Plate.—From the above description of the lumeter and luxometer it will be noticed that the test-plate is quite separate from the instrument. What has been said previously (p. 19) with regard to the variation of brightness of a surface viewed in different directions shows that it is

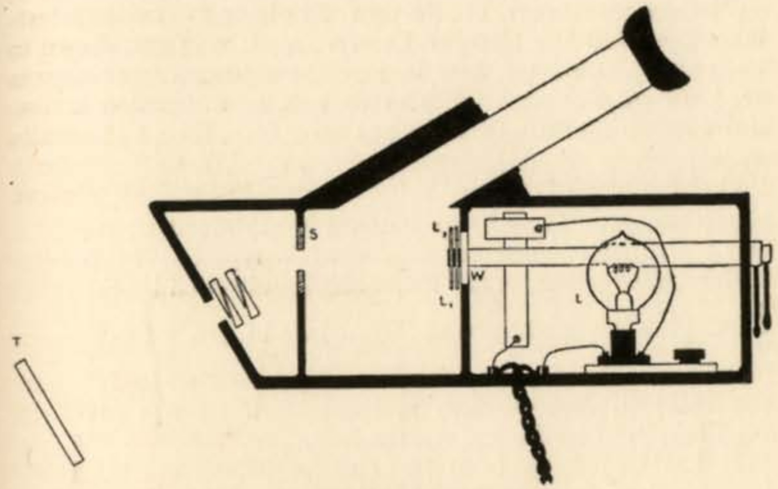


FIG. 37. The Holophane Lumeter

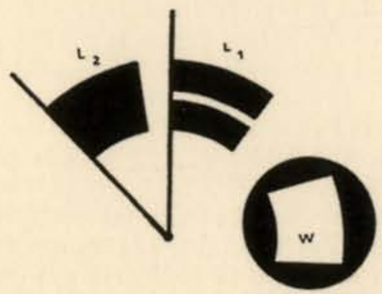


FIG. 37A. Detail of Lumeter Diaphragms

important to obtain a surface for this test-plate which is as truly matt as possible. A very frequently used substance is white celluloid, sandblasted on one side. This gives a good white surface which approximates very closely to a perfect diffuser, and is not readily destroyed by wiping over with a wet rag for cleaning purposes. White blotting paper is even better as a diffuser, but it has to be renewed frequently as it cannot be satisfactorily cleaned. In any case it is most important to avoid the angle of specular reflection. The most favourable position is that in which the light reaches the test-plate from a point on either side of the observer, and not directly in front of or behind him. It is clearly important that the instrument should be calibrated with the test-plate with which it is to be used, and naturally the substitution of a new lamp necessitates a fresh calibration.

The Measurement of Surface Brightness.—In both the luxometer and the lumeter, the test surface is quite separate from the photometer, and in fact these instruments may be used for measuring brightness as well as illumination. For if the reflection ratio of the white card be p, then an illumination of n metre-candles gives it a brightness of $\frac{np}{\pi}$ candles per square metre. Thus if the balance be obtained by means of the instrument when the test card is replaced by another surface, the reading of the instrument multiplied by the factor $\frac{p}{\pi}$ will give the brightness of the surface in candles per square metre. Similarly if the instrument be calibrated (as is usually the case) in foot-candles, multiplication by p/π gives the brightness in candles per square foot.

It has frequently been the custom to express brightness in equivalent foot-candles or in lamberts, i.e. in terms of the brightness of a perfectly diffusing surface of 100 per cent. reflection ratio, illuminated to the extent of one foot-candle or one phot respectively. This figure is obtained at once from the readings of an illumination photometer multiplied by the simple factor p. Unfortunately this system has given rise to much confusion between illumination and brightness, and it is desirable that the latter should always be expressed in candles per unit area.

Precautions in the Use of Portable Photometers.—It will have been noticed that a number of illumination photometers depend, for their standard of comparison, on a small 2 or 4-volt electric glow-lamp fed from a portable battery. Now, as has been already stated, the candle-power of an electric lamp varies as the fourth or fifth power of the voltage, so that constancy of battery voltage is of first importance. Most such photometers are provided with a switch so that the lamp can be switched on only when the readings are being taken. The discharge of the battery is thereby much reduced, and, as the current of the lamp does not generally exceed half an ampere, a storage cell of 10 to 20 ampere hour capacity will maintain a constant supply voltage over a considerable period

of use. The voltage of the battery on discharge must be frequently checked, and recharging should be commenced as soon as the voltage has dropped by 5 per cent. of its value. During this time the readings of the photometer must be reduced by 3·7 or 5 per cent. for every one per cent. drop in voltage, according as the lamp filament is of tungsten or carbon. The cell when first taken off charge should be discharged at about half an ampere for at least an hour before being used on the photometer. This avoids the initial over-voltage.

The most frequent source of trouble in portable photometers employing an electric lamp is faulty contact at some part of the circuit. At the very low voltage used, the slightest fault in a contact causes a noticeable decrease or fluctuation in the light.

The leads to the battery should be tightly screwed down on to perfectly clean terminals, and it is inadvisable to undo them during the taking of a set of readings. All contacts inside the photometer should be soldered, and the lamp cap must be of the screw type and well screwed down into the socket. If a switch is provided for the lamp, it is necessary to ensure that it makes good and constant contact when in the "on" position.

All portable photometers require frequent checking, at two or three points of their scale, against known illuminations provided by a standard lamp at definite distances from the test-plate. When all the precautions detailed above have been observed, the best of these instruments may be relied upon to an accuracy of about 2 to 3 per cent. over the most favourable part of its scale.

The Method of Illumination Measurement.—The method of making illumination measurements is to place the test-plate at the position where it is desired to know the illumination and to determine this by means of a photometer similar to one of those above described, taking care that the body of the observer shields as little light as possible from the test-plate. Unless otherwise stated or clearly implied, it is usual to assume that the test-plate is placed horizontally; and very frequently the floor level or the one-metre level is adopted for all the measurements. More frequently, however, the plate is placed horizontally on the desk, loom, bench, lathe, etc., where it is desired to know the illumination. Sometimes, as in the case of a picture gallery, the illumination of a vertical surface is of primary importance. In such cases, of course, the vertical position is adopted for the test-plate.

Systems of Light Distribution.—The method of measurement of illumination above described is equally applicable whatever be the system by which the illumination is produced; it is a test of the result obtained irrespective of the means adopted.

The remainder of this chapter will be devoted to the consideration of the various methods by which a given degree of illumination may be provided, and the characteristics, other than intensity, which these different methods possess.

The systems of lighting in use to-day may be grouped under three headings. The first, termed the direct system, is that in which the light from the source (regarding the actual lamp and its accessory shades, etc., as a single unit) reaches the place to be illuminated by a direct path and without the intervention of any reflecting surfaces. The second, or indirect, system is that in which the whole of the light from the source is cast upwards so that it only reaches the working plane after it has suffered reflection, and diffusion, at the ceiling or some equivalent reflecting surface of large area. The third system, called semi-indirect, is a combination of the two former, in which part of the light proceeds directly from the source to the working plane while the remainder is cast upwards as in the indirect system. Typical units of these three systems are exhibited in Fig. 38 where Diagram A shows a direct lighting fitting, Diagram B an indirect, and Diagrams C and D semi-indirect fittings.

Direct Lighting.—Until comparatively recently the vast majority of lighting installations were on the direct system, either with or without shades or translucent globes to protect the eyes from a direct view of the sources. Practically all the light reaching the working plane was that due to direct radiation from the lamps. The chief disadvantages of this system are its tendency to give a patchy illumination unless the units be carefully spaced, its production of dense shadows unless a large number of units be employed, and, finally, the difficulty of avoiding glare from the view of unscreened filaments or other sources of high brilliancy. On the other hand the light from the lamp, especially if the upward rays be redirected by an efficient reflector, is used to the fullest advantage and the minimum is lost by repeated reflections from the surface of the walls and ceiling or from surrounding objects. The chief desideratum in a direct lighting system is a correct relation between the height and spacing of the units to give (*a*) as even an illumination as possible over the working plane, and (*b*) freedom from glare. In cases where the area to be illuminated is so small as to be lit adequately by one or two units, consideration (*a*) does not, of course, apply, but in all other cases the ratio of the distance between the lamps to

their height above the working plane (termed the "spacing ratio") must be carefully chosen in relation to the characteristics of the particular fitting to be used.

In the case of direct lighting it is usual to regard all the light cast upwards, and in any downward direction making an angle of less than 30 degrees with the horizontal, as wasted

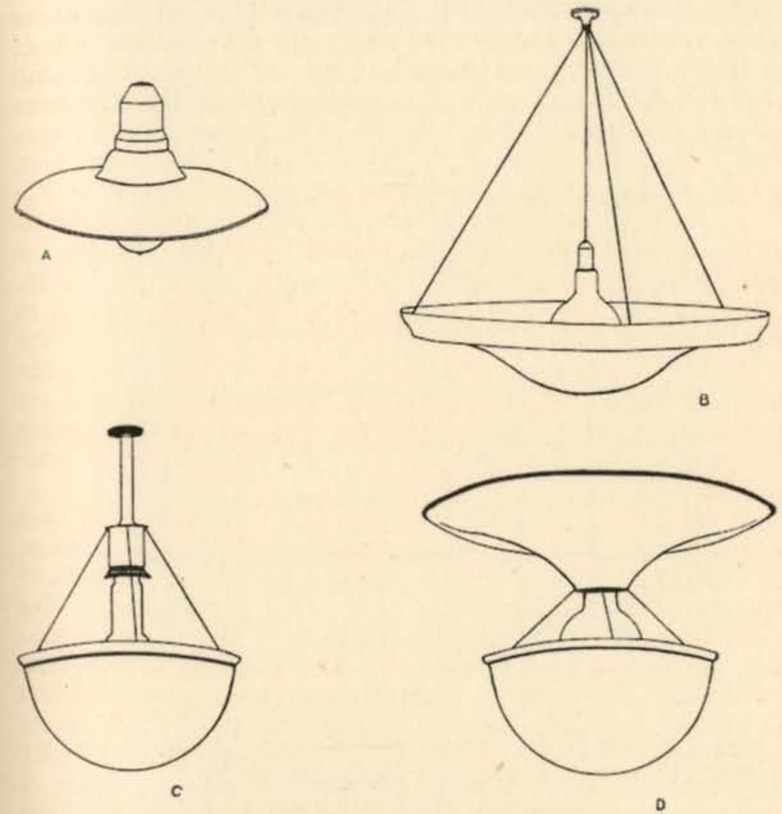


Fig. 38. Types of Lighting Fittings
A—Direct Lighting
B—Indirect Lighting
C—Semi-Indirect Lighting
D—Semi-Indirect with Over-Reflector

unless it can be diverted to the downward direction by means of some system of shades and reflectors. The first object of a direct lighting fitting is, then, to cause the greatest possible proportion of the light given by the source to be cast downwards within a cone having its apex at the fitting and its semi-vertical angle not more than 60 degrees. The distribution of the light within the cone must then be considered in relation to the particular requirements. If the sources are to be spaced far apart in comparison with their height above the working plane, it is clear that a considerable portion of the light must be sent out in directions making considerable angles with the vertical, and in fact the candle-power of the unit should gradually increase from a minimum in the direction of the downward vertical to a maximum near the edge of the cone referred to above. Otherwise the illumination will be "spotty," the region immediately below a source being much more highly illuminated than that mid-way between two

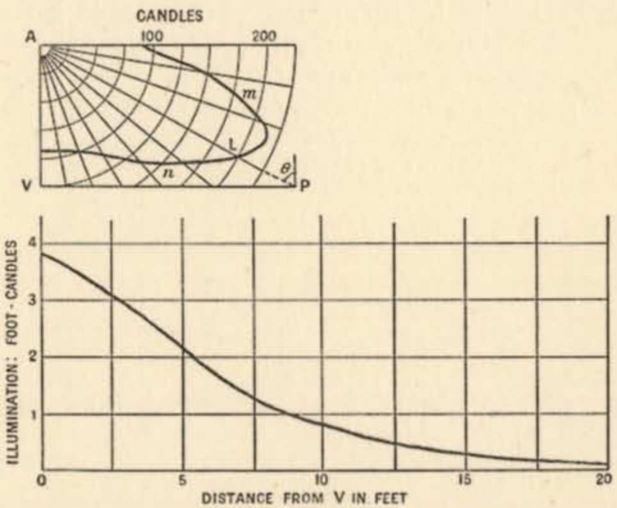


FIG. 39. Diagram Illustrating the Method of Calculating an Illumination Curve

sources, owing to its greater proximity to the lamp and the fact that the light is incident upon it normally.

If, on the other hand, the sources are high and relatively closely spaced, a unit concentrating most of the light within a cone whose semi-vertical angle is 30 degrees or less may be used with advantage. Such a unit may also be used if high illumination is desired over a comparatively restricted area of the working plane. In any case it is desirable to have the polar curve of light distribution from any direct lighting fitting, before its suitability for a given purpose can be determined. With such a curve it is a comparatively simple matter to predict what illumination is obtainable from any proposed arrangement of units, using any given size of source in each.

The Calculation of Illumination Distribution.—In Fig. 39, if A represent a source of light, V the point vertically beneath it on the working plane, and P any other point on that plane at which the illumination is desired, then if θ be the angle VAP, and J_θ the candle-power of the unit in the direction AP, the illumination at P will be (see p. 17) $(J_\theta/AP^2)\cos\theta$, i.e. $J_\theta \cos^3\theta/h^2$ where h=AV. In Fig. 39 let A represent the unit, VP the working plane, and let the thick line *mn* represent the polar distribution curve of the unit at A. The point L of *mn* which is cut by the line AP gives at once the candle-power of the unit in the direction of P (see p. 43). If the length of AL represents candles while AV is expressed in feet, then the illumination at P in foot-candles is equal to AL $\cos^3\theta/AV^2$. For example, if AL=200 and AV=5 while

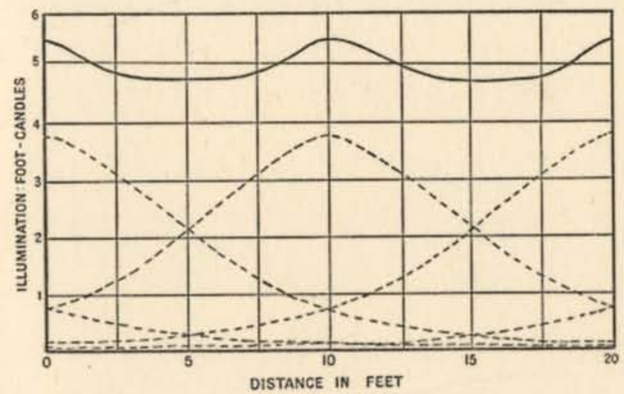


FIG. 40. Illumination Curve due to a Line of Similar Sources

θ=60 degrees, the illumination at P will be $200/8\times25=1$ foot-candle. A curve may thus be drawn as in the lower part of Fig. 39 to show the illumination at all points in a line passing through V. The distribution of illumination due to two or more sources may be similarly obtained by superposing a number of curves, one for each source, placed correctly in relation to the position of the source it refers to, as in Fig. 40, which shows the distribution of illumination along a line vertically beneath a row of the sources shown in Fig. 39, placed at intervals of 10 feet. By adding ordinates the curve showing the resultant illumination due to all the sources is at once obtained. Of course in this method the effect of reflections from the walls and ceiling is neglected, and this, in the case of light-coloured walls, or with a fitting which allows an appreciable proportion of its light to reach the ceiling, may appreciably increase the general illumination, especially in the case of small rooms containing only a few units.

It will be noticed that the curve of illumination in Fig. 39 only refers to the distribution of illumination along a line passing through the point vertically beneath a source. It is, of course, quite simple to draw a similar curve for any other line, the illumination at any point being $J_\theta \cos^3 \theta/h^2$, where J_θ is the candle-power of any source in the direction of the line joining the source and the point under consideration, θ is the angle which this direction makes with the vertical, and h is the height of the source. The summation is made, of course, for all sources contributing appreciably to the illumination at the point.

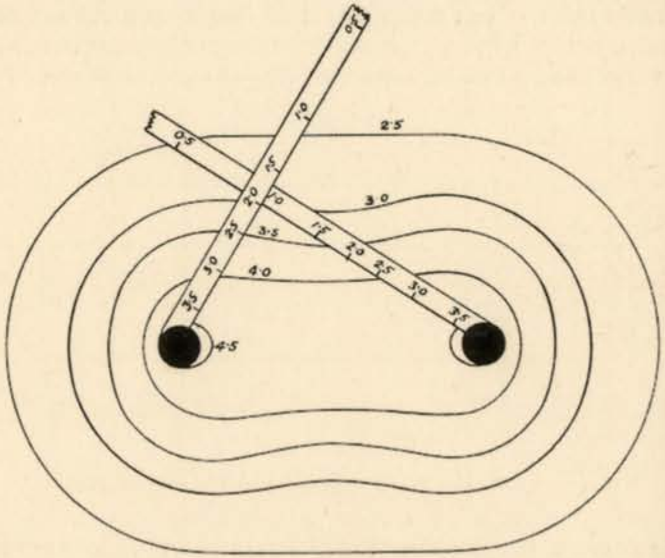


FIG. 41. Construction of an Isolux Diagram

The Iso-Lux Diagram.—It is sometimes desired to have a graphic representation of the evenness or otherwise of the illumination over the working plane, or a given portion of it. In such cases, the method described by Trotter for constructing what he calls a contour map, or iso-lux diagram, may be used. First a plan is drawn on a large scale, showing the position of each light source. A strip of paper is then marked with a scale representing the illumination due to one of these sources at various horizontal distances from it, and this strip is pinned to the plan at the point showing the position of this source. Similar strips are provided for each of the other

sources and marks are made on the plan at all the points of intersection of the scales where the sum of the graduations has a given value. Thus, for example, in Fig. 41 is shown the simple case of two similar sources, each giving the illumination curve shown in Fig. 39. The 2 foot-candle contour is the line joining the points where the coincident scale marks on the two scales are respectively 1·8, 0·2; 1·7, 0·3; 1·6, 0·4; etc. The larger and more varied the number of sources, the more complicated become the necessary calculations. Of course the further apart the contour lines, the more even is the corresponding illumination, and in fact the map may be read very similarly to an ordinary geographical map of contour levels. It will be noticed that this method of illumination calculation applies equally to indoor and outdoor lighting, except that in the former case the general average of the illumination will be somewhat increased by light reflected from the walls and ceiling.

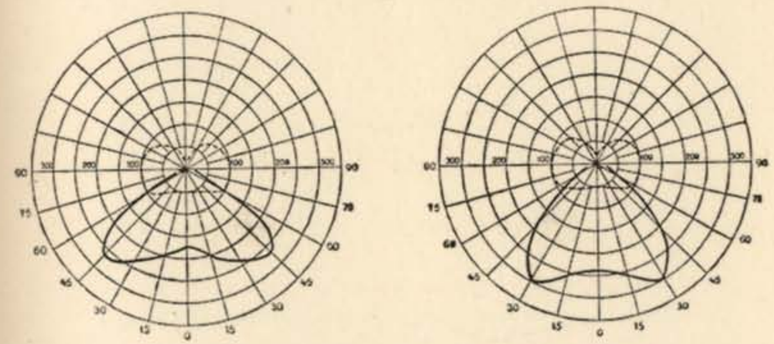


FIG. 42. Polar Curves obtained with Bowl Reflectors

Direct Lighting Reflectors.—The different patterns of reflectors which have been designed for direct lighting are exceedingly numerous. Ordinary conical shades, either of opal glass or of enamel, whitened inside, do little to modify the distribution of the illumination beneath a lamp, except to increase it just beneath the shade. Generally they are too shallow to shield the light from the eye, and are therefore objectionable on account of glare. They also absorb 25 to 40 per cent. of the light which falls on them, while an efficiently designed reflector should not, as a rule, absorb more than 15 to 20 per cent., and an even lower figure than this is frequently attained.

Deep inverted bowl reflectors, either of reflecting metal, silvered glass, or even enamelled iron, appreciably increase the effective candle-power of the source at angles up to from 45 degrees to 60 degrees from the vertical, according to the type, and so are useful in producing a more even illumination over the working plane. Fig. 42 shows the polar curves obtainable with two types of such reflectors. Dome reflectors, of the type shown in Fig. 58 of p. 127, increase the candle-power mainly in directions up to 45 degrees from the vertical. It is difficult to give polar curves for such fittings since the number of different types is very numerous and the exact characteristics differ in each case.

All the above reflectors are of opaque material but it is also possible to employ the total internal reflection of glass prisms, and this is done in the Holophane reflectors first introduced by Trotter in this country[1] and by Blondel and Psaroudaki in France. Fig. 43 shows the way in which the light rays

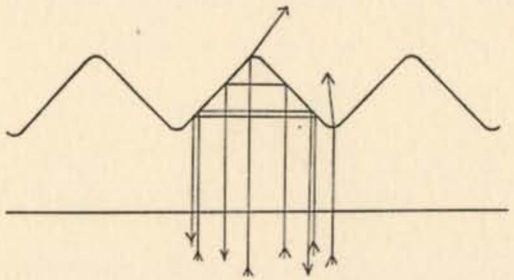


FIG. 43. Total Reflection in Holophane Reflector Prisms

from a source are reflected by a series of right-angled prisms, and the Holophane reflectors consist of a series of such prisms lying in the direction of the generators of the general surface of the reflector. These reflectors are made in three types, termed respectively "extensive," "intensive," and "focusing." The first gives the greatest spreading of the light, and the last the greatest amount of concentration, the intensive being midway between the others. The polar curves are shown in Fig. 44. It may be remarked in passing that these curves show very remarkably the illusion of a polar diagram. The total flux represented by each of the three curves of Fig. 44 is the same within a few per cent. The spacing ratios are respectively 2 : 1, 1·5 : 1, and 1 : 1 for the extensive, intensive, and focussing reflectors.

The Holophane system was originally devised to employ both refraction and total internal reflection for the production

[1] A. P. Trotter. "A Dioptric System of Uniform Distribution of Light." *Inst. Civ. Eng.* 78, 1884, p. 346.

of any desired light distribution from a source. Fig. 45 shows, on the left, the way in which rays are deflected downwards in their passage through a series of glass prisms, while on the right the diffusion produced by a series of flutings is shown. Such a system is used in the case of street lighting fittings, where the globe surrounding the source consists of a series of horizontal prismatic elements designed to give the maximum

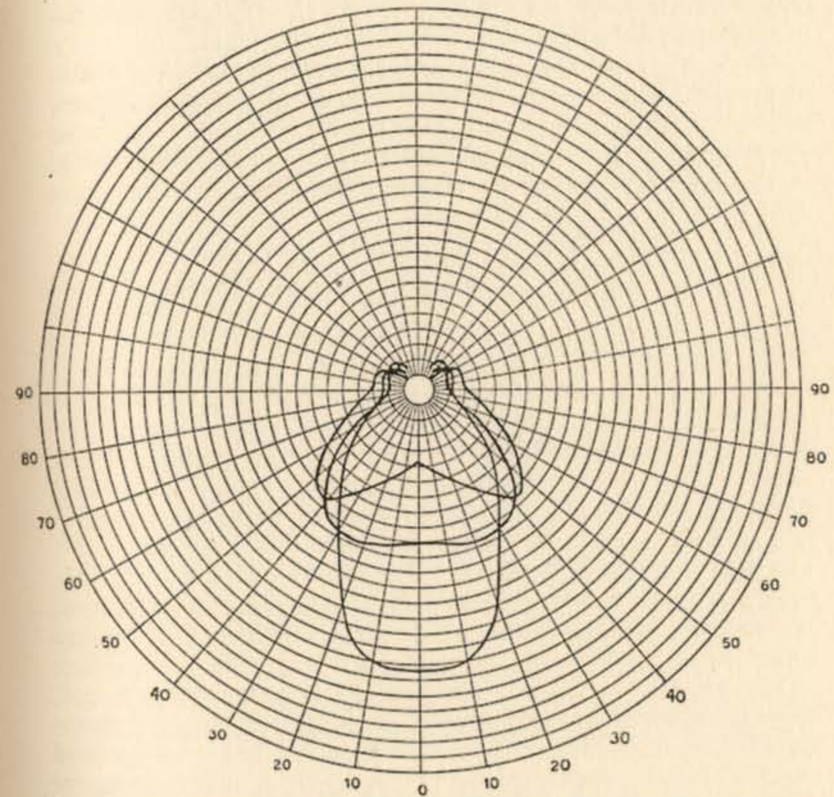


FIG. 44. Polar Curves obtained with Extensive, Intensive, and Focussing Holophane Reflectors

candle-power at an angle of about 15 degrees below the horizontal, while a series of internal vertical flutings gives an even distribution at all angles of azimuth.

The fittings used for local lighting do not require any special description as the area to be illuminated is so restricted that the type of reflector used is generally immaterial. The special reflectors used to produce an even illumination on an extensive vertical surface will be described on p. 117, while special fittings for outdoor illumination will be dealt with in Chapter VIII.

Indirect Lighting.—The indirect system of lighting is used where it is desired to avoid hard shadows and produce a "soft" effect, as in a drawing-room or a workshop with much machinery likely to cause inconvenient shadows. In this system of lighting all the downward rays from the source are intercepted by an opaque bowl lined inside with a good reflecting material. Thus all the light from the lamp is caused to strike the ceiling and upper part of the walls, and

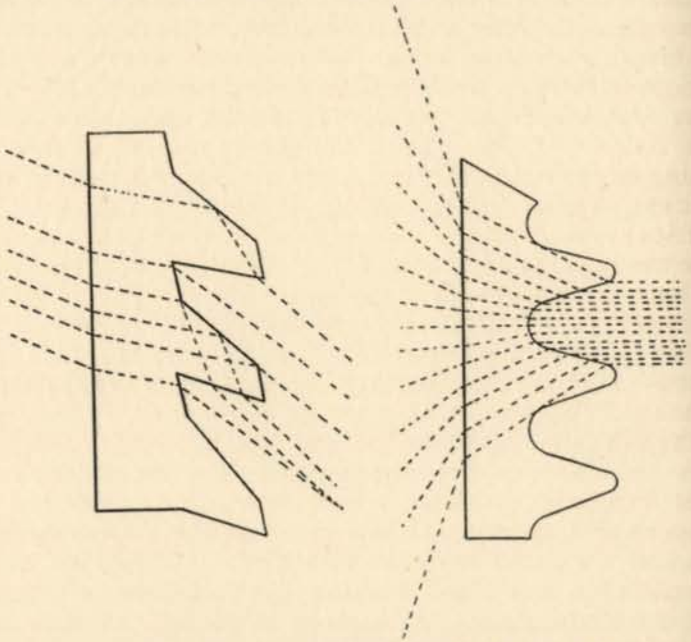


FIG. 45. Action of Prisms and Flutings in Holophane Refractor

from there it is diffused over the whole room. Owing to the great area of the effective illuminating surface, all possibility of glare is avoided and the light, instead of coming from a few isolated points, proceeds in all directions with a consequent diminution of shadow.

Instead of a bowl suspended beneath lamps hung from the ceiling, indirect lighting may be obtained by placing the sources, generally in the form of tubular lamps, in a cornice hollowed out where it meets the ceiling. A reflector of special design is then generally required to obtain a more or less even distribution of illumination on the ceiling. Otherwise the

excessive brightness of the ceiling edge, toning off to comparative darkness in the centre, is unpleasant in appearance, and gives an unsatisfactory distribution of illumination in the room.

In indirect lighting, the polar curve of distribution of the unit is of less importance than in direct lighting. The chief function of the fitting is to cause the greatest possible amount of the light from the lamp to reach the ceiling, and the only other desideratum is that it shall do this in such a manner that the ceiling shall not appear too uneven in brightness. If the reflector concentrates the light too much, or, what is equivalent, the lamp is placed too low in the bowl, there will be bright patches of ceiling just above the lamps with dark regions in between, and the general effect will be one of patchiness, and will be far from restful to the eye. Especially is this liable to be the case if the ceiling be low, so that the fitting has to be placed close up to it. The polar curve of an efficient type of indirect fitting is shown in Fig. 46. This particular fitting has a back-silvered bowl of fluted glass inside the metal bowl, so that a high reflection ratio is obtained as long as the glass is kept clean. The spacing of indirect units will be considered in a separate section.

Semi-Indirect Lighting.—This is, as its name implies, a compromise between the direct and the totally indirect systems of lighting. The bowl in this case is translucent, so that part of the downward light from the lamp is transmitted and diffused over the area underneath the unit. The remainder of the light illuminates the ceiling as in indirect lighting, and thus the properties of the direct and indirect systems are combined. Shadows are much less than with direct lighting, but not so completely softened as in indirect light. For many purposes this is an advantage. It has been shown that for some processes, such as sewing on a uniform-coloured cloth, ability to distinguish detail depends on the differences of brightness due to the shadows cast by the threads of the material. Work of this kind is far less comfortable and requires a much greater illumination by indirect than by direct or semi-indirect lighting.

Semi-indirect lighting is generally more economical than indirect, since part of the light is directly transmitted through the bowl to the working area. It is, for the same reason, less dependent on the high reflection ratio of ceiling and walls. It shares with indirect lighting the advantage of avoiding all possibility of glare if properly diffusing bowls are employed, and the effect of a semi-indirect system of units is, in general, more pleasing to the eye than a similar indirect installation, since the excessive contrast of the dark exteriors of the bowls seen against the bright ceiling is avoided. In both indirect and semi-indirect lighting in buildings where it is impossible to have white or very light-coloured ceilings, as, for example, where there are large roof windows, some white reflecting surface must be placed above the unit to act as an artificial ceiling. This arrangement may also be used when the ceiling

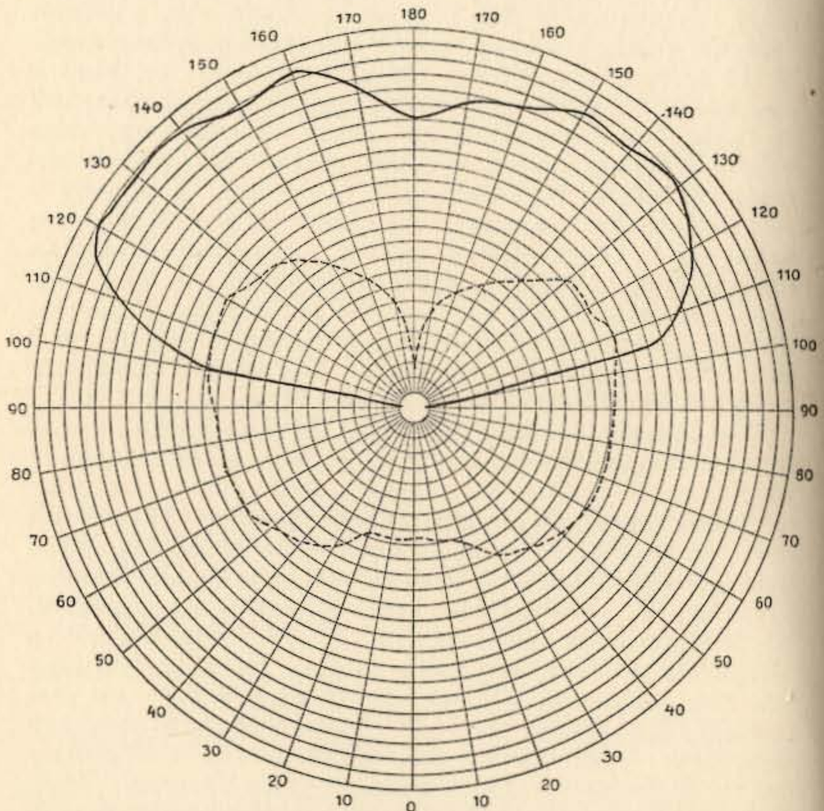


Fig. 46. Polar Curve obtained with Indirect Fitting (Curve for Bare Lamp shown by Broken Line)

is much cut up by girders, or when the room is very low. In the latter case, the false ceiling, or over-reflector, is not flat, but is curved upwards at the edges so as to produce a greater spreading of the light. Such a reflector is shown in Diagram D of Fig. 38, p. 87.

The bowl of a semi-indirect fitting is usually of opal glass, alabaster, or thin marble. The proportion of light directly

transmitted by the bowl depends, of course, on its thickness and opacity. It is usually from 25 to 50 per cent. of the direct light from the lamp. The indirect component of the light depends partly on the reflection ratio of the inner surface of the bowl, but the greater portion is due to direct light emitted upwards from the lamp. Figs. 47 and 48 show the polar

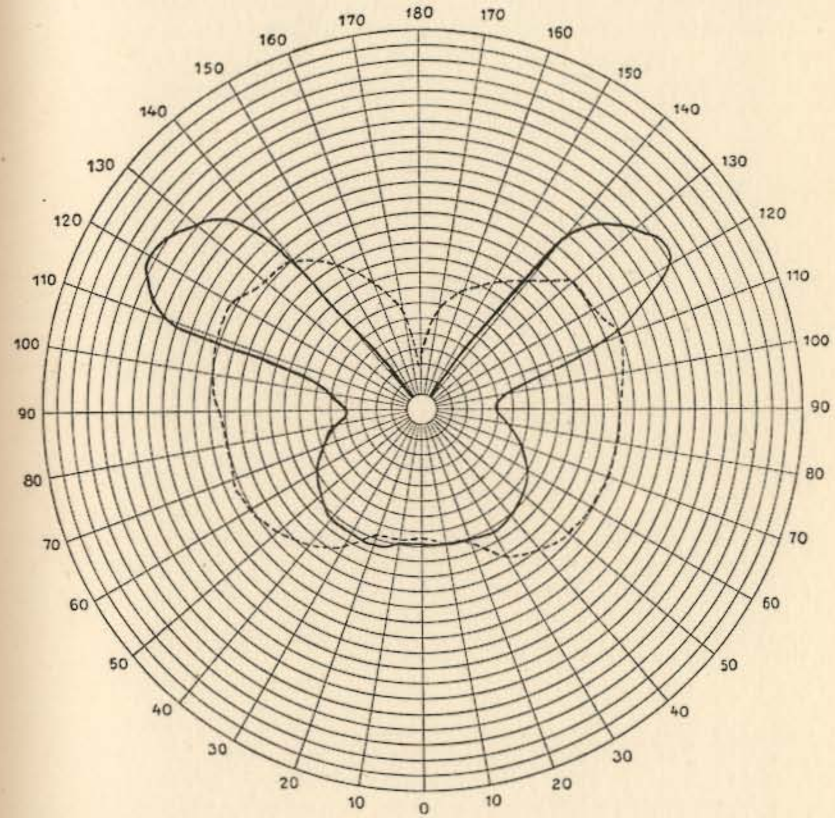


Fig. 47. Polar Curve obtained with Semi-Indirect Fitting, using an Over-Reflector

curves of semi-indirect fittings respectively with and without an over-reflector. The shape of the upper part of the curve in the first case depends almost entirely on the form of the reflector and its position in relation to the lamp.

Spacing for Indirect and Semi-Indirect Units.—The calculation of the distribution of illumination on the working plane from any given arrangement of units is less easy than in the case of direct lighting. As a rough working rule it may be assumed that a fairly uniform illumination (diversity factor less than 2 : 1) will be obtained with a spacing of from 1·0 to 1·5 times the height of the ceiling above the working plane. The distance of the unit from the ceiling is here assumed to be such as to give the latter the appearance of being well illuminated all over.

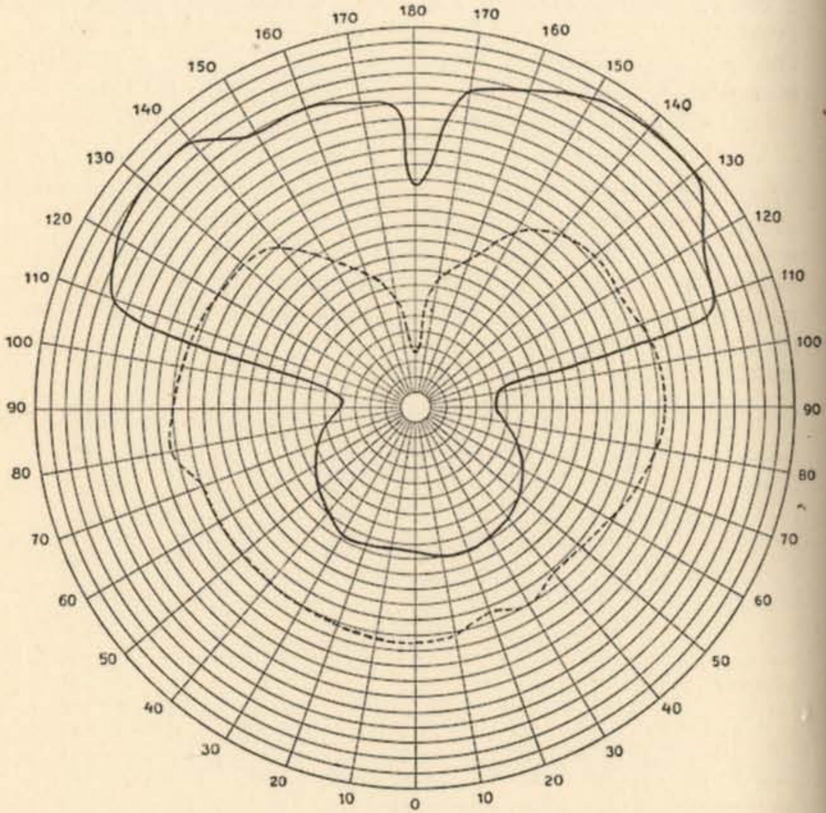


FIG. 48. Polar Curve obtained with Semi-Indirect Fitting having no Over-Reflector

The Efficiency of a Lighting System.—In planning any system of lighting, when the most suitable method has been agreed upon, it is necessary to determine the candle-power required in each unit to obtain the desired intensity of illumination. It is clear that the average illumination must vary directly as the candle-power of the sources employed, and a knowledge of the ratio of the flux reaching the working plane to the total flux supplied by the lamps gives, therefore, the

desired information. This ratio is termed the "*coefficient of utilization*" of the system of lighting employed and its use will be readily understood from the following example.

Suppose it be required to light a room of area A square feet to an intensity of E foot-candles with n units on a system of lighting of which the coefficient of utilization is u. The total flux required on the working plane is A $\times$ E lumens (since 1 foot-candle requires 1 lumen per square foot, see p. 17). Now if x be the required average candle-power of each lamp, the n lamps together supply $n \times 4\pi x$ lumens of which $u \times n \times 4\pi x$ lumens reach the working plane. Hence

$$4\pi unx = AE.$$
or
$$x = AE/4\pi un.$$

The coefficients of utilization of different systems of lighting are given in the following table[1] for various conditions of walls and ceiling, and for various sizes of room. Although figures are given for a direct system it is probable that the method outlined on pp. 89-90 will be found more suitable in direct lighting systems except in the case of very large installations where the number of units is considerable.

COEFFICIENTS OF UTILIZATION

SYSTEM OF LIGHTING	ROOM RATIO (*see next page*)	REFLECTION RATIO					
		Ceiling. Light (70%)			Medium (50%)		Dark (30%)
		Walls. Light (50%)	Medium (35%)	Dark (20%)	Medium (35%)	Dark (20%)	Dark (20%)
Direct.	1	·40	·37	·35	·37	·34	·34
	1·5	·47	·44	·42	·44	·42	·42
	2	·51	·48	·46	·48	·46	·46
	3	·56	·54	·52	·53	·51	·51
	5	·60	·58	·57	·56	·56	·55
Semi-Indirect.	1	·27	·24	·21	·20	·17	·14
	1·5	·34	·30	·27	·25	·22	·18
	2	·39	·35	·32	·29	·26	·21
	3	·45	·41	·38	·34	·31	·25
	5	·51	·47	·44	·40	·37	·29
Indirect.	1	·22	·19	·17	·14	·12	·07
	1·5	·27	·24	·22	·17	·15	·09
	2	·31	·28	·26	·20	·18	·11
	3	·36	·33	·31	·24	·22	·13
	5	·42	·39	·37	·28	·26	·16

[1] Adapted from a paper by W. Harrison and E. A. Anderson. *Trans. I.E.S.*, March 20, 1920, pp. 113–114.

The Room Ratio is defined as

(i) For direct lighting $\dfrac{\text{Room Width}}{2 \times (\text{height of lamps above working plane})}$

(ii) For indirect and semi-indirect $\dfrac{3 \times \text{Room Width}}{4 \times (\text{height of ceiling above working plane})}$

These ratios apply to square rooms. In the case of rectangular rooms, the room width may be taken as the average of the width and length, except for very long and narrow rooms, when it is best to find the coefficient of utilization for a square room of the narrow dimension, and add to it one-third of the difference between this value and the coefficient for a square room of the long dimension.

General Considerations.—There are several matters which require attention, to a greater or less extent, in every lighting installation.

First of these is the careful placing of every light source in its correct position with regard to the reflectors or refractors of the fitting in which it is used. Frequently the forms of these have been carefully designed to give a definite distribution of light with the source in a given position, and careless placing of the lamp, or the substitution of an old lamp by a new one of another type with the filament in quite a different place, may result in a distribution markedly different from that which had been allowed for when the installation was planned. For instance, the effect of lowering the source of light by three-quarters of an inch in an "intensive" holophane reflector is to destroy completely the intensification of the illumination immediately below the lamp. In the case of indirect and semi-indirect fittings without over-reflectors the position of the source is not so critical and is generally adjusted to be low enough to avoid glare, and high enough to spread the light well before it reaches the ceiling. An important detail, of a somewhat analogous nature, is the position of the shadow cast by the edge of the bowl of an indirect or semi-indirect fitting, on the wall of a room. If the room is provided with a frieze it is convenient to suspend the fitting at such a height that the edge of the shadow falls on the junction line at the base of the frieze. In this way the production of a hard edge of shadow on the wall may be avoided.

The importance of maintaining all lamps and fittings in a scrupulously clean condition cannot be over-emphasized. It will be referred to again in the next chapter, and the allowance to be made on account of depreciation both of the lamps used, and of the reflecting power of fittings, ceilings, etc., will be discussed in relation to the type of room to be lighted.

Although throughout this chapter electric lamps have been mentioned in connexion with the fittings, similar shades and reflectors have been designed, in most cases, for use with incandescent gas mantles. Indirect and semi-indirect lighting with gas are exactly similar in their characteristics to the corresponding system with an electric lamp, and the calculations of the size of unit required and of the spacing desirable may be carried out exactly in the same way for either illuminant. Top ventilation is, of course, essential in the case of gas, and it is also very desirable for gas-filled electric lamps, particularly if these are pendent, as the convection currents inside the bulb cause the top of the lamp to become exceedingly hot and there is danger of the lamp becoming loose in its cap, and of the insulation in the socket giving way, unless free access of air be provided.

CHAPTER VI

INDOOR LIGHTING

THE problems confronting the engineer in the design of lighting systems for the interiors of buildings are scarcely less varied than the buildings themselves. Just as it is a rare occurrence to find two rooms exactly alike as regards their architectural design, the scheme of their internal decoration and furnishing, and the purpose for which they are to be used, so no two rooms can, as a rule, be most suitably illuminated by exactly the same system of lighting. It is this very fact which makes the task of the lighting engineer so difficult and yet, at the same time, so full of interest. He has, in addition to his knowledge of engineering principles and of the general requirements of good lighting, to add a sense of the artistic, especially in domestic or public building lighting, and of the physiological characteristics of the eye as regards fatigue and capacity for sustained effort in the case of industrial or school lighting.

It naturally follows that to do more than outline the general principles suggested by past experience in the case of the different classes of indoor lighting commonly met with would be of little use. It cannot be too often emphasized that every individual case must be considered on its own merits, and any attempt at a stereotyped system will inevitably lead to bad practice in more cases than not.

In this chapter it is proposed first to consider some of the details which specially apply to indoor lighting and which have not already received attention. Then domestic lighting in its many forms, and the lighting of public meeting-places or places of entertainment will be considered.

"General" and "Local" Lighting.—In the last chapter a description was given of the direct, indirect, and semi-indirect systems of lighting as used for the purpose of illuminating the whole of the "working plane" in a room. In every case it was assumed that illumination would be needed over the whole room, although possibly it might be required in greater intensity at some particular places. Such a system would be called

a "general" system of lighting, as opposed to a "local" system in which each light source would be definitely arranged to light only a small area of the room, such as a particular object or machine, or even a portion of a machine. For example, the lighting of a church nave, where it is necessary to provide light for all the people seated there, is necessarily on a "general" system. Frequently, however, a special light is provided for the reading-desk or pulpit, and these lights belong to a "local" system. In this example, as is very frequently the case, both systems are provided and may be in use simultaneously, but the distinction is a useful one, and will be frequently used in what follows. The evenness of any system of general illumination, particularly on the "direct" system, will depend very greatly on the number of lighting points supplied. This is also a very large factor in the initial cost of the installation, so that it is necessary, in planning a lighting scheme, to decide on the maximum "diversity factor" (i.e. ratio of maximum to minimum illumination) and to determine the least number of outlets required to give this result. The diversity factor allowable will depend very greatly on the nature of the building to be lighted. The spacing figures given in the last chapter are generally for a maximum diversity factor of 1·3 to 1·5.

Effect of Colour of Walls and Ceiling.—In all interior illumination except, possibly, that of very large rooms lit entirely on a direct system, the colour and cleanliness of the walls and ceiling have a very great effect on the performance of whatever lighting may be installed, and it is most desirable that the nature of these surfaces should be carefully thought out when the choice of the lighting system is under consideration. It is clearly of no use to install a totally indirect system of lighting in a factory where the work is of such a nature that the maintenance of adequate whiteness of the ceiling is only possible at a prohibitive cost. On the other hand, for domestic lighting an indirect system may be perfectly satisfactory, but then the attention of those responsible for maintenance must be drawn to the fact that, unless the ceiling is kept in a reasonably satisfactory state of whiteness, the lighting will suffer. In general lighting, with a direct or semi-direct system, much of the light, especially if the room be small, is derived from the walls by reflection. If, then, a very dark wall decoration is to be used the light source must be of higher candle-power than would be needed in the case of a lighter-coloured wall. The effect of window spaces in this connexion should be carefully considered. In many modern factories the window space is made as large as possible, and at night this space becomes almost perfectly black, reflecting no light at all into the room, unless light-coloured blinds are provided *and used*. The same remark applies, of course, to all other classes of indoor lighting. The gradual decrease in the utilization coefficient of a room (see p. 99) as the reflection ratio of the walls and ceiling is reduced, shows this effect very clearly.

Effect of Cleanliness of Lamps and Fittings, and Replacement of Ineffective Sources.—Another detail of great importance in the maintenance of an efficient lighting system is the frequent cleaning of the lamps and fittings which has already been mentioned on p. 100 of the last chapter. It is seldom realized how much light may be absorbed by even a thin film of dust, or a smear due to inefficient cleaning. The glass bulbs of electric lamps should on no account be neglected when

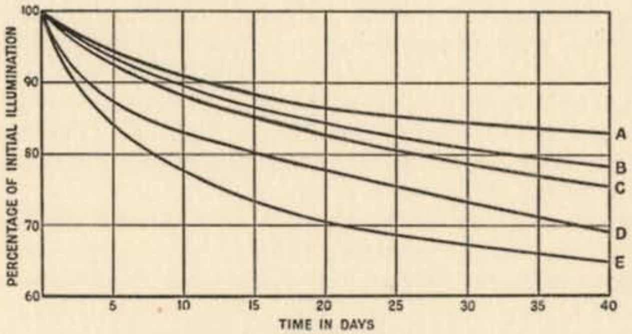


FIG. 49. Deterioration in Office Illumination (Direct)
Curve A—Dome Enamelled Steel Reflectors
Curve B—Bowl Enamelled Steel Reflectors
Curve C—Dense Opal Glass Reflectors
Curve D—Prismatic Glass Reflectors
Curve E—Light Density Opal Glass Reflectors

the cleaning is carried out. Modern wire filaments are now sufficiently strong to stand any reasonable usage, particularly if cleaned when alight. The replacement of electric bulbs, gas mantles, etc., which have become old and inefficient, should also receive careful attention. The fact of deterioration in the lighting due to fall in candle-power of the sources and to lack of perfect cleanliness of the fittings, has to be allowed for when any lighting system is first installed. It is usual to allow at least 30 per cent. as a factor of safety for this purpose, i.e. the illumination due to a freshly installed system should be at least 130 per cent. of that normally desired. When it is remembered that a fall to 80 per cent. of the initial value is very often regarded as the criterion of the useful life of the

light source itself, this over-all allowance does not seem at all excessive.

Naturally the amount of deterioration to be anticipated depends very greatly on the kind of building and the work carried on there. The above figure is generally applied in the case of domestic lighting, offices for clerical work, and similar cases where no great amount of dirt is caused by the operations performed in the room, and where the periodical cleaning is regular and efficient. For factory rooms where there is more dirt and dust due to machinery, smoke, or other causes, or where the cleaning is neither so frequent nor so thorough, the deterioration allowance should be increased to at least 50 per cent., and this still presupposes the replacement of old

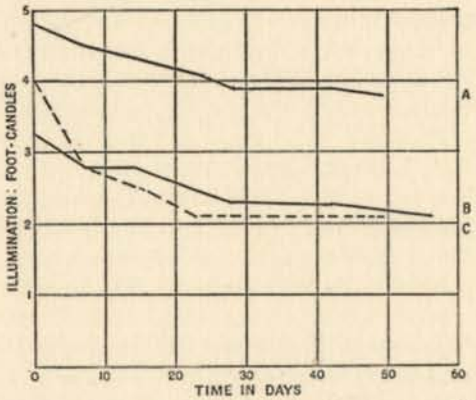


FIG. 50. Deterioration in Indoor Illumination under different Working Conditions
Curve A—Low Office Location (Glass Reflectors)
Curve B—Low Factory Space (Solid Ceiling, Glass Reflectors)
Curve C—Fairly High Factory Space (Open Girder Construction, No Ceiling)

lamps, mantles, etc., as soon as they have fallen to their lower permissible limit of candle-power.

Fig. 49 gives the results of some observations made in an office to show the extent of the deterioration which takes place in different lighting systems after installation, while Fig. 50 shows the effect of deterioration with glass reflectors (*a*) in a low office, (*b*) in a low factory space with solid ceiling, and (*c*) in a fairly high factory space with open girder construction and no ceiling.

Domestic Lighting: The Drawing-room.—With the above remarks, applicable to all systems of indoor illumination, the particular problems of domestic lighting may now be considered. Since the different rooms of a house are required for different purposes it is only natural that each room should be considered separately when the lighting of the house is under consideration. The drawing-room may be used for a number of different purposes. Pictures on the walls and *objets d'art* about the room will require sufficient illumination for them to be properly seen and appreciated. A suitable light for reading, or playing table games will also be necessary, while a very subdued and restful light will at times be desirable. It is clear that no single system of lighting can fulfil all these conditions, and probably the best solution of the problem is a combination of a general with a local system. The general lighting which will provide sufficient illumination to show up the beauties of the room may be either indirect or semi-indirect. This may be used either for reading, or for the general subdued light which is all that is required for conversation or for musical entertainment, by providing a single indirect or semi-indirect unit with the familiar two-switch and three-lamp arrangement. In this case, with a semi-indirect system, it is desirable to arrange the lamps in such a way as to prevent the bowl from appearing "patchy" when a single lamp is on alone. For reading or writing in one part of the room while the remainder is in a subdued light, some form of portable lamp is most convenient, and in the case of electric light the provision of several plugs at different parts of the room makes this arrangement very flexible and convenient. It has the further advantage of being economical, since if the rest of the room is not in use only one general lamp need be on in addition to the portable light needed for reading or writing at a single point. The degree of general illumination to be aimed at should be from 2 to 3 foot-candles, capable of diminution to about one-third or one-quarter of this value. Valuable pictures, or the music desk of a piano, may receive special treatment on the "local" system, using some form of fitting of the type described on p. 117. The wall decoration of a drawing-room should not in general be too dark, and a reflection ratio of at least 30 to 35 per cent. is desirable.

The Dining-room.—The dining-room of a house, being more restricted in the purpose for which it is intended, can be treated rather more definitely. The illumination of the table is the first consideration, combined with complete shading of the sources from the eyes of those seated in the room. Direct lighting units, properly shaded, are quite satisfactory. They may very conveniently be adjustable in height, and in any case should not be so low as to interfere with the view across the table. Ability to alter the intensity of illumination is not so important here as in the drawing-room, and an average of 3 foot-candles is not excessive. If the walls are very dark in tone, the contrast between them and the white table-covering may be considerable. In this case a general illumination may be necessary in addition to the local illumination on the table, if this is provided by direct lighting units alone.

The Bedroom.—In the bedroom the chief place at which a good light is required is the dressing-table. The remainder of the room, however, should be provided with a good general light, and unless the room is small a unit apart from that used for the local lighting of the dressing-table is desirable. The general system may well be of the semi-indirect type. The local light is usually direct, but its position requires careful attention. If only a single lamp be used, it is impossible to avoid shadows on one side or other of the face. Two lamps should therefore be provided, and if the position of these can be made adjustable so much the better. The lamps should not be low enough for them to be seen by oblique vision when the mirror is looked at. Clearly they must be in front of the person standing at the table, and probably the best position for them is in the same plane as, or *slightly* behind, the mirror at such a height that the line from them to the eye of anyone of normal height makes an angle of about 45 degrees with the horizontal. The illumination of the face of anyone at the dressing-table may be as high as 5 to 6 foot-candles, and wherever the source is placed it is essential that it should be properly screened from direct vision by means of a translucent globe or otherwise. The principal lighting system should, wherever possible, be provided with a control easily accessible from the head of the bed.

The Kitchen.—The lighting of the kitchen requires at least as much attention as that of the bedroom. Unless plenty of light be provided, it is difficult to ensure proper attention to cleanliness in all parts of the room. Direct lighting over the table is apt to leave the top of the kitchener in shadow, especially when it is necessary to stand in front of the range as is frequently the case. A general system of indirect lighting, with a local direct light over the table, is probably as good a system as can be devised. This diffused general illumination, which should be in the neighbourhood of 2 to 3 foot-candles, enables objects in cupboards or on shelves to be seen far more readily than would be the case with a direct lighting system. Hall, scullery, pantry, bathroom and coal-cellar should each be provided with sufficient light from lamps suitably placed with regard to the nature of the work carried on in them. The name or number of a house may be very conveniently shown by means of the neon bulbs described on p. 149.

The Study.—The library and study generally require a fairly strong local light over a desk or table, and if a suitable direct fitting be used a single source may give enough general illumination over a small room, especially if the shade be sufficiently transparent to allow some of the light from the lamp to pass through it in the upward direction. Otherwise a semi-indirect central light, with a portable or other local lamp on the desk, is the best arrangement. For reading and writing it is now generally agreed that an illumination of about 3 foot-candles is the most comfortable. With anything much below this figure the strain of working in a poor light is soon felt, while an illumination of more than 5 foot-candles is, after a time, felt to be glaring and uncomfortable. The mistake is sometimes made of providing only a shaded local lamp which casts the whole of the light downwards on the desk or table, and leaves the remainder of the room in almost complete darkness. In such cases the effect of excessive contrast, with a consequent attempt at adaptation on the part of the eye every time the gaze is transferred from the desk to the upper part of the room or back again, is very trying.

Office Lighting.—Next to domestic lighting, in natural sequence on account of its similarity, comes office lighting. The case of a small office designed for one, or even for two or three occupants, can hardly be distinguished from that of a study as described above, and the treatment for illumination purposes may be almost identical. Redecoration may, perhaps, be less frequent, so that the wall coverings are darker and the ceiling is less efficient from a lighting point of view. On the other hand, when offices are close together the upper part of the dividing wall is frequently of glass, so that a certain amount of "borrowed" light is available. A well-diffused general lighting of at least 1 foot-candle should be provided, with a local illumination of 3 to 4 foot-candles on the desk or table. This local illumination should be preferably from the left front, as otherwise the shadow of the writer's head or hand is thrown on the place of work. If a portable lamp be used, with a deep shade to shield the light from the writer's eyes, its position can be varied to suit the wishes of the particular individual who may happen to be working by it.

Massed Clerical Staff.—In the case of a large office, used for massed staff, a general illumination of fairly high intensity is required. Semi-indirect lighting giving an even distribution of 3 foot-candles over the whole of the working plane is quite satisfactory. The amount is quite adequate for all ordinary clerical work, and the degree of diffusion is sufficient to enable documents to be placed in or removed from pigeon-holes and trays. The number of units should not be too small or the illumination will be uneven. Also it will be uneconomical, for if a few persons be working in one part of the room after the normal hours, when the majority of the staff have left, it is clearly uneconomical to light those parts of the room which are not in actual use.

A typist's office requires a rather stronger light than that needed for general clerical work. Frequently it is necessary to decipher handwriting at a high speed and by comparatively brief glances. An illumination up to 6 foot-candles on the manuscript is not excessive in such cases, and this may be conveniently provided by a well-shaded local light in addition to the general illumination necessary for operating the typewriter. The latter illumination should be well diffused, for otherwise a shadow, either of the operator or of vertical parts of the machine, is liable to be cast on the keyboard.

Drawing Office.—Another special type of room which may be conveniently dealt with here is the draughtsman's office. The special nature of the work demands a high general illumination, and at least 5 or 6 foot-candles is required. It is difficult to lay down definite rules as to the nature of the lighting. Some draughtsmen prefer a local light which they can adjust to the most convenient position for any part of the work on which they happen to be engaged for the time being. If local lights are used they should certainly be adjustable, or shadows are sure to be thrown in most inconvenient places, when some part or other of the work is being done. Such a local light should, of course, be well shaded, not only from the eye of the draughtsman by whom it is used, but also from the eyes of all the other occupants of the room. A subdued general lighting is also required in order to avoid excessive contrast. In some drawing offices a high level of general lighting, by indirect or semi-indirect fittings, is alone employed. The chief objection to a too diffused light is that complete absence of shadow is not altogether desirable on the drawing table.

Library Lighting.—Before going on to the discussion of public hall lighting, brief notice may be taken of a problem intermediate between this and domestic lighting. This is the illumination of libraries, and more especially those open for public reading, and for reference purposes. The newspaper room is usually provided with a number of sloping desks, at an angle of about 20 to 30 degrees with the vertical. Very often these desks are placed round the room or in such a position that the reader must necessarily stand with his back to the principal source of light if this be placed in the centre of the room. Unless an exceedingly well-diffused light be provided, and of sufficiently high intensity, it is necessary to place a special reading light above each desk. The chief disadvantage of this is that unless it projects very far forward the illumination of the paper is very uneven, and small irregularities in the surface are exaggerated much as those of a road surface are shown up by the lights from a low motor-car. Probably the most satisfactory system is one providing a general intensity of from 2 to 3 foot-candles from semi-indirect fittings. This is also generally sufficient for rooms where magazines and other periodicals are read at horizontal tables distributed over the floor area. A Joint Committee of the Illuminating Engineering Society and the Library Association have recommended a minimum illumination on the desk or table of 2 foot-candles for ordinary reading, with a higher value of the order of 5 foot-candles for old manuscripts or fine print. They also recommend a general illumination of not less than 0·5 foot-candles on the working plane, with a minimum vertical illumination on the book shelves of 0·5 foot-candles.

The lighting of book shelves is a very difficult problem, as not only is the surface to be lighted a vertical one, but the reader must necessarily face the books and frequently bend down to examine the backs of those on the lower shelves. A diffused illumination is therefore most suitable for the purpose. Very frequently the book shelves are arranged to form small "bays" out of a large central room, each bay being provided with a small table or desk. If only a table lamp with heavy shade be provided, there is danger that unless the light in the centre of the room be very well diffused, the books on the shelves will be inadequately illuminated. A direct lighting fitting casting most of its light on the table, but sufficiently high to illuminate the shelves, is often found convenient.

Public Hall Lighting.—The lighting of halls for public meetings, concerts, and other entertainments requires much more care than is usually devoted to it. It is not uncommon to find a hall so badly lighted that the architecture, on which a great amount of care and money has been spent, is not seen to anything like the best advantage. Even the fittings themselves, when seen by daylight, are often extremely ugly and out of harmony with the general design of the building. It is in such a problem as this that close co-operation between the architect and the lighting engineer is so desirable if the work of each is to achieve its fullest success. For example, in a well-designed corridor nothing can be more ugly than a row of tungsten lamps, with conical opal shades, suspended by flexible wire from the ceiling. Not only do these leave the

roof of the corridor in complete darkness, and give a row of bright unshielded lamps most annoying to the eye by night, but even by daylight the architectural effect is very incongruous and lacking in dignity or beauty.

Similarly in a large hall a number of unshielded sources placed so low as to come within the field of view of those seated on the floor or in the balconies is not only very trying to the eyes but quite prevents any appreciation of the architectural beauties of the roof. The first requisites of public hall lighting are a sufficient general illumination for reading—probably 2 foot-candles is ample since it is not intended that reading or writing shall be carried on continuously for any great length of time—and a comfortable softness of shadow such as is given by indirect or semi-indirect systems. There is little doubt that one or other of these systems is better than the direct system wherever they are practicable, but it has to be remembered that in a number of cases the nature of the roof or its excessive height make the direct system inevitable, for an indirect system with a false ceiling is generally undesirable either on account of the lack of harmony of the fitting with the general design of the hall, or because it leaves the whole of the space above the fittings in a complete darkness which is not pleasing to the eye. In cases where there is a broad balcony round the sides of the hall, it may be necessary to supplement the general system of lighting by a local system, probably direct, to ensure that there is sufficient light for the side gangways and seats.

The lighting of the platform depends, of course, on the purpose for which the hall is to be used. For lectures it is usual to provide the speaker with a local desk light, especially if it may be necessary to lower the general lights in the hall for the exhibition of slides or kinematograph pictures. It is a great convenience to be able to turn off all the lights in the hall except those immediately over the platform. The most important precaution to take is that when the audience is looking at whatever may be going forward on the platform, the lights which illuminate it shall not come within their field of view unless adequately shaded. Even lights in opal globes or fittings may be very uncomfortable if looked at for a long time, and it is best to shield the light completely by means of an opaque reflector placed on the side of the lamps nearest to the auditorium. Alternatively, if a semi-indirect system is used, the translucent bowl should be sufficiently opaque to make it appear not much brighter than the wall or other background against which it is seen by the audience in the body of the hall.

Theatre Lighting.—The lighting of theatres and music-halls presents, of course, special problems of its own. Many of these are concerned with the production of spectacular or scenic effects and cannot be dealt with here. The auditorium of a theatre should be provided with a general illumination of between 1 and 2 foot-candles. Corridors and exits should naturally receive careful attention. The whitening of the edges of steps over which it may be necessary for members of the audience to pass during the period when the lights are lowered, is of great advantage. The lowering and raising of the auditorium lights before and at the conclusion of an act should preferably be done gradually through dimming resistances, and not by a sudden switching on or off. Though the transition may well be fairly rapid, it allows just sufficient time for the eye to accommodate itself comfortably to the new conditions of illumination.

Kinema Lighting.—The above remarks are equally applicable, in general, to kinema theatres. Here, however, there is the special feature of the picture screen. If this be placed too high, it is necessary for those members of the audience seated in the front of the theatre to keep the head and eyes continually tilted upward at an unnatural angle. This, in time, causes fatigue, and it has therefore been proposed by a Committee of the Illuminating Engineering Society that "the angle of elevation, subtended at the eye of any person seated in the front row by the length of the vertical line dropped from the centre of the top edge of the picture to the horizontal plane passing through the observer's eye, shall not exceed 35 degrees, the height of the eye above the floor level being assumed to be 3 ft. 6 in." They similarly recommend a limit of 50 degrees total angle for the lateral subtense of the vertical edges of the picture at the eye of anyone at the front of the theatre. With regard to the general lighting of kinemas they recommend that the illumination in all parts of the theatre should be not less than 0·025 foot-candle and that there should be a gradual diminution of the intensity of illumination in passing from the rear of the theatre (where illumination is chiefly needed to facilitate the work of the attendants) to the seats near the screen where stray light is most apt to affect the picture on the screen, and where such illumination is less needed because the seats are to some extent illuminated by light reflected from the screen. They add, of course, that no unscreened source of light should be visible to the observer in any seat in the theatre whilst looking towards the picture. The light system used in the projection of kinematograph pictures is briefly described on p. 191.

Church Lighting.—The lighting of churches is, pre-eminently, a problem requiring due consideration to be paid to matters which not only are outside the range of ordinary lighting engineering, but which are nearly always special to the particular case under consideration. Not only the æsthetic value, but also the sentimental and psychological result of any system of lighting must be carefully considered so as to avoid any lack of harmony with that tradition which it is the function of the architecture and decoration of the church, exhibited and assisted by the lighting, to express and emphasize. Generally speaking, the architecture imposes very severe limitations on the lighting engineer, and the only general principles which can be laid down are those which enjoin the avoidance of glare, particularly in those places towards which it is necessary for the worshippers to look constantly for any length of time, the provision of adequate illumination for

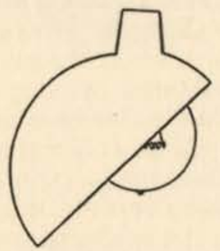


FIG. 51. Direct Lighting Reflector for Church Lighting

reading wherever this is customarily necessary, and the necessity for the lighting to show up and harmonize effectively with the architecture and decoration. Where reading is not necessary an illumination of between 0·5 and 1 foot-candle is generally ample.

The use of indirect and semi-indirect systems is often difficult on account of the great height or dark colour of the roof. In a direct lighting system, however, the pillars may often be used for the support and concealment of the light sources, and the fact that in many cases the worshippers all face continually in the same direction is of considerable advantage. It not infrequently happens that to effect a complete rearrangement of the lights in a church would be exceedingly costly, and much may be done to improve an existing system by the judicious provision of shades. Fig. 51 shows a shade which is suitable for a system of low-level light sources. As much light as possible is cast in the forward direction, while the eyes of those standing or sitting behind it are completely protected. The lighting of the pulpit should be provided by means of lamps with reflectors which completely screen the light from the eyes of the congregation. At the same time they should be sufficiently high to be outside the field of view of the preacher, while casting plenty of light on the pulpit desk. The possibility of glare from the surface of the paper, if this is shiny, should be avoided by placing the lamp away from the position giving specular reflection in the direction of the preacher's eyes. A strip lamp in a cylindrical shade placed at the top of the desk is not good unless some of the general lighting of the church is left on during the sermon, as otherwise the preacher's face is in complete darkness.

Museums and Art Galleries.—The lighting of museums and art galleries is again a problem calling for special treatment in each individual case. Often a judicious combination of general and local lighting is found to be most convenient. While the general light provides sufficient illumination for most of the exhibits, those requiring special treatment, either on account of the dark nature of their surfaces, or because they are placed in a position at which the general lighting is insufficient, may be provided with a supplementary local light. Small objects placed in glass cases may often be illuminated from concealed lights placed inside the cases.

In an art gallery, where the pictures are often covered with glass or highly varnished, one of the most objectionable defects of a lighting system is the production of bright images of the light sources by reflection at the front surface of the glass. With a picture hung at eye-level this is generally not difficult to avoid, but with pictures placed high up on the walls it is often impossible to get rid of. It is, of course, particularly objectionable in the case of a dark picture, and then even a completely indirect system sometimes fails to avoid the trouble. For example, in the case of Rembrandt in which the reflection ratio may be as low as 4 or 5 per cent., since the brightness of the image formed by reflection in the surface of the glass is about 4 per cent. of that of the object it comes from, it follows that even a bright ceiling, unless it be perfectly featureless and uniform, will cause a reflection which may seriously interfere with the proper appreciation of such a picture.

It has been contended that the artificial light in a picture gallery should, as far as possible, come from the same direction as, and be distributed similarly to, the daylight. Some large galleries are illuminated by means of gas-filled lamps placed above translucent glass in the ceiling, this same glass being used in the daytime to diffuse the light coming through a glass roof. One of the great difficulties of gallery lighting, whether by daylight or artificial light, is the formation of bright images

of light-coloured objects (dresses of people walking about the room in particular) in the glass covering the pictures. One scheme which avoids this effect to a considerable extent is the provision of a velum or false ceiling as shown in section in Fig. 52. While the light cast on the pictures is unaffected, the illumination of objects in the middle of the room is much reduced—and this, in fact, is apt to produce a general impression of gloom which is not altogether pleasing. Even this arrangement does not avoid troublesome reflections in the glass, notably of the frames and other bright points on the

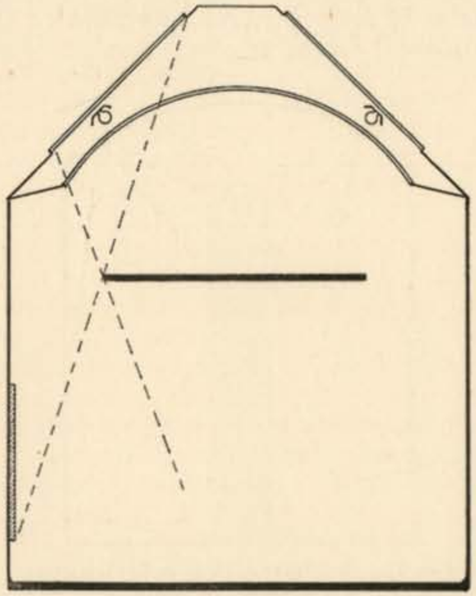


FIG. 52. False Ceiling in Picture Gallery Lighting

opposite wall, and only a dark-coloured partition down the centre of the room will remedy this defect. The use of bright gilt frames which produce points of specularly reflected light is to be avoided as far as possible.

A scheme of artificial lighting adopted in some galleries is that in which the light sources are placed inside the tops of large square pillars as shown diagrammatically in Fig. 53. This system, being totally indirect, depends for its effectiveness on the form and nature of the ceiling, and is not suitable for a gallery in which the daylight is admitted through large areas of glass in the roof, unless light-coloured blinds be provided for use at night.

For the lighting of individual pictures a reflector of the form shown in Fig. 54 is suitable. If the reflector is specially designed for the purpose, the illumination over the whole of the picture surface may be made exceedingly uniform.

Another feature of the artificial lighting which requires special attention in the case of a picture gallery is the colour of the light. Most pictures are painted in daylight, and therefore the hues of the pigments can only be seen at their true value when the picture is viewed by light of the same colour. Thus some form of artificial daylight is desirable (see Chapter X), but if this is not available, the artificial illuminant chosen should approach as nearly as possible to the ideal. It would clearly be fatal to light pictures by means of the mercury-vapour lamp alone. Of the sources at present readily available,

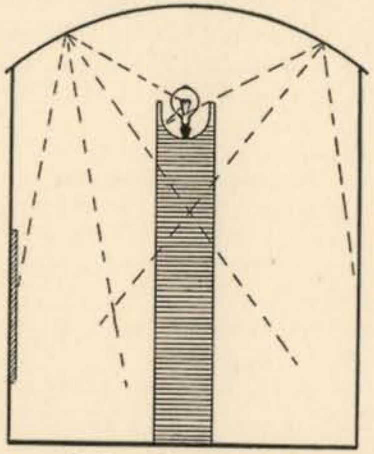


Fig. 53. Indirect Lighting in Art Galleries

probably the gas-filled lamp provides the best kind of light for the purpose. The plain arc is whiter, but it is apt to flicker.

One very important consideration is the avoidance of a strongly coloured decoration, especially at the top of the wall of a picture gallery, for the light reflected from the surface may be of such a strong colour as to alter quite noticeably the appearance of the pictures on the opposite wall. White, light cream, or neutral grey should always be used for the wall decoration of art galleries and studios.

Studio Lighting.—From the consideration of art galleries, it is a natural transition to studios, as the requirements in this case are very similar. The chief difference is that the light is required mainly at two positions, that of the model, and that of the canvas or drawing board. Totally indirect lighting, with extreme softness of shadow, is often undesirable for the illumination of a model. But direct lighting from a single point is considerably worse, especially if this point be vertically above the object illuminated. The best system is a semi-indirect one with fairly transparent bowls, two or three being placed at points surrounding the model and so that the light from them strikes the model at an angle of at least 30 degrees with the vertical. The illumination of the easel should, of

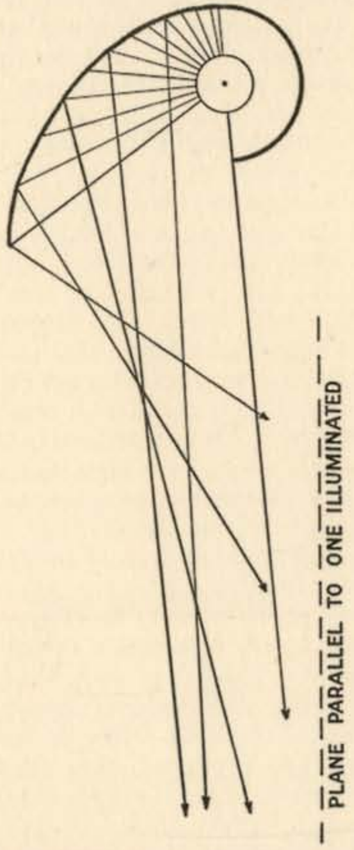


Fig. 54. Reflector for producing even Illumination of a Vertical Surface

course, be as even as possible, at least as high as 4 foot-candles (though for work on white paper 3 foot-candles may be enough) and free from excessively black shadows due to the hand or brush while work is in progress. The remarks made above as to the colour of the light desirable for picture galleries apply with even greater force to the lighting of studios.

Hospital Lighting.—There are two principal problems involved in the design of hospital lighting. The first of these is the illumination of the wards. There is a possible objection to the use of indirect or semi-indirect lighting for this purpose, since patients must necessarily gaze for a considerable part of their time at the ceiling or upper parts of the walls, and if these are the brightest surfaces in the room there is considerable danger of pronounced fatigue. For this reason some authorities have advocated direct lighting by means of lamps in some form of diffusing bowl which, while shading the lamp itself from the eyes of the patient and of the other occupants of the ward, will yet allow a certain part of the light to be diffused upwards in order to prevent the gloomy appearance of a ceiling in complete darkness. The provision of a light over each bed is considered desirable in case a critical examination by the doctor is necessary at any time. The general system of illumination should be capable of reduction to about 5 per cent. of its full value during the night.

The second problem, that of the illumination of the operating table, is one requiring highly specialized treatment and cannot be adequately dealt with here. One system which has been devised employs a searchlight beam, admitted to the operating theatre near the ceiling, and split up into a number of small beams which are caused to take different directions by auxiliary adjustable mirrors placed about the room in the neighbourhood of the table. By this means very high illumination intensities in all directions are obtainable, as much as 100 to 250 foot-candles being provided in one installation.

Shop-Window Lighting.—It is now necessary to turn to a form of spectacular lighting where the nature and suitability of the illumination provided may be of the utmost value, or may, on the other hand, completely defeat the purpose for which it is intended. The art of shop-window lighting is in many cases exceedingly well understood and carried out with a care and attention to detail which is well repaid by the excellence of the result produced. On the other hand, it is still far from uncommon to see a shop window lit by means of a large number of intensely bright sources completely unshielded, so that the eye is at once dazzled and unable to appreciate, or even to recognize the principal features of the objects on view. This is pre-eminently a case where the old illumination motto "light on the object and not in the eye" requires to be thoroughly appreciated and rigorously obeyed.

From a lighting point of view it is, perhaps, desirable to divide shop windows into two classes according as they approximate more closely to a large show-case where a few exhibits of a particularly attractive or artistic character are shown, or

to a collection of sample goods representative of the variety obtainable inside the shop. In the former case the windows are generally deep and often high, resembling the large show-cases of an exhibition or museum. The most suitable system of lighting is, in some cases, that obtained from lamps suspended above a sheet of translucent glass which forms the roof of the show-case window as shown in Fig. 55, supplemented by concealed lines of lamps in special reflector fittings placed either along the top of the front of the window or vertically at either side. Sometimes the light from the roof of the window is not available, and in that case the concealed top lighting may be employed alone as shown in section in Fig. 56.

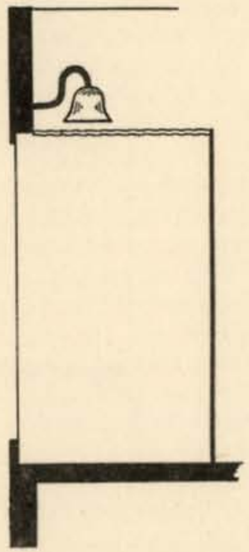


FIG. 55. Lighting of a "Show Case" Shop Window

The best direction from which the light should come must, of course, depend on the arrangement of the articles to be illuminated, and occasionally a completely different system of lighting may be best as, for example, when the window is dressed to represent a boudoir or other room. The lighting will then be most naturally derived from sources placed as they would be found in such a room.

The lighting of a window of the second class presents a more difficult problem. Such a window is, very often, comparatively shallow, and any attempt at top lighting leads to the goods in the lower part of the window being cast into shadow by the objects above them. Side lighting in concealed reflector fittings is generally better in such cases. The placing of sources in the body of the window is to be avoided if possible, but when it becomes necessary the first essential is the adequate shading of the light source from the eye of anyone facing the window from the street. Where it is desired to illuminate objects arranged more or less in a vertical plane, this may often be done effectively from sources placed outside the front of the shop and above the window. When these are fitted with suitable reflectors which shield the light from the eyes of those walking along the pavement, and reflect it downwards at a suitable angle, so that the maximum illumination is provided on the goods displayed, a very effective result is often obtained. Of course the sources must be so placed that

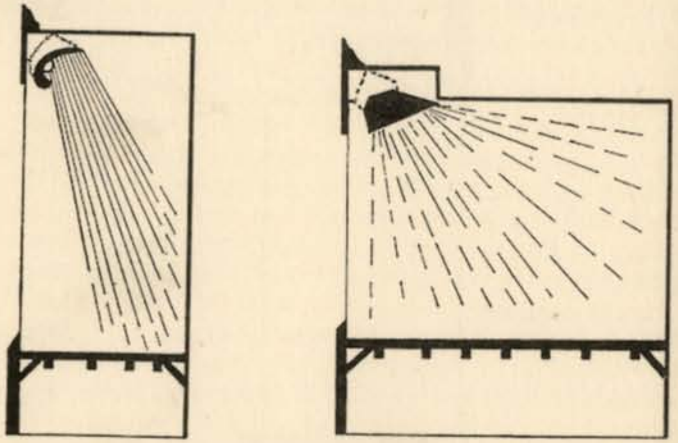


Fig. 56. Concealed Top Lighting for Shop Windows

the shadow of the person looking into the window is not thrown on the goods exhibited. It is also necessary to ensure that a glaring reflection of the light source in the front surface of the glass window is not visible to anyone examining the display.

Two other important features of shop-window lighting are adequacy and colour. As regards the latter, it is of course important that the colours of the goods shown in the window shall not be so changed by the artificial light that the effect produced is not as pleasing by night as by day. This is more particularly important in the case of the first class of shop window. Adequacy must be regarded from two points of view. Generally speaking, the passer-by does not gaze for very long at one particular window, and hence an illumination

which would be glaring for continual work is quite satisfactory for a short inspection. A bright object is much more attractive than one less highly illuminated, and it is the function of the light in a shop window to cause the articles displayed to attract the attention of the passer-by, and compel him to notice them among all the surrounding objects which meet his gaze. Shop-window illumination should therefore be on a much higher scale than that provided for ordinary purposes. For light-coloured articles an illumination of 10 foot-candles is not too high, while for dark goods 20 to 30 foot-candles may be employed with advantage. In this case it is desirable to ensure that white or light-coloured objects are not employed among the furnishings of the window. Glaring reflections from brass-fittings are disagreeable and tend to distract the attention from the articles on view. On the other hand, for an effective display of gold and silver ware and jewellery, the glitter due to direct reflection from the source of light is often desirable.

Showroom Lighting.—The interior of a shop or a showroom needs very good lighting both as regards adequacy and suitability. It is impossible to lay down any hard-and-fast rules on either of these points. Everything depends on the type of shop and the articles to be bought and sold. Generally speaking, a diffused light of at least 4 foot-candles on the working plane should be provided, and this should be supplemented with local lighting over counters, underneath heavy overhead obstructions, or anywhere else that common sense dictates. It is only comparatively recently that the value of lighting as an advertisement has come to be generally recognized, and even now it is frequently found that, while plenty of light is provided, the distribution is so unsuitable that much of its value to produce an attractive display is lost.

Needless to say, both in shop-window and in showroom lighting there are many special problems requiring individual treatment, and sometimes calling for a complete reversal of the general principles outlined above. Each of these problems must be treated on its own merits and the result arrived at, often by a process of trial and error, must be judged by the actual effect produced on the eye by any particular arrangement. Colour matching of materials is an important feature in some shops, and is catered for by the provision of artificial daylight in some region, or over a particular area in such a shop. Art dealers require a system of lighting approximating as closely as possible to that recommended for a picture gallery. Totally indirect lighting may tend to make many articles look flat and less pleasing than when direct lighting is employed. On these and numberless other points of a similar nature, only a wide experience can furnish rules for the determination of the most effective and most suitable illumination.

Buildings for Indoor Sports.—Apart from swimming baths, where a fairly uniform illumination from direct lighting fittings suspended over the bath is satisfactory, and gymnasiums where a well-diffused light is more necessary, the lighting of buildings used for indoor sports has not received so much attention in this country as in America. There seems to be little reason, however, why such places should not be satisfactorily illuminated, but of course the special features of each game require careful consideration. For rifle shooting, the chief need is a high even illumination of the targets (at least 6 or 8 foot-candles) by light sources completely screened from the marksman's eye. A moderate general illumination of about half a foot-candle at the butts is also desirable for loading, setting the sights, and general purposes. In a bowling alley the requirements are similar, viz. a high illumination on the pins by concealed lights, and a low illumination at the commencement of the alley. The intervening space, however, should not be left dark in this case, but should be provided with a graduated illumination from one end to the other, all sources being concealed from the player.

In the case of games such as indoor lawn tennis and badminton the system which has been found most suitable is that in which a general illumination of about 3 foot-candles is provided by several high candle-power sources placed in diffusing reflectors of special design at the sides of the court. These sources are placed at least 20 feet above the ground, and direct fittings give a stronger local illumination at the service lines. If white balls be used, the walls and floor should be of a dark tone in order to show up the ball as clearly as possible. The lighting of outdoor playing-grounds will be considered in Chapter VIII.

Kinema Studios.—A very specialized problem of lighting is that of the kinema studio where the artistic effect and photographic efficiency of the light are all-important. Large banks of mercury-vapour lamps, and "batteries" of arcs, either plain carbon or enclosed types, are used. Small projectors on separate stands are employed for lighting any particular section of a scene. The qualities chiefly aimed at in an installation are maximum efficiency as regards actinic value of the light, low intrinsic brilliancy, and absence of fumes or excessive production of heat. The illumination of the scene to be photographed is very high, 500 to 1,000 foot-candles being the lowest value generally employed.

CHAPTER VII

INDUSTRIAL AND SCHOOL LIGHTING

THERE are still two classes of buildings, the illumination of which must be considered separately on account of their great importance. These are schools, and factories and workshops. A great deal of attention has been paid to both of these problems in practical illumination, and in many countries legislation is in force prescribing a minimum intensity in some specific cases, as well as laying down certain principles of general arrangement which have to be complied with.

Industrial Lighting Codes.—In several of the American States very complete codes of lighting intensities required for various industrial processes have been adopted as legal requirements for factories in those States. The chief difficulty in drawing up any such code is to classify, in sufficient detail to be of practical use, the numerous processes carried on in factories of all descriptions.

The following table forms a summary of the codes at present (1922) in existence.

In connexion with this table it should be noted that:

(i) The values recommended in the British Home Office report refer only to the illumination necessary in the interests of safety and general convenience, and have no reference to the amount of light necessary for efficient work.

(ii) The American figures given are the general average of the codes adopted legally in eight states. These codes, while differing slightly in a few minor respects, are in general agreement with the recommendations of the American Illuminating Engineering Society. These recommendations, in addition to intensity specifications, include definite suggestions as to other aspects of good lighting, such as glare, and the provision of an emergency lighting system.

(iii) The figures given are in all cases intended as statutory minima, and do not at all represent what would be provided in good lighting practice. Probably double the above quoted figures would in most cases represent a fair illumination for obtaining the most satisfactory conditions of working.

(iv) The last column on the right represents the medium value of the observations published (1913-14) in the Report of the Home Office Committee, i.e. 50 per cent. of the observations made were below this value, and 50 per cent. were above it.

TABLE

Classification.	American Codes (Average)	British (Home Office Committee)[1]	German (Illuminating Engineering Society)	British Report (Observations)
(*a*) Roadways, yards, thoroughfares	0·02	0·05	0·1	—
(*b*) Storage places	0·25	0·25[2]	—	—
(*c*) Stairways, passages	0·25	0·1	0·5	0·5
(*d*) General Lighting for Workshops	0·25–0·5	0·25	1·0	1·3
(*e*) Toilets, wash-rooms, water-closets, dressing rooms, lifts	0·5	—	—	—
(*f*) Rough manufacturing, such as rough machinery assembling, bench work or foundry floor work	1·25	—	1·0	1·6
(*g*) Fine manufacturing, such as fine lathe work, pattern and tool making and light coloured textiles	3	—	—	1–2·5
(*h*) Office work, such as accounting, typewriting, etc.	3	—	2·5	—
(*i*) Specially fine manufacturing such as watch-making, engraving, drawing, and dark-coloured textiles	5	—	5	4–5
(*j*) Rough manufacturing, involving closer discrimination than (*f*)	2	—	—	—

[1] First Report of the Departmental Committee on Lighting in Factories and Workshops. Cd. 8000 (1915).

[2] For foundries 0.4 foot-candle.

Advantages of Good Industrial Lighting.—There are two aspects, not altogether unrelated, from which the necessity for good lighting in factories and workshops may be regarded. In the first place, the health, safety and comfort of the workers demand an adequate illumination for the avoidance of accidents, the prevention of eye-strain, and the promotion of a general impression of well-being and of working under comfortable conditions. In the second place, it is self-evident that work performed under an adequate illumination will be more efficiently and more quickly carried out than if the illumination be inadequate or unsuitable. The British Report above referred to is insistent on this point, and includes the following statement: "The effect of improved lighting in increasing both the quantity and quality of the work is generally admitted, and specific instances are quoted in the evidence. In one instance the output was diminished 12 to 20 per cent. during the hours of artificial lighting, and in another the earnings of the workers increased 11·4 per cent. after the installation of a better system of lighting."

There are many trades where the nature of the work makes a very considerable demand upon the accurate and rapid performance of the eye, and work for long periods under unsatisfactory lighting conditions may cause ophthalmic trouble which, unfortunately, is generally not apparent at once, but shows itself only after a considerable time, and when irretrievable harm has been done. These considerations apply, of course, with the greater force, the larger the proportion of time for which artificial illumination is normally in use. The question of daylight illumination will be considered later in a separate chapter (see p. 166).

Accidents and Lighting.—The avoidance of accidents, due as often to an unsuitable arrangement of the lights as to inadequate illumination, is a matter which has received considerable attention both in the United States and by the Home Office Committee in this country. Fig. 57 shows, for the different times of the year, the total number of accidents, due to persons falling, in the factories of England and Wales, from January, 1913, to February, 1914. The rise of the curve during the months of diminished daylight is very marked. One of the most frequent causes of accidents is inability to see obstructions lying in a gangway, owing to the dense shadow cast by a pillar or machine.

General Principles in Factory Lighting.—One of the most important problems, therefore, which comes within the practice of the lighting engineer is that of factory lighting. The nature of the work carried on, the architectural features of the rooms and the characteristics peculiar to the period at which they were built, economy in cost combined with necessity for a lighting system which will ensure the greatest efficiency of the workers, all unite to provide a problem which is often extremely complex and must necessarily lead to a compromise between ideals and practicability.

There are a number of considerations which apply, in varying degrees, to almost all lighting installations for industrial purposes, and these will first be dealt with in general terms before any attempt is made to consider the requirements of particular classes of work in detail.

Frequent inspection for the purpose of maintaining any lighting system in good order is a first essential. As already remarked in Chapters V and VI, it may be assumed that the

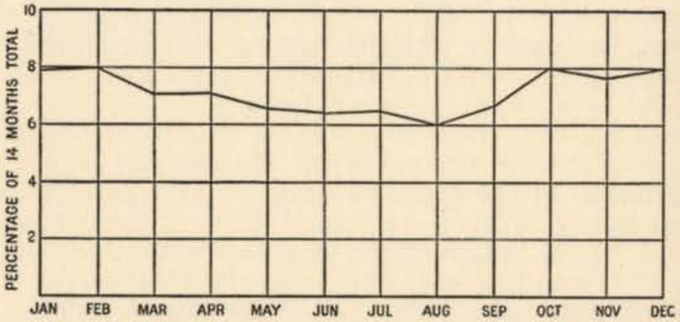


Fig. 57. Variation of Accident Incidence with Time of Year.

unavoidable deterioration of lamps and fittings after installation will cause a reduction of 30 to 50 per cent. in the illumination, and a large part of this drop will take place within a comparatively short period from commencement. This must be allowed for when the candle-power of the lamps required is being decided. The depreciation is, of course, greater in some industries (e.g. engineering, and particularly iron-founding) than in others (e.g. printing), and a higher allowance, as well as more frequent cleaning, is required in the former case than in the latter. At the same time it must not be lost sight of that careful attention to maintenance may be more economical, as well as more satisfactory, than the provision of lamps of higher candle-power which are allowed to become dirty and inefficient. The replacement of broken, or old and deteriorated lamps should also be carried out as frequently as possible.

The positions of the light sources and of machines should be mutually arranged so as to avoid the casting of shadows from

belts or other obstructions on important parts of the work. Also the distribution of light from the lamps should be such as to avoid sharp contrasts of light and shade on the work. Moving shadows are particularly annoying and should always be avoided, if necessary by the provision of a local light. Flickering or unsteady lights are similarly very trying and should be avoided.

One of the most important features of any industrial lighting installation is its avoidance of glare. The worker should not be able to see any object brighter than his work when looking at the latter directly, otherwise his visual acuity will be reduced and the accuracy of his work will suffer in consequence. It is also desirable that no very bright object should be visible

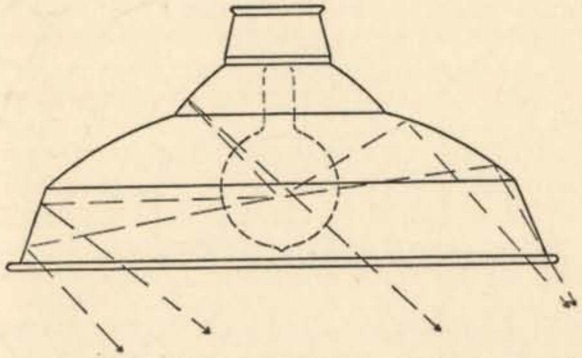


Fig. 58. R.L.M. Reflector for Direct Lighting in Factories

to the worker when looking in *any* direction, so that glare by successive contrast may be avoided. Otherwise if the eye is raised from the work to look across the room it may meet unshielded lights and thus be momentarily dazzled and prevented from seeing clearly when the work is again looked at. It cannot be too strongly emphasized that suitable arrangement of the light sources is quite as important as the provision of adequate illumination. Fig. 58 shows a form of enamelled iron (R-L-M.) reflector which has been found very suitable for *general* illumination by direct lighting in many kinds of factories. Glare is prevented and a good distribution of the light is achieved. This fitting is adapted to take gas-filled lamps, and the polar curve of light distribution ordinarily obtained is shown in Fig. 59.

There are two other details which should receive consideration when the lighting of a factory is being planned. In the first place, the grouping of lights to be controlled from a single switch requires careful consideration, particularly as regards the distribution of natural lighting. Clearly the parts of a room which will first require artificial lighting are those where daylight is least, so that it is economical to make the areas controlled by each switch correspond, as far as possible, with the contours of daylight illumination. In a room lighted from windows along one wall, for example, the most economical grouping is in lines parallel with this wall.

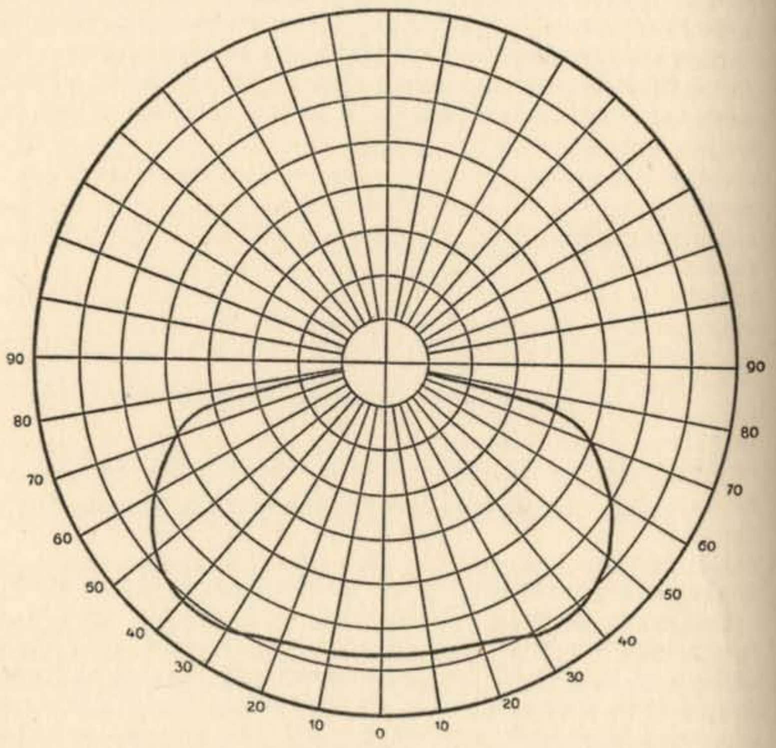


FIG. 59. Polar Curve obtained with R.L.M. Reflector

The other point, and one which is strongly emphasized in the American Report, is the provision of a system of emergency lighting which has independent connexion with the main source of supply, so that the failure of the main system from internal causes may not affect the emergency system. The same recommendation is made with regard to schools. The emergency wiring system should clearly supply the lighting for exits and stairways.

It is, of course, obvious that in addition to the above very general requirements, which may be said to apply without exception, there are others which must be borne in mind for application when dealing with certain classes of work. For example it is obvious from what has been said in Chapter I, that when the work is principally carried out on materials of a dark colour, i.e. with a low reflection ratio, a higher illumination is required than when light-coloured materials are used. The important factor in seeing is the brightness of the object looked at, and this is the product of the illumination and the reflection ratio.

Actual experiments to determine the illumination required for sewing on materials of various colours have shown that while an illumination of 1·25 foot-candles is the minimum required for a white material of high reflection ratio, 1·5 foot-candles is needed for a holland material of 52 per cent. reflection ratio, 2 foot-candles for a slate material of 12 per cent. reflection, and 4 foot-candles for a black material. All these figures refer to direct light. With an indirect system it is found that approximately double the intensity of illumination is required, as is only to be expected from the nature of the work carried out in this case.

In the course of a short survey of existing lighting conditions in three of the main industries, viz. the engineering, textile, and clothing trades, the writer had an opportunity of making over 4,000 illumination measurements in 57 different factories. Conditions are almost as diverse as the buildings. Only in a comparatively stereotyped process, such as weaving, can it be said that conditions are at all the same in different factories.

Gangways, Passages, and Stairs.—It is possible, therefore, to give only a very rough guide to the intensity of illumination which may be considered as generally satisfactory for various classes of work. Before proceeding to particularize in this way, however, the general illumination necessary for gangways, passages, staircases, and all parts of a factory over which people are liable to pass, may be specified. The recommendation of the Home Office Committee is that this should never fall below 0·25 foot-candles, but it must be remembered that this is recommended as a statutory minimum, and that therefore an average illumination of at least 0·5 foot-candles should be provided in such places, while on staircases or in places where obstructions are liable to be met with on the floor, this value should be again increased. In staircases it is important that the risers as well as the treads should be illuminated. A direct light from above is not satisfactory unless the edges of the steps are well defined by whitewashing them, or otherwise. Discontinuities in the surfaces of passages or gangways should be well lighted.

Foundries.—One of the most difficult factories to light is a foundry. The large area to be lighted,the dark colour of the material worked upon, and the impossibility of maintaining glass or any other surface in an adequately clean condition are all factors which tend to make the efficient lighting of such a building very difficult. General lighting by a direct system is almost essential. Arc lamps or gas-filled lamps placed high above the line of sight and provided with enamelled reflectors are very usual. High-pressure gas is also employed as a rather more local system of lighting. The avoidance of any deep shadows cast by pillars or other obstructions is very important, as they may conceal holes in the casting sand or obstructions of other kinds, and lead to accident or spoilage of work. The shadows which may be cast by travelling cranes should receive consideration and sometimes it is found convenient to place a light underneath the carriage of the crane in order to overcome this difficulty. Generally it may be said that an average illumination over the floor surface of at least 1 foot-candle is needed. The nature of the work makes it necessary to clean lamp bulbs, globes, or reflectors, at very frequent intervals.

Engineering Workshops.—Heavy engineering, e.g. boiler-making, planing, forging, rolling, etc., needs a similar general illumination of about the same intensity as that required for a foundry. Finer work, such as turning, drilling, pressing, etc., requires a higher illumination at the place of work. A general illumination of between 1 and 2 foot-candles over the whole shop, with a local light shaded from the worker's eyes, and preferably adjustable, giving 3 to 4 foot-candles at the working point of the machine is a very satisfactory arrangement. Bench work, such as filing, fitting, soldering, and vice work generally, is often provided with direct lighting from a row of small shaded lamps suspended over the bench at intervals of from 6 to 10 feet. At least 5 foot-candles, measured on a horizontal plane at the vice, should be provided. Specially fine work such as engraving, or the winding of fine coils for electrical apparatus, needs an even higher illumination, and the provision of arrangements for adjusting the position of the light to suit the worker is very valuable.

Weaving Sheds.—In textile factories the two chief processes are weaving and spinning. For the former it is usual to provide an illumination of from 2 to 4 foot-candles on the loom where the shuttle is travelling. Often one lamp to every two or every four looms is considered sufficient, but one lamp to

each loom is preferable in order to avoid the necessity for the operator to be in his own light when attending to the work. Direct lighting is general owing to the prevalence of overhead glass for roof lighting by day. The shades should always be sufficiently deep to shield the bare lamps from the eyes of the operatives working in other parts of the shed. Wherever practicable, the light should be increased to at least 5 foot-candles when dark materials are being woven. Overhead obstruction, either by belting or Jacquard harness and similar overstructures, must be carefully considered when the lighting points are being planned.

Spinning Rooms.—Spinning provides a rather difficult lighting problem. Vertical illumination is chiefly wanted, but the gangways between machines are usually too narrow to allow the light to reach the bottom in a sufficiently horizontal direction. Semi-indirect lighting with "false-ceiling" units is very efficient. A vertical illumination which should not fall below 1 foot-candle anywhere on the front of the machine, is required, though here, again, the darker the material the higher the necessary illumination. Winding, again, requires a high general illumination of from 4 to 6 foot-candles. Warping is very exacting since each individual thread has to be clearly visible. A general illumination of at least 5 foot-candles is required. Such processes as carding and drawing, and wool washing, are less fine, and an illumination of 2 to 3 foot-candles is generally sufficient. For mule-spinning 3 to 4 foot-candles, and for silk throwing a general illumination of at least 3 foot-candles is required. Lace and hosiery machines are generally semi-automatic, but an adequate illumination is required for mending the thread. A portable lamp, or one on an adjustable arm is frequently provided in addition to the general illumination of the room.

Burling, the process of removing small imperfections from a woven material, and mending, being very fine work, require a high illumination, and 6 to 10 foot-candles, according to the colour of the material, is provided. Direct lighting, generally local, is most suitable. This process may be regarded as typical of a number of different classes of work all requiring very close examination of fine detail, e.g. invisible mending, embroidery, etc.

Clothing Factories.—In the clothing trade there are, in the main, two kinds of work to be provided for. Sewing comes under the head of fine work, and requires a very high illumination, the exact amount depending on the reflection ratio of the material. It has been found that for white material an illumination of 3 to 4 foot-candles is necessary, so that for a very dark-coloured cloth at least twice this, or even more, should be provided. This applies also to machine sewing, the high intensity being required on the bed and needle of the machine. A very convenient arrangement is that in which a small hooded lamp is attached to each machine near the needle, so that a very high illumination is provided at the point of work. Of course a good general illumination of 2 to 3 foot-candles is necessary in addition to the local light. This degree of illumination is also necessary for cutting, ironing, and other processes less fine than sewing. Indirect lighting is not suitable for sewing, and when semi-indirect is used the direct component should provide at least 50 per cent. of the total illumination at the point of work. This is necessary in order that the individual threads may be distinguished, and the sewing-thread easily recognized, by means of the shadow due to the unidirectional component.

Dressmaking and millinery require lighting very similar in character to that needed for tailoring. The proportion of "direct" light should be at least 50 per cent. and may be as much as 80 per cent. in many cases without causing trouble due to excessive shadow. Sometimes the matching of coloured materials and threads is necessary, and some form of artificial daylight must then be provided. Embroidery and specially fine work, such as buttonholing by hand, require an illumination of at least 5 foot-candles even with light-coloured materials.

Printing and Engraving.—A printing works provides a number of special problems in lighting engineering. Composing frames need a fairly strong light which is frequently provided by a local lamp suspended over the frame, above and slightly in front of the compositor. It is very important that glare should be avoided, and some form of deep reflector, preferably opaque, should be provided to prevent any possibility of the bare lamp being seen, either by the compositor whose frame it is illuminating, or by any other worker in the same room. This plan of local illumination possesses the advantage that when any particular frame is not in use the lamp over it, if provided with a local switch, need not be put on. It is desirable that a general illumination of from 0·5 to 1 foot-candle should be provided in addition to the local light, which should give at least 5 foot-candles.

Engraving, especially on copper or other polished metal, calls for very special lighting treatment. Direct lighting from any bright source, even when adequate shades are provided to shield this from the eyes of the worker, causes glare due to the specular reflection of the source in the polished surface of the metal. This is well-known to engravers, and a

diffusing screen is nearly always introduced between the lamp and the work. This should be quite featureless, and as uniform in brightness as possible. It frequently takes the form of a sheet of tissue-paper placed behind the work at an angle of about 60 degrees with the horizontal. This sheet should be larger than the total area of the metal to be worked on at one time, and it should be sufficiently far from the source to receive a nearly uniform illumination. A suitable arrangement is shown in Fig. 60.

For a printing machine a good general illumination of 2 to 3 foot-candles is the best. Local lighting is not generally satisfactory, though the general illumination may often be

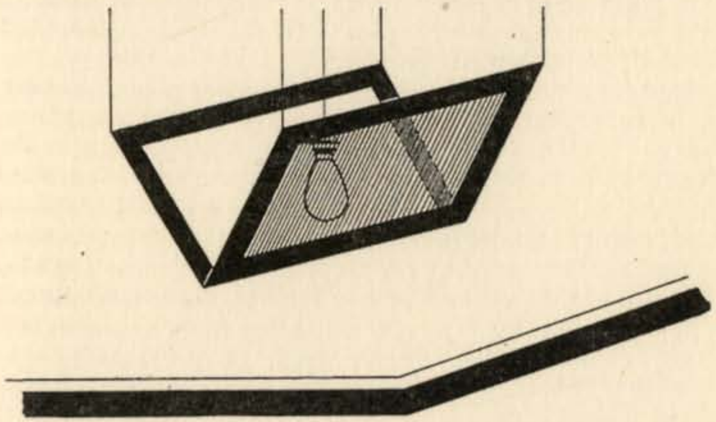


FIG. 60. Translucent Shade used by Engravers

usefully supplemented by a local light placed over the bed of the machine where the work is delivered and looked over. A portable light for the examination of lower parts of the machine is very useful in this as in other similar cases.

Colour printing may require accurate matching of the pigments used, and here again artificial daylight finds a very useful application. Cutting, folding, and other general processes require a good diffused light, but a guillotine bed may need local illumination as well.

Proof-reading demands a strong local light and from 3 to 5 foot-candles is desirable. A higher illumination than this is probably bad, as tending to produce fatigue, due to prolonged gazing at such a bright surface. If glazed paper is used, specular reflection may cause glare, as in the case of copper-plate engraving. An arrangement similar to that described above may be used in this case also to overcome the difficulty.

Miscellaneous Processes requiring High Illumination.—Trades such as jewellery and watchmaking involve the discrimination of exceedingly fine detail, and are generally regarded as in the class of work requiring the highest degree of illumination. A fairly well-diffused general illumination of 3 to 5 foot-candles should be supplemented by a local light, the position of which is under the control of each workman. Under this heading such processes as stone-setting, inlaying, enamelling, and fine chain-making are included. Eye-punching in needle-manufacture, hand-painting in the pottery trade, and the various processes involved in cut-glass manufacture and finishing, are all examples of work requiring the highest degree of illumination.

The lighting of drawing offices has already been dealt with in the previous chapter (p. 109). In places where work with coloured inks or pencils is common, a higher illumination is required than that recommended for general purposes. Tracing, in particular, is very exacting and should receive preferential treatment. Sometimes translucent glass tables illuminated from below are used.

Lighting in Mines.—The illumination of a mine is extremely limited owing to the large number of special conditions existing. The necessity for avoiding the accidental production of a spark or the use of a bare flame of any kind makes it impossible to use any of the ordinary means of lighting in any mine liable to contain explosive gas. Some form of portable lamp is universal. This may be a modified design of the Davy lamp, burning a liquid paraffin or light petroleum, or it may be an electric lamp containing both bulb and storage battery in the same case. The mean horizontal candle-power is, in either case, approximately 1 to 1·5 candles, so that the illumination produced at the working surface is very low. Safety devices have to be provided so that the lamp cannot be opened without being brought to the pit head. Lamps must, therefore, be capable of burning for at least 9 hours without refilling or charging. They must also be made capable of withstanding any reasonable jar without being extinguished, as the loss of time entailed in bringing them to the surface for re-lighting may be serious.

School Lighting.—It is only natural to find that the artificial illumination of schools has received much less attention than the daylight requirements. At the same time there is a not inconsiderable part of the total school hours during which artificial light is needed, especially if evening and continuation classes be included. The matter has been carefully considered by a committee of the Illuminating Engineering Society and

their recommendations are divided into three main sections dealing respectively with the amount of illumination required, the prevention of glare, and the avoidance of inconvenient shadows.

For illumination on the desk surface, where reading and writing are normally in progress, a minimum intensity of 2 foot-candles is prescribed. More recently 3 foot-candles has been recommended in America. For special work, such as art classes, drawing offices, work on dark materials, etc., a higher illumination is required and 4 foot-candles has been recommended. For assembly halls, and for general illumination in parts of rooms where no reading, writing, or other similar work is carried on, one foot-candle would probably be sufficient, but if this minimum were the only lighting provided in a hall there can be no doubt that the general effect would be very gloomy. Gymnasiums need at least 2 foot-candles, while in workshops and laboratories a good general illumination of at least 3·5 foot-candles should be provided.

The committee above referred to has laid down the recommendation that in rooms where the students are distant more than 20 feet from the blackboard, and where it is customary to use diagrams in coloured chalk, an illumination on the blackboard of 60 per cent. in excess of that in the rest of the room is desirable. The board should be maintained a dead black and repainted at regular intervals. In America a slate surface has been recommended in preference to wood.

Avoidance of Glare.—The above remarks concerning the surface of the blackboard have reference to avoidance of glare due to specular reflection of bright surfaces by polished parts of the blackboard surface. This is a very important matter since the pupils may be required to keep their attention fixed on the board for comparatively long periods. For a similar reason it is desirable that the surface immediately behind the board should not be too light, so that excessive contrast between the brightness of the blackboard surface and of the surrounding portions of the field of view may be avoided. The avoidance of glare from this cause is dealt with by the committee above referred to when they recommend that no lamps should come within the solid angle subtended at the eye by the blackboard and a space two feet above it, unless they are completely screened from the eye by a shade impervious to light. They add the general recommendation that no incandescent surface should be visible to the eyes of students or teachers while carrying on their ordinary work.

Another source of glare is the direct reflection of light from the polished surfaces of the desks or paper. It is therefore recommended that school books and exercise books should be of matt paper or, at any rate, paper which gives no appreciable specular reflection even at large angles of incidence. Semi-indirect lighting is favoured in America, but in any case the use of shades or diffusing bowls having a brightness of not more than 3 candles per square inch is strongly recommended. It should be noticed that a glazed or semi-glazed surface for walls or ceilings is objectionable for the same reason as non-matt paper is considered undesirable. These surfaces should be as matt as is consistent with cleanliness and ease of maintenance. The avoidance of inconvenient shadows is fully dealt with by the committee of the Illuminating Engineering Society which recommends that in a class-room the lights should be so arranged that inconvenient shadows cast by the body on the desk should be avoided as far as possible. They go on to recommend the use of light-coloured walls for the avoidance of dense shadows, and, in fact, their requirements would be admirably met by a semi-indirect system, with a moderately light-tinted scheme of decoration.

A lecture theatre, where it is not generally intended that the students shall take notes, presents a rather different problem. In this case a well-diffused general illumination of low intensity, probably 0·5 to 1 foot-candle, would be sufficient. The illumination on the blackboard and demonstration table, however, should be at least 2·5 foot-candles, and may often be conveniently provided by direct lights well screened from the eyes of those in the body of the theatre.

CHAPTER VIII

OUTDOOR ILLUMINATION

When designing a system of illumination for any open space, the lighting engineer is confronted with two difficulties. In the first place the general necessity for placing the lamps on standards, or otherwise suspending them at a convenient height means that their number must be kept as small as possible, so that each lamp is required to illuminate a comparatively large area. Secondly, no help can be obtained, as in the case of indoor lighting, from the reflections due to walls and ceiling, so that direct lighting is alone admissible, and reflectors are almost invariably needed in order to redirect the light emitted upwards by the lamps and cause this to reinforce that emitted in the lower hemisphere.

In the main, three chief classes of outdoor lighting may be distinguished. In the first of these, requiring by far the highest intensity of illumination, work has to be carried on and an endeavour must be made to provide as much light as in an indoor installation. Examples of this class are a railway station, a shipyard, or a roadway under repair. In the second class, requiring only sufficient illumination for people to move about comfortably and without danger of collision, a comparatively low intensity of illumination is all that is needed. This class includes ordinary street lighting, the lighting of railway goods yards, squares, and open spaces generally. In the third class, of which beacon lighting is the most common example, no attempt is made to provide any uniform illumination, however low, but the light sources themselves are used for the purpose of marking out a direction and for indicating special points of danger, signposts, etc. This last system is used when the area to be dealt with is too vast for adequate treatment by the methods applicable to the second class. Street lighting outside cities and towns is generally on this principle. From an illumination point of view nothing further need be said concerning outdoor lighting of this description.

Street Lighting.—With regard to street lighting in towns there are so many different conditions which may need to be fulfilled, and the systems in common use are so various, that a brief description of these and of the performance of some of the many different types of units available must be given here. The first two requirements of any system of street lighting, viz. reasonable uniformity of illumination and absence of glare, may be said almost at once to be incompatible. For unless the units are placed at a height greater than about one-third of the distance between them, the light reaching the road at a point mid-way between the units makes an angle of less than 30 degrees with the horizontal, so that the nearest unit is liable to come within the field of view of the foot-passenger and thus cause glare. Such a close spacing of units as would be called for by this consideration is generally out of the question. The height of the units is more usually of the order of one-tenth of their distance apart, sometimes less, for if the units are placed very high, so as to obtain a large spacing ratio, much of the light is usually lost at the sides of the road. Some improvement in this respect can be obtained by placing the lamps above the centre of the roadway either on tall standards, or by suspension from cables attached to high buildings on either side of the road. Both of these plans are adopted in London, the former notably in Oxford Street, and the latter in the City. Where neither of these alternatives is possible, either on account of the narrowness of the thoroughfare and the bulk of traffic or because the facilities for the attachment of the cross-cables do not exist, it is necessary to abandon the central lighting plan, and then the scheme of staggering the lamps at the edge of the pavement on either side of the road is generally adopted.

One of the chief disadvantages of a lofty suspension of the lights is the expense and size of the standards necessary, and the special arrangements needed for cleaning and maintenance. This is particularly the case with arc lamps where the carbons have to be renewed at comparatively frequent intervals, and some means of lowering the lamp to ground level by a windlass or otherwise is commonly provided.

If a lower position for the light sources be adopted, the standards have to be placed closer together and a large number of units, each of lower candle-power, is required. It is for this reason that arc lamps or high candle-power high-pressure gas systems are generally placed on very lofty standards, while incandescent lamps or low-pressure gas systems are generally used on shorter standards placed nearer together. Even in these cases, however, a value of one-tenth for the spacing ratio is general, and glare cannot, therefore, be alto-

gether avoided. It may be minimized by increasing the light-giving area, placing the actual light source in some form of diffusing globe which will not only give the correct distribution of light for a fairly even illumination over the roadway, but also present to the eye a surface which, while still much brighter than the surrounding objects, is considerably less glaring than the naked filament of an electric lamp, or even an incandescent gas mantle.

Street Lighting Fittings.—Many different types of globes and reflectors have been designed for street lighting purposes. With the present practice of spacing it is easily shown that the greatest candle-power is required from the unit in a direction about 10 degrees to 20 degrees below the horizontal, depending on the spacing ratio. This maximum should be at least ten times as great as the candle-power given in the vertically downward direction. It is not at all clear that the illumination measured on a horizontal surface, placed at a

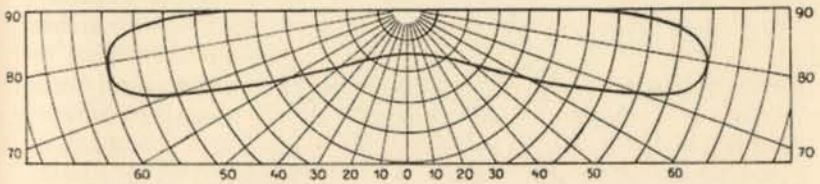


Fig. 61. Theoretical Polar Curve of Street Lighting Fitting

given height above the roadway, is really the best criterion of the satisfactory performance of a street lighting installation. The illumination on the vertical surfaces of people and moving objects is of even greater importance than the horizontal illumination, and since, at a distance from a lamp equal to ten times its height, the vertical illumination is ten times the horizontal illumination, it becomes a matter of considerable practical importance to decide which is the best criterion to adopt. Probably some form of compromise is the most satisfactory plan.

The view is widely held in America that uniformity of incident light on the street is unnecessary because, at points nearly midway between the lamps, the light, being incident at a small angle with the horizontal, shows up with great clearness the surface irregularities of the road. It is also considered that one of the chief factors in good visibility of objects is an effective silhouette and that this is obtained even more surely in the dimly lighted regions than in the brightly lighted areas. Further, it is pointed out that with a smooth road surface specular reflection of the light from street lamps is so prominent that there is generally a band of light from a point near the observer to the position of the light, and that objects crossing this band are equally clearly seen at all points of its length.

A perfectly uniform horizontal illumination is not practically obtainable, and a diversity factor of 10 to 1 or even 15 to 1 seems a reasonable allowance on this basis when the influence of the vertical illumination is considered. Fig. 61 shows the theoretical polar curve of a source giving a horizontal illumination varying from 10 to 1 along the line joining the points vertically below the centre of a series of such sources placed at a distance apart equal to ten times their height above the line. An approximation to such a curve is obtained by several fittings available on the market. These depend, generally, on reflection from a white enamelled surface or on refraction through prismatic glassware: frequently a combination of both reflection and refraction is used. The holophane system has

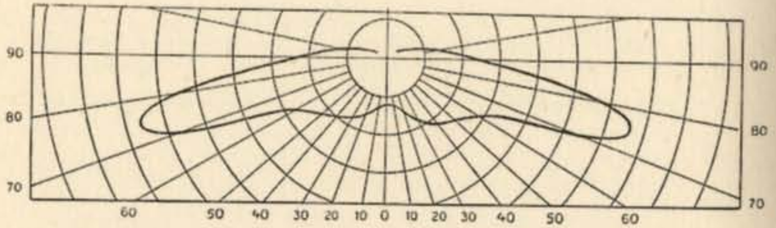


Fig. 62. Polar Curve of Holophane Bowl Refractor for Street Lig hting

already been briefly described in Chapter V, p. 92, and the polar curve of a holophane bowl refractor designed for street lighting is shown in Fig. 62. A refractor which modifies in a somewhat similar way the distribution of light given by a flame arc has also been found to give good results.

A reflector designed to concentrate nearly all the light in directions along the line of the roadway, and to prevent any considerable portion of it from being cast on to the buildings at the side of the road, has been designed in America. It consists of two deep metal reflectors, approximately semi-paraboloids, one on each side of the lamp, so arranged as to project a beam down the street in both directions.

A new form of fitting for street lighting purposes has recently been introduced by H. T. Harrison. It is shown, in principle, in Fig. 63. The light source is placed very nearly at the focus of a curved reflector so that the rays emitted upwards from the source are concentrated into a downward beam of very small divergence. This beam is then divided into two, and deflected

into directions approximately 10 degrees below the horizontal by two plane mirrors which are so placed that their planes pass through the source of light so that they intercept very little of the direct light emitted in downward directions. The area and angle of tilt of the mirrors are adjusted to suit the breadth of the road, the spacing ratio of the units, and the degree of uniformity of illumination desired in any particular case. Fig. 64 shows in the upper diagram the polar curve of light distribution from the lamp, while the lower diagram gives the corresponding distribution of horizontal illumination along the line of lamps, assuming the latter are placed at a height of 24 feet and a distance of 180 feet from each other. It will be noticed that the direct light from the lamp in the lower hemisphere is not interfered with in any way, so that the extra

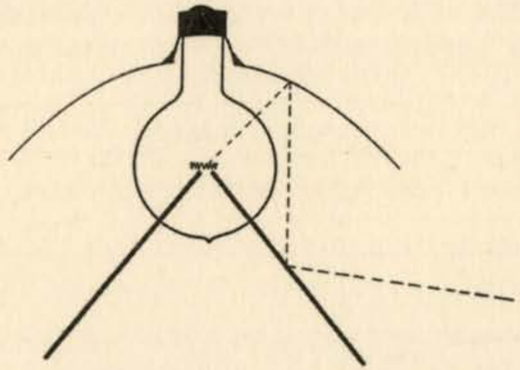


Fig. 63. Diagram of L.L.L. Street Lighting Unit

illumination at the parts of the road mid-way between lamps is all obtained from that part of the light which is emitted upwards and therefore frequently wasted either wholly or in considerable part. Fittings for use with incandescent gas mantles generally depend mainly on reflection from white enamelled surfaces in order to obtain a lateral spreading of the light from the source. The higher brilliancy of the high-pressure gas mantle renders this method of redistribution more effective than it is in the case of upright or even inverted low-pressure systems.

A very important consideration with all fittings designed for street, or indeed for any outdoor, lighting is their suitability for rapid and efficient cleaning. Prismatic elements in glassware, therefore, should be covered with an outer glass globe, so that a smooth surface is presented for cleaning. The tendency for insects to be attracted to a street lamp and their accumulation within the globe, if there be any opening by which they can approach the light source, must also be allowed for in the design of fittings, especially if these are to be used in tropical climates. At the same time adequate ventilation of the light source, either for the purpose of efficient combustion or for the prevention of excessive temperature rise, must be provided, and the probable exposure of glassware or other vitreous material to strong winds and driving rain must receive careful consideration if excessive cost for replacement of fittings is to be avoided.

Intensity of Illumination required for Street Lighting.—In all that has been said above, while the distribution of the light has been considered, no attention has been paid to the amount provided. This must clearly depend on the importance of

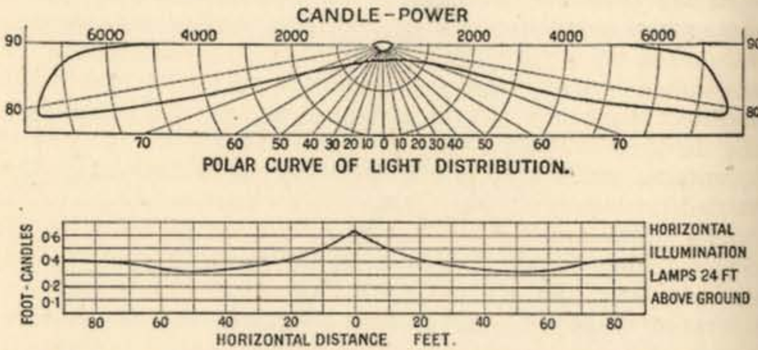


FIG. 64. Performance given by the L.L.L. Street Lighting Fitting

the thoroughfare to be lighted, and a convenient classification that has been proposed divides streets into five main classes, according to the average illumination required for them. The most important main thoroughfares of cities, carrying a great amount of traffic, are considered to require a *minimum* horizontal illumination of 0·1 foot-candles. This means that with a diversity factor of 10 : 1 the maximum illumination would be at least 1 foot-candle. For less important main thoroughfares a minimum of at least 0·06 foot-candles has been prescribed while important side streets are considered to need 0·04 foot-candles as a minimum. The lowest two classes are those requiring 0·025 and 0·01 foot-candles respectively, and comprise side roads of less importance, foot-walks, and other streets where vehicular traffic is comparatively scarce. Anything below 0·01 foot-candles must be regarded as coming under the heading of beacon lighting, for this

illumination is less than that obtained on a clear moonlight night.

When coming out of a dimly lighted side street into a brilliantly lighted main thoroughfare, a driver may be temporarily dazzled just at the time when he requires to be able to see most clearly. For this reason it is a very useful practice to grade the illumination of such side streets at the end next to the main street, so as to lessen the contrast when passing from one to the other.

A subject which is very intimately connected with street lighting is that of the driving lights on vehicles. This will be dealt with later in a special section (see Chapter XI, p. 184), but it is referred to here because of the necessity for the appreciation of the effect of street lighting when the subject of vehicle lights is under consideration.

Bridge Lighting.—Bridges, while naturally coming in the same class as roads on account of their similar requirements, may often be treated somewhat differently with considerable advantage. A bridge is frequently a structure of considerable architectural beauty, and it is important that the harmony of the design shall not be spoilt by the imposition of ugly or unsuitable lamp standards. In some cases the lamps are carried on pillars or other parts of the main structure of the bridge. Sometimes special stone pillars are provided in the design of the bridge for carrying the lamps and it is most desirable that the lighting system should be taken into consideration when the bridge is being designed. A good illumination is, of course, needed for the road surface and the pavement, and it is frequently undesirable that the light from the lamps shall be emitted outwards over the river. A reflector on this side of the lamp may then be used to assist in the illumination of the bridge.

Public Square and Park Lighting.—The lighting of squares and public places of large area is a special problem requiring rather different treatment from that accorded to street lighting. For one reason, the light is required over a considerable area, and not along a comparatively narrow strip of ground. Fittings which give a general spreading of the light must therefore be chosen with due regard to the height at which it is possible to place them. Very often this height is strictly limited by their daytime appearance in relation to the architectural nature of the monuments or other objects in the space to be lighted. In such cases a large number of sources on low standards must be used and they must be placed so as to illuminate all the surrounding objects to the best advantage. For this purpose it may be necessary to employ fittings in which a portion of the light is emitted in directions above the horizontal. Since the amount of traffic in such places is generally small and consists entirely of foot-passengers the danger of glare is not so important, and very often the illumination may be low compared with that provided in a main thoroughfare. Probably a minimum of 0·05 foot-candles would be ample unless it were desired for special reasons to have a more brilliant display. The actual illumination of monuments is a very difficult matter requiring special treatment. It will be briefly touched upon in Chapter XI.

In parks all that can generally be done is to provide a low illumination along the paths and roadways, so that this problem really reduces to one of road lighting.

Railway Goods Yard and Dock Lighting.—Under the heading of open spaces it is convenient to deal with the lighting of railway goods yards and similar areas. Here enough light is required to enable men to distinguish objects on the ground level, and to illuminate trucks and other moving objects quickly and certainly. Illumination is also required for coupling and uncoupling trucks, for the operation of truck brakes and point levers, and for similar purposes. A system depending on a small number of high-power sources placed at a great height is not entirely satisfactory owing to the dense shadows cast by objects under such an arrangement of lights. At the same time, a large number of smaller power sources on comparatively short standards are often difficult to provide conveniently, and the same uniformity of illumination cannot be ensured. Probably the best system consists of a combination of the two. A few high candle-power sources at a great height give a low uniform horizontal illumination over the whole area, while a number of short standards at 100 ft. intervals, with smaller lamps, supplement this lighting with a vertical component of higher intensity coming from several different directions. Neither horizontal nor vertical component should fall appreciably below 0·03 foot-candles in any part where work is likely to be carried on. Positions such as scale platforms, where the reading of identification numbers, etc., has to be carried on, require special treatment.

Docks and similar places require lighting in very much the same way as goods yards, but the problem is complicated by the presence of cranes which seriously limit the height and location of lamp standards. Attempts have been made to mount lamps on the crane structure itself, but connexion to a suitable source of supply, as well as the excessive vibration, offer difficulties to the application of this system.

Railway Station Lighting.—The lighting of railway stations,

although generally classed among the problems of outdoor illumination, is in certain of its phases similar to indoor lighting. Thus booking-halls, waiting-rooms, cloakrooms, and other similar covered spaces may be treated in an exactly similar manner to corresponding rooms in a factory. For the booking-hall a fair general illumination is required, with plenty of light at the actual booking-office where tickets are bought and money counted. Waiting-rooms should be provided with ample illumination for reading purposes, and semi-indirect lighting is beginning to find favour with the most progressive companies in new installations. Bookstalls and similar special places also require individual treatment.

In underground railways full use may be made of the reflecting properties of walls and ceilings to assist in providing a satisfactory lighting arrangement. Semi-indirect systems again, are in use at a number of stations. The lighting of corridors, stairways, and escalators provides a very fruitful field for the application of scientific methods of lighting. Very frequently the traffic in such places is always in the same direction, and in this case the lights may be shielded with opaque reflectors placed on the side facing the on-coming passenger. An excellent example of this system is to be found on the escalators at several of the underground stations in London. The most difficult problem in railway lighting, however, is presented by the large open station or terminus where it is required to light a considerable area sufficiently for passengers to be able to see their way about easily and comfortably. Labels and notices on the doors and windows of carriages and on luggage must also be easily legible, and the edges of platforms and the steps and entrances to carriages must be well lighted in order to avoid accidents. In this connexion, at many stations the excellent plan is adopted of whitening the edge of the platform, and if this is maintained in good condition it avoids any possibility of accidents due to equality of tone of the platform and permanent way so that one cannot be distinguished from the other without careful observation.

With regard to the lighting of large stations the present practice of the different railway companies in England varies enormously. At the chief London termini the average platform illuminations vary from 0·2 to 2·5 foot-candles. It has been noticed, however, that a station with a higher platform illumination than another does not always appear to be better lighted. This is probably because if the illumination be obtained exclusively from units with large enamelled reflectors which prevent any light from being cast in the upward direction, the whole of the station above the level of the lamps is in complete darkness, and this gives an impression of gloom which is not felt when the upper structure of the station is illuminated even to a slight extent. From the æsthetic and advertising points of view, therefore, units which emit some light in the upward direction are desirable.

In general, an average illumination on the platform of at least 0·5 to 1 foot-candles is desirable, and this should be derived from units which are not placed so high as to cause inconvenient shadows underneath portions of the structure or other objects. In the case of small stations where trains are not frequent, the plan is often adopted of having a permanent lighting installation for the central covered part of the station, and supplementing this with a series of lamps placed so as to illuminate the remainder of the platform. The latter are only put on when a train is due and in this way a satisfactory intensity may be obtained at a low cost for power.

The illumination of station names is a matter which is frequently neglected. The most satisfactory system is to provide a bracket lamp or lamps placed over and in front of the name-board, and shielded from the direct view of passengers by means of reflectors which serve to concentrate the light on the name of the station.

The extensive use of illuminated signs is one of the features of the Underground Railways. These are frequently constructed of a diffusing glass, covered with opaque metal in which the lettering is cut away, and illuminated from behind by electric lamps. Such an arrangement lends itself very readily to indicator devices such as are used at many stations.

Vehicle Lighting.—Although not strictly a problem of outdoor illumination the subject of interior lighting of vehicles may be dealt with here. As in all other cases of lighting for interiors where reading may be carried on, a good general illumination of 2 to 3 foot-candles on a plane 3 feet above the floor should be provided. This illumination should be well diffused, and, if the sources be not placed sufficiently high to be out of the normal field of view of the passenger, diffusing shades or globes should be used.

The use of the high-power units in hemispherical diffusing bowls placed at comparatively long intervals down the centre line of the roof of a car is replacing the older system of two rows of small-power units, one on each side of the car above the seats. In this way equally good diffusion of the light may be secured with a smaller number of units and consequently smaller cost for maintenance and cleaning. An emergency system of plain frosted bulbs providing sufficient light to distinguish objects in the car should be available on an independent source of supply, for use in case of breakdown of the normal power supply.

In steam-train compartment lighting the space to be illuminated is generally small, so that it is difficult to provide a good reading illumination and at the same time to avoid glare. Further, since the amount of power available is limited, the lighting system must be economical, and the use of dense diffusing bowls is therefore generally out of the question. The lighting is frequently on a direct system with either inverted mantles for oil gas, or low-voltage electric lamps for an electric supply. In the case of corridor carriages, however, semi-indirect systems have been employed quite satisfactorily. The electric supply is obtained from accumulators charged by a dynamo run from the axle of the carriage-wheel, automatic devices being employed to prevent either overcharge of the battery or its discharge through the dynamo when the latter is not running. In the case of railway compartments, the lights are sometimes adjustable at will by the passenger, so that a subdued light for sleeping can be obtained.

The light sources used in vehicles, especially electric trains, omnibuses, and trams, which are liable to considerable vibration, must be of specially robust construction. Electric traction lamps are usually so constructed that the filament is supported in much shorter lengths than is usually the case with a lamp to be used for ordinary purposes. Gas mantles are small and generally of the inverted type. In electric trains and trams it is usual for the power supply to be used also for the lights. In this case the lamps are subject to big fluctuations of voltage, and all that can be done is to design them for a voltage slightly less than the maximum they will have to withstand, and to put in a sufficient number to give an adequate illumination when the voltage is at its lowest point. As the power required for lighting in such cases is usually a small fraction of the whole, this arrangement presents no great difficulty. A typical curve of fluctuation of illumination due to voltage change on an electric railway is shown in Fig. 65.[1]

Ship Lighting.—Many of the problems met with in the illumination of passenger boats are similar, at least in their requirements, to problems of interior domestic lighting already dealt with. The conditions to be complied with in meeting these requirements, however, are frequently somewhat severe, and special means have to be adopted for the purpose. Particularly important is the restriction of the ceiling height with

[1] J. T. Magregor Morris. "Illumination on Tube Railways," *Illum. Eng.* 4, 1911, p. 328.

consequent necessity for the fittings to be placed either on the walls, or close up to the ceiling. Frequently small frosted bowls, each enclosing a single lamp, are placed between the ceiling beams in such a manner as not to project below the general level of the beams.

The intensities required are similar to those previously given for indoor lighting in the case of rooms for corresponding purposes. For freight, deck, baggage rooms, and similar areas where storage is the principal item, an illumination of 1 to 1·5 foot-candles may be considered ample.

The question of ships' navigation lights is a light projection problem which will be briefly dealt with in Chapter XI.

Sports Ground Lighting.—Very little has been done in this country towards the artificial illumination at night of grounds and arenas used for outdoor sports such as football and hockey

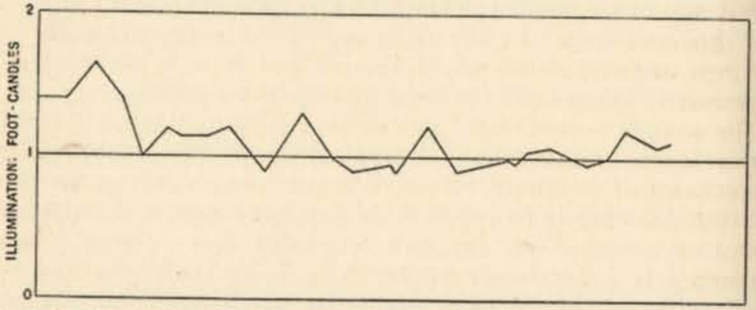


FIG. 65. Variation of Illumination during Journey on an Electric Train

grounds, racing tracks, polo fields, etc. In America, however, some very successful installations of this kind have been put into use. The degree of illumination provided is of the order of 1 to 2 foot-candles and the system used depends, of course, on the nature of the problem. For such cases as football grounds a number of high-power units may be suspended on cables run at as great a height as possible across the ground. For a racing track a succession of lamps on goose-neck standards may be used, particular care being taken to shade the lamps in the direction facing the competitors.

Exhibition Lighting.—The lighting of exhibition buildings is a very complicated and specialized subject which can only be briefly dealt with here. The old system of outlining the form of a building in gas flames or small electric lamps has now been largely superseded by the use of floodlighting projectors (see Chapter XI) which illuminate the whole exterior of a building, or any desired part of it, in such a way that its

decorative features are seen as clearly as in the daytime. Further, by the use of coloured lights extremely beautiful or bizarre effects may be obtained, especially if a combination of colours be used to produce a gradual change of hue from, say, the top to the bottom of a building. Wonderful effects of this kind were a special feature of the Panama-Pacific Exhibition at San Franscico in 1915, and there is little doubt that the exhibition lighting of the future will depend on the use of floodlighting designed to produce the most striking colour effects, and to show off to the best advantage the beauty of form and decoration of the buildings and their surroundings.

Sign Lighting.—Although not strictly a problem of outdoor lighting, it is convenient here to deal with the use of lights for advertising and similar signs. There are various types of these, the simplest, perhaps, being that in which the sign is in the form of a transparency illuminated from behind. In this type the enclosure for the lamps is whitened inside, and if this enclosure be at all shallow it is necessary to shade the lamps in front with translucent or opal glass, so as to avoid excessive unevenness in the illumination of the sign face. The second type of sign consists of a large number of electric glow lamps arranged to form letters or other devices. Flashing mechanism, by means of which lamps of one colour are substituted for those of another, or the whole sign is switched on and off at intervals, are of very general use. Proper maintenance is a first essential in illuminated signs, particularly where lamps are wired in series, for then the failure of one may produce a very noticeable gap in a letter or other device. Neon tubes have been used with great effect for sign work. The tube itself forms the letter which thus glows throughout its length with a very striking red light. A new form of sign lamp consists of a spherical bulb filled with neon at low pressure, the anode being of the form of a letter, while the kathode is a smaller rod placed immediately behind it. When the discharge takes place, the anode glows with a peculiar pink light. Any word may be thus shown by means of the proper set of lamps, each of which only takes a current of the order of 0·02 amperes on a 200–250 volt circuit.

CHAPTER IX

DAYLIGHT ILLUMINATION

THE provision of good daylight illumination is, for most buildings, even more important than a satisfactory system of artificial lighting, since the number of hours spent in a school or workshop under daylight conditions is, in general, far greater than the number of hours during which work is carried on by artificial light. At the same time, the provision of tolerably satisfactory natural lighting frequently presents no great difficulty and, although the best possible result may not be obtained, the intensity of daylight is generally so great that the only defect which is really noticeable is the necessity for the use of artificial light at an earlier hour than is the case in a room better provided with windows.

On the other hand, in buildings where there are special conditions limiting the amount of daylight available, it is of the utmost importance to see that the very best use is made of all that can be obtained by any possible means. It often happens, too, that the work carried on in a building needs the light to be distributed in some particular way in order that the best results may be obtained. In both these cases the lighting engineer and he architect must co-operate to produce the most suitable system of lighting under the conditions that exist, so that a discussion of the special problems relating to daylight illumination must necessarily form a part of any book professing to deal, however briefly, with the whole subject of illumination.

Measurement of Daylight Illumination.—The measurement of daylight illumination is but little more difficult than that of artificial illumination. A portable photometer of one of the types described on pp. 81 and 82 is generally used. The first noticeable peculiarity of daylight is its colour, which is very much whiter than the light given by the ordinary tungsten lamp used in the photometer. If, then, such a portable photometer be used for measuring the brightness of a white card illuminated by daylight, the two portions of the field of view appear of a sky-blue and a deep-yellow colour respectively,

and most observers find considerable difficulty in obtaining consistent readings of illumination. Further, no two observers will obtain the same result under similar conditions, and differences as great as 20 per cent. are quite common.

The most convenient and direct method of overcoming this difficulty is to place a yellow colour filter somewhere in the path of the light coming from the test plate, so as to bring the daylight to an approximate colour match with the light from the lamp inside the photometer. The colour match can only be approximate since daylight is very far from being constant in its colour composition. The light from a blue sky differs very markedly from that given by a dull grey sky, and this again is not nearly as yellow as that received directly from the sun. This variability of colour is very noticeable when large white cumulus clouds illuminated by the sun are travelling across a clear blue sky. The colour of the light received by a surface placed under a short vertical tube changes rapidly to a distinctly whiter hue as the cloud moves into the part of the sky vertically over the tube. It follows that it would really be more accurate to place a blue filter in the path of the light coming from the photometer lamp, for in this case there could be no danger of a change of transmission ratio of the filter. The disadvantage is that such a method would cause a reduction in the brightness of the field of view, which is undesirable in the case of most portable photometers. The yellow filter is generally of gelatine dyed to the correct hue and mounted between glass cover plates. Its transmission ratio must be accurately known, and is generally determined from the mean of a large number of observations made by different observers in a photometric laboratory. The readings of the photometer, supposing this to have been calibrated without the filter, must be divided by the transmission ratio of the filter when the latter is in use.

It will be seen presently that the intensities of illumination to be measured indoors are generally of the same order as those met with in artificial illumination. Out of doors, however, illuminations running into thousands of foot-candles have to be measured, and for these the ordinary range of the portable photometer is not sufficient. The difficulty is overcome, either by inserting a neutral filter of known transmission ratio (0·01 or 0·001) in the path of the light from the test plate, or by substituting a grey plate of low reflection ratio. The chief objection to the latter plan is the difficulty of making an accurately reproducible surface of low reflection ratio (of the order of 4 to 5 per cent.) which is capable of being cleaned at intervals without altering its reflecting properties.

Variability of Daylight.—Very few of those who have not studied the subject realize the enormous intensity differences of which daylight is susceptible over even a short period of time. The eye is so adaptable, provided the changes of illumination be not too sudden, that large differences go quite unperceived. There are three conditions affecting the intensity of daylight, viz. season of the year, time of day, and meteorological conditions. These may be dealt with very briefly in turn.

As regards time of year, all that can be done is to give some idea of the average illumination, measured at the same time

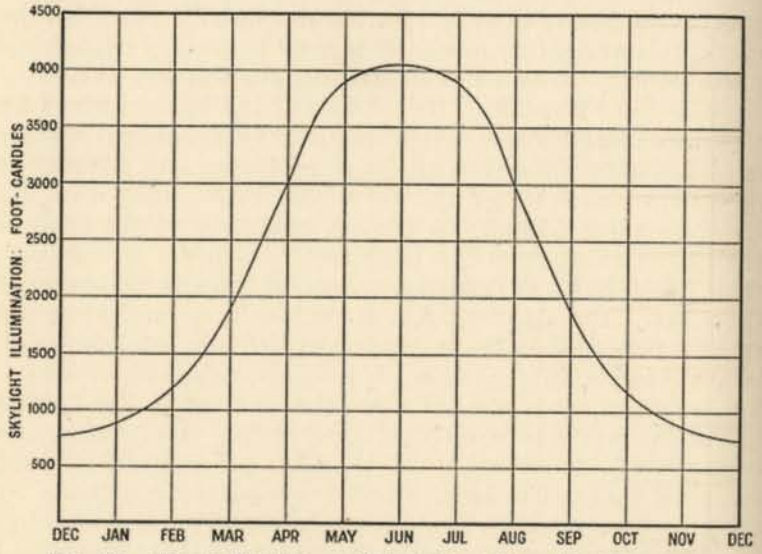


FIG. 66. Yearly Variation of Skylight at Noon (Teddington)

of day on a large number of occasions, at different times of the year. The results which have been obtained in this way are shown in graphical form in Fig. 66, where the curve shows the average illumination found at midday at Teddington during different months throughout the year. In all these tests the illumination measured was that on a horizontal plane with a practically unobstructed hemisphere of sky, but with direct sunlight cut off.

The variation with time of day is more difficult to express in generalized form. The curves of Fig. 67 show the gradual decline of illumination from noon to sunset on two days in September, one (curve A) for that on which the sky was sunny and cloudless, the other (curve B) when there was a dull grey

sky of very uniform brightness. On the former day, the brightness of the sky varied greatly according to the distance from the sun. Actual sunlight, was, however, excluded from the test card on which the illumination measurements were made. Another series of experiments showed that the sunset and sunrise illuminations do not vary with the time of year, but only with the state of the sky and atmosphere. An illumination of 25 foot-candles may be regarded as a fair average value, although the values observed ranged from 4·4 to 62 foot-candles.

The approximate average value of the daylight illumination

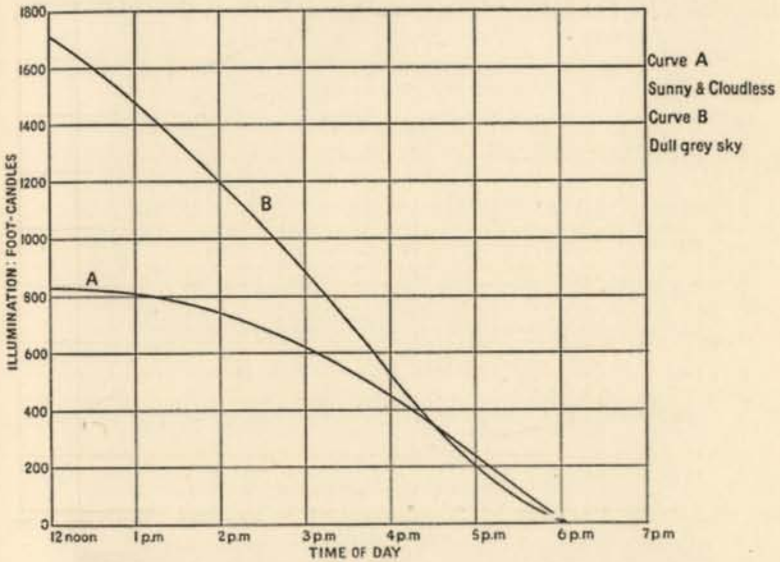


FIG. 67. Fall of Skylight Illumination from Noon to Sunset

at different times of the day is shown in Fig 68, which represents the variation to be expected on average days in June, September, and December. It is scarcely necessary to remark that such a diagram can only give the merest idea of the order of illumination to be expected at different times of the day and year. The enormous variations with different meteorological conditions may readily result in a lower illumination on a given day in June than at the same time of day in December. Such curves are, however, useful for showing the *average* performance of a daylight scheme. For instance, Fig. 68 shows that for a room in which the indoor illumination is 0·2 per cent. of that existing simultaneously in the open, the daylight will be less than 1 foot-candle before 10 a.m. and after 2 p.m. on an average day in December, while in June the corresponding times are 6 a.m. and 6 p.m. (G.M.T.) respectively.

The variations in the daylight illumination (apart from direct sunlight) arising from even small changes in atmospheric or cloud conditions are often surprisingly great, and take place with remarkable rapidity. The diagrams of Fig. 69 show the magnitude of such variations on representative days. The first refers to a bright day in March, with white and grey clouds passing rapidly over a blue sky. The second refers to a dull grey day about a fortnight later. Apart from the absolute difference in the illumination values (of the order of 6 to 1),

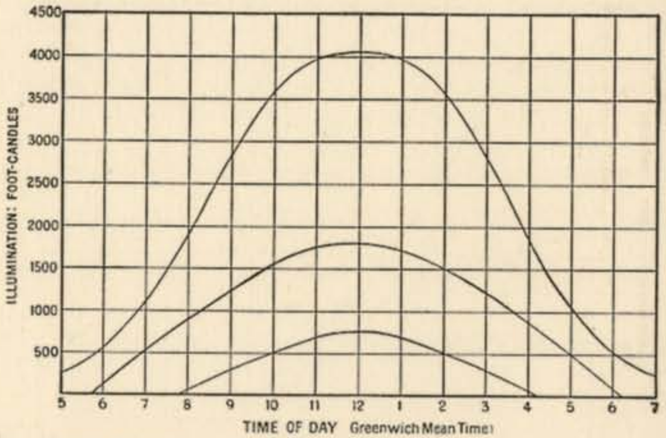


FIG. 68. Daily Variation of Illumination at Midsummer, Equinox, and Midwinter

it will be seen from the first curve that the illumination may vary by upwards of 60 per cent. within a few minutes. The value of midday illumination at the same time of year has been found to vary in the ratio of nearly 20 to 1.

Daylight Factor, or Window Efficiency.—On account of the extreme variability of the daylight illumination it will be obvious that any measurement, on an isolated occasion, of the illumination at a point inside a building is of no value whatever as a criterion of the efficiency of the daylight scheme, unless it be related to the simultaneous value of the outdoor illumination in the neighbourhood of the building. For this reason the ratio of the indoor and outdoor illuminations, measured simultaneously, is called the " window efficiency " or " daylight factor " of a point inside a building, and is taken as the criterion

of the efficiency of natural lighting at that point. It is generally expressed as a percentage, and may vary from 0·1 to 10 per cent. or even more according to the kind of window scheme provided and the depth of the room. It will be noticed that this method of evaluation assumes that the ratio of indoor to outdoor illumination remains constant whatever the meteorological conditions or the time of day. Actually, of course, this is not strictly true, and the orientation of the windows providing the daylight at any point in a room will have a considerable effect on the value of window efficiency assigned to that point from

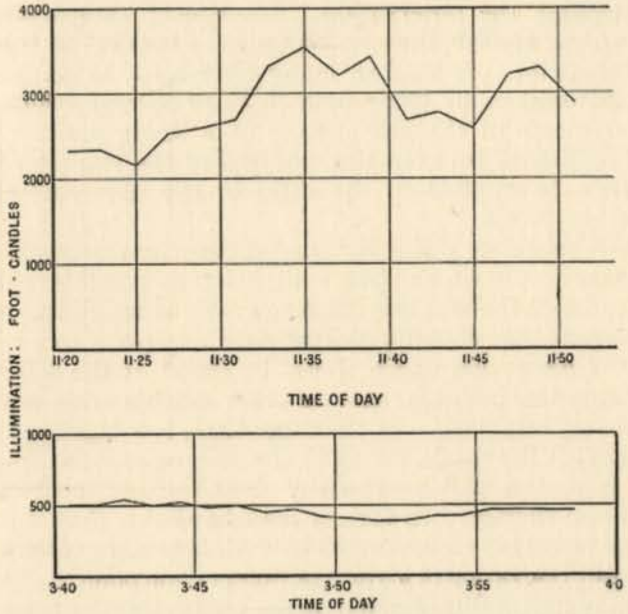


FIG. 69. Dependence of Variation of Illumination on Meteorological Conditions

measurements made at any particular time of day. For instance, on a sunny day, a point receiving most of its light from east or south-east windows will have a higher window efficiency in the morning than in the afternoon, even when direct sunlight is excluded from the test cards, as it always should be when measurements of daylight illumination are being made. The best conditions are those prevailing under a uniform dull grey sky; the worst are the extremely variable figures obtained on a sunny day with bright clouds covering a large part of the sky. The brightness of such a day is very great, owing to the reflection of the sunlight by the clouds, and this brightness changes distribution as the sun moves round, so that a value of window efficiency measured in the morning may be as much as twice that measured in the afternoon or *vice versa*.

To obtain truly simultaneous measurements it is necessary to have two observers, one making the indoor observations, while the other makes a measurement of the outdoor illumination at intervals of a minute for the whole time that the work is in progress. If the two observers synchronize their watches before starting work, it is quite easy for the indoor observer to make each of his readings at an exact minute, noting the time against the observation. Subsequent comparison with the outdoor records then enables him to obtain the true ratio for each point. It is often found convenient to compare the two photometers by using both to make several simultaneous measurements of the illumination at a single position. Any small difference between the readings of the two instruments can then be applied to the ratio of the observations as a correction factor.

When selecting a site for the outdoor measurements, it is necessary to obtain as open a situation as possible, since the true value of the window efficiency ratio is really the ratio of the illumination actually measured at any point in a building to the illumination which would be found at the same point supposing the building, and all other neighbouring buildings, completely removed. At the same time, low buildings do not much affect the result, owing to the oblique angle at which the light from the part of the sky near the horizon reaches a horizontal surface. In fact, it may be shown that if the test surface be entirely surrounded by buildings whose roof line has an angle of elevation of θ from the observation point, the percentage reduction of illumination on the card is less than $100 \sin^2 \theta$. For $\theta = 20$ degrees this is 11·7 per cent., and for $\theta = 10$ degrees it is only 3 per cent. Very often the roof of the building provides a suitable position for the outdoor measurements if the day be not too windy and the test card be firmly fixed in position.

It occasionally happens that it is impossible to find a suitable site for making the outside measurements, and in this case an attachment has been designed as shown in Fig. 70. This consists of a tube T, closed at the upper end by a metal diaphragm with a hole in it of such a size that the illumination at the plate P due to the light received from a small region of sky at the zenith, is a definite fraction, 1/100 or 1/1000, of that which a horizontal plane would have if open to the whole hemisphere of sky, unobstructed by buildings. This attachment is fitted to a portable photometer as shown, and the brightness of the plate P is measured with the photometer in the usual way. The reading is then divided by the diaphragm ratio in order to obtain the outdoor illumination on a horizontal card placed in the open. The chief objection to this apparatus is that unless the average brightness of the whole sky is the same as that of the portion vertically over the zenith attachment the value obtained for the open card illumination will clearly be in error.

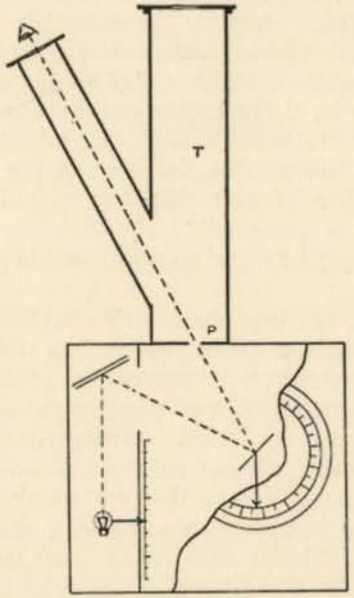


FIG. 70. Daylight Attachment for Trotter Photometer

Effect of Neighbouring Buildings.—Before considering specifically the most suitable arrangement of windows for the provision of daylight illumination in certain classes of buildings, a brief general description may be given of the effect of various factors on the window efficiency of interiors. By far the largest number of rooms derive their daylight from windows placed in the side walls. Roof-lighted rooms will be considered later. There are at least three important matters affecting the efficiency of any system of lighting by side windows apart from the total glass area. These are:

(i) The effect of neighbouring buildings,
(ii) The aspect of the windows, and

(iii) Their position in the wall, principally as regards height above the floor level and distance of the tops from the ceiling.

The effect of neighbouring buildings may be very great in towns or crowded areas where it is impossible to avoid the close proximity of very lofty buildings. In such cases the lighting efficiency of the windows in the lower floors may be very low. For example, if a window be faced by a building whose upper edge has an angle of elevation of 70 degrees when viewed from a point just inside the window (by no means an unusual occurrence in towns), the efficiency will be only about 15 to 20 per cent. of that which would be obtained with an uninterrupted outlook. This value depends very greatly on the reflection ratio of the opposite wall, and frequently use is made of white or cream enamelled bricks to improve the lighting in such cases. Needless to say the same facts apply in the case of the interior windows of a building in which "well-lighting" is provided. The interior walls of the well should in all cases be of a material which will retain a high reflection ratio.

In cases where the obscuration by neighbouring buildings is very great, recourse is often had to the use of large mirrors placed outside the lower windows and tilted at an angle of about 45 degrees with the horizontal, so that the light from the sky is reflected into the room. When this device is used it is important to remember that frequent cleaning of the mirrors is even more important than that of the windows. Prismatic glass is also used in such cases, but it is chiefly intended for the improvement of the lighting in deep rooms, and will be referred to under that heading.

Effect of Aspect.—The aspect of the windows which light a room has, in this country, a great effect on the window efficiency. Days on which the brightness of the sky is greatest near to the sun are far more numerous than those on which a uniform dullness prevails. There is also the effect of the sunlight itself to be considered, and consequently, other things being equal, a south window is more effective than a north window of the same size. On the other hand, special conditions may make a north window more desirable in certain cases. The comparative uniformity of a north light is well known, and it is frequently desirable to prevent direct sunlight from entering a room, particularly in summer. Again, where most of the light is obtained by reflection from a wall facing the window, a north window is more effective than one facing south under otherwise identical conditions, for the former

receives light from a south-facing wall which is often partly illuminated by direct sunlight. Local conditions generally determine the most efficient aspect for the windows, and frequently it is possible to obtain lighting from two walls, an opportunity for better diffusion of light which should never be lost except for special reasons, e.g. avoidance of glare.

Full use is not always made of the possibilities of obtaining "borrowed" light in a deep room by providing large glass areas in the dividing walls of rooms.

Height of Windows.—Perhaps the most important factor

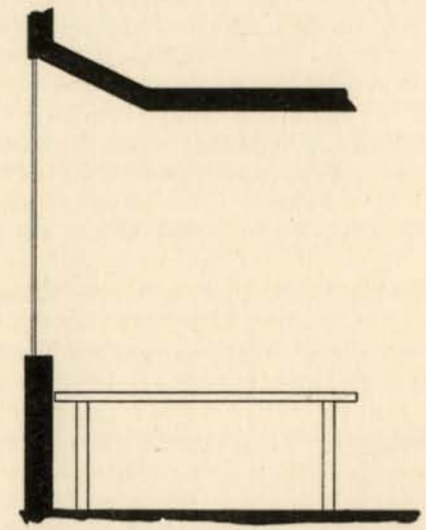


Fig. 71. Arrangement for Improving the Natural Lighting of Deep Rooms

in efficient lighting by side windows is the provision of the maximum glass area obtainable in as high a position as possible above the floor level. This is particularly the case with deep rooms, but it is always an important matter and should receive the most careful consideration. The parts of the room most remote from the windows, and where the window efficiency is consequently lowest, receive most of their light from the upper portion of the windows. It is, therefore, recommended that in every case where this is practicable, the windows should be carried up to the ceiling level. In fact, for very deep rooms it is frequently the practice to carry the windows above the ceiling level by giving the floor above the form shown in section in Fig. 71. This is very effective not only in deep rooms, but in those where there is much lofty machinery or other obstruction which interferes with the light and prevents much of it, especially that coming from the lower parts of the windows, from reaching the interior of the rooms. In connexion with the height of windows it may be remarked that it is not uncommon to find several inches of the top of a window shaded by a blind either badly mounted or not properly rolled up.

Another device used in such cases is prismatic glass, one form of which is shown in section in Fig. 72. It will be seen that this glass redirects the rays which reach it, so that much more light is made use of than is generally the case, and the

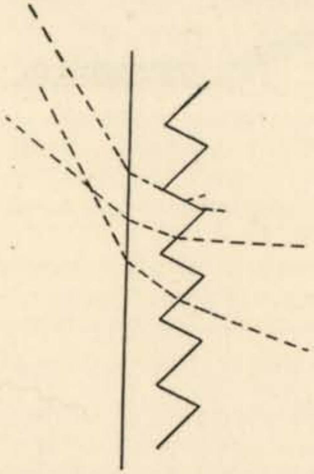


FIG. 72. Use of Prismatic Glass for Increasing the Natural Lighting from Obstructed Windows

rays are redistributed in such a manner as to give the interior of the room a far bigger proportion than it would have were ordinary sheet glass to be used. One objection to prismatic glass is that in cleaning it requires much more care than ordinary glass, as the inside angles of the prisms are apt to accumulate dirt unless carefully attended to. It seems scarcely necessary to remark that when this glass is used the edges of the prisms should be arranged to be horizontal, but the author has seen a vertical arrangement adopted on more than one occasion !

Roof Windows : North Light.—By far the most efficient system of natural lighting from the point of view of window efficiency and evenness of distribution is that provided by roof windows. There is no obscuration by neighbouring

buildings or other obstructions, and the light, coming as it does from above, may be arranged to reach all parts of the room if the windows be suitably distributed. Thus a well-diffused lighting is obtained and the shadows cast by machinery or structural features in the case of lateral lighting are avoided. The chief disadvantage is that only one floor of a building can be lighted by such a system, and it is, therefore, principally of use where the floor area covered is of little consequence, so that a building of one story is practicable.

A common form of roof lighting is that known as the "saw-tooth" roof, in which the roof consists of a series of parallel ridges, one side, generally at an angle of about 30 degrees with the vertical, being glazed, while the other side, more sloping, is solid and whitened underneath. Frequently the glass slopes of the roof face northwards, so that the whole system of lighting is then due to the brightness of the northern hemisphere of sky, and is correspondingly uniform and freer from variation than that which would be received from a similar system facing south. The admission of direct sunlight is also avoided. The effect of such an arrangement of roof lights is to give an exceedingly uniform and diffused lighting over the whole floor area, and, in fact, the distribution obtained approximates as closely as possible to that prevailing out of doors on a sunless day. The whitening of the under surfaces of the solid parts of the roof is quite important in securing this result.

Effect of Interior Decoration.—Just as in the case of artificial lighting, the colour and state of cleanliness of the decoration plays a very important part in obtaining the most efficient result from any system of natural lighting. Light-coloured walls and a white ceiling assist materially in the proper diffusion of the light admitted by the windows. Dark walls or a dirty ceiling mean a corresponding loss of light. Proper attention to cleaning or redecoration may mean less expenditure on artificial light as well as a general increase in efficiency. Needless to say window glass requires very frequent cleaning, especially in towns or in rooms of factories where the processes carried on lead to the production of dust and dirt. For this reason the use of translucent or rough-cast glass, which is rough on one or both sides, and so is more difficult to clean, may be objectionable. It is sometimes used to prevent a clear view either of what is going on inside the building by those outside, or *vice versa*. In such cases it is often sufficient to have the lower panes of such glass and to leave the upper ones clear, so that the most effective part of the window, from a light-giving point of view, is not interfered

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with. The use of opal glass in the lower parts of windows is objectionable on account of the glare produced by the excessive brightness of such glass. This objection does not apply to ribbed or rough-cast glass.

The entry of direct sunlight into a room, through either side or roof windows, is sometimes objectionable for one reason or another. If translucent glass be used on this score its presence in the winter may be a disadvantage, and it is generally better either to provide light-coloured blinds to the windows (these are also most useful in adding to the efficiency of the artificial lighting, see p. 104), or the windows may be temporarily covered with some form of obscuring paint which can be removed as soon as the need for it has passed.

Mixed Lighting.—When daylight fails, or even during the middle of the day in basements or other rooms where the window efficiency is low, it frequently happens that the work is carried on in a mixture of daylight and artificial light. There is a very widespread belief that such a light is bad for the eyes, and that a higher illumination is needed by mixed lighting than by artificial light alone. This has even been given statutory effect in America where the industrial lighting code of at least one State prescribes that artificial light shall be put into use as soon as the daylight illumination has decreased to a value which is double that specified for the artificial light alone. There seems to be no evidence that a higher illumination is needed by daylight than by artificial light, other conditions being the same, and it is difficult to find any reason *a priori* why a higher degree of illumination should be required with a mixture of daylight and artificial light than with either system of lighting alone. The suggestion has been made that, if work is being carried on by a mixed light near a window which for some reason is giving an insufficient illumination on the work, glare may be experienced due to the worker raising his eyes at intervals and looking at the (comparatively) bright sky. The objection seems to exist just as much, however, in cases where this explanation cannot be applied. There is no doubt that the eyes are in a different state of adaptation at night and during the day, and it is possible that during the transition period a higher illumination is needed than when adaptation is complete. This, however, does not afford a complete explanation of the phenomenon.

Natural Lighting of Interiors.—The above description of the features peculiar to natural lighting have been quite general in their application, and it is now necessary to treat separately the different classes of buildings which were dealt with in the chapters on the artificial lighting of interiors. As regards

domestic lighting, this is usually by side windows often in two walls, the rooms are not deep, and great uniformity of illumination is not necessary. Consequently the provision of a sufficient window area is all that is required. A good working rule is that the glass area should be not less than one-sixth of the floor area. It is generally possible to arrange the points requiring specially good illumination in convenient proximity to a window. A south or south-west aspect for living-rooms and a south-east aspect for bedrooms is desirable, as the provision of blinds makes it an easy matter to shut out direct sunlight in the summer. Desks or writing-tables should receive their light from the left front. The nursery, kitchen, and scullery should be as well provided with windows as the other rooms in the house, for the hygienic value of daylight is now well established.

Art Galleries.—The arrangement of the daylight in art galleries is exceedingly difficult on account of the reflections mentioned in connexion with the artificial lighting (see p. 114). This difficulty, while practically precluding the use of ordinary roof lighting, unless the velum system be adopted, makes it also very objectionable to have side windows in such a position that a reflection of the sky may be seen in the picture glass. One system which has recently been adopted is that shown in section in Fig. 73. The amount of direct daylight received by objects more than about five feet from the wall is very small, and the direction of regular reflection of the light from the window is too low to come within the range of vision of the spectator except for very high pictures.

School Lighting.—The daylight illumination of schools is a matter which has received much attention in many countries, and it was, in fact, the first lighting problem to receive scientific attention on a large scale with consequent legislation. In this country a very full report on the subject has been published by a committee of the Illuminating Engineering Society. The summarized conclusions of this report are as follows :—

"(1) No place is fit for use in a schoolroom where diamond type cannot be read easily by a normal observer at a distance of half a metre.

This is Diamond Type.

"(2) The darkest desk in any schoolroom should receive . . . not less than 0·5 per cent. of the unrestricted illumination from the complete sky hemisphere (i.e. the minimum window efficiency should be at least 0·5 per cent.).

" (3) The windows should be located in the wall to the left of the pupils, and the glass should be carried to the ceiling and not interrupted by cornices, pillars, or decorations.

" (4) No desk in a schoolroom should be farther from the window wall than twice the height of the top of the glass above the desk surface.

" (5) The ceiling should be white. The wall opposite to the windows and the wall behind the children should

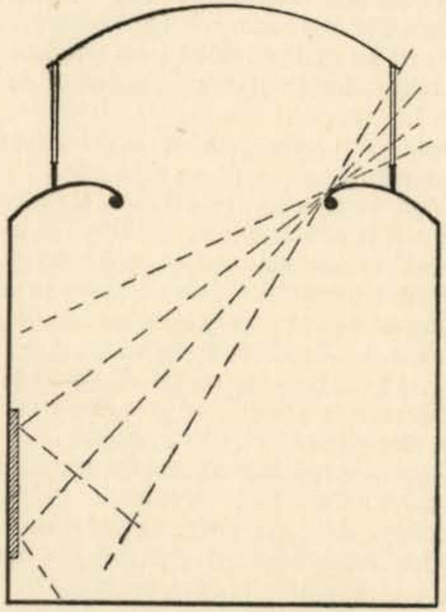

FIG. 73. Method of Natural Lighting for Picture Galleries

be lightly coloured from 30 inches above the desk level. The wall around or behind blackboards should be somewhat darker than the rest of the room.

" (6) All furniture, desks, and surfaces in the lower part of the room should be furnished in an unobtrusive colour, dark shades and black being avoided."

The committee observes that the area of window glass should not be less than one-fifth of the floor space in rooms up to 20 feet across, and one-quarter of the floor area in wider rooms. They recommend that, as the lighting of a many-storied school with surrounding buildings will be worst in the lower floors,

the ground floor should be used for offices, cloakrooms, bathrooms, dining-halls, etc. It would be advantageous to increase the height of the windows in the lowest schoolrooms, reducing the height of the top floor if necessary.

Right-handed lighting is deprecated as causing confusing shadows. In general bilateral lighting is considered to be less satisfactory than left lighting, although in some special circumstances it may be permissible. Lighting from behind the teacher is usually a source of glare to the children who face the window. Similarly, lighting from behind the children is apt to cause glare and discomfort to the teacher. It is also apt to cause shadows of the children to fall on their work, and may lead them to assume unnatural and harmful positions.

Roof lighting generally provides an abundant light, but, unless used with discretion, gives a comfortless and "imprisoned" impression. It is useful in workshops, carpentry and manual training centres, and is often desirable as a secondary means of lighting. The committee condemns the use of glass partitions for securing borrowed light, and remarks that such partitions transmit noise easily and so have a distracting effect on a class.

The internal decoration of a schoolroom should be arranged with a view to good diffusion of light. Glare from excess of sunlight can be avoided by the use of light blinds and curtains. West rooms sometimes cause trouble owing to the low incident rays from the setting sun.

It will be noticed that the committee's recommendation of 0·5 per cent. for the minimum window efficiency at a schoolroom desk means that the illumination will exceed 5 foot-candles whenever the outdoor illumination is 1,000 foot-candles or over, i.e. according to the curves in Fig. 68, during the hours of 8 a.m. to 4 p.m. from March to September, so that artificial light will probably be required only for a short period at the end of the day from October to February. The committee recommends that when the illumination on the worst-lighted desk falls to 2 foot-candles (i.e. an outdoor illumination of 400 foot-candles), the standard recommended for artificial lighting, the daylight should be *excluded* and artificial light used alone. It will be remarked that the committee here prescribes the same minimum intensity for daylight as for artificial illumination, and thus does not endorse the proposal mentioned above (p. 162), to turn on the artificial light before the daylight has fallen to the minimum prescribed for the artificial light, but on the other hand the exclusion of the daylight is evidently directed to the avoidance of mixed lighting.

Factory Lighting.—The natural lighting of factories and workshops, while demanding the full application of the general principles outlined earlier in this chapter, presents a number of special features according to the nature of the work carried on. It has already been pointed out that not only does due attention to the natural lighting of a workshop improve the efficiency throughout the day, but it also diminishes the hours during which artificial light is necessary, and by far the greater number of processes are better performed by daylight than by even a well-designed system of artificial lighting.

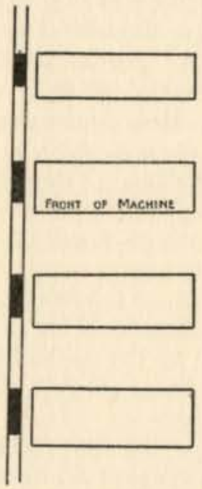

FIG. 74. Arrangement of Machines in Relation to Windows in a Factory Room

Weaving sheds are generally roof-lighted and present little difficulty, except as regards the overhead obstruction from Jacquard harness. Spinning rooms, on the other hand, are frequently placed one above another in many-storied buildings, and the amount of obstruction by machinery is great. The best arrangement is for the machines to be arranged round the room as far as possible in the manner shown in Fig. 74. The gangway between the machines is then lighted by a window and the worker receives his main light from the side and is neither in his own light, as he would be if the machine faced the window, nor working with the window facing him and tending to produce comparative glare. The same arrangement should be followed in the case of benches for such work as tinsmiths', fitting, sewing, and all other similar processes, except that the ends of the benches should be more centrally

placed with respect to the window openings. If possible it is far better to arrange for the work to be done only on that side of the bench which receives light from the left.

For very fine work, such as burling, the cloth is placed on a nearly vertical board, close to, and facing the window, and the operative works with his back to the window.

For offices, the distance of any position of work from the window should never exceed two and a half times the height of the window above the working plane. It will be noticed that this distance is rather greater than that allowed in the recommendations for schools quoted above. The latter represent an ideal which should be aimed at in the case of large offices as well.

When considering the lighting of an existing building it should always be remembered that generally the natural lighting can only be altered at considerable cost, so that the places of work should be arranged to suit the natural lighting, and the artificial lighting should then be designed to suit the arrangement of working areas thus arrived at. This apparently obvious order of procedure has sometimes been ignored, with very unfortunate results.

CHAPTER X

COLOUR IN ILLUMINATION AND PHOTOMETRY

The wide range of colour met with in ordinary artificial illuminants is not always realized, and, more particularly, the fact that in almost every case artificial light is much less "white" than daylight is seldom appreciated. The general tendency in the production of more efficient illuminants has been towards an increase in the temperature of the radiating source, and consequently the production of a whiter light, and it is still quite common to hear objections to a new illuminant based on the fact that the light it gives is too "white," or "blue" as it is sometimes called, due, no doubt, to contrast with the yellower light from sources of lower temperature. The colour of daylight, on the other hand, is generally accepted as the ideal for most ordinary purposes, and yet it is far richer in blue rays than that of the gas-filled lamp, for example. There seems to be little doubt that an important factor in causing the objection is not colour at all, but intrinsic brightness, and if the source itself be shaded, less trouble is experienced in its introduction.

On the other hand there is still a general prejudice in favour of a yellower artificial illuminant, and for certain social purposes there is no doubt that the comparatively yellow light of the carbon filament lamp, for example, is preferable to that of any higher temperature source. This factor should not be lost sight of when the design of an installation for such purposes is under consideration. Amber-coloured glass shades are sold for use with such sources as gas-filled lamps in order to produce the desired "warmth" of tint in cases of this kind.

With an indirect or semi-indirect system of lighting, the effect of the interior decoration on the colour of the light must not be forgotten. The ceiling will generally weight the yellow rays rather more than the blue, and the colour of the walls has, of course, a marked influence on the general hue of the illumination of the room. The importance of this effect in the case of studios and picture galleries has already been pointed out (see p. 116).

Uses of Coloured Lights.—There are certain problems in lighting engineering in which the use of definitely coloured lights plays an important part. Scenic effects in stage lighting may depend very much on the proper use and combination of lights of various colours. The use of coloured light for producing spectacular effects in exhibition lighting has already been referred to (see p. 149).

Another important application of colour is its use for railway signals, ships' navigation lights, and similar purposes. In cases of this kind there are two main characteristics which have to be considered, viz. (i) the power of the light, which must be sufficient for it to be visible at considerable distances, and (ii) the hue which must be such that the red, green, and yellow (the three colours ordinarily employed) must be readily distinguishable from one another and from white at the greatest possible range. It is a matter of common observation that while a red signal light will be easily recognizable as such at great distances, a green and still more a yellow light are sometimes very difficult to distinguish from a white. It has been found that in the case of green signals the proportion of yellow rays should not exceed a very small amount, and in fact the glass used for green signal lights is what would generally be described as a "blue-green," for anything approaching a "grass-green" has been found to be quite unsuitable. Too great a preponderance of blue rays is also undesirable, since a really blue light is difficult to distinguish from a white when very faint.

The above examples do not by any means exhaust the applications of colour in illumination, but perhaps the most important colour problem in artificial lighting is the production of a really white light, i.e. an artificial daylight. When it is realized in how many cases the correct appreciation of the colour values of objects is of the first importance, both for such utilitarian processes as the colour matching of fabrics and the mixing of dyes and of pigments in colour printing, as well as in the more æsthetic realm of viewing paintings and other objects in which a large part of the beauty depends on colour, the importance of being able to obtain an artificial illuminant capable of showing up all colours in the same relative values as they possess under daylight conditions will be readily appreciated.

Unfortunately the term "daylight" is in itself a vague one. As has been remarked already in Chapter I, daylight varies considerably in its colour composition, for light from a clear blue north sky is very much richer in blue rays than direct sunlight, while the light under a dull grey sky is intermediate in character. It is, therefore, necessary to define more accurately the light which shall be taken as representative of natural lighting conditions. Frequently sunlight is taken for this purpose, as, being richest in yellow rays, its reproduction from a yellower source is more economical than the production of the bluer skylight. The following table shows the relative compositions of daylight and of some artificial sources.

TABLE

	Red	Green	Blue
Noonday Sunlight (taken as) -	100	100	100
North blue skylight - -	78	82	140
Tungsten vacuum lamp - -	183	96	21
Tungsten gas-filled - - -	164	102	34

Artificial Daylight.—Many attempts have been made to obtain an artificial light which will at least approximate daylight in colour. Owing to the fact that nearly every artificial illuminant is poorer than daylight in light of the shorter wave-lengths (blue and violet), and since the addition of these rays presents very great practical difficulties, the line of approach has generally been in the direction of absorbing the excess of red and yellow rays from the light, and leaving only enough of these rays to form, with the unabsorbed blue and violet rays, a composite light of approximately the same spectral composition as daylight.

Subtractive Methods: The Colour Screen.—The simplest way of effecting this is to place a blue glass or gelatine screen in the path of the light coming from the lamp, the exact tint of the screen being chosen in such a manner as to give the correct spectral distribution of the light. It will be clear that since the different kinds of sources give lights of different spectral compositions, the exact colour of the absorbing screen must be chosen with regard to the nature of the source with which it is to be used. Clearly the bluer the light given by the source, the less the necessary absorption by the glass, so that the most usual source to employ in this method of producing artificial daylight is a gas-filled lamp. Gelatine films have been produced to transmit the light from a gas-filled lamp in such a way as to give the resulting light a spectral distribution very close indeed to that of daylight. The production of a glass to do the same thing is more difficult and has only recently been achieved.

Fig. 75 shows the degree to which a light of the same composition as daylight may be obtained, using a gas-filled lamp

and a daylight glass. Curve (a) shows the spectral distribution of the light from a gas-filled lamp, the ordinate at any wave-length showing the amount of light in that wave-length compared with daylight, which is taken as 100 per cent. throughout. Curve (b) therefore shows the distribution which would be obtained from a gas-filled lamp transmitted through a piece of ideal daylight glass (i.e. a horizontal straight line), while curve (c) shows the result actually obtained. The transmission ratio of this glass is 36 per cent., but if a somewhat thinner sheet be used noon sunlight can be imitated with an

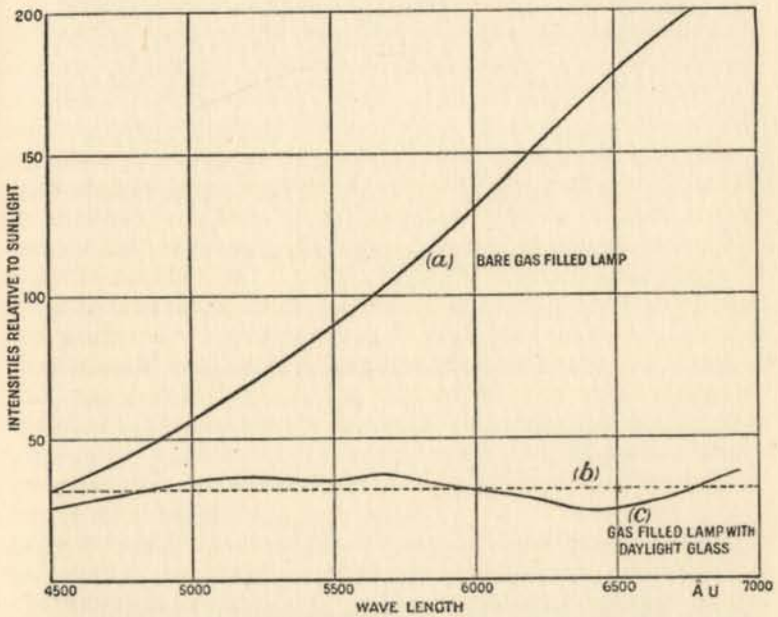

FIG. 75. Spectral Distribution Curve of Chance Daylight Glass. (Curve supplied by the Research Laboratory of Messrs. Chance Bros. & Co., Ltd.)

efficiency of 44 per cent. The chief advantage of the glass over the gelatine is its permanence and strength, and the ease with which it can be cleaned.

The Coloured Reflector.—A second "subtractive" method of producing artificial daylight is that in which the source (again generally a gas-filled lamp) is placed in a kind of indirect fitting in which the light is cast upwards upon a reflecting shade made up of a very large number of different-coloured patches of reflecting material. The relative areas of the different colours are so proportioned that the reflected light has approximately the same spectral composition as daylight, either sunlight or north sky light according to the purpose for which the particular shade is designed. In this device, again, permanence and ease of cleaning are of the greatest importance. Fig. 76 shows the relative intensities of the light from (a) a gas-filled lamp and (b) a reflector approximating daylight. The intensity of blue sky light is taken as 100 throughout the spectrum.[1]

Daylight Incandescent Vapour Lamps.—Other methods of producing a rough approximation to daylight have been used.

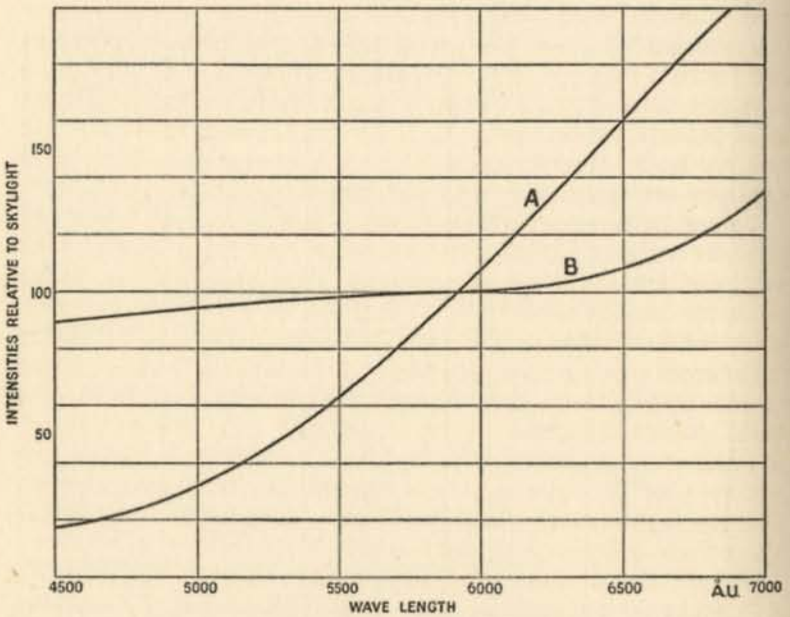

FIG. 76. Spectral Distribution Curve for Sheringham Daylight Lamp.
Curve A—Gas-filled lamp alone.
Curve B—With Sheringham Reflector

The carbon dioxide Moore tube gives a light in which most objects have the same appearance as in daylight.

The great preponderance of violet rays in the mercury arc has led to the proposal to use this lamp in conjunction with a tungsten lamp, the two being correctly proportioned in relative candle-power to give the best approximation to daylight. Units have been made up in which two lamps have been combined in this manner in a single fitting. A combination of mercury and cadmium in a vapour lamp has also been employed.

[1] *Illum. Eng.*, 12, 1919, p. 322.

For special colour-matching purposes it is sometimes sufficient to illuminate a small area by means of artificial daylight. For such purposes small boxes have been made up with a gas-filled lamp and coloured screen at the top, and these are placed over the area to be viewed. In other cases a small part of a room is screened off and provided with a daylight lamp. It should be remarked that for colour matching it is not generally sufficient to have a source which produces light giving the sensation of daylight, but consisting, in reality, of a combination of different-coloured lights, for it may well be that a hue in which such a light is weak is that needed for the discrimination of two pigments, and in this case the effect of light with a more or less discontinuous spectrum may be quite different from that of daylight where every colour is present in a definite proportion. It is for this reason that the first two methods, described above, for the production of artificial daylight are superior to any approximate additive method.

Colour Difference in Photometry.—Since coloured lights are used for various illumination purposes, and since, as has been said, the lights given by the various artificial illuminants differ from one another and from daylight in their spectral composition, it follows that in photometry the comparison of two lights of different colours must frequently be carried out. As a matter of fact in all practical photometry the presence of at least a small colour difference is the rule rather than the exception, so that it is necessary to consider the effect of this on the accuracy of photometric measurement and to describe briefly the special methods which have been adopted in cases where the colour difference is considerable.

A very slight amount of work on any ordinary photometer will serve to demonstrate that even a slight colour difference is sufficient to reduce quite seriously the accuracy of a photometric balance. The colour difference makes it impossible to obtain exact equality between the two halves of the field, and the eye has to allow for the difference in *hue* when endeavouring to obtain a balance of *brightness*. Serious differences are met with in practice when comparing electric glow-lamps with flame standards, or when measuring gas or acetylene sources by means of electric glow-lamp sub-standards. When it is a case of measuring daylight illumination, or the light from a high-intensity electric arc by means of tungsten-filament sub-standards, direct comparison becomes very inaccurate indeed, and the majority of observers will, on different occasions, obtain readings differing by as much as 20 per cent. Further, different observers do not obtain results in agreement with one another, and it is therefore necessary that special methods should be adopted for the comparison of lights in which the colour difference exceeds even a small amount.

Theoretically no physical equality can ever be obtained between lights of different colours, because the things being compared differ in kind as well as in degree. But physiologically it is a matter of experience that, provided the difference in kind be not too great, equivalence in degree can be established within assignable limits by observers having normal vision. For even when signal green and ruby red lights are being compared it is possible to raise the brightness of the green to such a degree that no doubt is left in the observer's mind that the green is definitely the brighter of the two, while similarly there is a much lower intensity at which the red can quite confidently be asserted to be the brighter. The aim of heterochromatic photometry is to reduce these limits as much as possible for the cases met with in practical photometry, and this problem has been attacked, in the main, along three lines, viz. (i) the flicker method, (ii) the use of coloured glass or gelatine filters or solutions, and (iii) the division of the colour difference to be dealt with, into a number of smaller colour steps.

The Flicker Photometer.—When two bright surfaces are presented to the eye in rapid alternation, a flicker is perceived, depending both on the rapidity of the alternation and also on the identity of the two surfaces as regards brightness and colour. The more nearly identical the surfaces, the slower the speed at which flicker ceases to be perceptible, and the principle of the flicker photometer lies in producing a rapid alternate presentation of the two comparison surfaces to the eye of the observer, and the adjustment of their relative brightnesses until no flicker is observed at a comparatively low frequency of alternation.

Several instruments have been designed on this principle. In that of Simmance and Abady a plaster disc consisting of a combination of two truncated cones is used. Its formation may be best understood from Fig. 77. ABCD and EFGH are two exactly similar truncated cones, divided respectively by the planes AC and EG. The portions ABC and EGH are removed, and EFG is then placed on ACD so that the resulting solid has the form shown in Fig. 78 which represents it as seen edge-on in four positions 90 degrees apart. It will be clear that if the two sides of such a disc be illuminated by the two sources to be compared, the line of demarcation will swing back and forth across the field of view for every rotation of the disc, and thus a flickering field will be obtained.

The flicker photometer designed by Wild consists of a

Bunsen disc in which a semicircle or two quadrants are waxed, the remainder of the disc being plain. It is mounted so as to be perpendicular to the direction of the beams of light to be compared, and both sides of the disc are viewed simultaneously by means of mirrors. Rotation of the disc by clockwork, or by a small electric motor, produces the field alternation. The criterion in this photometer is not absence of flicker, but equality of flicker on both sides of the field. It therefore possesses the advantage that the appearance of the field, when out of balance, indicates the direction in which the head has to be moved. This instrument has been stated to have a sensitiveness of 0·5 per cent. with lights of the same colour, and 0·9 per cent. when comparing red and green lights.

The speed of a flicker photometer has a very noticeable

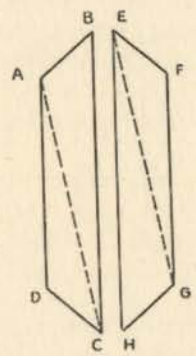

FIG. 77. Formation of Simmance-Abady Flicker Disc

influence on its sensitivity. The most favourable speed varies both with the illumination and with the difference of colour of the two fields, the results obtained when comparing green and white lights being shown graphically in Fig. 79. The abscissæ are frequencies of field alternation (i.e. the number of changes per second), while the ordinates show the percentage change of illumination which can be made without flicker, i.e. the difference between the illumination ratios at the two positions at which flicker just begins to appear. The accuracy of setting can be made much closer than this, since the mean of the two positions at which flicker is just perceptible may be taken as the position of balance. For illuminations greater than 20 metre-candles the range of sensitivity is approximately the same as for that illumination, while it can also be assumed that a colour difference less than that of the experiments will give a greater range of speed for maximum sensitivity and that the actual speeds will be lower, tending to limits of 500 to 100 per minute for lights of the same colour when the illumination is 2 metre-candles.

The Coloured Screen Method.—A second method by which it has been proposed that lights of different colours should be compared is that involving the use of some coloured medium which will bring the hue of one light to approximate equality with that of the other. Such are the "Wratten" photometric gelatine filters, which will enable a colour match to be obtained between tungsten-filament lamps operated at different efficiencies.[1]

By means of a spectrophotometer it is possible to find the transmission ratio of such a filter for light of each wave-length throughout the visible spectrum, and then by weighting the ratio at any wave-length in accordance with the sensitivity

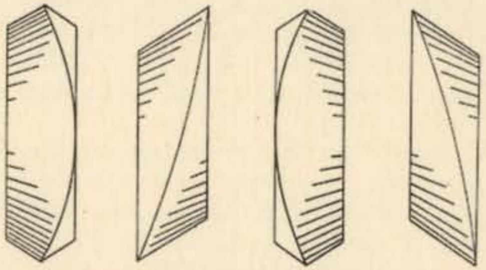

FIG. 78. Simmance-Abady Flicker Disc. Seen in Four Positions

of the average human eye to light of that wave-length, it is possible to obtain the over-all transmission ratio of the filter for light of any known spectral composition.

This method of finding the transmission ratio of a colour filter, however, is very laborious, and a less fundamental but much simpler method is that employed at the Bureau of Standards and at the Physikalisch-Technische Reichsanstalt. In this method it is assumed that the mean value of candle-power obtained by a large number of observers with a direct comparison photometer such as the Lummer-Brodhun approximates very closely to the true value even when the colour difference involved in the comparison is considerable. The transmission ratio of a colour filter is determined by comparing the candle-power of a given lamp with a standard (*a*) without the filter and (*b*) with the filter placed between the lamp and the photometer head. The ratio of the candle-power in case

[1] C. E. K. Mees. "Light Filters for Use in Photometry," *Trans. I.E.S.*, 9, 1914, p. 990.

(*b*) to that in case (*a*) is then assumed to be the transmission ratio of the filter for light of the colour of that given by the lamp, and the combination of lamp and filter is used for the determination of candle-power of test lamps in the usual manner.

The advantage of this method over a direct comparison involving colour difference in every case is that the determination of transmission ratio can be made by a large number

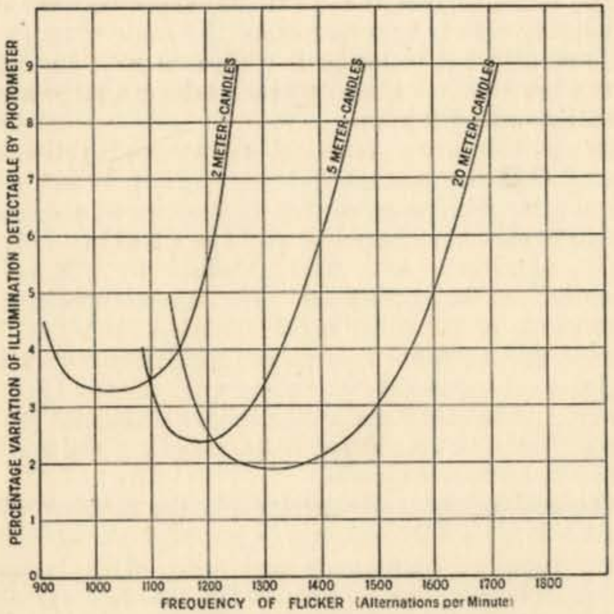

FIG. 79. Sensitivity of Flicker Photometer at various Illuminations

of observers and, when this has been done, the photometry of test lamps involves no further colour difference, so that a much smaller number of observers is sufficient.

Thus a tungsten-filament lamp or even daylight may be compared with a flame standard by using a blue colour filter which, when placed between the standard and the photometer, will produce a colour match in the photometer head. Instead of a blue filter in front of the standard it is often desirable to use a yellow filter in front of the light of higher efficiency. In this way an undue reduction of candle-power on one side of the photometer may be avoided, but it is important that the transmission ratio of the yellow filter should be determined for light of the same colour as that with which it is to be used.

The Cascade Method.—This method does not attempt to eliminate the colour difference, but simply divides it into a number of small steps, and it is the method employed for the measurement of the electric sub-standards used at the National Physical Laboratory. Between the flame standard, in this case the Vernon-Harcourt pentane lamp, and the highest efficiency sub-standards used, viz. those operating at 0·65 candle per watt, four sets of tungsten- or carbon-filament sub-standards are interposed. The efficiencies of these sets of lamps are such that the colour difference between any two neighbouring sets is approximately the same throughout the series, and each set of lamps is compared with the set below it by not less than six observers each taking a large number of observations on each lamp.

There is one great practical advantage in the cascade method. Ordinary photometric comparison is made by not more than two observers, so that in the case of a considerable colour difference the chance of any two observers obtaining a result in agreement with that obtained by a much larger number has to be considered. The intercomparison of the sub-standards on the other hand is carried out by at least six observers, and then for any subsequent photometry there is available a sub-standard of a colour quite close to that of the test lamp. The small remaining colour difference is then all that remains to be considered when assigning the accuracy of comparison by two observers.

In the measurement of illumination the problem of colour difference is of great importance on account of the many different types of illuminants met with, often in the same building. Further, the brightness of the test surface may sometimes fall below the limit at which the Purkinje effect cannot be neglected, so that colour difference between the light to be measured and the comparison source may cause considerable errors at these lower values of illumination. Above all, the colour differences met with in ordinary photometry never approach the difference experienced when measuring daylight illumination by means of a portable photometer in which the comparison lamp is an ordinary tungsten-filament vacuum glow-lamp. The use of a colour filter is almost universal for daylight illumination measurements on this account. (See Chapter IX, p. 151.)

CHAPTER XI

LIGHT PROJECTION

The use of optical apparatus, mirrors and lenses, for the production of beams of light of very high intensity, is now a common feature of lighting engineering. Lighthouses, searchlights, automobile headlights, floodlighting projectors and similar apparatus are common examples of this, and the special features of these appliances, and the application to them of the principles of illumination and photometry will form the subject of this chapter.

The principles of geometrical optics involved in the design of these lights will not be considered here, but only the performance required of them, and the general outline of the method by which this is attained, and the means employed for checking it by photometric measurement.

Lighthouses and Buoys.—The chief problem in the design of the powerful signal lights required for marking the position of localities dangerous to navigators is one of the production of a beam of maximum candle-power with very small vertical divergence.

In the case of lighthouses, the use of fixed lights has now been almost abandoned in favour of the flashlight in which a beam with small horizontal, as well as vertical, divergence is caused to revolve in a horizontal plane so as to give a succession of flashes of definite duration and at fixed intervals at any one place within its range. In this way a much greater concentration of the light and hence a more powerful beam can be obtained, the glaring effect of a powerful fixed beam at comparatively close ranges is avoided, and the interval between flashes, or their grouping, can be employed for the identification of the particular position of the light.

The source used must be exceedingly reliable in action as well as high in brightness and in absolute candle-power. The most commonly used source at the present time is a paraffin-vapour flame with a large incandescent mantle which has a brightness of 0·5 to 0·6 candle per square millimetre. Mantles of 100 mm. diameter and over are used.

The arc lamp has not proved very satisfactory, both on account of its tendency to flicker and the wandering of the crater, and also because the beam obtained from it has been found less effective for fog penetration than that given by the oil burner.

Recently, high-efficiency gas-filled tungsten-filament lamps in sizes up to 4,000 watts have been employed with success.

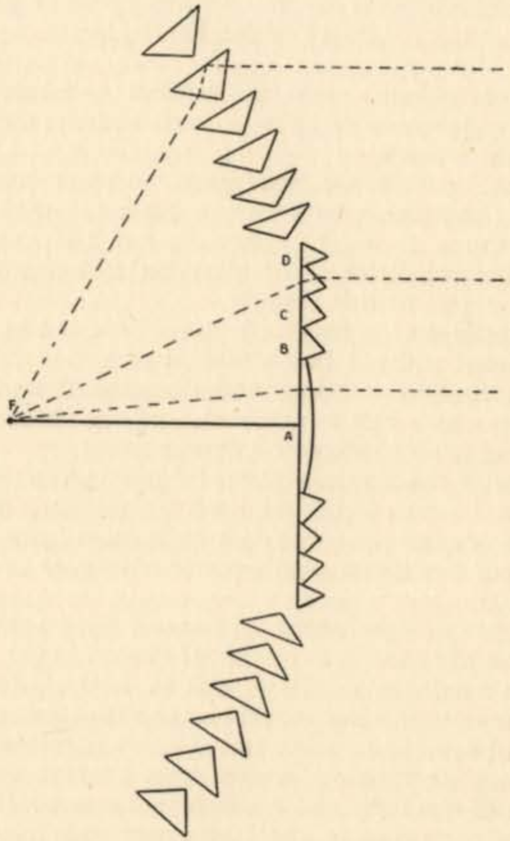

FIG. 80. Dioptric System of Lighthouse Lens

The source is here concentrated into a space about 50 mm square with a mean horizontal candle-power of about 8,000. The filament, being of the size required to take currents up to 50 amperes, is very robust.

The optical system consists, in the flashing type of light, of a series of annular prisms surrounding a central bull's-eye element, as shown in Fig. 80. F is the position of the source,

and is the focal point of the lens of which A, B, C, and D are component parts. The other elements above and below act as totally reflecting prisms, as the use of further refracting elements of the same nature as D is attended by too great a loss of light due to reflection from the glass surfaces. All the elements are designed and arranged to give a beam which is as nearly parallel as possible. The divergence obtained is thus entirely due to the magnitude of the source. It is sometimes necessary, however, to displace some of the elements in order to deflect a part of the light downwards for special purposes. The divergence actually obtained in hyper-radial and first-order lights (the largest sizes) is about 3 degrees, while the effective candle-power in the beam is probably from 2 to 4 million candles.

The lens system is generally floated on mercury for ease of rotation. The rate varies in the different lights, but it is generally thought that the interval between flashes should not exceed 5 seconds, while it has been shown that if the duration of a flash is less than one-tenth of a second, the effect on the eye is equivalent to that produced by a diminution in the candle-power of the beam. Very often two or more sets of lenses are mounted on the rotating head so that, for example, two flashes may occur in rapid succession and then be followed by an interval of darkness. The problem presented by the lights used for aerial navigation is quite different in that the beam can no longer be confined to the horizontal or any particular plane. The ordinary principles otherwise apply except that a wide cone of light in the upward direction is needed. The source of light used in such cases may be acetylene, and in this case a flashing beam is obtained by an automatic extinction and ignition of the flame at regular intervals of time in a fixed lens. The means employed for this purpose are similar to those used in buoys and described below.

The problem of the buoy light is different from that of the lighthouse since the light has often to remain unattended for long periods—sometimes as much as three or four months. In such cases the use of acetylene as an illuminant is general. Either dissolved acetylene is used or the gas is generated automatically. The latter system allows a larger supply of gas to be stored within the same space.

For the sake of economy of gas a flashing light is frequently employed. The gas flows into a closed vessel until the pressure rises to a certain value. This automatically cuts off the supply of gas (except that to a by-pass) until the pressure has fallen, and thus an automatically flashing light is obtained.

Automatic devices for extinguishing unattended lights and beacons during the daytime are in frequent use. These depend on the closing of a valve governing the supply of gas by some effect of radiation absorption, such as the unequal expansion of blackened and polished metal rods (the Dalen valve) or the inequality of vapour pressure produced in two vessels partially filled with a volatile hydrocarbon, one vessel being of clear glass while the other is blackened (the Chance valve). In this way it has been found possible to design beacons capable of operating for a whole year without attention.

Searchlights.—The use of the ordinary form of searchlight projector is to produce a beam of small divergence but very high intensity so as to illuminate objects at distances of two miles or more in such a manner as to make them recognizable to an observer situated in the neighbourhood of the projector.

The chief requirements are, therefore, a source of light of the highest possible brightness and so small as to give only just the necessary divergence to the beam. Some divergence is unavoidable on account of the imperfections in the optical system which consists, usually, of a parabolic back-silvered glass mirror, so that it is not desirable to have a source much smaller than 1/20 of the focal length of the mirror, i.e. one producing a total divergence of about $2\frac{1}{2}$ to 3 degrees.

The source of light most commonly employed is the electric arc with the positive carbon horizontal and, of course, facing the mirror. The negative is often inclined downwards at an angle of about 30 degrees with the horizontal, although the total amount of light reaching the mirror is not very greatly increased by this arrangement. For a 36-inch diameter mirror of about 20 inches focal length, a positive carbon of about $1\frac{1}{2}$ inches diameter is commonly employed with currents of 150 and 200 amperes. The average candle-power being of the order of 30,000 and the mirror receiving about 70 per cent. of the whole flux given by the crater, it follows that after allowing for losses at the mirror surfaces and at the front glass, the effective candle-power of a beam of 3 degrees divergence is of the order of 5×10^7 candles. The distribution of candle-power in a searchlight beam may be of the kind shown in Fig. 81.

In one widely used type of searchlight projector there is no large barrel bearing both mirror and front glass, but the arc is maintained within a small metal container rigidly attached to a framework holding the mirror, and the front glass is altogether dispensed with. The gain in lightness of this type is offset by the exposure of the mirror to all weather conditions.

One of the principal matters to be attended to in the oper-

ation of a searchlight is the maintenance of the positive crater in the exact focal point of the mirror, and although automatic feeding of the carbons is generally provided the arc requires constant attention to ensure the continuance of a good crater in the correct position.

It will be evident that even with the enormous candle-power available from a modern searchlight, at distances approaching two miles the illumination of the object is only of the order of half a foot-candle, so that its brightness, if the surface has a low reflection ratio, is on the limit of visibility even on a very clear night. With any appreciable atmospheric absorption the range of action of a searchlight is much reduced, for not only is the illumination of the object reduced, but its visibility by an observer is lowered also. This con-

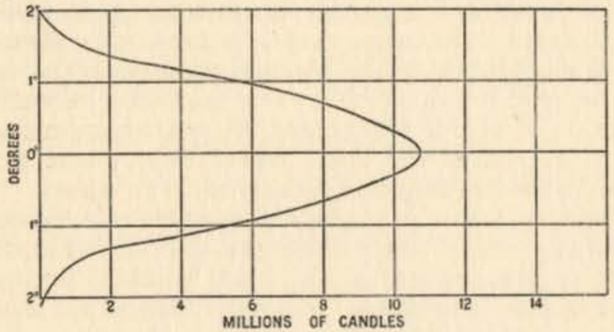

FIG. 81. Candle-power Distribution Curve for a Searchlight Beam

sideration makes the use of searchlights on any but a tolerably clear night practically valueless except for aerial objects, for haze and mist are frequently confined to a very shallow layer often covering the ground to a depth of not more than 20 or 30 feet. In nearly all cases there is sufficient foreign matter in the atmosphere to cause the path of the beam to be visible throughout, and the glare due to the reflection of light by the floating particles, as well as the diffused illumination in the neighbourhood of the projector renders it necessary to station the observer, who is endeavouring to recognize objects by the aid of the searchlight, at some considerable distance from the projector itself. This necessitates remote control of the light, generally by some electrical means.

Small projectors for signalling purposes have been designed to employ an acetylene flame impinging on a pastille of refractory material as a light source. Some forms of high-intensity incandescent lamps have also been used.

Automobile Headlights.—Driving lights for road vehicles are now most commonly of projector type. The source of light used is either an acetylene flame or a gas-filled electric glow-lamp of candle-power between 10 and 50 candles. The projector system may be either a lens-mirror of the Mangin type, or a paraboloid, with a front glass which may be plane, of lens or prism form, clear or diffusing, or of some special design intended to produce a beam with some advantageous characteristic (generally a combination of a good driving light with a non-dazzle effect).

The requirements of a satisfactory headlamp are mutually antagonistic. The first necessity is, of course, that the driver shall be able to see the form of the road quite readily, and to recognize at once any obstructions or other vehicles, especially those approaching him, at the greatest possible distance. On the other hand, it is a matter of common observation that with headlights of ordinary projector form with plane glass fronts, the brightness of the lights of an approaching vehicle is so great that it is impossible to see any other object in the neighbourhood of this vehicle and, even after passing it, the eye is so dazzled that a short period elapses before it has regained its normal degree of sensitivity.

To avoid this source of danger a number of devices have been proposed in order to limit either the intensity of the whole beam or of that portion of the beam which is particularly effective in producing dazzle. The first scheme, i.e. a general reduction in the intensity of the whole beam, has been found to be quite useless except in the form of a dimming device which enables the driver to reduce the intensity of his lamps (*a*) when approaching another vehicle, (*b*) in a town where the general street illumination is sufficient for driving purposes. Such a device may take the form of a resistance which can be switched into the lamp circuit of an electric system, or a throttling down of the supply of gas to acetylene lamps.

Many devices have been put forward which have for their object to limit the power of the headlight beam in directions above the horizontal. The ideal polar curve (in the vertical plane) for a headlight would be of the general form shown in Fig. 82. A certain amount of light is required on the road immediately in front of the driver, but the most powerful light is needed just below the horizontal, for it is upon this part of the beam that the driver depends for the illumination of the distant part of the road, and of objects upon it. Finally, above the horizontal, the less the intensity of the beam, the less the dazzling effect upon approaching traffic and pedestrians at the sides of the road.

As regards the side spread of the beam the requirements are less difficult of fulfilment. There must be sufficient light on the near side to enable the driver to see the edge of the road quite clearly for some distance ahead, and it is also desirable that signposts, etc., on the near side should be visible.

It is, of course, impossible to obtain exactly the distribution of light shown in the figure, and in practice it has been found impossible, with any simple device, even to approximate closely to it. The devices (apart from rather complicated apparatus) which have attained most success so far have consisted of either (i) a series of horizontal louvres of thin metal, whitened on the underside and blackened above to absorb the light which would otherwise be cast upwards, or (ii) a front glass made up of a series of shallow prismatic elements

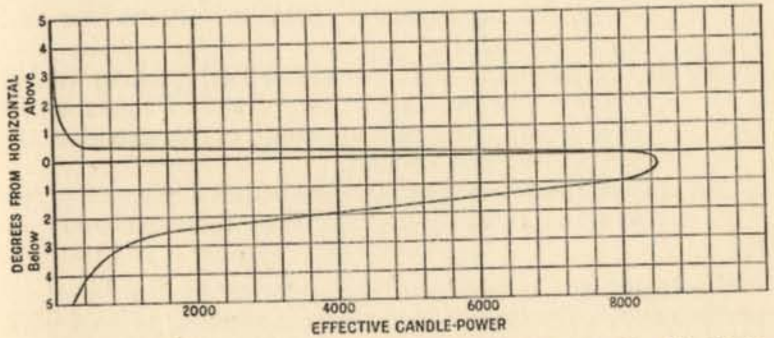

FIG. 82. Ideal Candle-power Distribution Curve for Motor Car Headlight

so designed in relation to the rest of the lamp that they produce as near an approximation as possible to the ideal distribution (Fig. 83).

Another device, which has proved most successful in the case of an acetylene flame, consists of a small semicircular blackened metal shield placed close to the flame on the side facing the mirror, and supported in such a position that the light from the lower half of the flame is cut off from the mirror. Since the illumination produced on a distant screen consists of a magnified inverted image of the flame, it follows that the upper half of the image is cut out by the screen, and thus an approximation to the desired result is obtained.

Numerous other devices, some fairly effective and others of no advantage at all, have been patented and placed on the market, so that it has been proposed that a standard test should be specified for determining the effectiveness of any device. This has already been done in America where many

States have adopted variously modified forms of the recommendations of the Illuminating Engineering Society[1] according to which the following measurements are made on a screen placed between 60 and 100 feet from a pair of lamps, each fitted with a bulb giving an average candle-power of 21 candles (gas-filled):

(*a*) In the right ahead direction level with the lamps the apparent candle-power of the combined beam must be between 1,800 and 6,000 candles.
(*b*) In the direction 1 degree below the horizontal plane through the lamps, the candle-power must be at least 7,200 candles over an angular distance of 1 degree right and left of the centre line.
(*c*) In the direction 1 degree above the centre line of the lamp, the candle-power must be between 800 and 2,400 candles.
(*d*) In the direction 1 degree above and 4 degrees to the *left* of the centre line (i.e. on the *off* side with a right-hand rule of the road) the apparent candle-power must not exceed 800 candles.
(*e*) Lower limits are specified for the lateral spread of the beam at 1½ and 3 degrees below the horizontal.

In calculating the apparent candle-power of the beam, as specified above, the inverse square law is assumed to hold with sufficient accuracy at distances of 60 feet or over.

Another test which has been proposed is that in which a test object, intended to present much the same appearance as an inconspicuously dressed pedestrian, is set up in a specified position to the left-hand side of, and slightly behind, the headlamps. It is faintly illuminated by an auxiliary source, and then an observer, walking down the centre line towards the lamps, notes the position at which the test object becomes visible to him. The distance of this point from the headlamps is then termed the dazzle distance, and forms a criterion of the efficiency of the device.[2]

In this connexion the proposal has been made that vehicles should carry a lamp giving a certain amount of light in such a manner as to illuminate any object on the off side of the vehicle. This would, no doubt, materially assist in the detection of such an object, and the required result might in some cases be provided from the off-side driving light.

[1] *Trans. I.E.S.*, 17. 1922. p. 103.
[2] *Ministry of Transport Departmental Committee on Lights on Vehicles, 3rd Report*, 1921. App. 3, p. 8.

It is, of course, to be noted that any device which depends on the reduction of power of the upper portion of the beam can only be effective so long as the car and road remain in their normal relative positions. Clearly when the vehicle is passing over the brow of a convex slope, the lower part of the beam will be cast upwards and may dazzle an approaching driver; and, again, if a car be very heavily loaded so as to cause the body to tilt upwards, the same effect will be produced.

It is probable that the nearest approach to a satisfactory solution of the dazzle problem lies in a double system of lights, or in the use of lights which can be reduced in intensity to those whose function is simply that of recognition lights. The latter are all that is needed in towns where the street lighting is adequate for safety in driving, and where, also, the effect of

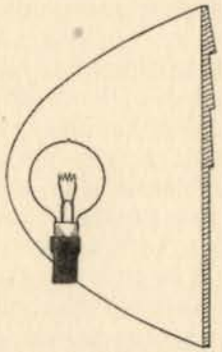

FIG. 83. Prism Device for Avoiding Dazzle in Motor Headlights

dazzling headlights is most objectionable. On country roads, however, where powerful driving lights are required, the chief danger is to the eyes of an approaching driver, and by momentarily switching off both sets of driving lights during the period when two vehicles are meeting, this danger can be avoided without seriously affecting the ease of driving either car.

Floodlighting.—Under this heading are included all problems in which an extended surface, whether it be the walls of a building, an area of ground, or a monument or statue, is illuminated more or less uniformly by high-intensity beams of fairly wide divergence given by a number of high candle-power sources concealed from the spectator. This particular branch of illumination engineering has so far been almost entirely neglected in this country, but in America it has received much attention and, from beginning as a spectacular art, it has found many applications both utilitarian and æsthetic.

The units generally employed for floodlighting purposes consist of small searchlight projectors or, rather, enlarged automobile headlights, except that the mirror is more shallow and the beam consequently more divergent. The illuminant generally employed is a gas-filled electric lamp, although gas and acetylene units have also been used quite successfully, the last-named particularly in districts where no electric supply is available. The units generally employed range from 100 to 500 watts, though still larger units have been used in special cases.

Naturally the power required follows the degree of illumination aimed at, and this must be decided with reference to the background, the degree of illumination of surrounding objects, and the reflection ratio of the surface of the building.

The different kinds of floodlighting systems may be conveniently classified into four groups according to the purpose for which the lighting is intended. These groups are protective, advertising, industrial, and spectacular.

Protective Floodlighting.—Floodlighting is used as a protective device to illuminate the surroundings of a large building or enclosed area, where it is only possible to have watchmen on patrol. A general illumination of walls, both inside and outside, adds enormously to the effectiveness of the patrol. Quite a low illumination, with a minimum of about a quarter of a foot-candle, is sufficient for the purpose. The very high candle-power flares and star-shells used for military purposes must be regarded as coming under the head of protective floodlighting.

Floodlighting for Advertising Purposes.—The floodlighting of hoardings, business house or theatre signs, and similar advertising devices may generally be treated similarly to the floodlighting of buildings for spectacular purposes.

Industrial Floodlighting.—The illumination of open spaces where work has to be carried on temporarily and where no permanent system of lighting is available, may often be carried out satisfactorily by a floodlighting equipment, acetylene units being particularly useful in this case. Such places are roads, the permanent way of railways, and buildings in course of rapid construction, away from a source of supply such as can provide an ordinary lighting system. In this case the nature of the work to be carried out must determine the degree of illumination to be provided. For rough work on a road, half a foot-candle is probably sufficient, while for work needing some accuracy at least one foot-candle must be provided.

One very important feature of floodlighting is that the light

from each projector is extremely unidirectional, and hence sharp and intensely black shadows will result unless a number of projectors be used and so arranged that the light from the different beams reaches the illuminated object from various directions. At the same time the extremely dazzling effect of the projector face makes it essential to guard against the possibility of any worker having one brought within his field of view.

Sometimes it is practicable to throw a very powerful beam on to a highly reflecting surface, and thus produce a well-diffused light of sufficient intensity. Thus, 100 square feet of wall of 50 per cent. reflection ratio, with an illumination of 10 foot-candles, will act as a source of about 1·5 candles per square foot of projected area, i.e. 3 candles per square foot in a direction perpendicular to the wall, and 0·75 candle per square foot of actual area in a direction making an angle of 30 degrees with the wall surface. Actually, of course, if the area be large the illumination can be roughly estimated by means of the formula $\frac{Ja^2 \cos \theta}{a^2 + d^2}$ where J is the candle-power per unit area, a the radius of the illuminated patch (supposed circular), d the length of the line from the centre of the patch to the point considered, and θ the angle which this line makes with the wall surface.

Spectacular Floodlighting.—This class of floodlighting is probably the most widely used of all at the present time. For commercial purposes it resolves itself into the provision of a fairly high general illumination over the whole of the frontage of a building, so that that building is brought into prominence as compared with its surroundings. The floodlighting of hoardings, or large signs is of a similar nature and may receive similar treatment. The illumination needed is generally fairly high, from 2 to 5 foot-candles being commonly used, according to the intensity of the general illumination in the neighbourhood of the building. The projectors may be arranged high up on a building on the opposite side of the roadway or on standards like those used for street lighting (in certain cases the latter have been employed for both purposes simultaneously). One essential feature is that the projectors themselves shall not dazzle or prove a source of annoyance to pedestrians or traffic; neither should they be arranged in such a way as to be unsightly during the daytime.

It has been suggested that for installations where the object is at a considerable distance from the projectors, the latter may conveniently give a beam of 10 degrees divergence. This will give a circle of illumination about 175 feet in diameter at 1,000 feet distance, and a 1,000 watt unit will produce an average illumination of about one quarter of a foot-candle. For positions where the area to be illuminated is large compared with the distance away of the projector, the latter may usefully have a beam of wider divergence (up to 20 degrees or more).

For exhibition buildings spectacular floodlighting is particularly suitable, and extremely fine effects may be produced, particularly by a judicious use of coloured light on buildings of a light cream tint. The effect of a well-designed floodlighting system is far more pleasing to the eye than the outlining in bare electric lamp bulbs, which was the old system of exhibition lighting for spectacular purposes.

Monument Lighting.—Another class of spectacular floodlighting is that of the illumination of monuments and statues. The chief desideratum in this case is an illumination which is not so diffused as to give a flat appearance to the form of the

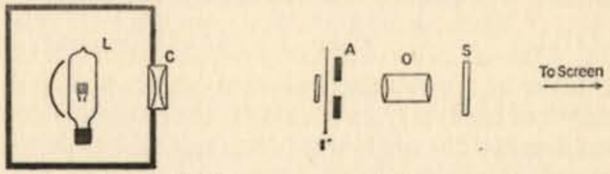

FIG. 84. Optical Arrangement of Kinema Projector

sculpture, nor so directive as to produce harsh and black shadows. Generally four units or unit positions are employed, and frequently these are situated near the base of the monument so that the light is directed upwards at an angle of about 45 degrees. A high illumination is generally needed, and from the nature of the problem a considerable loss of light is generally unavoidable. At the same time the area to be illuminated is usually not so large as in the case of a building.

Floodlighting for Sports and Amusements.—It has already been mentioned in the chapter on Outdoor Illumination that the playing of outdoor games by night is now possible with modern lighting equipment. Such spaces as a football field or a polo ground can quite readily be floodlighted, and indeed this system has even been proposed for adoption in the case of golf. There can be little doubt that a further application of this branch of lighting engineering is destined to produce very striking and valuable results in hitherto unexpected directions.

Kinematograph Projection.—The optical train generally used for the projection of moving pictures will be best understood from the diagram of Fig. 84. L is the light source which must be of high brilliancy, C is the condenser, I the film immediately behind the aperture plate A, O is the objective, and S the shutter. The light then passes on to form an image of I on the screen. A fire shutter is generally placed close to the film on the side facing the source of light.

With an equipment of usual pattern, the total amount of light which actually reaches the screen may be only about 3 to 5 per cent. of that actually produced by the source (neglecting losses in the film) so that it is clearly of importance to use a source of light of as high a brilliancy as possible. Until quite recently the electric arc was used almost exclusively, currents of 20 to 50 amperes being used with a horizontal positive carbon, and a negative slightly inclined downwards so as to enable the positive crater to be used to the best advantage. Specially designed gas-filled lamps are now coming into use, however. In these the filament is disposed in the form of a grid of vertical close spirals concentrated in the centre of the bulb, while a spherical mirror placed behind the lamp forms an image which fills up the gaps between the coils of the original filament. The lamps are forced up to a very high efficiency (of the order of 2·5 candles per watt), and the life is correspondingly reduced to something of the order of 100 hours. The lamps generally operate at about 25 volts, and take 20 to 30 amperes.

The position of the picture on the screen relative to the eyes of the spectators has already been discussed (Chapter VI, page 112). Recommendations have been made by the Illuminating Engineering Society of New York that the brightness of the picture should correspond with that of a screen illumination of from 0·5 to 12·5 foot-candles when no film is in the machine. A greater brightness leads to fatigue of the eye and accentuates the ill effect of flicker. In this figure a screen diffusing equally in all directions (a perfectly matt surface) is assumed, but screens are now in common use where the light reflected in the forward direction is several times that reflected at an angle of 45 degrees from the normal. This clearly allows a large saving of light for any given intensity of brightness, as the screen is mostly looked at from directions in the neighbourhood of the normal.

The Photometry of Projectors.—The photometry of light projection apparatus falls into a class by itself on account of the many difficulties involved and the special means which have to be employed in order to overcome them. At the same time it is of the utmost importance to obtain information as to the relative performance of different types or patterns of apparatus of this kind.

The chief difficulties met with in these tests arise from the fact that the light does not diverge from a source of which the dimensions may be neglected in comparison with the distance from it at which the measurements are made. In all the cases mentioned above, the light from the source is redistributed by optical devices, and it is therefore necessary to ensure that the measurements are made at such a distance from the apparatus that the inverse square law may be assumed to hold within the accuracy desired. It is not necessary, of course, that distances should be measured from the source itself, and often it is assumed that the optical centre of the device lies at the meeting point of the extreme rays of the projected beam. This assumption, however, is generally no more than a convenient approximation to the truth, for it cannot always be assumed that the light is emitted in all directions from a single point. Often the light emitted in two different directions may behave as if it emanated from points which are separated by a distance far from negligible in comparison with the distance at which measurements have to be made.

It may be generally assumed that the inverse square law holds for distances greater than 50 to 400 times the diameter of the optical aperture with beams of 20 degrees to 2 degrees total divergence. As a very approximate guide it may be assumed that the inner limit of distance at which the beam has attained its final distribution is given by $\frac{Kd}{\theta}$, where θ is the total angle, measured in degrees, of the cone of light formed by the beam, d is the diameter of the aperture, and K is a constant lying between 600 and 1,000.

This rule leads to the result that for such apparatus as motor-car headlights, where the diameter of the mirror is of the order of 10 inches, and the divergence may be as little as 5 degrees, photometric measurements should always be made at least 100 feet away from the headlight. On the other hand, for a lens such as that used in a ship's navigation light, where the divergence may be as much as 20 degrees with a lens height of 7 inches, a distance of about 20 feet is sufficient. In both these cases the chief difficulty is that of obtaining sufficient light to enable measurements to be made at these comparatively great distances, and very often a compromise has to be effected by making measurements at two shorter distances, and obtaining an approximation to the desired result by an extrapolation.

The information usually desired is that given by a curve of distribution of illumination on a screen placed so as to be perpendicular to the axis of the beam at a convenient distance

from the source. This distribution may often be conveniently found by actual measurement of brightness at different portions of a white screen placed in the path of the light, using a form of portable illumination photometer (see p. 81). It is often more convenient, however, to keep the photometric apparatus fixed in position and to move the source either in altitude or azimuth. Measurements of illumination can then be made by means of a photometer head fixed in a given position, with a comparison lamp movable along a bench directed away from the source. Alternatively, the test surface of a portable photometer (see p. 83) may be fixed in a convenient position and measurements of illumination at this position may then be made for any desired orientation of the projector. The results may be expressed either directly in terms of illumination or, by calculation, in terms of the candle-power which would be required of a point source placed in the position of the projector in order that it might produce at the screen the illumination actually measured there. The latter figure is generally termed the "effective candle-power" of the source in the direction considered. Whichever method of expressing the results is employed, the distance from the source at which the measurements have been made should always be stated.

The results may be exhibited graphically by means of a curve in which the abscissæ represent either illumination at a given distance or effective candle-power, while the ordinates are the corresponding angles of deviation from the axis of the apparatus. Such a curve, for a floodlighting projector beam of small divergence, is shown in the upper diagram of Fig. 85. The lower diagram is a polar curve for the same beam and illustrates strikingly the failure of a polar diagram to give an intelligible representation of light distribution from any form of projection apparatus.

For photometry of small projection apparatus, such as motor headlights, ships' light lenses and hand-signalling lamps, the distances required by the formula given above do not generally exceed 100 feet, and consequently measurements can be carried on in the laboratory where all that is required, in addition to ordinary photometric equipment, is a tilting table for movement in altitude, and a horizontal turn-table for variation of angle of azimuth. If the beam is roughly symmetrical about its centre, sufficient information is generally given by a curve, such as that shown in Fig. 85, representing the mean of measurements made across the horizontal and vertical diameters of the beam. If the beam is not symmetrical in shape, similar curves are obtained along other specified lines of traverse. Occasionally the patch of screen illuminated by the beam is divided into squares, and the illumination on each of these squares is measured and noted on a figure representing the appearance of the patch.

Photometry of Searchlights.—In the photometry of searchlight projectors matters are very different. The divergence of the beam may be as little as 2 to 3 degrees, while the diameter of the mirror is from 2 to 4 feet. Consequently, distances of at least 500 to 1,000 feet are necessary for accurate beam tests, and in practice it is customary to employ distances of ½ to 2 miles. At such distances as these, attainable only in

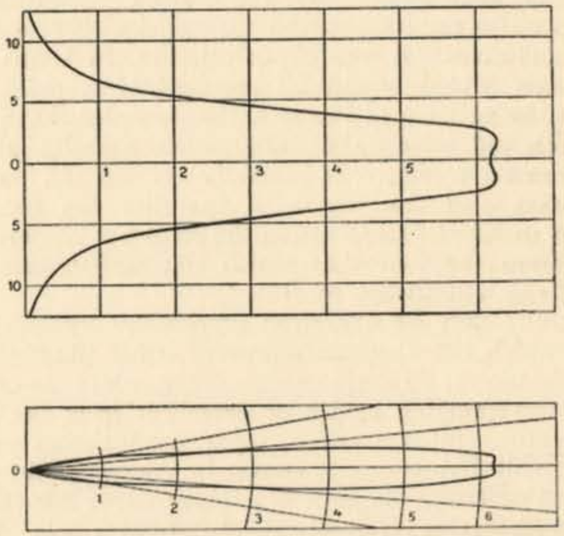

Fig. 85. Curve of Light Distribution of Floodlighting Projector

the open, atmospheric absorption cannot be neglected. Even a slight ground mist may cause errors of as much as 50 per cent. which are by no means constant from hour to hour, or even from minute to minute.

The effect of atmospheric absorption may be allowed for in one of three ways. First, a "standard" searchlight beam of known constant characteristics may be used. This beam directed towards the distant measuring station at intervals throughout a test will give, by measurement of its candlepower, the correction to be applied on any given night to the observations made on the other searchlight beams tested during that night. Such a beam may be that given by a large size tungsten arc, or a steady carbon arc burning under standard

conditions. In either case the source of light must be used in conjunction with a given parabolic reflector as no two reflectors can be relied upon to give exactly the same distribution of light in the beam.

A second method depends on the use of a telephotometer, in which a simple double convex lens forms an image of a large screen (situated at the observing station), on the centre of a Lummer-Brodhun cube. This cube forms part of a photometer of ordinary construction at the station where the searchlight is placed. Simultaneous readings of the brightness of the screen as measured by the telephotometer, and by an ordinary portable photometer at the observing station, give at once the atmospheric absorption when the calibration of the telephotometer is known.

The third method is more direct than either of the foregoing. In this two observing stations are used at known distances d_1 and d_2 from the searchlight. The light is directed first to one station and then to the other, and measurements of the illuminations are made. If these be E_1 and E_2, and τ the transmission coefficient of the atmosphere per unit length (assumed to be the same throughout the region over which the measurements are made), while J is the effective candlepower of the searchlight, then

$$E_1 = \frac{J}{d_1^2}\tau^{d_1} \text{ and } E_2 = \frac{J}{d_2^2}\tau^{d_2} \text{ so that}$$

$$E_1 d_1^2/E_2 d_2^2 = \tau^{(d_1 - d_2)}$$

If, for convenience, $d_1 = 2d_2$, then $J = E_2^2 d_2^2/4E_1$.

Another difficulty in the beam testing of searchlights is the necessity for ensuring that the arc crater is kept constantly in the same position with respect to the mirror. This can be done either with a special "focus-scope" fitted to the side of the projector case, or by observation of the divergence of the resulting beam. All searchlight photometry is affected by difficulties of colour difference, and the use of coloured glasses is general on this account (see p. 173).

CHAPTER XII

BIBLIOGRAPHY

It will, no doubt, have been remarked that in the course of this book very few references have been made to the original sources of information on any particular part of the subject. The reason for this somewhat unusual omission is that this book, as its title indicates, does not profess to deal with more than the very elements of what is now a vast subject with an extensive and ever-growing literature.

The facts given are thus not generally such as will be found exclusively in any one book or scientific paper. Most will be found in at least several publications, and in quite a number of cases the facts relating to a particular branch of the subject have already been collected in one form or another.

In these circumstances, therefore, it seemed more helpful to the inquirer in any particular branch of the subject to direct him to that literature where he could obtain the most comprehensive and up-to-date information on that branch. In many cases this literature itself contains a multitude of references to original publications, and this very fact will demonstrate the practical impossibility, even if it were desirable, of inserting references to the original work in the case of every fact of which mention has been made. This bibliography, therefore, contains the titles not only of books, but also of the more important papers which have appeared in periodicals or in the transactions of learned societies, notably the *Illuminating Engineer*, of London, and the *Transactions of the Illuminating Engineering Society of New York*, both of which journals are exclusively devoted to the subject of lighting in all its aspects.

The selection of the references has been by no means the least difficult task in the preparation of this book, and it seems too much, indeed, to hope that no paper of first-class importance on any of the subjects dealt with has been omitted. The papers included fall into two classes: (1) a comprehensive and up-to-date treatment of an important problem in illumination engineering such as "factory lighting," "visual acuity," etc.; (2) a source of information on special subjects which are not sufficiently treated in any of the references given under heading (1), such as "stage lighting," "the neon tube," etc.

In short, the aim has been to enable the reader readily to obtain further information on any of the subjects mentioned in this book. Papers or books marked with an asterisk are specially important as affording an unusually large amount of information on the subject indicated.

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APPENDIX

OFFICIAL DEFINITIONS OF QUANTITIES USED IN LIGHTING, WITH THEIR UNITS AND SYMBOLS

AT a meeting of the International Commission on Illumination held in Paris during July, 1921, the following definitions were officially adopted :

(1) **Flux Lumineux** : C'est le débit d'énergie rayonnante évalué d'après la sensation lumineuse qu'il produit.

Quoique le flux lumineux doive être regardé strictement comme le débit de rayonnement tel qu'il vient d'être défini, il peut cependant être admis comme une entité pour les besoins de la photométrie pratique, étant donné que, dans ces conditions, le débit peut-être considéré comme constant.

(2) *L'unité de flux lumineux est le* **Lumen.** Il est égal au flux émis dans l'angle solide unité par une source ponctuelle uniforme d'une bougie internationale.

(3) **Éclairement** : L'éclairement en un point d'une surface est la densité de flux lumineux en ce point, ou le quotient de flux par l'aire de la surface lorsqu'elle est uniformément éclairée.

(4) *L'Unité pratique d'éclairement est le* **Lux.** C'est l'éclairement d'une surface d'un mètre carré recevant un flux d'un Lumen uniformément réparti, ou l'éclairement produit sur la surface d'une sphère d'un mètre de rayon par une source ponctuelle uniforme d'une bougie internationale placée à son centre.

Par suite de certains usages reconnus, on peut aussi exprimer l'éclairement au moyen des unités suivants :

Si l'on prend pour unité de longueur le centimètre, l'unité d'éclairement est le lumen par centimètre carré appelé **Phot.** Si l'on prend pour unité de longueur le pied, l'unité d'éclairement est le Lumen par pied carré, appelé " **Foot-Candle.**"

1 **Foot-Candle** = 10·764 Lux = 1.0764 milli-phot.

(5) **Intensité Lumineuse.** L'intensité lumineuse d'une source ponctuelle dans une direction quelconque est le

flux lumineux par unité d'angle solide émis par cette source dans cette direction. (Tout flux émanant d'une source de dimensions négligeables par rapport à la distance à laquelle on l'observe peut-être considéré comme provenant d'un point.)

(6) *L'Unité d'intensité lumineuse est la Bougie Internationale* telle qu'elle résulte des accords intervenus entre les trois laboratoires nationaux d'étalonnage de France, de Grande-Bretagne et des États-Unis en 1909.[1] Cette unité a été conservée depuis lors au moyen de lampes à incandescence électriques, dans ces laboratoires qui restent chargés de sa conservation.

The following versions in English of these International definitions, and a few further definitions have been adopted by the National Illumination Committee of Great Britain :

(1) **Luminous Flux** is the rate of passage of radiant energy evaluated according to the luminous sensation produced by it. Since for all practical photometric purposes the velocity of light may be regarded as constant, luminous flux may be treated as an entity, and is so treated in the definitions which follow.

(2) *The Unit of Luminous Flux is the* **Lumen.** It is equal to the luminous flux emitted per unit solid angle by a uniform point source of one international candle.

(3) **A Luminous Source** is one which emits luminous flux. A point source is one which subtends a negligibly small angle at the point from which it is observed.

(4) The **Luminous Intensity,** or **Candle-Power** of a point source in any direction is the luminous flux emitted in that direction by the source per unit solid angle.

(5) *The Unit of Luminous Intensity or Candle-Power is the* **International Candle.** This unit is the outcome of agreement arrived at by the three National Standardizing Laboratories of France, Great Britain, and the United States of America in 1909. The unit has since that time been preserved by these Laboratories by means of electric incandescent lamps, and the Laboratories are still responsible for its preservation.

(6) The **Average Candle-Power** of a luminous source is the average value of the candle-power in all directions. (This term is recommended in place of the term " mean spherical candle-power.") When it is desired

[1] Ces laboratoires sont : le Laboratoire Central d'Electricité à Paris, le National Physical Laboratory, à Teddington, et le Bureau of Standards, à Washington.

to define the average value of the candle-power in a given zone or given hemisphere, this should be specified thus: "average candle-power (upper hemisphere)."

(7) The **Illumination** at a surface is the luminous flux reaching that surface per unit area.

(8) *The Practical Unit of Illumination is the* **Lux.** It is the illumination at the surface of a sphere of one metre radius due to a uniform point source of one candle placed at its centre, i.e. it is equal to one lumen per square metre.

If the centimetre be taken as the unit of length the unit of illumination is the lumen per square centimetre known as the phot. If the foot is taken as the unit of length, the unit of illumination is the lumen per square foot known as the foot-candle.

1 foot candle = 10·764 lux = 1·0764 milli-phot.

(9) The **Brightness** of a surface in a given direction is the candle-power per unit projected area of the surface in that direction. It is expressed either in candles per square millimetre or per square metre.

(10) The **Specific Output** of an electric lamp is the ratio of the luminous flux to the power input. It is expressed in lumens per watt. The specific output of a source depending on combustion is similarly expressed in lumens per British Thermal Unit per hour.

(11) The **Specific Consumption** of an electric lamp is the ratio of the power input to the average candle-power. It is expressed in watts per average candle. The specific consumption of a source depending on combustion is similarly expressed in British Thermal Units per hour per average candle.

(12) The **Reflection Ratio** of a surface for radiant energy of given spectral distribution is the ratio of the luminous flux leaving the surface to the luminous flux incident thereat, both being expressed in lumens. (This quantity has hitherto been termed the "coefficient of reflection.")

(13) The **Absorption Ratio** of a body for radiant energy of given spectral distribution is the ratio of the luminous flux absorbed by the body to the luminous flux incident thereat, both being expressed in lumens.

(14) The **Transmission Ratio** of a body for radiant energy of a given spectral distribution, is the ratio of the luminous flux passing through the body, to the luminous flux incident thereat, both being expressed in lumens.

LIST OF TERMS DEFINED WITH THEIR UNITS, ABBREVIATIONS, SYMBOLS, AND DEFINING EQUATIONS

The following abbreviations and symbols have been put forward by the British Committee, with the object of avoiding, as far as possible, confusion with the International Symbols for Electrical Quantities:

s is the area of a surface, ω a solid angle.

Name of Quantity.	Unit and Abbreviation.	Symbol (in italics).	Defining Equation.
Luminous Flux	Lumen (lm)	F	—
Candle-Power	Candle (c)	J	$J = \frac{dF}{d\omega}$
Average Candle-Power	,,	J_o	$J_o = \frac{F}{4\pi}$
Illumination	Metre-Candle (mc.) or lux Foot-Candle (fc.)	E	$E = \frac{dF}{ds}$
Brightness	Candle per metre² Candle per mm.² (c/m² or c/mm²)	B	$B = \frac{dJ}{ds}$
Reflection / Absorption / Transmission Ratios	Pure Numbers	ρ* / α* / τ*	Percentage or ratio.

* For any body $\rho + \alpha + \tau = 1$.

NOTE: For a perfectly diffusing surface $B = \frac{\rho F}{\pi s}$

Conventions Suggested.

(1) In polar curves, the vertical direction shall be taken as 0 degrees downward and 180 degrees upward.

(2) Angles of incidence and reflection shall be measured from the normal to the surface as zero line.

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