THE ARTIFICIAL LIGHTING OF BUILDINGS.

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The subject of illumination, treated from a utilitarian point of view, has not yet, so far as the authors are aware, been brought forward before any of the various Engineering Associations of the State, and as there appears to be a great disregard, one might also say contempt, among many of those who have to deal with the problem of any system of lighting based on scientific principles, this paper is presented before the Society with the hope of making better known a subject which is at present receiving very great attention both in England and in the United States.

Even now the majority of the residential lighting is left in the hands of a plumber, and it is not uncommon to see a desk lighted with an inverted Welsbach burner or a Tungsten filament lamp mounted about one foot from the eye, without any protection whatsoever. It is true that until the introduction of the modern illuminants, there was not the necessity for much attention to be turned in this direction; but now illuminants are almost in every household (illuminants of such high intensity as to be detrimental to the eyesight, if not properly protected), it is necessary that every care should be taken in securing the best arrangement and distribution of light with a minimum consumption of power.

The demand for light has grown rapidly of late; and the whole tendency of the increase is to condense as much light as possible into as small space as possible. Theoretically speaking, this is a step in the wrong direction, as the ideal system of lighting is that of an infinite number of light sources of low intensity spread over the whole area. This ideal is practically fulfilled by diffused daylight in a well lighted room, and it is possible, by properly studying the conditions, to approximate to this ideal under almost any circumstances. The means whereby this object is attained is explained later.

Since, as stated above, the lack of knowledge of the general principles and theory underlying a great many illumination problems is unfortunately only too apparent, the authors have taken the liberty of explaining these principles and a general discussion of the light units, measurements, etc., is given, so that those who have not as yet had an opportunity to study these principles may follow the latter part of the paper with greater ease.

In doing this, reference has been made to several text-books and publications dealing with the subject (a list of which is given at the end of this paper), and as far as this portion of the work is concerned no originality is claimed.

As continued work in a badly lighted room injures the eyesight, the failure to carry out the proper precautions, on the part of an illuminating engineer, amounts almost to criminal negligence; and it is hoped that the insertion of these fundamental principles will be the means of bringing them into prominence and cause more consideration to be given to illumination problems.

Although electric light in its various forms is almost entirely the illuminant dealt with, yet the principles laid down, and results obtained would apply, with modifications, as well to any other illuminant.

In the study of illumination we have two main factors to consider. On the one hand there is the transmitter, i.e., the light producer, and on the other hand the receiver, i.e., the eye. The study of the former, the means of producing light and the efficiency of production, belongs to the domain of physics; the properties of the light source—such as wave lengths, etc.—can be measured by accurate physical instruments. With the latter, however, the human element must be considered; in other words, we must approach the subject not only from a physical but also from a physiological point of view. It is quite possible, as has been frequently pointed out, to have two rooms illuminated by different methods, both having the same uniform intensity and perhaps the same efficiency, and yet the lighting of the one may be very good and the other impossible for any continuous working, the reason being that in the former the physiological side has been considered, and in the latter it has been neglected.

LIGHT PHYSICALLY CONSIDERED.

Dealing first of all with the physical aspect of the question, light is that form of radiation with which we are most familiar. The wave-lengths of radiation, which appear visible to us (and which we term light rays), range from 76×10^{-6} cms. to 39×10^{-6} cms. Between these extremes we get the well-known colours of the solar spectrum from the long wave-length low-frequency red-rays to the short wave-length high-frequency violet-rays.

Outside these extremes we have the infra red-rays, which can be perceived as heat by putting the hand close to the object producing the rays, and the ultra violet rays (such as the X rays) which are made perceptible to us by the chemical effects —e.g., sunburn—they produce on the skin (these effects, it might be added, are not immediate, and do not appear till three or four hours after exposure to the rays).

The production of rays outside the visible range represents from an illuminating standpoint waste of energy, and the chief problem in designing an illuminant is to get the maximum amount of the emitted rays within the visible range.

The fundamental unit adopted in the measurement of light is that of intensity, and is termed the candlepower. This is a linear function, and determines the intensity in magnitude and direction.

With a point source of light, the intensity is the same in every direction, and in this case the candlepower is directly proportional to, and is to some extent a measurement of, the total light flux. With the light sources adopted in practice, the intensity is by no means constant in every direction; but in many cases varies considerably. In order to obtain a figure for comparing their total light fluxes we must find some common basis. If I is the intensity in any direction (the light sources being considered as the origin) the total light flux would be represented by the area of the surface of the solid, made by joining the extremities of the radii. Dividing this quantity by 4π (the surface of a sphere of unit radius) will give us the "mean spherical candlepower."

This quantity would represent and be proportional to the total light flux. It is, however, very seldom used in practice, with the result that when makers state that they supply a light giving so many candlepower, no very definite information is given unless it is specified what is meant by the term. With electric incandescent lamps, the mean horizontal candlepower is almost universally that referred to, and it is singularly fortunate that with this type of lamp, the ratio of the mean spherical to the mean horizontal candepower is almost constant and independent of the shape of the filament. (This constant is .78.)

The term "candlepower," unless more completely specified, is therefore somewhat uncertain, and this difficulty is still further increased by the fact that there are two standards of measurement at present in use. In Germany, what is known as the Hefner candle is adopted, and in England, France and America, the International candle, the latter being about 1.1 times the former. It is hoped, however, that with the attention which this matter is now receiving, a definite standard will shortly be fixed for all countries.

The total light flux, although proportional to the mean spherical candlepower, cannot be measured directly by it, since the dimensions of the two units are not the same. If we consider the light source the centre of a sphere of radius equal to I (the mean spherical candlepower), then the surface of this sphere would be directly representative of the total light flux. This value is $4\pi I$, the unit of light flux being termed the lumen, which is the total light emitted by a light source having a mean spherical candlepower equal to $\frac{1}{4\pi}$ candlepower.

The law of inverse squares holds good for light, i.e., the intensity of light (or rather illumination) varies inversely as the square of the distance; the intensity of illumination of a light of one candlepower, on an object one foot distance away being known as one foot candle; the same intensity of illumination would be experienced at four feet distance from a sixteen candlepower light. An illumination intensity of one foot candle over one square foot area represents a total light flux of one lumen.

These three units, the candlepower, the foot candle, and the lumen are the three principal units required for the measurement of light and illumination.

The instruments adopted for measuring light are known as photometers; the principle of the majority of these instruments is the same, two screens are illuminated, one with a light of known intensity and the other with the light source to be measured, one screen or the other is then moved till they both appear to be equally illuminated.

The chief limitation of the photometer is that it is only useful for comparing light sources of approximately the same colour. This point will, however, be referred to later. It will be seen also that defects in the eye are liable to cause considerable errors in photometer measurements, and for this reason as many independent observers should be obtained as possible in carrying out any such measurements, and the mean of their readings taken.

Thus, the measurement of light has a physiological aspect as well as a physical; this we will now proceed to discuss.

LIGHT FROM A PHYSIOLOGICAL POINT OF VIEW.

The general construction of the eye is too well-known to need a long description here. The light is received and transmitted through the cornea, iris and pupil to the retina, whence the rays are taken by numerous nerves, scattered all over its surface, through the main optic nerve to the brain. Where this optic nerve enters the retina is the "blind spot," the existence of which has long been known. The central part of the retina or "fovea centralis" is more liberally endowed with nerves than the rest, and consequently is the spot on which we focus objects when we wish to see them clearly; the remainder of the retina is used purely for orientation, i.e., for picking up objects quickly and referring them to their relative position with regard to other objects.

A peculiar feature of the fovea is that it is blue blind. This can be shown by passing the light from a mercury vapour lamp through a solution of potassium permanganate; with the light thus obtained we get the irritating effect of being able to see an object, but not to look at it. This particular blue colour is then to be carefully avoided in all illumination work where any colour effects are desired.

Perhaps one of the most important properties of the eye (a property that is more or less common to the other senses) is that of "fatigue." It is well known that, when entering a very dimly lighted room after having been in the bright sunlight, nothing can be seen until the eye has rested for some minutes. This is due to the nerves at the back of the retina increasing in sensitivity in light of low intensity; the reverse happens when proceeding from a dark to a light room. The property of "fatigue," as it is called, partly enables the eye to adapt itself to the enormous range of intensity to which it is daily subjected; two other properties, however, combine with the fatigue effect to secure this result. These are in the first place the adjustment of the size of the pupil to let in more or less light (this action is practically automatic) and secondly Fechner's Law of Sensation.

The fact that the eye is not achromatic, although it has been known for some time, does not seem to have been realized till quite recently. This achromatism can be easily demonstrated by means of a simple experiment. A number of strips of purplish red paper, about a quarter of an inch wide and a quarter of an inch apart are stuck on to black paper. In ordinary light, the edges of these strips cannot be seen distinctly; but on looking through a red or a violet glass, a sharp definition can be obtained. It was therefore thought by Dr. Louis Bell that if it was possible to see clearly with the ordinary artificial illuminants at present used (which have an almost continuous spectra) that a far more distinct vision could be obtained by using monochromatic light. Accordingly, he investigated the subject, and found by direct comparison of a monochromatic light source with a Tungsten lamp of equal intensity as measured by physical means, that the former *appeared* 1¾ times brighter than the latter, i.e., to produce an equal clearness of vision as with the Tungsten lamp a monochromatic light source giving only $\frac{1}{1\cdot75}$ times the candlepower (the consequent proportion saving of energy) is required. It would therefore appear that the next radical improvement in artificial lighting will be in this direction.

Although the physical method of measuring light (ie., with the photometer) is perhaps the most convenient method to adopt, yet it is not by any means accurate, when there are large colour differences in the light sources to be compared. Physiologically, this can be done with a fair degree of accuracy with the luminometer. This consists of a box in which an ophthalmic chart is placed and the light is allowed to fall directly on to this chart. The box or light source is then moved, until a position is reached when the capital letters of the chart can be clearly distinguished, while the small letters are unreadable. The distance between the light source and the chart is then measured, and forms the means of comparison.

It has been found by this means that the sensitivity of the eye is very different for lights of different colours, and that the power required to produce a given physiological effect (i.e., the mechanical equivalent of light) varies not only with the colour but with the intensity of that colour. Thus, when comparing light sources of low intensity, the green is the most efficient colour to produce, while for high intensities the yellow. If we see two light sources, one yellow and the other green, of apparently equal intensity close together, on approaching them the yellow would appear to get brighter than the green; while the opposite would occur on receding. For this reason it is possible to use a lower intensity of yellow coloured light for ordinary interior illuminants—which requires light of comparatively high intensity—than would be required for a green light, while for lighthouse work and street-lighting in outlying districts the green light source is eminently suitable.

The following table gives the lowest intensities at which lights of different colours are just perceptible, and the relative power required to produce this intensity:

TABLE I.

MINIMUM PERCEPTIBLE INTENSITIES OF LIGHT WAVES.

Colour.	Red.	Orange.	Yellow.	Green.	Blue.	Violet.
Wave Length x 10-6 cms.	67	60·5	57.5	50·5	47	43
Foot Candles Intensity x 10-6 ..	56	5·2	2·7	·16	·11	·11
Relative Radiation Power	10,000	1,000	100	1	2	20

LIGHT PRODUCTION.

Having now discussed some of the more general properties of light, we now come to the question of producing it and the mechanical efficiency of its production. The most common way, and until recently the only way, of light production was to heat a body to a sufficiently high temperature till it emitted light, or, as usually expressed, became incandescent. This method is generally known as "temperature radiation."

As a body is heated and the temperature increases it gives out radiant energy over a wide range of frequencies, amongst which the light waves are included, provided the temperature is sufficiently high. With increasing temperature a larger proportion of light rays are given out, and thus the efficiency of light production increases. This increase in efficiency is not proportional to the temperature rise; but gradually lessens till a temperature is reached when the efficiency is a maximum, and any increase in temperature will only lead to a decrease in efficiency. This temperature is about 5700 degrees absolute on the Centigrade scale, and the light energy would represent at this temperature about 20 per cent. of the total emitted energy. As the most refractory substance known—carbon—boils at 3750 degrees Centigrade, this temperature efficiency is quite unattainable. By heating carbon to its boiling point (as is the case in the carbon arc lamp) the efficiency obtained is probably below 10 per cent. It is, however, possible to exceed this efficiency in practice by means of what is termed "coloured body radiation." A body which absorbs all the impinging radiation is known as a "black body," and gives a maximum temperature radiation; a body which absorbs no impinging radiation and gives no temperature radiation, is called a "white body." Intermediate bodies would be known as "grey." Certain bodies, however, have a preference for emitting rays of a particular frequency, and when heated, although the intensity of radiation can never exceed that of a black body at the same temperature, yet provided the frequency favoured by the body falls within the range of the light waves the efficiency of light production may be higher; since a larger proportion of the total emitted radiation is within the light area. Bodies which have such characteristics are "coloured" bodies.

The best example of coloured body radiation is the fire-fly, in which the whole of the emitted radiation is within the light area. This is a very good instance of the perfection in which nature performs her tasks; the means whereby this extraordinary efficiency is produced are as yet unknown; but probably the majority of the researches carried out on light sources is to discover coloured bodies approximating to this ideal. Examples of black and coloured body radiators, as used in practice, are:

Black Body.—Carbon Arc Lamp, Carbon Filament Lamp and Tungsten Filament Lamp.

Coloured Body.—The Welsbach Mantle, Nernst Lamp.

Besides temperature radiation, the other methods of light production can be classed under the one heading of "Luminesence." The best known of these are:

1. Chemical Luminensence, which can be illustrated by the flame arc lamp and the mercury vapour lamp.

2. Electro-Luminesence, as in the Geissler Tube. The Moore Tube light is an example of the production of this method on a commercial scale.

Several attempts have been made to produce a light approximating in colour to daylight, as for dye works and other industries of a like nature, where accurate colour comparison is essential. Such attempts have mostly been in the direction of combining the lights from several different coloured light sources, and have not been very successful.

Messrs. Ives and Luckiesh have, in a recently published article described a colour screen which, used in conjunction with a Tungsten lamp, gives almost a daylight effect; but the efficiency of light production is poor—about 10 watts per candlepower being required.

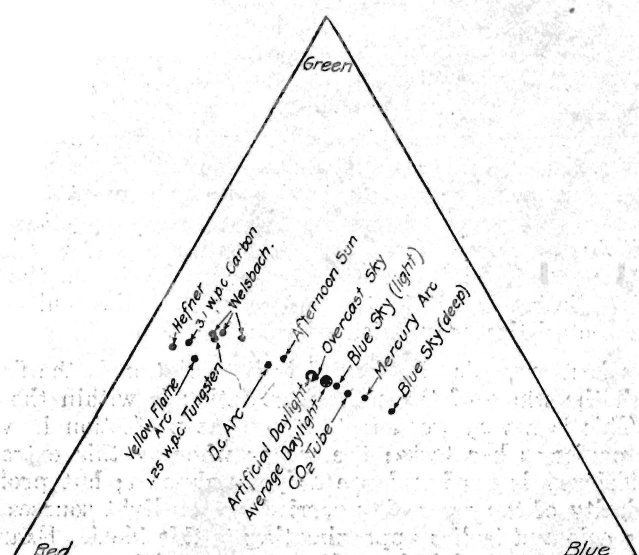

Fig. 1.

The colour triangle (Fig. 1) shows in a graphical form the different colour effects of various commercial illuminants in comparison with daylight, while the table below gives the relative efficiency in units per 100,000 lumen hours of the best known sources of light by electricity.

TABLE II.

COST OF PRODUCING LIGHT WITH VARIOUS ILLUMINANTS.

From Paper by Bryant & Hake, before Chicago Section of Illuminating Engineering Society, held on December 15.

Electrical World, December 29th, 1910.

	Amps.	Terminal Watts.	Lumens.	K.W. hours for 100,000 Lumen hours.	Total Cost per 100,000 Lumen Hrs at 10 cents. per k.w. hour
Regenerative d.c. series arc ..	5.5	385	11,670	3.3	0.339
,, d.c. multiple arc ..	5.5	605	11,670	5.18	0.527
Magnetite d.c. series arc	6.6	528	7,370	7.16	0.729
Flame arc d.c. inclined electrodes..	10.0	550	8,640	6.37	0.837
Mercury arc d.c. multiple.. ..	3.5	385	4,400	8.75	0.89
Flame arc d.c. inclined electrodes	8.0	440	6,140	7.16	0.966
,, ,, vertical electrodes	8.0	440	6,140	7.16	0.966
Luminous arc d.c. multiple ..	6.6	726	7,370	9.85	0.988
Open arc d.c. series	9.6	480	5,025	9.55	1.079
Magnetite arc d.c. series	4.0	320	2,870	11.15	1.13
Flame arc a.c. vert. electrodes ..	10.0	467	5,340	8.75	1.275
,, a.c. inclined electrodes	10.0	467	5,340	8.75	1.275
Open arc d.c. series	6.6	325	2,920	11.15	1.305
Tungsten series	6.6	75	626	12.0	1.384
Flame arc a.c. inclined electrodes	8.0	374	3,910	9.55	1.405
Inclosed arc d.c. series	6.6	475	3,315	14.32	1,459
Luminous arc d.c. multiple ..	4.0	440	2,870	15.32	1.547
Tungsten multiple	0.545	60	475	12.6	1.55
Nernst a.c. 3-glower	1.87	414	2,160	19.2	1.88
Nernst d.c. 3-glower	1.87	414	2,160	19.2	1.90
Inclosed arc a.c. series	7.5	480	2,410	19.9	2.05
,, ,, ,, ...	6.6	425	2,020	21.3	2.193
Tantulum d.c. multiple	—	40	199	21.1	2.31
,, a.c. ,, ...	—	40	199	21.1	2.504
Carbon 3.1 w.p.c. multiple ..	—	49.6	166	29.9	3.24
Carbon 3.5 w.p.c. series	6.6	210	626	33.6	3.47
,, ,, multiple ..	—	56	166	33.7	3.50
Inclosed arc d.c. multiple.. ..	5.0	550	1,535	35.8	3.66
,, ,, ,, ...	3.5	385	1,030	37.4	3.84
,, ,, ,, ...	6.0	430	1,124	38.3	3.94
Inclosed arc a.c. multiple.. ..	4.0	285	688	41.4	4.265