FLUORESCENT LIGHT SOURCES AND THEIR APPLICATIONS

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A paper read before the Illuminating Engineering Society, on 14th April, 1942

Introduction

During the last few years there has occurred both in America and in this country a remarkable expansion in the use of fluorescent substances as sources of light. A phenomenon which until a few years ago was of theoretical rather than of practical importance now forms the basis of a rapidly growing branch of the electric lighting industry.

Fluorescent substances of types long known, but now made with greatly improved properties, are being used in conjunction with mercury vapour lamps of various kinds. New fluorescent compounds have been developed specially suitable for excitation by the resonance radiation from the electrically excited mercury atom. Combinations of suitable powders have been achieved by which white light can be produced efficiently. Probably the most important of these developments are those sources in which the major proportion of the emitted light is produced by fluorescence, as distinct from those in which fluorescence is used to modify the colour from an already efficient light emitter. Both classes, however, have distinctive features and will be considered separately in the following order :—

(1) Sources in which fluorescence is used to produce modulation of the colour of the primary light —Light Modulators.
(2) Sources in which the emitted light is produced almost entirely by fluorescence.

The principal sections of the present paper will be devoted to reviewing the development of these two important categories of light source, some mention will be made of certain aspects of the application of fluorescent tubular lamps, while the concluding section will consist of a short review of some other possible lines of development.

Class 1—Light Modulators

The primary source of light in this class of lamp is an electric discharge through a metallic vapour. The resulting radiation is either reflected from or transmitted by a coating or layer of fluorescent substance, the purpose of which is to modify the colour of the primary light in order to render it more suitable for illumination purposes. Proposals for the use of fluorescing materials in this way were made by P. Cooper-Hewitt early in this century in connection with the mercury vapour lamp bearing his name. One of the reasons for the lack of success at that time was the inefficiency of the fluorescent material available, and its rapid deterioration when exposed to mercury vapour radiation. Cooper-Hewitt apparently carried out experiments with the organic dyestuff rhodamine, which fluoresces red under the stimulus of radiation of shorter wavelength. Unless the dyestuff is disposed in a special manner in suitable media it slowly decomposes when exposed to bright light, and this phenomenon alone would perhaps account for the lack of success of this early work.

Proposals were made early in the last decade for the association of rhodamine coated reflectors with lamps of the high pressure mercury vapour type. These reflectors and panels were designed to be used in fittings of various kinds in association with the 400 watt mercury lamp Type MA, and by transforming a proportion of the incident radiation into orange red light would have the effect of improving the colour rendering properties of the source. Some excellent results may be obtained in this way, but even specially prepared rhodamine dyed surfaces were not found to be sufficiently stable under high intensity irradiation. Various schemes of this kind did not find any extended practical field of use. One reason for this was probably the development of improved fluorescent substances which had excellent stability, because unlike rhodamine and kindred materials they were inorganic. Zinc cadmium sulphide was one of the first of these substances to find practical use in the construction of fluorescent light sources. In the first instance experiments were carried out to incorporate in special fittings, panels coated with the fluorescent material. Considerations such as the necessity for maintaining a clean powder surface, as well as the need for properly regulating the powder disposition and density, soon led to incorporation of the powder on the inner surface of the lamp bulb.

The mercury vapour discharge itself takes place in a tubular bulb constructed from either a special borosilicate glass or from quartz, and the concentration of mercury vapour ions corresponds with a vapour pressure in excess of 400 mms. of Hg. Suitable fluorescent substances are coated on the inner surface of the outer bulb in which the discharge tube is mounted. They are of a type which strongly absorbs energy of wavelength between 3,000 Å and 4,000 Å. In the design of lamps of this type, account must be taken of the temperature characteristics of the powders employed, as in most cases an increase in the temperature of the fluorescent powder layer reduces the ability of the powder to transform ultra-violet radiation into light. In some cases also the colour of the fluorescence is modified at increased temperatures. These effects are shown in Fig. 1, where the relative efficiency of various powders is indicated over a range of temperature. From these curves it will be seen that to be effective the temperature of the fluorescent layer should be as low as can conveniently be achieved.

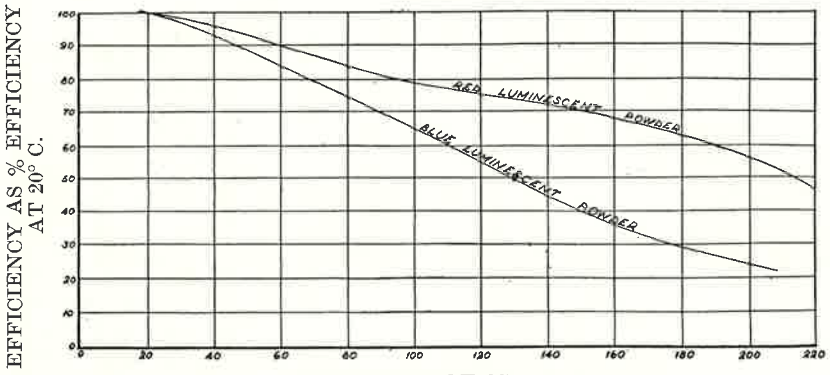

Fig 1. Relative efficiency of blue and red fluorescent powders over a range of temperature.

In the case of the well-known 400 watt fluorescent lamp, in order to keep the outer bulb size as small as possible, compatible with the above considerations, an isothermal contour for the bulb wall was worked out corresponding with a powder temperature not exceeding 160° C. The luminescent material most generally used is a zinc cadmium sulphide which absorbs the blue and near ultra-violet radiation of the mercury and cadmium high-pressure discharge, and transforms it into orange-red radiation. Zinc cadmium sulphide exhibits both fluorescence and phosphorescence, *i.e.*, it meits light simultaneously with the absorption of radiant energy and continues to emit it for a measurable time after cessation of the incident radiation. For this reason in the 400 watt fluorescent lamp there is a noticeable reduction in the flicker associated with electric discharge lamps when operated on alternating current supply mains, as the phosphorescent light helps to bridge the gap between the cyclic rise and fall of the primary light emission.

A later development was the application of fluorescent powders to the 80 and 125 watt quartz high-pressure mercury lamps. The spectrum of these lamps is very suitable for colour modulation by fluorescence as the high pressure at which the mercury vapour operates results in an improved distribution of energy in the visible spectrum. In the ultra-violet spectrum also the distribution of energy between 2,500 Å and 4,000 Å is favourable for the excitation of both blue and red luminescent materials, both of which can usefully complement the primary radiation from the discharge tube ; see Fig. 2 (*a*). For this purpose, as in the case of the 400 watt fluorescent lamp, the powders are coated on the inner surface of the bulb which

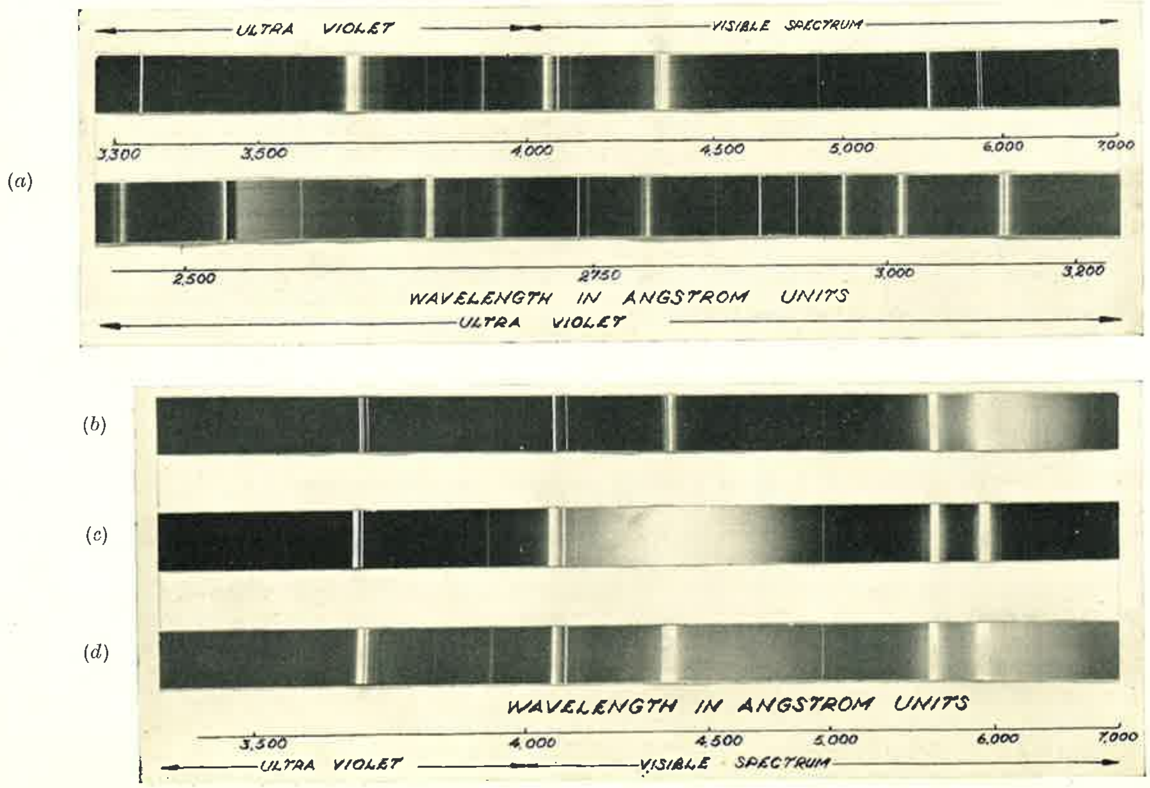

Fig. 2.

encloses the discharge tube. The proportions of the blue and red fluorescent powders are chosen to give the optimum colour modulation in those portions of the spectrum to which they contribute. A spectrogram of the radiation from the quartz burner of a 125 watt high-pressure mercury lamp is given in Fig. 2 (*a*). It will be appreciated that the outer bulb in which this burner is mounted will be subjected to radiant energy emitted at a large number of wavelengths from about 2,000 Å in the ultra-violet region up to at least 8,000 Å in the infra-red. Some of the energy is absorbed by the fluorescent powder layer and re-emitted as light, while below about 2,800 Å practically all the remaining energy is absorbed by the glass bulb. The spectrograms in Fig. 2, marked (*b*), (*c*) and (*d*) show, respectively, the effect of red, blue and a mixture of these sulphide powders when coated on the inner surface of the outer bulbs enclosing 125 watt quartz HPMV lamps. The blue powder is very effective in providing radiation in the region 4,200-4,800 Å, while the fluorescence of the red powder is mainly above a wavelength of 5,700 Å, *i.e.*, in the orange and red region of the spectrum.

Bulbs of approximately spherical form are used, and the dimensions are chosen so that the temperature of the powder is sufficiently low to allow of the development of a high efficiency. The characteristics of these lamps are now well-known, but for the sake of completeness they are given in Table I. below :—

TABLE I.

SIERAY LAMPS, TYPE MBF/V.

Wattage.	Bulb Diam.	Over-all length.	Cap.	Init. Effy.	Av. Effy.	1,500 hrs	% red approx.
	mm.	mm.		L/W.	L/W.	L/W.	
80	110	178	3-pin Bayonet	38	30	28	5%
125	130	233	GES	40	32	30	5%

A word of explanation is perhaps necessary in regard to the figures given in the last column of the above table. The percentage red, which is of the order of five, is obtained by measuring the proportion of the total light emitted from the lamp which will pass through a Wratten No. 25 red filter. The implication of the statement is, therefore, that the distribution of radiant energy from these high-pressure fluorescent lamps is such that about 5 per cent. of the luminosity is due to energy which has a wavelength greater than about 6,000 Å. The absorption curve of an average Wratten 25 filter being similar to that shown in Fig. 3*. It will be realised that this index figure for percentage red gives nothing more than an indication that in the spectral region from 6,000 Å to 7,000 Å the various types of H.P. fluorescent lamp emit a proportion of light which lies between the corresponding values for the uncorrected mercury lamps on the one hand and daylight on the other, as shown in the following Table II. :—

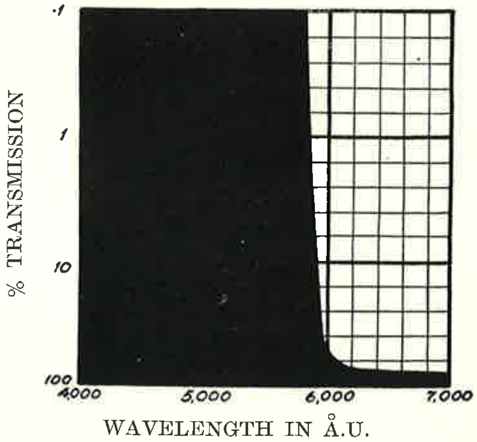

Fig. 3*. Transmission of Wratten Filter 25.

TABLE II.

COMPARISON OF RED CONTENT OF LIGHT FROM CORRECTED AND UNCORRECTED MERCURY VAPOUR DISCHARGE LAMPS AND THAT OF DAYLIGHT.

	Uncorrected.	Corrected.
High-pressure mercury vapour in hard glass envelope.	Approx. 1%	Approx. 5%
High-pressure mercury vapour in quartz envelope.	Approx. 2%	Approx. 5%
Daylight	Approx. 15%	

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* Illustration taken from "Wratten Light Filters," by kind permission of Messrs. Kodak, Ltd.

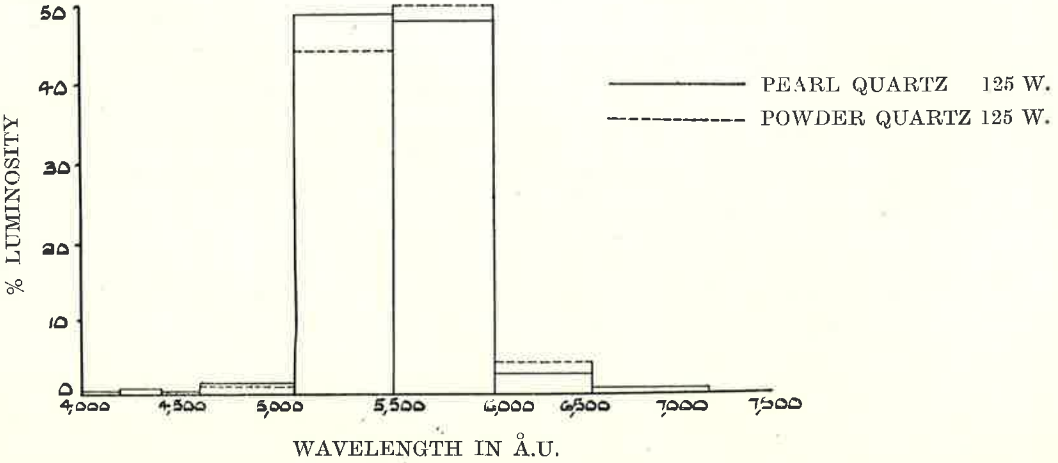


Fig. 4. Block diagram from spectral luminosity data.

Methods for assessing the colour rendering properties of a light source must take account of the luminosity of the radiation which is being studied not in one limited region only, but over the whole visible spectrum between the approximate limits of 4,000 Å and 7,000 Å. An approximate method for doing this has been developed and consists in measuring the relative luminosity of the radiation in eight bands covering the visible spectrum. Some experience is necessary to enable the results of such measurements to be interpreted. The results may, for example, be studied in the form of a series of measurements as in Table III below, or may be considered graphically, as in Fig. 4. In each case a knowledge of the corresponding results for a light source of known character is useful as a basis of comparison. Further reference will be made to this method in connection with the assessment of the colour of the latest type of fluorescent light sources which will now be considered.

Table III.

SPECTRAL BAND LUMINOSITY DATA.

Wavelength Bands in Angstrom Units.	400 watt Sieray (Clear Bulb).	400 watt Sieray (Isothermal).	125 watt Pearl quartz.	125 watt Powder quartz.
4000-4200	·002	·002	·005	·002
4200-4400	·64	·30	·50	·32
4400-4600	·044	·07	·11	·15
4600-5100	·68	1·7	1·5	1·7
5100-5600	54·0	46·2	49·8	44·2
5600-6100	44·3	48·7	47·8	50·0
6100-6600	·4	3·0	1·3	3·6
6600-7200	·13	·19	·17	·25

Class 2—Sources in which the emitted light is produced almost entirely by fluorescence

In the types of lamp just described, only a limited region of the ultra-violet spectrum of mercury is utilized, namely, radiation occurring at wavelengths above about 3,000 Å. The spectrum of mercury is, however, particularly rich in short wavelength radiation, and under low temperature conditions the dominant wavelength at which energy is radiated from the electrically excited mercury atom is 2,537 Å. Energy of this short wavelength is a very powerful activator, and is capable of exciting to fluorescence many of the substances which are normally used on the screens of cathode ray tubes.

The fact that many types of glass exhibited a certain amount of fluorescence when bombarded with either cathode rays or short wavelength ultra-violet radiation had been known for many years. Certain constituents in the glass composition were found to influence this effect beneficially, subsequent to about 1920, and a number of special glasses were introduced which fluoresced quite strongly under the direct radiation from the low-pressure mercury discharge. One of the first practical uses of this effect was the production of green high voltage sign tubes. A uranium glass which exhibited a bright yellow fluorescence was used for making up high voltage sign tubes of the mercury type; that is tubes which in clear glass would give a pale blue light. The combined effect of the blue mercury glow and the yellow fluorescence of the uranium glass was a pleasing green. A later introduction was that of a whole series of special fluorescent glasses which were fabricated into two or in some cases three ply tubing. For example, the finished tubing would have its inner surface of special fluorescent glass, and its outer surface of a more ordinary glass better able to resist thermal and mechanical shock, and more resistant to weathering than the fluorescent layer. These developments enjoyed a certain popularity, but there were disadvantages when the tubing was used for the manufacture of coloured sign tubes of the high voltage type. The peak fluorescent effect was produced with quite low current densities, and unless very special precautions were observed in processing the tubing the fluorescence was often rather transient and, hence, the tube colour was not very stable. The next stage was reached when methods were worked out for the application of a layer of fluorescent powder to the inner surface of glass tubing, and the results obtained thereby stimulated the development of new powders more effectively excited by the dominant radiation from the low-pressure mercury discharge. Under the optimum condition of temperature and therefore of mercury vapour pressure more than 60 per cent. of the energy in the discharge is radiated at

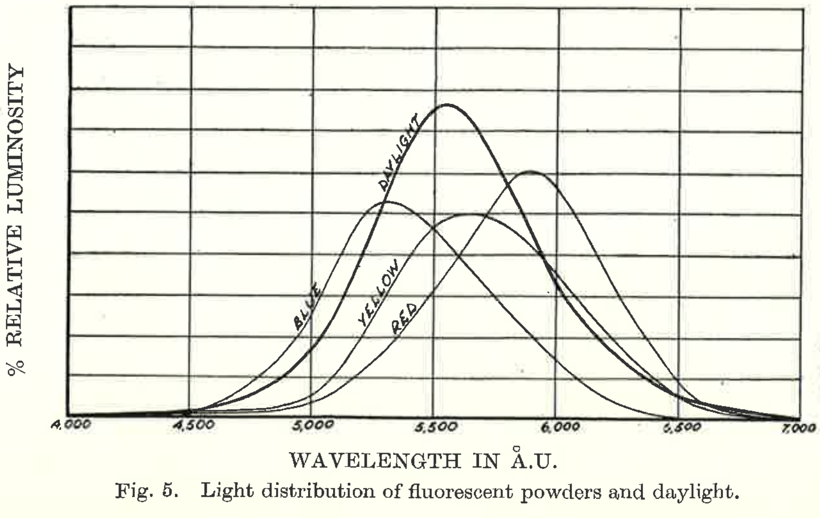


Fig. 5. Light distribution of fluorescent powders and daylight.

the resonance wavelength of 2,537 Å. It was, therefore, evident that the most efficient types of fluorescent powder for operation on the inner surface of low pressure mercury discharge tubes would be those which are designed to absorb strongly radiation of 2,537 Å. It will be appreciated from the earlier section that the type of powder, used for the colour modulation of HPMV lamps and designed to absorb blue and near ultra-violet radiation, would probably not be suitable for lamps of the low-pressure type. Certain powders were, however, available which had the requisite properties, and due to intensive research since that date quite a useful list of fluorescent inorganic compounds have been developed which are efficiently activated by 2,537 Å radiation ; see Table IV.

Table IV.
DATA FOR VARIOUS FLUORESCENT COMPOUNDS USED IN EXPERIMENTAL LOW-PRESSURE MERCURY TUBULAR LAMPS.

Compound.	Colour.	Approx. Dominant Wave-length in Angstrom Units.	Efficiency in Lumens per watt.	Relative Efficiencies with equal energies, concentrated at each Dominant Wavelength.
Calcium Tungstate	Blue Violet.	4400	20–25	2·3
Magnesium Tungstate.	Blue.	4800	30–35	13·9
Zinc Silicate ...	Green.	5500	80–90	100
Zinc Beryllium Silicate.	Yellow.	5700	50–55	95·2
Zinc Beryllium Silicate.	Orange.	6000	45–50	63·1
Cadmium Phosphate.	Red.	6100	45–50	50·3
Cadmium Borate...	Red.	6200	30–35	38·1

i.e., assuming that the various powders all emit a given amount of energy and that this is concentrated at the dominant wavelength.

The first use of some of these powders was to add to the range of colours available from low-pressure high voltage cold cathode discharge tubes such as those used for decorative effects and sign work. The range of colours thus made available led to combinations of tubes so related that daylight effects were simulated. The manner in which this desirable result can be achieved is illustrated in Fig. 5. The three smaller curves represent the luminosity of blue, yellow and red tubes. By varying the wattage relationships between tubes of the various colours a combined effect could be produced similar to that shown by the heavier curve which represents the luminosity of daylight. In the earlier work the blue tubing was provided by a coating of calcium tungstate activated by the low-pressure mercury discharge. Yellow light was provided by a coating of zinc silicate on the inside surface of a tube in which the pure neon discharge was taking place, and red light was given by a plain neon tube.

The utilization of such combinations for illumination purposes as distinct from effects of a purely decorative nature required that the various coloured tubes should be mounted close together, otherwise, highly coloured shadows would result which although often beautiful might be objectionable for certain purposes. The ideal arrangement would obviously be one in which the various sources of light were combined into a single tube, and this has now been achieved as will be described later. An interesting intermediate stage was reached when the combination necessary to produce white light was reduced to two tubes mounted close together. Both tubes were of the low-pressure type with powder coated on the inside surface and the primary discharge was in each case neon. The fluorescing material in one tube was calcium tungstate and in the other zinc silicate. The tubes appeared pink and yellow respectively, but light was contributed over each portion of the visible spectrum. The advantage of using a neon discharge for activating the powders was twofold, for besides providing light at the red end of the spectrum it was found that the maintenance of light emission was excellent. These results stimulated research in a number of directions which eventually matured in the form of the present mains voltage fluorescent tubes now available in both this country and in America.

Mains Voltage Fluorescent Tubes

The simplest way of introducing the subject of mains voltage tubes will be to describe the Sieray 80 watt lamp type MCF/U. Its general appearance and characteristics are now well known. It is of tubular form some 5 ft. in length and $1\frac{1}{2}$ ins. in diameter, and emits when new 2,800 lumens for a nett consumption of 80 watts. A full table of characteristics is given in Table V. overleaf, and some of these will repay further study.

The MCF/U lamp consists of a glass tube which has emissive electrodes sealed into its ends and a coating of fluorescent powder on its inner surface. It contains a gas filling consisting of a very low pressure of argon, together with a small amount of mercury.

Fig. 6 gives a general view of the lamp.

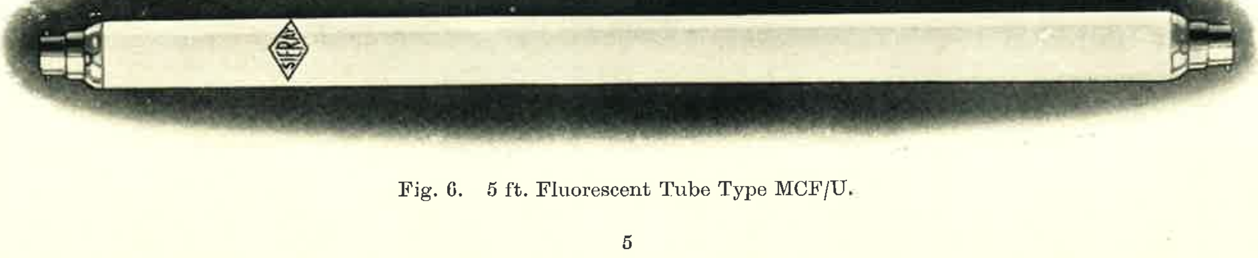


Fig. 6. 5 ft. Fluorescent Tube Type MCF/U.

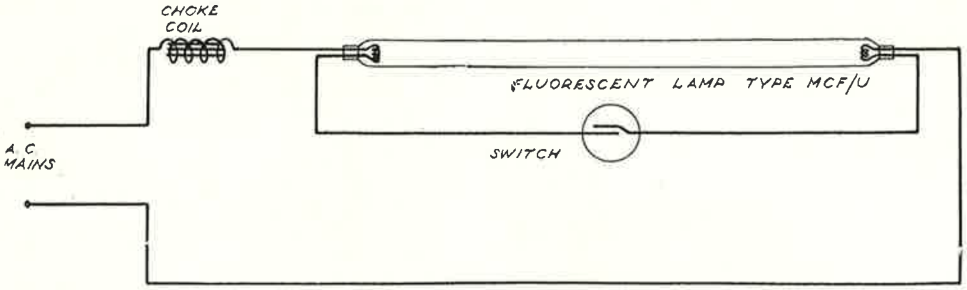


Fig. 7. Circuit elements for operation of low-pressure Fluorescent Lamp Type MCF/U.

TABLE V.

DATA FOR COLD WHITE FLUORESCENT TUBE.

TYPE MCF/U.

Length	60±0·5 inches.
Diameter	38±1·5 mm.
Cap	B 22/25×26
Nominal lamp watts	80
Arc length	1445±10 mm.
Lamp operating volts	115±10
Nominal lamp operating current	0·8 amps.
Initial efficiency	35·0 L/W.
Average life	2,000 hours
Supply volts	200-250

The MCF/U lamp consists of a glass tube which has emissive electrodes sealed into its ends and a coating of fluorescent powder on its inner surface. It contains a gas filling consisting of a very low pressure of argon together with a small amount of mercury.

Fluorescent light sources of this type are designed to play such an important part in the lighting of the future, and have features which are of such general interest that it will be useful to consider their various aspects in some detail. Convenient sections in which to do this are given below :—

(1) Operating circuit.
(2) Electrode system and tube characteristics.
(3) The fluorescent powder layer and its light emission.
(4) Control gear.
(5) Application of low-pressure tubular fluorescent lamps.

(1) **Operating Circuit.** It is necessary to operate electric discharge lamps in series with some form of current limiting device. The 80 watt MCF/U lamp is not an exception to this general rule, and due to its considerable length and the fact that it is designed for operation from ordinary mains voltages an automatic starting switch is generally provided to assist in the production of a high voltage impulse to initiate the discharge. A schematic diagram of the essential circuit elements is shown in Fig. 7.

It will be noticed that the tube electrodes which are designed for *series heating* are connected to the contacts of the bayonet cap at each end. The current limiting device is in series with one electrode, the other end of the same electrode being connected via the starting switch to the electrode at the opposite end of the tube. The circuit is completed by connecting the remaining free electrode end and the free choke connection to the A.C. mains. In the diagram above, the switch is shown as a simple on and off type. An ordinary tumbler switch is quite suitable for manual operation. In practice, an automatic switch is provided, and a discussion of switch types and characteristics is given in section (4).

(2) **Electrode System and Tube Characteristics.** The electrode of the Sieray 80 watt MCF/U lamp consists of a cathode coil of tungsten wire impregnated with active material and mounted on a pair of electrodes which are extended alongside the tungsten coil to form the anode. A view of this arrangement is shown in Fig. 8. The cathode coil is designed to reach an emitting temperature with a current of about 1·2 amperes, and with this current flowing to have a voltage drop across its ends of about 10 volts. As a matter of fact the volt ampere curve of one of these electrodes will repay study ; see Fig. 9. It will be seen that from 0 to about 9 volts the current rises in a fairly linear relationship with voltage. At higher current values the volt drop across the electrodes rises much less rapidly, and in fact the electrodes begin to develop characteristics similar to that of a voltage stabiliser. This phenomenon is due to the development of a gas current in parallel with the current carried by the electrode coil itself. At low voltages and therefore at low electrode temperatures the gas current is almost negligible, but in the neighbourhood of 9 volts the gas current rises rapidly. Above 9 volts the gas and mercury vapour in the atmosphere surrounding the electrode becomes ionized and current flows in two parallel paths across the electrode ends, the first component of the current being that carried by the tungsten wire, the second component being that carried by the ionized gas. This effect explains the development of a glow round the electrode ends when the tube is first switched into circuit and before the starting switch opens. The ionized gas and mercury vapour produce sufficient ultra-violet radiation to excite the fluorescent powder for an inch or two from each end. When the starting switch opens a voltage surge is produced which starts the tube, the ionized gas at each end assisting in the process and ensuring reliable ignition of the discharge. It will be appreciated that on starting from cold, the tube temperature rises slowly until the equilibrium value is reached. During this warming up period the light output also rises, as shown in Fig. 10. This effect is very interesting as it occurs simultaneously with

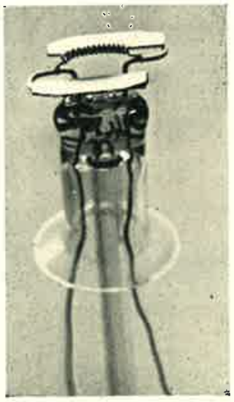


Fig. 8. Electrode arrangement of 80 Watt low - pressure tube.

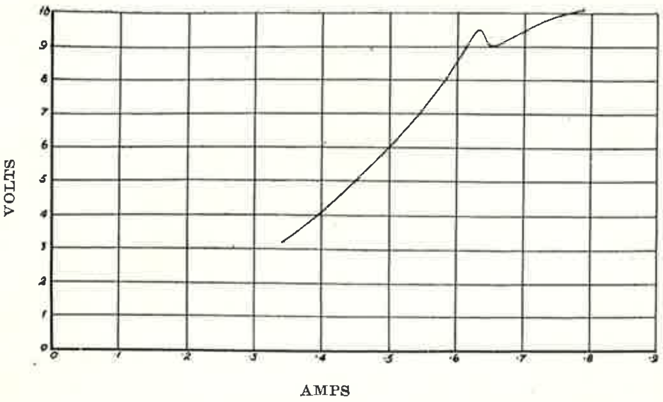


Fig. 9. Electrode characteristics of Sieray 80 Watt Type MCF/U Lamp.

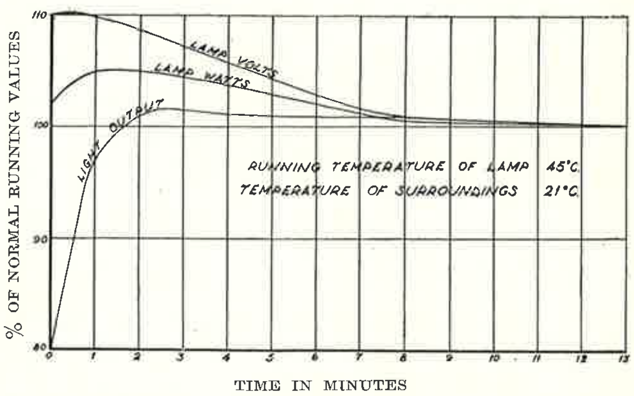


Fig. 10. Characteristics of Sieray 80 Watt Type MCF/U Lamp.

changes in the electrical characteristics of the tube. It will be seen from Fig. 10 that the tube voltage gradually falls until temperature equilibrium is reached, and consequently the tube watts fall slightly. All these effects are due to the fact that when the tube is first switched on a proportion of the current is carried by argon ions, and as the temperature increases the concentration of mercury ions increases and the proportion of the total current carried thereby gradually reaches a maximum. This maximum corresponds with a tube temperature of approximately 45° C. At higher temperatures the light output falls off due to absorption of the mercury resonance radiation which increases progressively at mercury vapour pressures above about 0.009 mm., corresponding with a temperature of 45° C. As the fluorescent powder layer is designed to be preferentially activated by the mercury resonance radiation a decrease in the proportion of radiation at this wavelength causes a decrease in the brightness of the powder and, hence, a reduction in light output. Co-operation is therefore necessary between the lamp maker and the fittings designer. The former must design the 80 watt MCF/U lamp to reach the operating temperature corresponding with the optimum efficiency, while the latter must understand

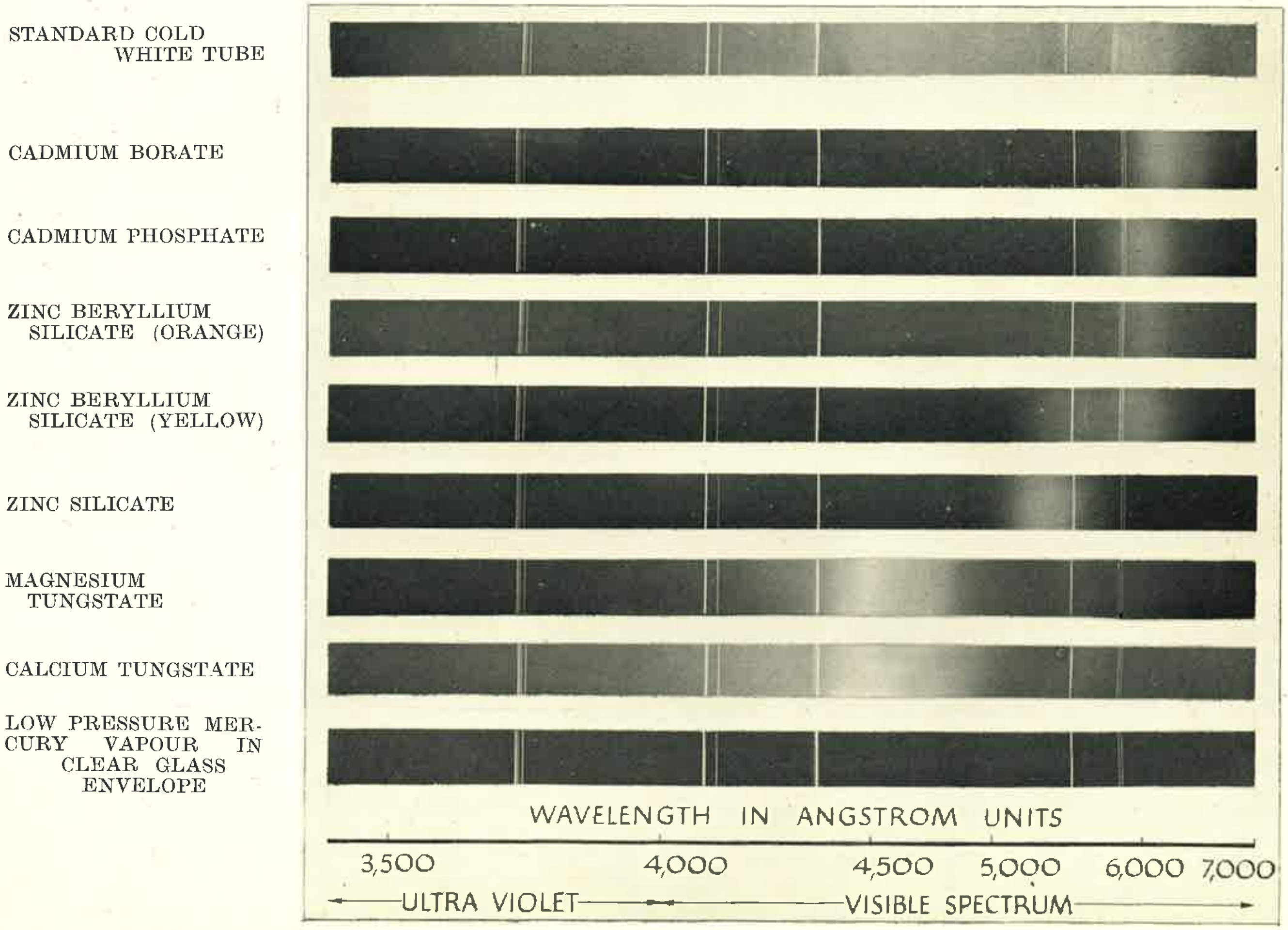


Fig. 11.

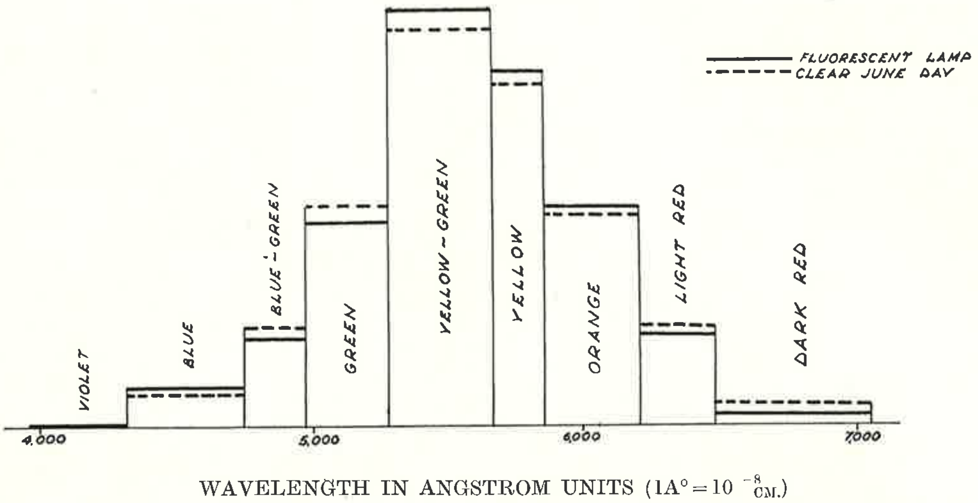


Fig. 12. Spectral luminosity distribution of the Sieray Fluorescent Tube compared with that of noon sunlight on a clear June day.

lamp characteristics in order to avoid fittings designs which would give rise to excessive tube temperature.

(3) **The Fluorescent Powder Layer and its Light Emission.** It has been indicated above that the fluorescent powder layer consists of an intimate mixture of several powders each contributing a proportion of the emitted light. The component powders are so proportioned and chosen that a light approximating closely to north daylight is produced. The powders which separately would give blue, yellow and red light, are used as an intimate mixture, the grain size of which is so small that the eye cannot distinguish separate colours and a white light only is seen. This is a most interesting effect. The spectrograms in Fig. 11 show the fluorescence of a selection of substances all strongly activated by energy radiated at about 2,537 Å. It must be realised that the exact response of a particular powder is to some extent dependent on its method of preparation. The spectrograms are, however, typical of the response obtained with powders suitable for use in the 80 watt MCF/U lamp. It will be seen that in most cases the fluorescent light appears as a single structureless band covering a fairly wide region of the visible spectrum. In the case of calcium tungstate and to some extent magnesium tungstate the fluorescent radiation extends well into the near ultra-violet region. It is interesting to notice also that there is little or no absorption of the 3,650 Å line, thus sharply differentiating these powders from the sulphide group.

Each particle in the powder layer glows with its characteristic colour, and under a low power miscroscope the powder surface of the MCF/U lamp appears like star dust rainbow hued. It is possible by varying the proportion of the component powders to vary the colour of the emitted light. Strict control is therefore necessary at each stage of manufacture to ensure a colour which remains constant within close limits. From a wide range of possibilities the present colour appears most satisfactory for general factory lighting and similar purposes. The distribution of luminosity is shown in the block diagram below Fig. 12, which also gives a comparison with noon daylight. The method of production of these block diagrams deserves mention, as this form of representation can be used for indicating the colour and assessing the colour rendering properties of any light source. A pure spectrum of the light source under test is produced by suitable apparatus and arranged to fall on a photo-electric cell connected with a sensitive galvanometer. It is important that the photo-electric cells should have a response closely similar to the luminosity curve of the normal eye. A series of masks subdividing the visible spectrum into eight bands are interposed in turn into the spectrum beam so that the luminosity in each of the following wavebands can be calculated from the readings of the galvanometer. Table VI below gives the wavebands and luminosity results for typical blue, green, yellow and red fluorescent powders. From the results of such measurements and a knowledge of the relative brightness of the various powders it is possible to calculate combinations for a wide range of hues. The relative luminosity figures for the Sieray 80 watt MCF/U lamp are given in column 5 above.

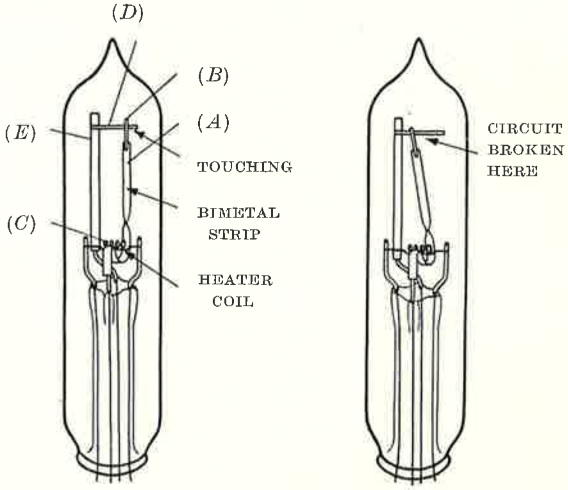
Table VI.

SPECTRAL LUMINOSITY DATA FOR VARIOUS FLUORESCENT POWDERS.

Wavelength Bands in Angstrom Units.	Magnesium Tungstate.	Zinc Silicate.	Yellow Zinc Beryllium Silicate.	Cadmium Chloro Phosphate.	Standard Cold White.
	PERCENTAGE LUMINOSITY.				
4000-4200	·022	—	—	—	·012
4200-4400	·52	·12	·18	·02	·38
4400-4600	·70	·05	·17	·01	·50
4600-5100	14·20	5·90	1·70	·85	7·40
5100-5600	52·00	77·70	38·90	19·80	41·50
5600-6100	27·70	14·80	45·80	60·60	40·30
6100-6600	4·50	1·13	12·30	17·90	9·25
6600-7200	·02	·10	·40	·60	·33

(4) **Control Gear.** The function of the control gear which is used for this type of low-pressure lamp is threefold : (*i*) a choke is used to limit the lamp current to the desired value ; (*ii*) a starting switch is provided for initiating the discharge ; (*iii*) condensers are provided, viz., a radio suppressor condenser across the

Fig. 13. Thermal Switch.



General view of switch

Heater coil energised Circuit broken

Fig. 15. Action of Thermal Switch.

switch contacts, and a power factor correction condenser across the mains leads.

(*i*) *Choke.* In a paper of this type little requires to be said on the subject of the current limiting choke. It is important, of course, that this choke should have the correct electrical characteristics, and that it should have insulation between turns and to earth adequate to withstand the surge voltages produced when the starting switch opens. It is important for the choke to be so arranged that the electrodes are not overheated during the period before the starting switch opens, and also that the tube current is maintained at the correct value of 0·8 amperes during normal operation.

(*ii*) *Starting Switch.* The function of the starting switch is to provide a short period for preheating the electrodes to an emitting temperature, and to cause the production of a surge voltage sufficient to ignite the tube. As electrodes are designed to reach an adequate emitting temperature on the choke starting current in one to two seconds, starting switches are usually designed to remain closed for a second or two and then to open sharply so that an inductive surge is produced due to interruption of the choke current. This inductive surge is impressed across the tube electrodes and must be of sufficient magnitude to initiate the discharge. Three types of starting switch will be mentioned each of them having distinctive features :—

(*a*) The thermal switch.
(*b*) The thermal glow switch.
(*c*) The magnetic switch.

(*a*) *Thermal Switch.* This type of switch is mounted inside a small tubular bulb, as illustrated in Fig. 13. It is connected in circuit, as shown in Fig. 14.

A bimetal element (*A*) carries a contact (*B*) ; the element (*A*) is bent so as to partially enclose a heating element (*C*) consisting of a short low resistance nichrome helix. A stationary contact (*D*) is carried by a second bimetal element (*E*) which serves to compensate for ambient temperature changes. The arrangement is shown diagrammatically in Fig. 15. The switch contacts (*B*) and (*D*) are normally closed and are connected across one end of each of the lamp electrodes, as shown in Fig. 14. The heater element (*E*) is connected in series with the choke. This type of switch requires four current carrying leads. The contacts open by the passage of current through the heating element (*E*) and remain open while current flows through the choke via the tube. On cessation of the flow of current the switch contacts (*B*) and (*D*) close, the tube is shorted out and on remaking the circuit, current flows through the electrodes raising them to incandescence. The switch contacts (*B*) and (*D*) re-open after about three seconds, and the inductive kick so produced is adequate to re-start the tube.

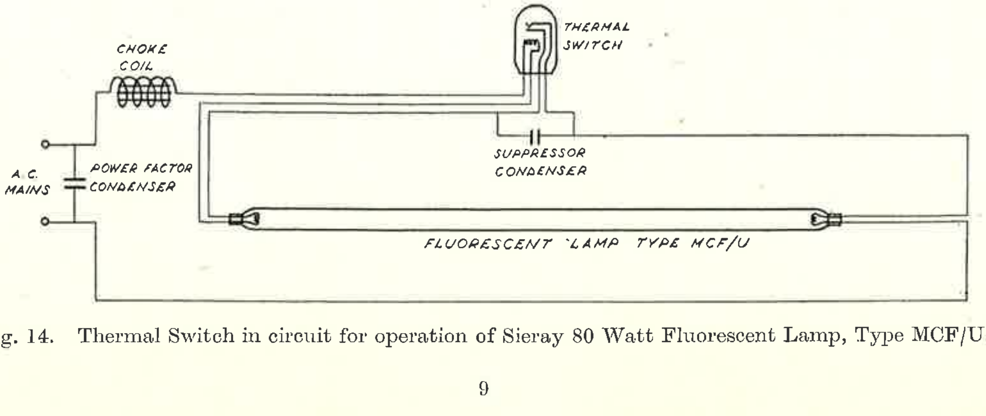


Fig. 14. Thermal Switch in circuit for operation of Sieray 80 Watt Fluorescent Lamp, Type MCF/U.

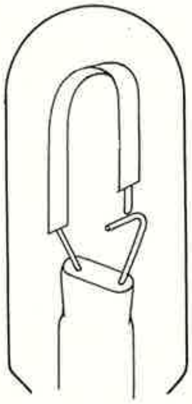


Fig. 16. Thermal Glow Type Switch.

(*b*) *Thermal Glow Switch.* In this type of switch, one form of which is shown in Fig. 16, a bimetal element (1) carries one contact, another contact being provided on a fixed electrode (2). The electrode system is mounted in a glass tube which is filled with a low-pressure of neon, helium or other suitable gas. The switch contacts are connected across the tube electrodes and in its normal position the switch is open. The operation is as follows :—

When the tube circuit is closed the mains volts are impressed across the switch contacts and a glow discharge results. A fairly heavy current is passed, the bimetal element heats up and is arranged so that the switch contacts close. The heating effect then ceases, the switch contacts therefore open, producing an inductive kick which is sufficient to start the tube. The voltage now impressed across the switch contacts is, of course, equal to the tube voltage, and is normally about 115 volts which is insufficient to cause a cathode glow. The switch therefore remains open until the tube is extinguished. On remaking the circuit the above cycle of operations is repeated.

(*c*) *Magnetic Switch.* Various types of magnetic switch have been suggested, some of which have interesting possibilities. For example, it is possible to use the stray flux at the choke air gap to actuate a light spring loaded armature carrying contacts which when the choke is unenergised closes the series circuit of the electrodes, as in other forms of switch which have been described. Immediately current flows through the circuit, the switch opens and closes very rapidly, producing a series of voltage impulses and at the same time causing the electrodes to be heated to an emitting temperature. Within a very short period the tube strikes up. The switch contacts then remain held open by the magnetic flux of the choke. Various designs of switch have been worked out employing this principle, and one experimental form of oil immersed switch is shown in Fig. 17.

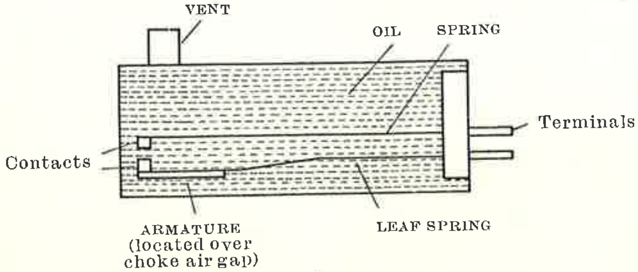


Fig. 17. Diagrammatic representation of a Magnetic Switch.

The fact that a voltage surge is required to start this type of lamp has been mentioned several times, and it is interesting to study the magnitude and characteristics of the voltage impulses produced by the various types of switches which have been referred to. The figures given do not pretend necessarily to settle the question as to which of the three types of switch is preferable, but they do indicate the magnitude and type of voltage impulses produced by particular designs of the thermal, thermal glow, and magnetic switches.

THERMAL SWITCH

THERMAL GLOW SWITCH

MAGNETIC SWITCH

Fig. 18. Oscillograms showing starting surges produced by various types of control gear for 80 Watt Type MCF/U Lamps.

The magnitude of these transient voltages depends on the instant at which the switch opens. As far as could be ascertained from a visual inspection of a cathode ray oscillograph the maximum transient voltages obtained with the different switches, tested with a ·04 microfarad condenser connected across them in each case, were approximately as shown in the following table :—

Thermal switch	750 volts.
Thermal glow switch	1,000 ,,
Magnetic switch	1,250 ,,

These values did not appear to be appreciably affected by the capacity of the condenser used.

Typical oscillograms for the various types of switches are shown in Fig. 18. These have been drawn from the mental impression obtained from successive observations made with each type of switch. The delineations represent in each case the sequence of events, but do not necessarily show the lapse of time between one event and the next. In the case of the thermal glow switch for instance, the period between closing and re-opening is longer than that represented by the practically straight line of zero mean voltage shown. In the case of the magnetic switch the peaky voltages shown over a period of two cycles are actually present over a period of possibly a second or more.

(*iii*) *Condensers.* Suitable values for 80 watt MCF/U tubes are 0·05 mfd. for the radio suppressor, and 8·0 mfd. for the power factor correction condenser.

Application of low-pressure tubular fluorescent lamps

During the past two years one dominant consideration has influenced the application of low-pressure fluorescent tubular lighting in this country, namely, the necessity for providing a standardized industrial lighting unit capable of being produced in quantities sufficient for the demands of industry almost entirely engaged on war production. It is a matter of some satisfaction to the electric lamp manufacturers concerned to know that coincident with the need for a day and night industrial output, often in totally blacked-out factories, the 80-watt MCF/U lamp was already sufficiently developed to enable it to be marketed in March, 1940.

During the two years which have elapsed since its introduction, the 80-watt lamp has proved of immense value for industrial lighting, and it has been installed not only in new factories, but also to replace existing lighting installations where the standard of illumination was inadequate for present day conditions.

Prior to the introduction of the fluorescent lamp, it would be generally true to say that improvements in electric lamps resulted simultaneously in increases in source brightness. At a certain stage the developing science of illuminating engineering began to exercise its important functions and to show the best way of utilising light sources so that the maximum benefit could be derived from their use. The development of the low-pressure lamp marks a unique step not only for reasons such as the high efficiency, colour qualities or long life which can be obtained, but because the source brightness is low enough to enable new standards of illumination to be applied commercially. The fitness for purpose of these fluorescent lamps is especially noteworthy when one considers how the requirements of the lamp designers and those of the illuminating engineer are merged together.

Low source brightness is particularly advantageous in industry where in many cases it is impossible to avoid the use of brightly polished machine parts and large surface areas of high reflectivity from which source images may reach the worker's eye. In the case of installations with high brightness sources these images often have disastrous effects on visual/acuity, and are a potent cause of eye strain. It is acknowledged that in a well designed incandescent lamp installation such effects can be reduced to a minimum, but the ease with which they are overcome in a fluorescent lighting installation generally comes as a revelation to those seeing a large installation for the first time.

It is interesting to compare American practice with that in this country. During the first two years of war, while developments in fluorescent lighting in this country had been confined by common consent to a standard size and colour of lamp, in America, where the need for such restrictions had not yet arisen, amazing developments took place in the use of this new form of lighting. A range of lamp sizes and wattages have been made available and most of these are obtainable in the form of coloured tubes as well as in two variants of so-called white light. It is interesting to note that it is the white tube which is the most popular, and the tendency appears to be that the greatest demand will develop for lamps rated at wattages of the same order as the standard English tube, notwithstanding the fact that the first lamp marketed in America was rated at 25 watts and was much smaller in size. Certain factors are worthy of mention which contribute to the unique place which these lamps are already filling in industrial

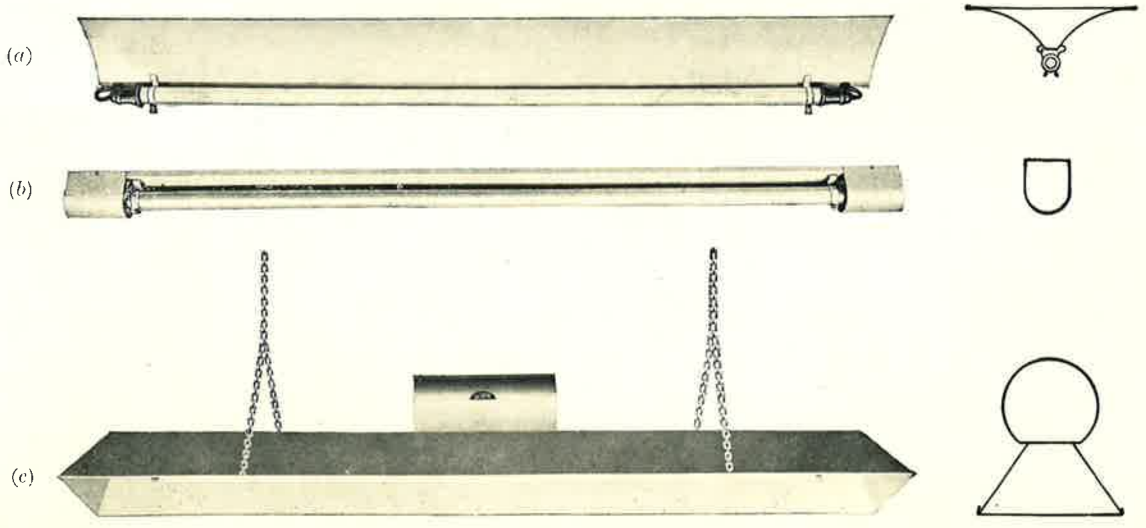


Fig. 19. Industrial fittings for 80 Watt Fluorescent Lamp, Type MCF/U.

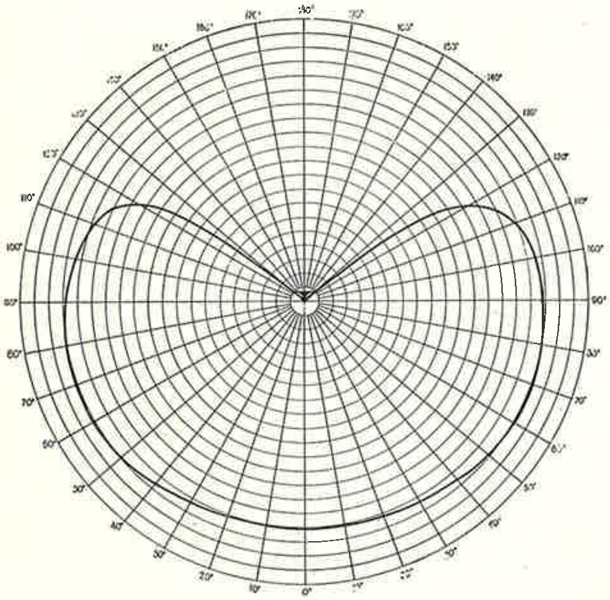


Fig. 20 (a). Distribution of light from an 80 Watt Fluorescent Tube in a Distributive Type Reflector shown in Fig. 19 (a).

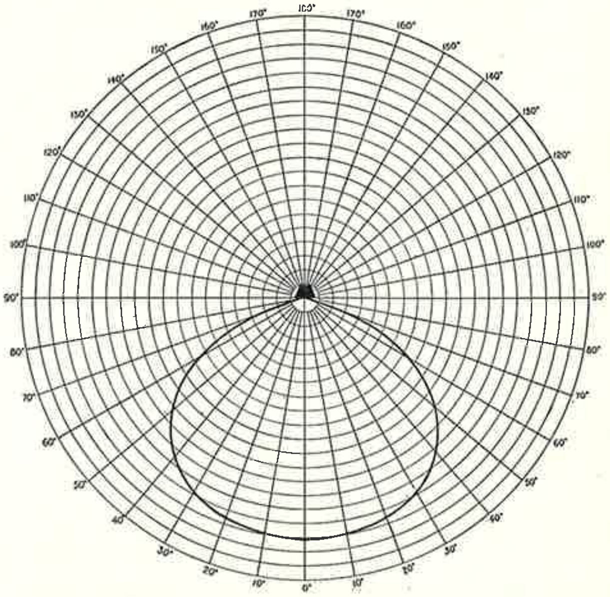


Fig. 20 (c). Distribution of light from an 80 Watt Fluorescent Tube in a Dispersive Type Trough Reflector shown in Fig. 19 (c).

lighting installations, and which justify the belief that they will find use in a rapidly extending field when conditions return to normal.

The low surface brightness of approximately 0·5 stilb. renders the 80-watt MCF/U lamp eminently suitable for use with simple reflectors of both concentrating and dispersive types without the need for any intermediate diffusing medium. It is important, however, even with this low order of brightness to avoid the use of unshielded lamps at or about eye level, otherwise due to the large projected area of the source (0·625 sq. ft. in the case of the 80-watt lamp) discomfort glare may be experienced.

Typical industrial lighting fittings are shown in Fig. 19 (*a*), (*b*) and (*c*). It will be seen that these fittings are of a simple functional type allowing for ease of cleaning and maintenance. Polar curves of the fittings shown in Fig. 19 (*a*) and (*c*) are given in Figs. 20 (*a*) and (*c*).

Most industrial type reflectors are designed to provide a large area of low brightness, enabling the production of a general effect not dissimilar to that produced from a good natural roof light. Shadows are, therefore, reduced to low intensity and the effect on the light distribution of a moderate amount of overhead pipework can generally be ignored. Sometimes, however, cases are experienced in which there is a considerable amount of pipework and other equipment lying parallel and near to the lamp axis. In such cases it is advisable to arrange a proportion of the lighting fittings at right angles to the main direction of distribution. In America, in some cases, tubular fluorescent lamps have been arranged diagonally, particularly when small workshops and offices are being illuminated. This special arrangement has the advantage of cutting down the intensity of shadows occurring in one direction on benches which would normally be located parallel to the main walls of the room. Fluorescent lamps are well adapted for use at low mounting heights although this is by no means necessary. It does, however, enable the production of high illumination values on vertical surfaces—a factor often of great importance in industry.

Since the advent of electric discharge lamps into industry, the question as to whether stroboscopic effects on moving machine parts would be of any importance has given rise to some study. Due to the phosphorescence of most of the powders used in the production of 80-watt MCF/U lamps stroboscopic effects are much less noticeable than would be the case with a mercury or sodium discharge lamp installation. It is, however, desirable wherever possible to wire the lighting fittings on a three-phase distribution according to one of the well-known arrangements, and so to practically eliminate stroboscopic flickers.* A similar result can be obtained on a special two lamp circuit from a single-phase supply, one of the lamps in the fitting being operated with inductance control and the second lamp on a capacitance control unit. With this arrangement the currents through the two lamps are practically 90° out of phase, and the changes in light output due to the cyclic changes in the current value through the tubes are largely compensated.

A consideration of importance to the lighting engineer is the effect of ambient temperature on the lamp efficiency. As was indicated in an earlier section, very low or very high temperature conditions will result in a decrease in the light output of the fluorescent lamp.

It may be shown that the types of powder used in low-pressure fluorescent lamps, and which is mainly activated by 2537 Å radiation, is practically unaffected

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* *See* for example "Stroboscopic Effects from Discharge Lamps" by J. N. Aldington, *Electrical Times*, 23/9/37.

by temperature over the range likely to be met with in industrial lighting installations. The temperature efficiency characteristic of the lamps is, therefore, dependent only upon changes in the effectiveness of transformation of electrical energy into radiation at 2537 Å.

The magnitude of the efficiency changes resulting from changes in ambient temperature are shown in Fig. 21. It will be seen that the maximum efficiency is developed at about 15° C. ambient, and that the slope of the efficiency temperature characteristic is greatest at temperatures below 15° C. In this region the pressure of mercury vapour is too low for maximum production of 2537 Å, radiation and non-effective energy conversions are occurring in the rare gas-filling of the lamp.

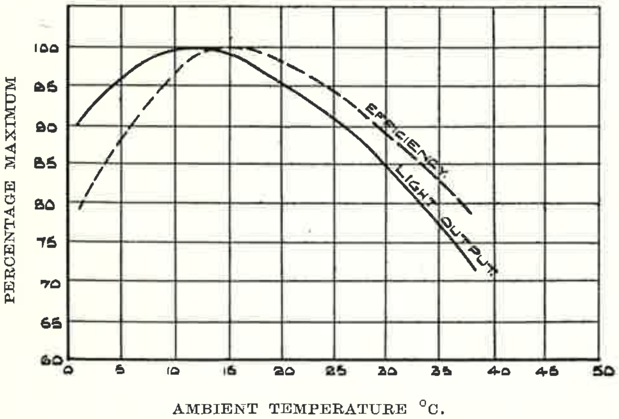

Fig. 21. Effect of ambient temperature on luminous efficiency and light output of 80 Watt Sieray Fluorescent Tube.

At temperatures in excess of 15° C. absorption of 2537 Å, radiation occurs progressively with increase of temperature resulting in the emission of radiation less effective in exciting the fluorescent powder layer and therefore a decrease in the efficiency of light production.

It follows from the above that account has to be taken of a complex series of inter-related factors to produce a lamp design which develops its maximum efficiency at the temperatures normally available under good industrial conditions. Similarly, the fittings' designer must be aware of the lamp characteristics to ensure the development of the maximum lamp efficiency and its most adequate utilization. Special care is necessary in the design of fittings embodying two or more lamps side by side or in fittings of a totally enclosed type to prevent excessive rise in tube temperature which would have the effect of somewhat reducing the total light output.

The effect of voltage variation on light output and performance is also of importance and in Fig. 22 the effect of a ±5 per cent. change in applied voltage is shown to correspond with less than ± 5 per cent. change in light output. This is an extremely low figure due to certain self-compensating effects in the lamp and control circuit. For a tungsten filament lamp corresponding values would be ± 17 per cent. change in light output for a ± 5 per cent. change in voltage. When operated under normal conditions the 80-watt fluorescent lamp has an average initial efficiency of 35 L/W which falls to 32 L/W after 100 hours. Thereafter the rate of change of efficiency with time is much less rapid and at 2,000 hours the average efficiency of these lamps is 24 L/W. A number of causes can contribute to the determination of the life of any particular lamp. Experience has shown that the shape of the survivor curve for these lamps is similar to that of other devices of a similar nature, and the average life of 2,000 hours is based on data taking into account not only the lamp survivor curve but also the lumen maintenance characteristics.

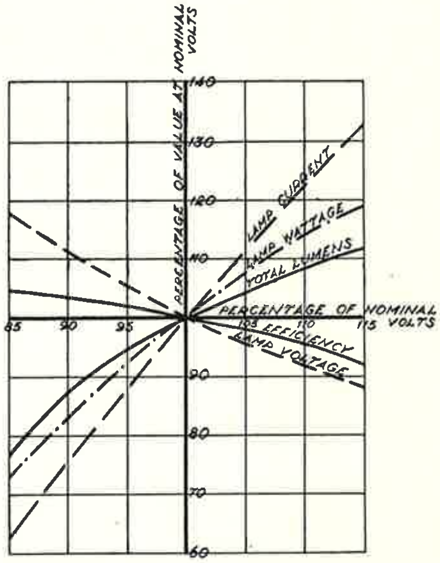

Fig. 22. Effect of variation of mains voltage on characteristics of 80 Watt Sieray Fluorescent Tube.

One general point is worthy of mention in view of the wide adoption of this new form of lighting and its future prospects. Failure in the case of a filament lamp is generally occasioned by the lamp filament having reached its appointed end and diagnosis is simple. In the case of fluorescent lamps, however, where the most general cause of ultimate failure is loss of emission from the electrodes a " blinking " or " hunting " effect may be the first sign of the need for a new lamp. Lighting engineers and users must recognise this effect, and arrange to replace or switch off the lamp without delay to avoid the possibility of damage to the starting switch. It will, of course, be understood that in the case of the supply voltage being too low this effect may occur with a perfect lamp, and hence care must be taken in the diagnosis of the fault.

Conclusion

In the preceding sections of this paper attention has been devoted almost entirely to reviewing the main lines along which progress has been achieved in the development and application of practical fluorescent light sources. No one should conclude therefrom that the developments which have been mentioned have proceeded in the direct manner in which they have been described, or that they are the only lines along which work has been done or progress achieved. Much interesting material had necessarily to be excluded from this paper owing to very wide scope of the subject. Some mention will, however, be made in this concluding section of certain other developments which might become of increased importance in the future.

The use of large areas of fluorescent material continuously irradiated by energy of appropriate wavelength must not be disregarded as a possible source of illumination for special purposes. At the present time the so-called black glass lamp is the only practical source of ultra-violet radiation for such a purpose, and as its effective energy lies in the region between 3,000 and 4,000 Å suitable phosphors are to be found among organic dyestuffs or the metallic sulphides. Use has already been made of this combination of lamp and phosphor in theatre work and for advertising and display. The low overall efficiency of the combination, however, tends at the present to exclude its use for general illumination purposes. Difficulties arise in the utilization of radiant energy of lower wavelength which would enable the range of possible phosphors to be extended tremendously, but these difficulties are of a kind which need not be regarded as insoluble.

The use of rare gases and metals other than mercury for producing the primary radiation has received some study, and the possibilities are by no means exhausted. Whereas the positive column or the arc is the principal source of radiation in most practical forms of discharge lamp used for exciting fluorescent substances, ultra-violet radiation can be produced from the glow discharge and some interesting results have been achieved both of the type in which fluorescence is used to modulate the primary light and that in which fluorescence is the dominant effect. The tungsten filament operating at high temperatures is also a sufficiently powerful source of near ultra-violet and violet radiation to activate quite strongly certain fluorescent materials.

The fluorescent light sources which have been described have opened up new possibilities for the lighting engineer. There are indications that the progress which has been made marks the beginning of a new era in the development and utilization of light sources, probably as important as that which followed the advent of the gasfilled tungsten filament lamp.

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