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SOME DEVELOPMENTS IN THE PRODUCTION OF LIGHT BY THE ELECTRIC DISCHARGE THROUGH MERCURY VAPOUR

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Between the wide range of frequencies used for radio transmission and the penetrating energy known as X-rays there is a relatively narrow band of radiation to which the retina of the eye is responsive and which, therefore, produces the sensation of light.

This visible radiation can be produced in various ways: by chemical means, by high temperature, by direct transformation of electrical energy and by methods employing the phenomenon of fluorescence. Whatever method is used, however, must produce radiation of wavelengths between about 4,000 Å and 7,000 Å in order that a visual effect shall be obtained for it is to this region only that the human eye responds.

Most methods of light production involve processes which produce at the same time energy of wavelengths outside the limits given above. This non-effective energy is often the major radiation from the particular transformation involved in the light producing process and, therefore, the absolute efficiency of the light production is generally very low. For this reason, as well as for a number of others, lamp research engineers are investigating new methods for producing light as well as seeking means for improving the effectiveness of the already established light sources.

In order to appreciate the relation of light waves to the longer and shorter wavelength radiation with which they form a continuous spectrum, the diagram, Fig. 1, has been drawn to indicate the various wavelength bands which are embraced by the terms radio waves, heat rays, visible light rays, ultra-violet rays and X-rays. Although different in the way they are produced, these various types of radiation all consist of vibrations in the electromagnetic ether. Their different properties are due to the differences between the wavelength bands into which they are separated, but as they form a continuous series it is apparent that there can be no sharp distinction between the properties of adjacent bands.

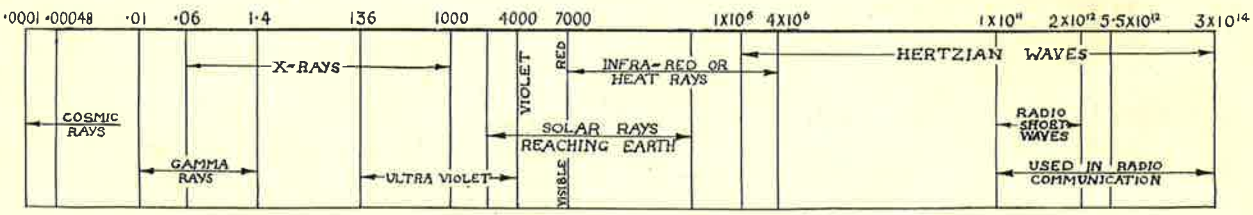

Fig. 1. Spectrum of Radiant Energy.

That narrow band of radiation between 4,000 and 7,000 Å is, however, unique as it alone produces, through the mechanism of the eye, the stimulus of vision. When the eye is irradiated by energy in which all the wavelengths between the above limits are equally represented then the sensation of white light is produced. Deficiency of energy in any part of the spectrum tends to produce the phenomenon of colour, an effect which is most pronounced in the radiation from certain types of electric discharge lamps in which the radiant energy is often emitted over quite limited regions of the visible spectrum.

If most of the energy is emitted in the region from 6,000 to 7,000 Å, the eye perceives a red light, whereas the region from 4,000 to 5,000 Å produces the sensation of blue. In the intervening region, to which the eye is most sensitive, the coloured light is green or yellow according to its wavelength. These facts are shown in

TABLE I.

HIGH-VOLTAGE, LOW CURRENT SIMPLE DISCHARGE TUBE.

- Mains voltage Cathode Glow
- Mains voltage Hot cathode Low-pressure Type MC (Floodlighting)
  - Mains voltage Hot cathode Low-pressure Fluorescent Type MC/F (General Lighting).
- Mains voltage Hot cathode High-pressure Type MA (Street Lighting and General Lighting).
  - Air-cooled High brightness Type ME (Projection).
  - Fluorescent Types :— MA/F, MB/F (General Lighting).
  - Dual combination with incandescent filament Type MAT (Street and General Lighting).
- High voltage Cold cathode
  - High-voltage Cold cathode Fluorescent (Sign and special Lighting Effects).
- High voltage Linear Source.
  - Water cooled Type MD.
  - Air-cooled Type MB.
  - (Floodlighting and Projection).

the following table which gives the generally used colour description to eight sections, making up the complete visible spectrum :—

Wavelength Range.		*Colour.*
Below 4,000 Å	..	Non-visible ultra-violet.
4,000-4,200 Å	..	Far violet.
4,200-4,400 Å	..	Violet.
4,400-4,600 Å	..	Blue.
4,600-5,100 Å	..	Blue-green.
5,100-5,600 Å	..	Green.
5,600-6,100 Å	..	Yellow.
6,100-6,600 Å	..	Light red.
6,600-7,200 Å	..	Dark red.
Above 7,200 Å	..	Non-visible infra-red.

Although a large number of gases and vapours have been examined with a view to determining their suitability as light sources, only a very limited number have, so far, found practical application. Of these, mercury appears to offer the greatest possibilities, and this article will be devoted mainly to a consideration of the trend of present developments in mercury discharge lamps.

Table I indicates the main lines of development which have been announced up to the present time and indicates stages in the production of the more advanced types of mercury vapour lamp.

It will be seen that from the simple discharge tube which may consist of a piece of glass tubing exhausted of most of its air and having pieces of wire hermetically sealed into its ends, and which glows when connected to the terminals of an induction coil, there has now been developed a range of electric discharge lamps which cover practically every lighting field. In each of these lamps there are certain common features of construction which are set out below.

A modern mercury vapour discharge lamp consists of a transparent vitreous envelope containing a small pressure of a rare gas together with a little mercury. Sealed into the envelope are electrodes of a type designed to operate at a high temperature and which freely emit electrons. These electrodes carry current into the lamp and are separated from each other by only a few millimetres in the case of certain types of lamp, while in others they may be several feet apart. In all cases they are connected to a source of electrical energy through a suitable current controlling device. Most types of mercury vapour lamp are designed to operate on alternating current circuits ; a few types are, however, specially designed for use on a direct current supply.

The properties of the 80, 125, 250 and 400 watt mercury vapour lamps are well-known. Developed, primarily, for street lighting they are designed to operate at high efficiencies and to have a long useful life. They have several interesting features such as the fact that they are self-igniting under the influence of the ordinary mains potential. A typical 400 watt mercury lamp, type MA, is shown in Fig. 2. Its operation is as follows :—

When the lamp is switched into circuit there occurs a rapid movement of electrons between the main electrodes of the lamp and the auxiliary or starting electrodes which are situated, in the form of a coil of wire, round these main electrodes and which are connected through a high resistance to the opposite main electrodes.

As the full mains voltage is impressed between the main electrodes and the starting electrodes over a gap of only two or three mms., the gas becomes conducting and an arc discharge then strikes up along the full length of the tube and takes the form of a soft hazy blue glow. Surprising though it may seem this glow discharge carries a current of between 5 and 6 amperes and the voltage drop across the tube is about 20 volts.

The heat developed by the passage of this relatively high current raises the temperature of the inner glass bulb and evaporates the small globule of mercury within the lamp. During this process the discharge becomes progressively brighter until all the mercury is evaporated. It is interesting to try to understand what is happening inside the lamp during the evaporation of this mercury and to examine the reason for the characteristic blue-green intense cord of light given by high pressure lamps when fully run-up.

When a gas or vapour is carrying a current the jostling together of the electrons and the atoms of the gas upsets the distribution of energy in some of the atoms. A simple analogy which serves to illustrate the point is to regard the atoms as rubber balls which are distorted by collision with other balls in rapid motion. They naturally try to return to their normal shape on the rebound. In the case of the gaseous atoms this return to normal shape or stability takes place in a series of definite jumps characteristically related to the particular atoms concerned. Each jump in the atom results in a pulse of energy which appears as radiation, some of which is visible to the eye as light and some of which may be in the ultra-violet region. The characteristic radiation from mercury at low pressure is rich in ultra-violet energy and also includes violet, yellow and green light in the visible spectrum. At higher pressures, however, the arc changes in appearance and becomes brighter and well-defined. A simple explanation of the phenomenon is as follows :—

In a rarified gas the atoms are widely separated from one another and thus can travel much further without collision than in a lamp where the pressure is much higher. The spread of the discharge or its diffuseness depends on the amount of travel of the gas atoms before they lose so much energy that they are no longer able to emit light. Thus, at the low pressure of argon when the lamp is first switched on, the atoms can travel long distances before they give out light and many of them lose their energy finally by hitting the walls of the bulb. For this reason, in the initial stages after switching on, the inner tube of the high-pressure lamp appears to be filled with a hazy blue glow, but when all the mercury is evaporated the atoms are packed together 150 times more closely and, therefore, any individual atom can only travel a short distance before it has collided many times and thus lost its energy. As a discharge naturally tries to take the shortest path between the electrodes, the energized atoms cannot stray far from this straight line without suffering a large number of collisions. It is for this reason that light is concentrated in a relatively narrow column between the electrodes when all the mercury has evaporated and the high-pressure condition has been attained.

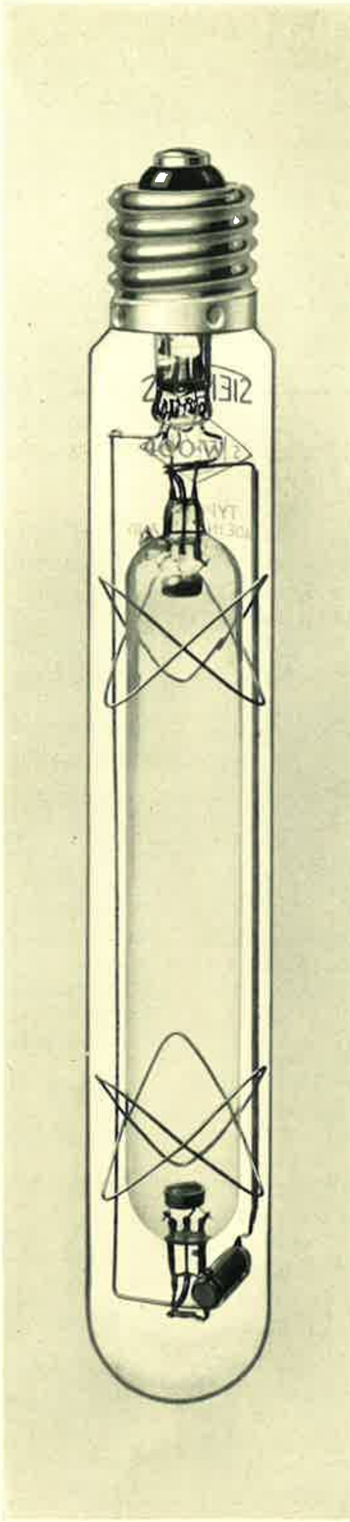

Fig. 2. 400 Watt "Sieray" Lamp, Type MA.

Two distinct types of lamp will now be described in order to illustrate the possibilities of mercury vapour as a source of light. In the first type the mercury operates at a very low pressure, while in the second the mercury vapour pressure may exceed 10 or even 20 atmospheres.

Low-Pressure Fluorescent Lamps

The fluorescence of certain chemical compounds is readily excited by ultra-violet radiation of short wavelength. Those compounds which are able to transform radiant energy of wavelengths less than 4,000 Å into visible light are particularly suitable for use with the glow discharge from mercury vapour at very low pressures because this glow, although of low luminosity, is particularly rich in ultra-violet radiation.

The fluorescent chemical compounds may be used in the form of finely divided powders which glow strongly when activated by ultra-violet light. They thus act as transformers of energy from the invisible region into those regions of the spectrum which produce visibility. A large number of different materials are now available which possess this remarkable property and which will produce distinctive colours varying with the chemical composition of the powder and to some extent with the treatment it has received during the course of its preparation.

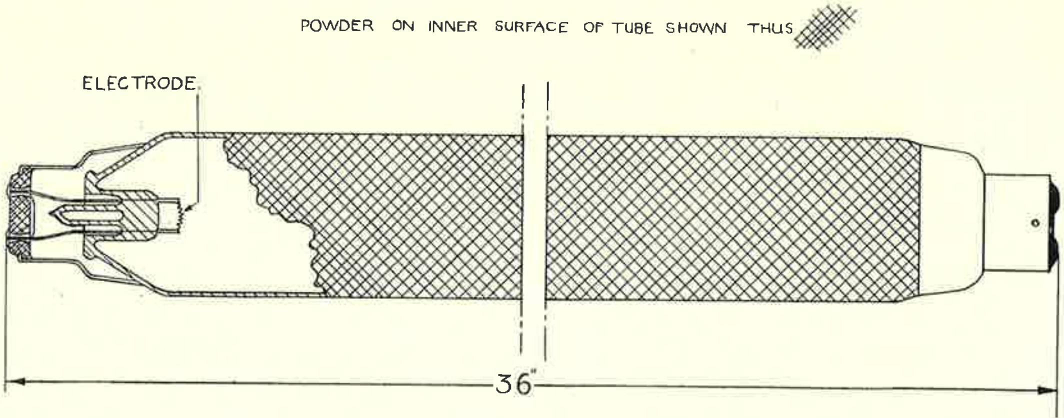

Fig. 3. Low-pressure Mercury Fluorescent Discharge Lamp, Type MC/F.

The fluorescent powder may be regarded as the filament of the lamp. Instead of being directly excited by the current, however, the powder acts in a secondary manner by utilizing energy which would normally be invisible to the eye and converts it into visible light.

The most efficient way of utilizing the radiation from the low-pressure mercury discharge is to allow the fluorescent powder to be in direct contact with the electrically excited mercury vapour. This may be done by coating with an appropriate powder the inside surface of a glass tube within which an electric discharge takes place in a mixture of rare gas and mercury vapour. A suitable arrangement is shown in the diagram, Fig. 3.

Since by using various fluorescent powders it is possible to produce a very wide range of colours, a suitable combination of powders yields white light at a high efficiency.

It is interesting to consider the operation of a low-pressure fluorescent lamp designed to produce white light. For a consumption of 25 watts the glass tubing, within which the discharge takes place, is about 36 ins. in length and about 1½ ins. in diameter. Into either end is sealed an electrode which is of light filamentary form and which has been impregnated with suitable emissive material. The inside surface of the glass tubing has been coated with a combination of powders which when suitably activated emit light in the form of a continuous spectrum.

The activating radiation consisting largely of a wave-length of 2,537 Å is produced by the excitation of mercury atoms under the stimulus of the electric discharge but very little luminosity is due to the mercury vapour discharge itself, the main light source being the glowing powder which transforms the ultra-violet radiation from the mercury into visible light.

It is possible to combine together on the surface of the tube fluorescent powders which separately would glow with blue/green, yellow and red light. Due to the very fine state of division of these powders and their intimate mixture the resultant effect resembles the illumination of daylight. Even on a very close inspection it is hardly possible to detect the distinctive colours of the individual particles. By combinations of suitable powders the light can be made warmer or colder while still preserving the characteristics of reasonable colour rendering essential in a general purpose illuminant.

Electrical Characteristics. These new lamps are not designed for direct connection to the mains, but must be operated in association with suitable control gear. This gear may be of various types but in all cases it involves means for starting the discharge as well as a current limiting device for regulating the wattage of the lamp. One simple arrangement which gives satisfactory results consists of a small choke in series with the lamp and an automatic switch connected across the lamp electrodes as shown in Fig. 4.

When the lamp is switched into circuit, with the automatic switch closed, current flows through the electrodes quickly raising them to an emitting temper-

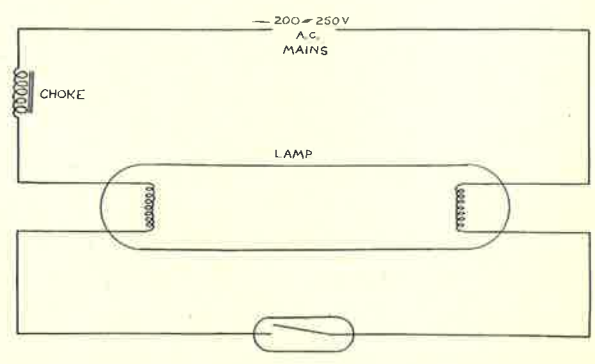

Fig. 4. Circuit for operation of Type MC/F Lamp.

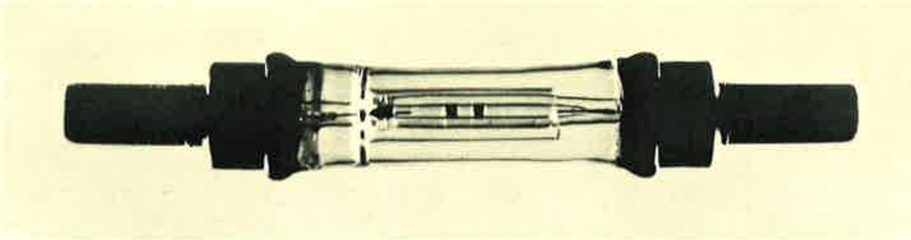

Fig. 5. 2,000 Watt Water-cooled Mercury Discharge Lamp, Type MD.

ature. The automatic switch then opens and by breaking the inductive circuit causes a voltage impulse to be impressed across the electrodes thereby striking the lamp. The switch is designed to remain open while the lamp is alight but will automatically re-close when the flow of current is interrupted.

PROPERTIES. Because of their high efficiency and excellent colour, low-pressure fluorescent lamps are destined to play an important part in lighting schemes in the future. The softly glowing bar of light presented by these lamps opens up a new field for lighting engineers— a field in which many of the difficulties of colour and glare are considerably reduced and where the light source itself, by virtue of its shape, is capable of being introduced into architectural features in a way not feasible with many types of filament lamp.

High-Brightness Mercury Vapour Lamps

The far-reaching changes which take place in the quality of the radiation from the mercury atom, when the mercury vapour pressure is increased, were appreciated many years ago. It is only recently, however, that practical types of mercury vapour lamps have been developed which utilize these changes to produce light sources of high brightness. As explained in the previous section, under low-pressure conditions the mercury discharge appears as a diffuse blue glow of low luminosity but rich in ultra-violet radiation and of an essentially discontinuous character.

It has now been found possible to construct lamps in which the concentration of mercury atoms is more than a million times as great as that obtaining in the previously described low-pressure mercury fluorescent lamp. At this greatly increased concentration the resultant radiation from the arc discharge has a character which approaches that of a solid incandescent radiator at a very high temperature. The characteristic spectral lines of mercury, greatly broadened, appear superimposed in a bright continuous spectrum which extends into both the ultra-violet and infra-red regions.

A study of the requisite conditions for the production of the high-pressure mercury arc has resulted in the development of two different lamp designs both of which are limited by the properties of available refractory materials.

In the first type the quartz tube in which the arc is developed is cooled in a transparent fluid and in the second type the quartz bulb, enclosing the arc space, is of such dimensions as will allow of its dissipating heat at a sufficient rate to keep its temperature below the safe maximum. In the first case the arc is conveniently of linear form while in the second it is feasible to produce both spherical and disc like arc forms.

FLUID - COOLED HIGH - BRIGHTNESS MERCURY DISCHARGE LAMPS. In this type the arc takes place between electrodes hermetically sealed into a quartz tube of capillary bore. In the 500 watt size the space between the electrodes is about 12 mms., and in the 1,000 watt size about 25 mms. Fluid-cooled lamps are usually of the high-voltage low current type. They may be operated from leakage transformers and, in general, the cooling fluid is mainly water. A typical lamp of 2,000 watts is shown in Fig. 5, from which the lamp proper and surrounding water jacket can be seen. The arc in this case is 50 mms. in length and about 1 mm. in diameter, and is of great brilliance.

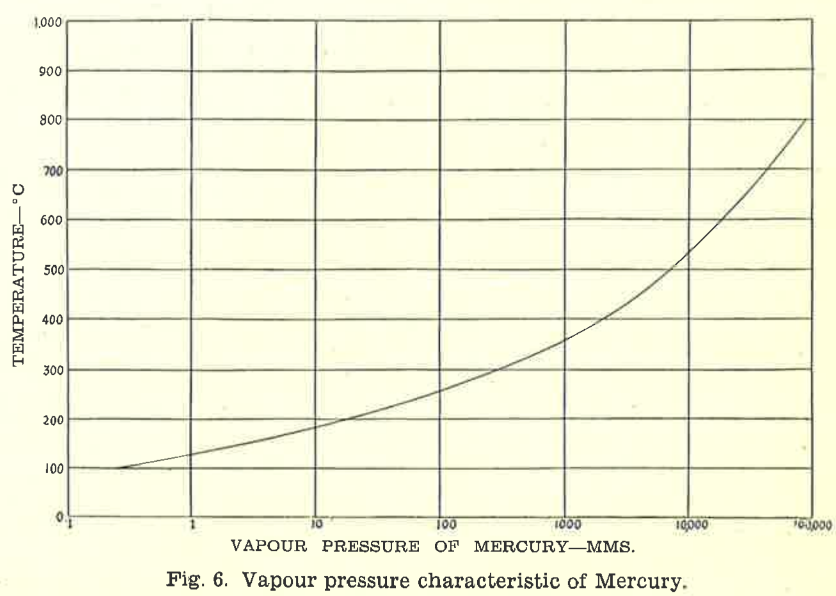

Fig. 6. Vapour pressure characteristic of Mercury.

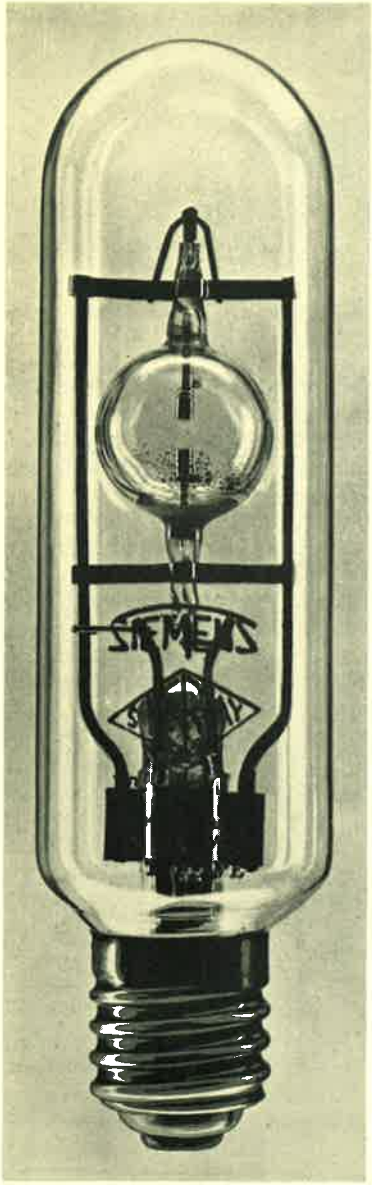

Fig. 7. 500 Watt "Sieray" Compact Source Lamp, Type ME.

Air-Cooled High-Brightness Lamps. For the development of a mercury vapour pressure greater than 10 atmospheres it is essential that the minimum temperature of the bulb containing the mercury shall be above 600° C. The temperature vapour pressure characteristic for mercury is given in Fig. 6, in which the ordinates are °C. and the abscissae are given in mms. of mercury.

It will be seen that a bulb designed to contain mercury vapour at high pressures must have a very considerable strength to resist the thermal and mechanical stresses to which it will be subjected. Quartz has been found to be a suitable material as it can be fabricated into transparent bulbs of considerable strength. The necessary bulb temperature to produce the requisite mercury vapour pressure is obtained by properly relating its dimensions to the watt dissipation of the arc which takes place within it. In order to keep the maximum bulb temperature as low as possible it is usual to design the bulb and the electrode system within it in such a way that the bulb contour is isothermal. Low temperature spots on the bulb must be avoided or otherwise for a given vapour pressure other parts of the bulb will be at a higher temperature than is conducive to the best performance.

Considerations such as the above have led to the production of high-pressure mercury vapour lamps in which the bulb is symmetrical about the axis through the electrode system and in which the arc takes place at a point somewhat below the mid point of the axis when the lamp is operated with its electrodes vertical. The design is shown in Fig. 7.

In such lamps the weight of mercury is suitably related to the bulb size so that when it is all evaporated the requisite vapour pressure is produced. Actually, the lamp is designed to give a somewhat higher temperature at the bulb walls than is required to evaporate all the mercury. In order to obtain a stable characteristic there is a limited region of temperature after the mercury has all evaporated over which it behaves approximately according to Charles Law.

Too high a temperature at the bulb walls is, however, undesirable as this might lead to devitrification of the quartz. An isothermal contour is, therefore, preferable. Symmetry of the bulb about the axis of the electrodes is also a desirable feature as, thereby, the powerful convection currents produced in the mercury vapour when the lamp is in operation produce the minimum disturbance of the arc.

It has been suggested that suitable deflecting shields should be fitted symmetrically around the electrodes to prevent these currents from deflecting the arc. These shields produce stability even when the arc length is many times its width. On the other hand, if the desired arc form is that of a practically spherical light ball then the electrodes must be brought nearer together and, generally, must be separated by a distance not greater than twice their diameter. It is found that under these conditions a stable arc can be produced without the use of deflecting shields.

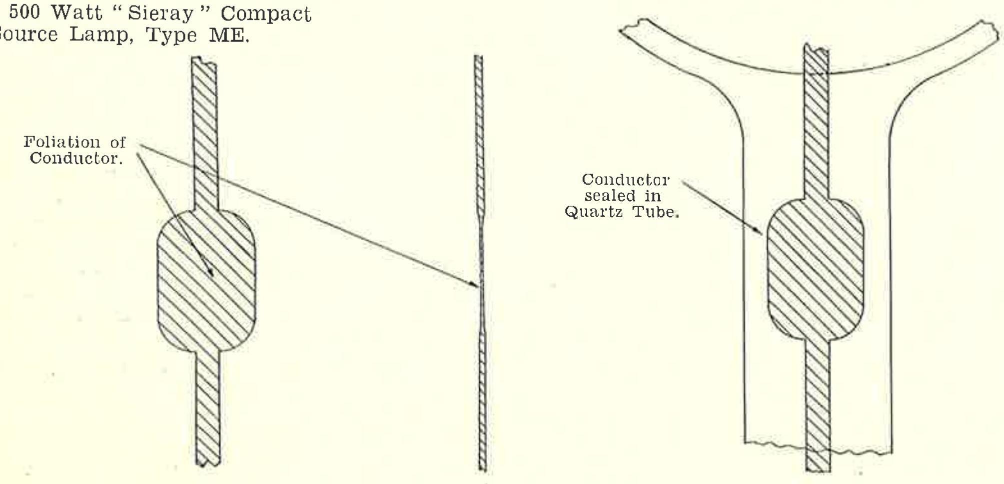

Fig. 8. Diagram showing production of Hermetic Seal through Quartz.

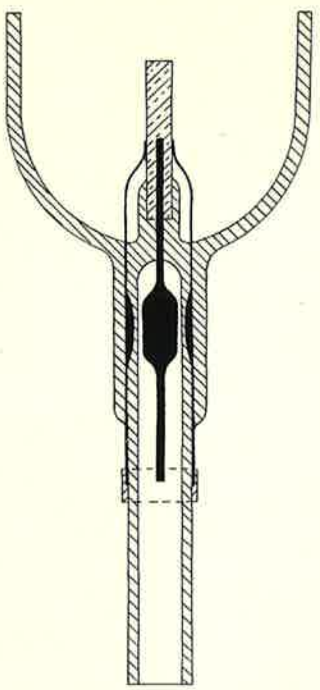

Fig. 9. Arrangement of High-current Multi-foil Hermetic Seal through Quartz.

The Electrode System for Air-Cooled High-Brightness Discharge Lamps. In the foregoing section reference has been made to the electrodes between which the arc takes place. These electrodes must have special characteristics and must be capable of withstanding the very high temperatures to which they are subjected, particularly at the cathode spot. Suitable materials are found among the refractory metals and it has been found that, in an atmosphere of mercury vapour at high pressures, tungsten can be operated as a cathode without suffering serious evaporation.

In the simplest form of high-pressure compact source lamp the arc then plays between solid tungsten electrodes which may be separated by perhaps 5 mms., although this distance may be varied over quite wide limits.

These electrodes must be electrically connected to sealing foils which are capable of forming vacuum tight joints with the quartz tube into which they are located. The development of satisfactory hermetic seals through quartz has necessarily been a pre-requisite of the development of high-pressure mercury vapour lamps. Particularly in the larger sizes of air-cooled high-brightness lamps, currents of the order of 50-100 amperes must be continuously carried by the leading-in wires of the lamps, and the development of satisfactory seals has only been accomplished after years of patient work.

A type of seal which has proved very satisfactory is produced by suitably working molybdenum wire to produce a foliated portion as shown in Fig. 8 (*a*), the cross section of this foliation is shown in Fig. 8 (*b*), and the appearance of a completed seal in Fig 8 (*c*). Seals so produced can be operated at temperatures of the order of 600°C and will remain vacuum tight. One such seal will carry 20 amperes continuously and for higher currents a number of seals may be combined together as shown in Fig. 9.

Properties of the Arc. Lamps of the type described in this section are designed for mains voltage operation and in this respect they are similar to the MA lamps already described. They may be operated in series with a choke coil and are self-igniting. That is to say, in general, they do not require any special starting circuit but an arc discharge is set up immediately the circuit is closed. This arc takes place in a low pressure of rare gas and brings about rapid incandescence of the electrodes. By this means the bulb, which contains a suitable quantity of mercury, quickly increases in temperature and thus the mercury is vaporized. After a period of perhaps 3 minutes equilibrium is reached and the arc plays between the tips of the adjacent electrodes, in a high pressure of mercury vapour the effect is shown in Fig. 10.

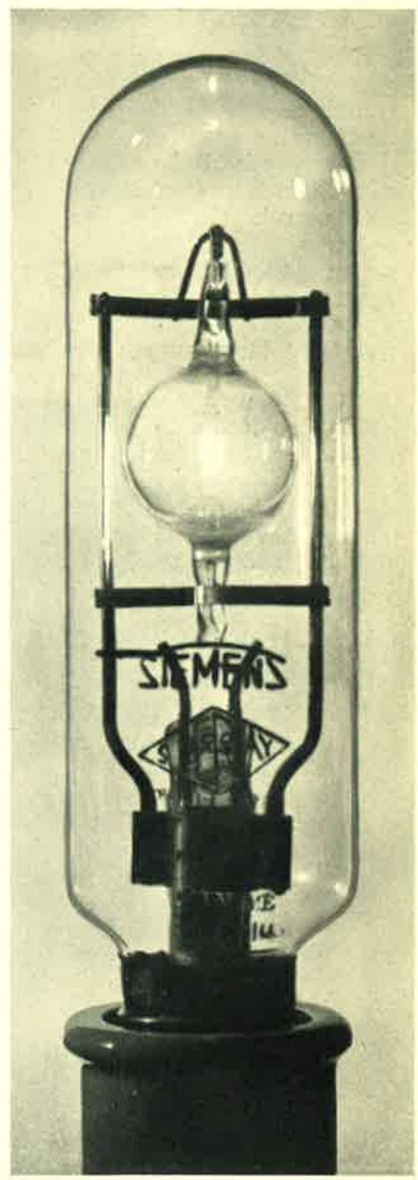

Fig. 10. 500 Watt "Sieray" Compact Lamp, Type ME, seen in operation through a dark screen.

It is interesting to speculate on the various processes which occur in lamps of this type during their operation. A study of the brightness distribution both in a line through the major axis of the arc and at right angles to it at a point midway between the electrodes, results in curves of the form shown in Fig. 11, which were taken on a 2,000 watt lamp with the electrodes spaced 5 mms. apart.

It will be seen that the points of highest brightness occur immediately adjacent to the electrodes, i.e., at the cathode spots. The brightness distribution curve taken at right angles to the axis of the arc indicates a peak value of 74,000 candles/sq.cm. in the central core of the discharge, with a gradually declining brightness on each side of this maximum. An enlarged photograph of the arc of this 2 k.w. lamp is shown in Fig. 12, on which some of the above brightness values have been indicated. It is apparent that the highest brightnesses are produced where the concentration of ions is likely to be highest.

An analysis of the colour of the light from these lamps also reveals that in the region of most intense ionization the light more nearly approximates to that of an incandescent radiator. In contrast with that from the mercury vapour discharge at low-pressures, the radiation is much richer in the blue and red regions of the spectrum, probably due to the extremely high temperature which obtains in the central core of the discharge.

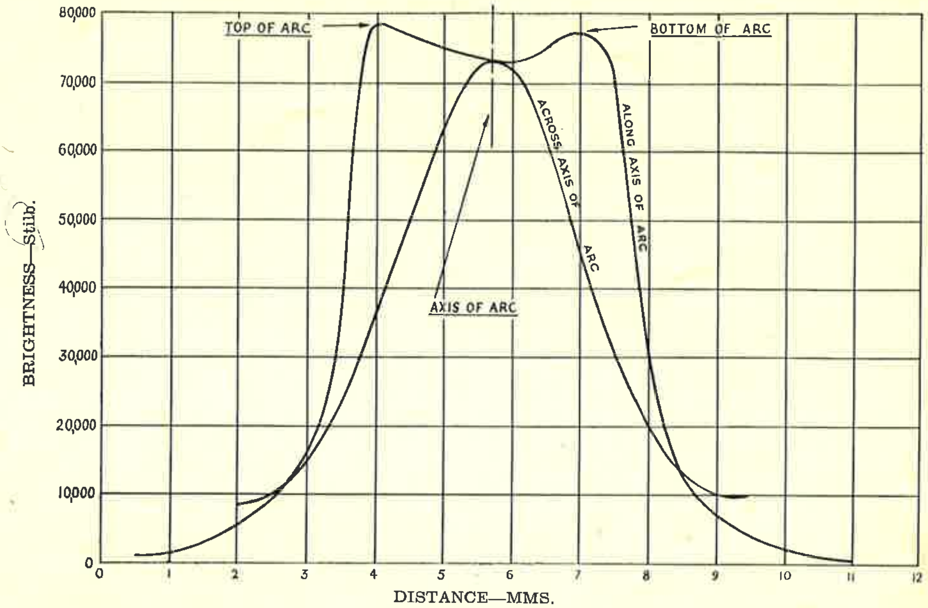

Fig. 11. Brightness distribution curves of Arc of 2,000 Watt Compact Source Lamp.

Due to the fact that a very large amount of energy is radiated from a very small area these lamps are eminently suitable for projection work, for searchlights and other purposes where a focussed beam is required.

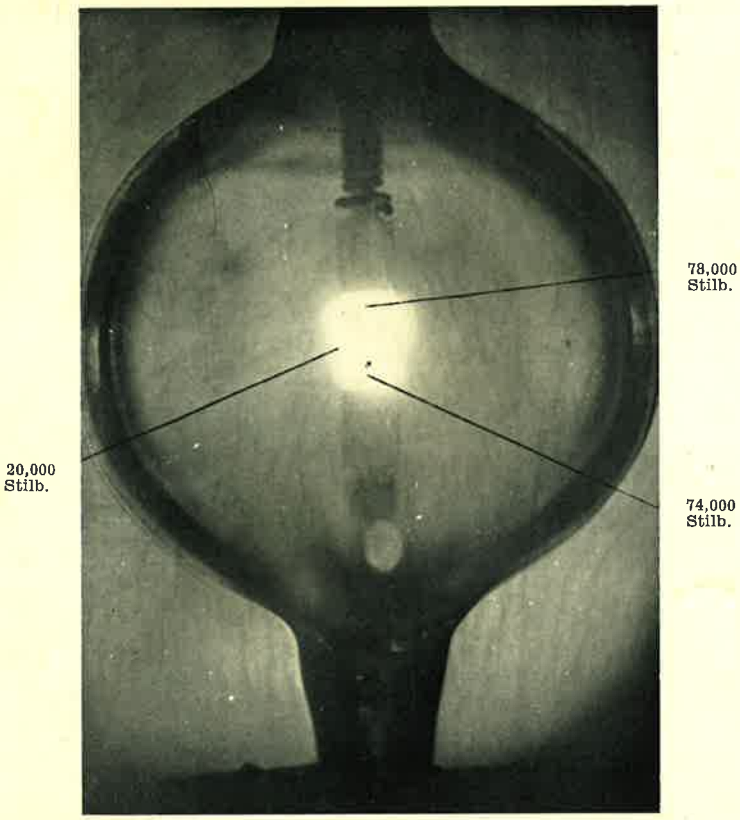

Fig. 12. Arc of 2,000 Watt Compact Source Lamp in operation.

Conclusion

Between the two extreme conditions of high and low mercury vapour pressures, examples of the utilization of which have been described above, there is a region of operating conditions in which lies all the remaining practical forms of mercury vapour discharge lamps. In some of these forms the mercury vapour discharge itself serves as the light source. In others its colour is modified by admixture with other metals or by fluorescent powders coated on an outer bulb surrounding the arc tube proper.

Each of these lamps has its special purpose and properties. Each is an example of the production of light by the electric discharge, and indicates the remarkable flexibility of electrically excited mercury vapour as a source of light.

Siemens Electric Lamps & Supplies Ltd., London.