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THE ELECTRIC DISCHARGE LAMP.

A SURVEY OF DEVELOPMENT.

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Park Street, St. Pancras, London, lighted by "Sieray" Lamps in Regent-Sieray Lanterns.

Introduction.

The production of light by means of the electrical discharge is still a source of wonder even to those whose association with it has rendered the phenomenon familiar. Unlike other methods of artificial light production where advances in technique may cause increases in efficiency of a few per cent only, the possibilities of more efficient light production by means of electric discharge lamps seem to have no such limitation.

Commercially available electric discharge lamps may be divided into three main classes :—

(1) Lamps employing rare gases or metallic vapours working at comparatively low pressures.
(2) Sodium lamps employing the electrically excited vapour of sodium as the light source.
(3) High-pressure mercury lamps in which the mercury vapour develops a pressure greater than one-half atmosphere when the lamp is in operation.

The purpose of this paper is to indicate some of the more recent developments in discharge lamps which may be included in the last of the three classes mentioned above.

Electric discharge lamps of the so-called high-pressure mercury vapour type have been available commercially for some three years. The 250 and 400-watt ratings have been applied to such widely divergent fields of use as street lighting, factory lighting, and flood-lighting. There can be no doubt that their introduction was an important step in the search for a more efficient light source. The efficiency of the standard mercury lamp is of the order of three times that of the gas-filled lamp of equivalent wattage, and there is already some evidence that this ratio may be increased for lamps of lower wattage. In subsequent references the term "standard high-pressure lamp" will be used to refer to the hard glass lamps already familiar to lighting engineers and which operate with internal pressures of one-half to one atmosphere. Actually, the term "high-pressure" applied to these lamps is a misnomer, as quite recently lamps employing mercury vapour pressures of 100 atmospheres or more have been developed. In general, where the mercury vapour pressure exceeds about 30 atmospheres the lamps are artificially cooled and will be referred to as "super high-pressure lamps," although any such distinction is arbitrary, as the point at which high pressure merges into super high pressure is not capable of accurate definition.

The Mercury Discharge Lamp—General Considerations.

The standard high-pressure mercury discharge lamp and its characteristics have been described elswhere.* An addition to the watt ratings of these lamps has recently been made by the introduction of a 150-watt lamp of essentially the same construction and characteristics as the 250 and 400-watt lamps. In general, these lamps are so designed that in the fully run-up condition the arc voltage has an optimum value which is a function of the mains voltage. Lamps designed for a given mains voltage have the same arc voltage while the current is controlled to give the designed watts. At the same time account must be taken of the temperature at which it is allowable to operate the hard glass tube in which the arc takes place. Too low a temperature on the surface of this tube tends to produce an unstable characteristic; too high a temperature may seriously affect the performance of the lamp during life.

Bearing the above facts in mind it will be seen that the lamp current of a 150-watt lamp will only be ⅜ of the current of a 400-watt lamp and it is found that this reduction in current for lamps of the same essential type has an influence on the initial efficiency. Fig. 1. shows the relation between initial efficiency and lamp wattage for standard high-pressure lamps.

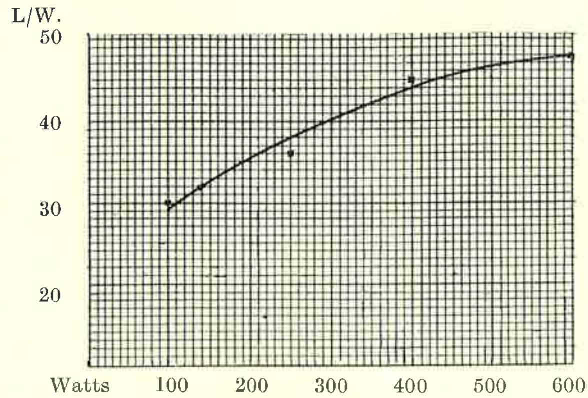


Fig. 1.

It will be seen that whereas at 150 watts an efficiency of 32 lumens per watt can be obtained, in the case of the 400-watt lamp the efficiency is 45 lumens per watt. In this connection it is interesting to remember that unlike the incandescent filament lamp, the discharge lamp does not automatically operate at its rated wattage. Due to the negative resistance characteristic of the arc, the current must be controlled by means of an impedance so that the lamp, when fully run up, operates at its designed rating. If a standard high-pressure lamp is operated in such a way that its designed wattage is seriously exceeded, then among the effects which may be expected will be a more rapid falling-off in the efficiency of the lamp through life and a greater possibility of premature failure. The relation of the wattage of a discharge tube to its volume determines the temperature at which the walls of the discharge tube operate. The loading of discharge lamps may, therefore, be described in terms of watts dissipation per unit volume of the tube in which the discharge takes place. It has been found that with the types of glass which are at present available for constructing the inner tubes of standard high-pressure lamps a loading of some 3.0 watts per cubic centimetre gives a high value of efficiency maintenance through life. Typical efficiency maintenance curves for 400-watt, 250-watt, and 150-watt lamps are given in Fig. 2.

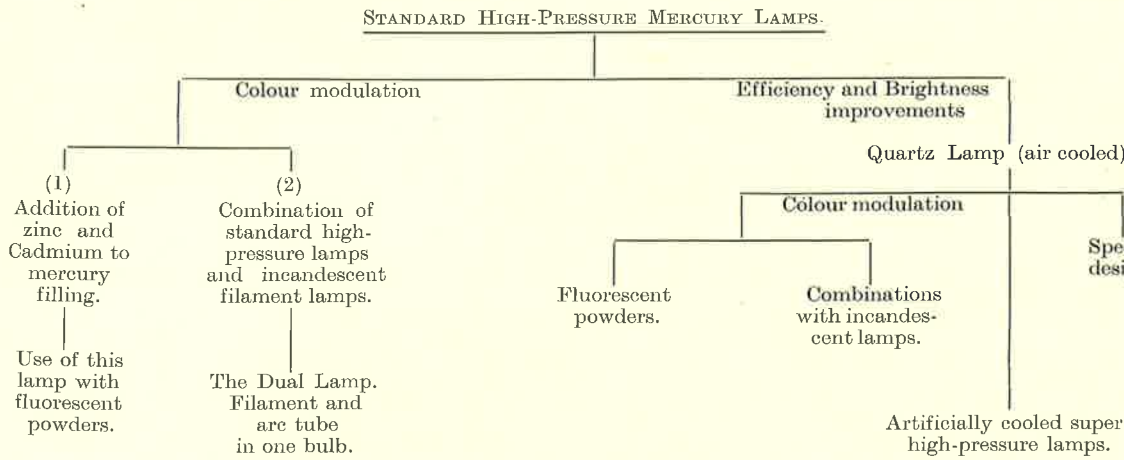
These curves indicate that the average efficiency maintenance of standard high-pressure lamps up to 1,500 hours life varies between 82 per cent and 86 per cent of the initial efficiency for the different wattages. Attempts to increase the initial efficiency by increasing the loading of the discharge tube in watts per cubic

Electric Discharge Lamps and their Application to Public Lighting. Association of Public Lighting Engineers, September, 1933. G. H. Wilson.

Electric Discharge Lamps. Journal of the Royal Society of Arts. Vol. 82. J. W. Ryde.

Electric Discharge Lamps and their Application to Road Lighting. L. J. Davies and H. Warren. Institution of Automobile Engineers December, 1934.

High-Pressure Mercury Vapour Lamps in Public Lighting. G. H. Wilson, E. L. Damant, J. M. Waldron. Institute of Electrical Engineers. February, 1936.



centimetre result in a greater slope of the lumen maintenance curve. For example, the effect of overloading a 250-watt lamp to 400 watts, *i.e.*, working at a watt loading of nearly 4.3 watts per cubic centimetre, results in a higher initial efficiency, but a greater fall through life, as shown in the dotted line in Fig. 2. It will be seen that in this overloaded condition the initial efficiency is of the same order as that of the standard 400-watt lamp, but the average efficiency over life is less by some 4 or 5 lumens per watt. The major portion of this loss of light output over life must be attributed to discoloration and deposits on the hard glass tube which encloses the mercury arc. Although, therefore, it has been known for some years

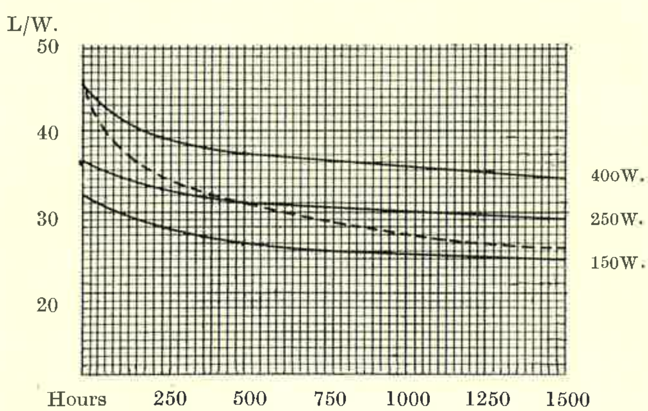


Fig. 2.

that lower wattage mercury discharge lamps could be made to operate at similar initial efficiencies to that of the 400-watt lamp by using higher loadings, considerations of the shape of the efficiency maintenance curve rendered it inexpedient to do this with the hard glass lamp.

Having now briefly outlined some of the characteristics of the standard high-pressure mercury lamp, it is proposed to discuss more recent developments and to show how these have followed a logical sequence which is indicated by the scheme set out above.

It is obvious that different investigators will tend to emphasize certain directions of development more than others. In the present paper each of these main trends will be separately indicated and an attempt made to assess the relative merits of the various classes.

Colour Modulated High-Pressure Discharge Lamps.

(1) By use of mercury, cadmium and zinc. The use of a mixture of metallic vapours in the discharge tube of the hard glass lamp enables the excitation of the spectra of each of the metals provided that the following principles are observed.:—

(*a*) The minimum temperature in the discharge is sufficient to produce an appreciable vapour pressure from each of the constituents.

(*b*) The metals are sufficiently similar as to allow of their atoms being excited in the presence of each other.

Condition (*a*) may be taken care of by a suitable design for the inner tube of the lamp and by taking care to position the electrodes correctly. Condition (*b*) is fulfilled in the case of mercury, cadmium and zinc, which have been used for some two years in the "colour modified" 400-watt commercial discharge lamps.

The spectrograms below show the visible light radiation from a standard 400-watt mercury lamp,

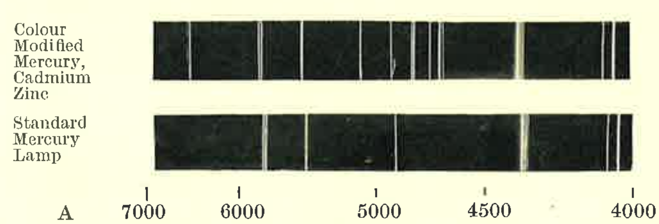


Fig. 3. Spectrograms of Visible Radiation from 400-watt Discharge Lamps.

and also that from a standard 400-watt colour modified lamp.

It will be seen that the cadmium and zinc introduce both blue and red light into the spectrum in which colours the mercury lamp is deficient. It has been found that for an initial efficiency of 37 lumens per watt the amount of red light which can be introduced in this way is 2.3 per cent on a scale in which daylight has 15 per cent of red. The colour modified lamp gives better colour rendering of objects than the plain mercury lamp, but some sacrifice in initial efficiency is entailed.

Several patents have been taken out in this country dealing with the use of lamps of the colour modified type with fluorescent powders. These powders enable a useful addition of red light to be made to the spectrum. As the subject of fluorescence will be treated later in the paper, no further reference will be made to it here.

(2) **Combinations of Incandescent Lamps and Discharge Lamps.** The fact that in many respects the light from an incandescent filament lamp is complementary to that of the mercury discharge lamp enables them to be combined with very satisfactory results. The overall efficiency depends on the distribution of wattage between the two types. In general, the overall efficiency for the usual watt distribution lies between 20 lumens per watt and 30 lumens per watt and the percentage of red light lies between 5 per cent. and 10 per cent. of the total light on a scale on which daylight has 15 per cent. of red.

These combinations may be of two distinct types, (1) those in which high-pressure mercury lamps operating on their usual circuits, *i.e.*, with choke or leak transformer control, are combined in the same fitting, or in separate fittings with incandescent filament lamps, the main object being to modify the colour of the resultant total radiation, (2) combinations in which, besides fulfilling the function described in (1) above, the incandescent tungsten filament also serves as a stabilising resistance in the discharge tube circuit. Special fittings designed to take a mercury high-pressure discharge lamp and one or more incandescent filament lamps are now in use in many places and the method was described before the Association of Public Lighting Engineers in a paper by G. H. Wilson, September 6th, 1933. The circuit arrangement was that described in (1) above.

Combined units of either of the main types mentioned above are very suitable for use in situations where the colour distortion, caused by the use of the plain mercury lamp, is undesirable. With the advent of the Dual lamp, which was developed in the laboratories of the Siemens Lamp Works, Preston, the necessity for using the combination mentioned in (1) above has been obviated. The Dual lamp produces a light of pleasing colour and does not require a choke coil or auxiliary gear. A full description of this lamp has been given elsewhere,* but for the sake of completeness it may be mentioned that this lamp is a combination of a gaseous discharge tube of the standard high-pressure colour modified type, mounted in an outer envelope which contains argon. In the enlarged spherical end of the outer envelope is mounted a 500-watt tungsten filament which is connected in series with the discharge tube. When the lamp is first switched into circuit, the filament dissipates most of the energy, but after about 10 minutes when the discharge tube has reached its designed voltage, the thermal switch inside the lamp closes and shorts out a portion of the tungsten filament equivalent to the arc tube voltage. The Dual lamp then operates in its normal condition and has an efficiency of 25 lumens per watt and gives approximately $7\frac{1}{2}$ per cent. of red light which has been found quite suitable for most ordinary lighting purposes.

Improvement in the Efficiency and Brightness of Mercury Discharge Lamps.

In order to take advantage of the known increase in efficiency which could be obtained by operating mercury lamps at higher vapour pressures than those used in the standard lamps, it was necessary to use some material other than hard glass for the containing vessel. Fused silica or quartz has many of the required properties for such use and in certain respects is superior to hard glass for enclosing a mercury arc discharge.

The main difficulty which had to be overcome before high-pressure mercury discharge lamps in quartz could be satisfactorily developed was bound up with the production of an hermetic seal for the current leads. Methods of producing vacuum seals between metallic conductors and quartz have been known for at least 25 years. Most of these methods depend on producing the seal by running into a cavity between the electrode lead and the quartz tube a metal such as mercury or lead which could be made to adhere closely to a clean surface of fused quartz. The lead seal was put into extensive use in 1913. Although such methods of producing vacuum tight joints between metallic conductors and quartz are perfectly satisfactory for a large variety of uses, they can hardly be regarded as suitable for the leads of high-pressure mercury discharge lamps, where very severe temperature gradients occur at the junction between the metallic conductor and the quartz. This very real problem of producing a seal similar to that between platinum and soft glass has now been overcome in a variety of ways. One of these methods consists in interposing between the metallic conductor and the quartz tube a number of intermediate seal glasses having co-efficients of expansion graded between that of the metal and the

**Some Recent Developments in the Electric Lamp.* Belfast Association of Engineers. 5th February, 1936. J. N. Aldington.

Some Further Aspects of the Electrical Discharge in Gases and Vapours. Engineering Supplement to the Siemens Magazine, No. 131. April, 1936. J. N. Aldington.

quartz. Such graded seals have found some limited use, but they are too cumbersome for many purposes.

In 1935 the Phillips Lamp Company announced the successful development of a single seal glass which would join to quartz and also to thin tungsten wires. Using this sealing glass, the Phillips Company developed high-intensity hot cathode discharge lamps which were artificially cooled and with which they claimed that extremely high light intensities could be obtained.

Meanwhile, investigation into the problem of producing hermetic seals with quartz suitable for low-wattage lamps had been proceeding in the laboratories of the leading British, European, and American lamp factories. During the autumn of 1935, the molybdenum foil seal was first used in this country by the British Thomson-Houston Company who, by its use, were enabled to make successful vacuum tight lead-in connections through quartz without the use of intermediate glasses. During the spring of 1936 a method was developed by the Siemens Works, Preston, which enabled thin wires of molybdenum, which had been locally flattened, to be sealed directly into quartz and so obviated the necessity for spot welding the separate pieces of molybdenum foil in the electrode leads.

These developments have opened the way for rapid progress in the production of quartz lamps which can be operated over life at higher efficiencies than lamps of similar wattage constructed in the available hard glasses. Some of these developments will now be described.

Air-Cooled Quartz Discharge Lamps.

The use of quartz for constructing discharge lamps enables higher temperatures to be obtained without the risk of fracturing the containing vessel. Due also to the chemical simplicity of quartz, it is more resistant to the attack of metal vapours at high temperatures than many of the hitherto used glasses. Experience has shown that it is also less liable to electrolytic decomposition under the electrical stresses which are produced in mercury discharge lamps at high pressures. Having these facts in mind, it is obvious that once the difficulty of producing a reliable vacuum tight seal with metallic conductors had been overcome, the way was open for the production of mercury discharge lamps which could be operated at higher loadings per cubic centimetre than were possible hitherto. Experiment has shown that, providing quartz tubes are kept clean, they can be operated at temperatures below 1,000° C. without suffering any material devitrification or damage. The most obvious way thus became that of reducing the dimensions of mercury discharge lamps for a given wattage to the lowest possible value consistent with the quartz tube operating at a temperature of not greater than 1,000° C. Considerations such as the foregoing indicated that a quartz lamp mounted in an exhausted envelope would operate at a loading about 20 times that possible with a hard glass lamp of the same wattage. The effect of increasing the loading from about 3 watts per cubic centimetre to 60 watts per cubic centimetre for the quartz lamp is to increase the initial efficiency from some 32 lumens per watt to about 40 to 50 lumens per watt, assuming the lamp wattage in each case to be of the order of 100 to 150 watts. This is an increase of some 30 per cent. in efficiency. It is thus evident that the successful development of lamps operating in quartz tubes will give a new weapon to the lighting engineer in his constant fight for better lighting conditions.

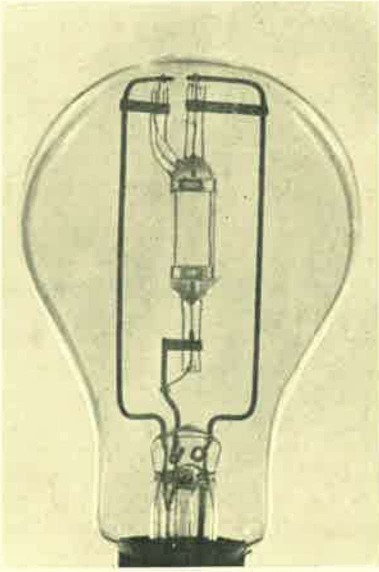
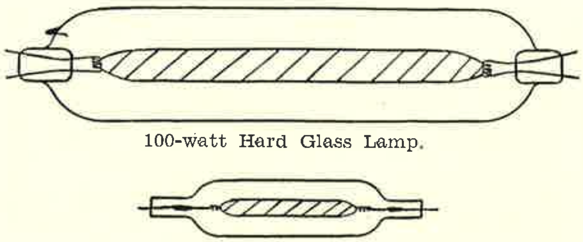


Fig. 4.

Fig. 4. is a photograph of a mercury vapour discharge lamp designed for 100 watts and capable of being operated from the ordinary supply mains. This lamp is of an experimental type and the discharge tube is constructed entirely from quartz without the use of any intermediate seal glasses. The electrode seals are constructed from locally flattened molybdenum wire and terminate in activated electrodes which can be seen at each end of the quartz tube. Immediately in front of each electrode is a constriction in the quartz tube which serves to confine electrode splutter to a limited portion of the tube. The third electrode sealed into the quartz tube in proximity to the main electrodes is connected via a resistance situated in the lamp cap in such a way as to produce the full mains potential between its end and the adjacent main electrode. The use of such starting electrodes for producing preliminary ionization and low voltage starting has now become familiar in the standard 250 and 400-watt mercury discharge lamps. The small amount of mercury which is required in quartz lamps of the type shown in Fig. 4. can be seen from the two globules deposited about the centre of the quartz tube. The actual size of such a quartz lamp can be realised when is it stated that the lamp bulb in which the quartz tube is mounted is of the ordinary 100-watt dimensions.

In Fig. 5. the relative dimensions of the quartz discharge tube are compared with that of a similar wattage lamp constructed in hard glass. The dimensions are as follows :—

		Hard Glass Lamp.	*Quartz Lamp.*
Arc length	..	70 mms.	25 mms.
Tube width	..	20 mms.	10 mms.



100-watt Hard Glass Lamp.

100-watt Quartz Lamp.

Fig. 5.

This reduction in the size of the quartz lamp compared with the hard glass lamp decreases the thermal capacity and enables the lamp to reach full brightness in a much shorter time than is possible with the lamp constructed of hard glass. By switching on two 100-watt mercury dischargelamps, one constructed in quartz and one in hard glass, it is possible to see the difference in operating characteristics and the general differences in the shape, size, and brightness of the light sources. The light output from the quartz lamp is of the order of 4,000 lumens, whereas that from the hard glass lamp is of the order of 3,000 lumens. It isprobable that the efficiency maintenance of these lamps over life will be of a similar order.

Effect of Pressure on the Characteristics of the Mercury Discharge Lamp.

One of the salient differences between the discharge in the hard glass lamp and that of the quartz lamp is the physical dimensions of the light column itself. In the hard glass lamp the pressure of mercury vapour is of the order of one atmosphere, whereas in the 100-watt quartz lamp the pressure is probably of the order of five atmospheres. The effect of this increased pressure is to cause (*a*) an increase in the volt drop per unit length of the arc column, and (*b*) a decrease in the width of the arc column. Approximate dimensions of these two arc columns are shown in Fig. 5. As the area of the light column of the quartz lamp is only one-fifth of that of the hard glass lamp and, at the same time, it has a light output of 4,000 lumens against 3,000 lumens for the hard glass lamp, the relative brightness of the two sources is in the ratio of nearly 7 to 1. One of the main differences, therefore, consequent on the higher temperatures and vapour pressures, which have been made possible by the development of the quartz lamp, is the increase in the brightness of the light source, which in the 100-watt quartz lamp described above is of the order of 500 to 600 candles per square centimetre. It is possible by still further increasing the vapour pressure inside the mercury discharge lamp to develop intensities as high as thirty or forty thousand candles per square centimetre. Further reference will be made to these super high-pressure lamps later in the paper.

Though, perhaps not so easily demonstrable, the changes which occur in the spectrum of the radiation emitted by mercury vapour at higher pressures are both interesting and significent from the lamp development point of view. The discontinuous nature of the radiation produced by an electrically excited gas at low pressure is bound up with the nature of the atom itself. In the case of mercury vapour, a high percentage of the total energy absorbed by the vapour during the passage of an electric current is emitted at wavelengths below those to which the eye can respond, some small proportion of the energy being in the visible spectrum. This state of affairs is entirely opposite to that which obtains in the case of an incandescent radiator whose spectrum is of a continuous nature, extending from the near ultra-violet through the visible spectrum and which emits its greatest energy in the infra-red at wavelengths greater than those which the eye can perceive. Also, in the case of the tungsten filament operating in an inert gas, efficiencies in lamps of the highest wattage as high as 25 lumens per watt are commercially obtained. The efficiency of the medium wattage types more generally used is of the order of 15 lumens per watt which corresponds with the highest temperature at which tungsten can be operated to give an economic life to the lamp. There does not appear to be much hope of the conversion of the large amount of infra-red energy, emitted by a tungsten filament lamp, into visible light and so increasing the efficiency. In the case of the spectra of gases and metallic vapours, however, methods have already been tentatively explored whereby some at least of the ultra-violet radiation can be converted effectively into light of higher wavelengths, with beneficial effects both on efficiency and colour.

It is helpful in this connection to study the spectrograms of discharges through mercury vapour at one or two different pressures. These are shown in Fig. 6.

It may be seen from the spectrum of mercury at a pressure less than one atmosphere that in the visible spectrum, which we may regard as being from 4,000 to 7,000 angstrom units, there are only four main wavelengths at which light is emitted, while in the ultra-violet portion of the spectrum, from 4,000 to 2,000 angstrom units, there are a large number of main lines. At a higher pressure of the order of 4 to 5 atmospheres many of the lines present in the lower pressure spectrum have been broadened and the radiation has a tendency to become of a continuous nature with intensity peaks at wavelengths previously occupied by sharp spectral lines. At still higher pressures, of the order of 200 atmospheres, the development of this continuous radiation becomes of extreme significance and probably owes its origin to the extremely high temperatures which are developed in the central

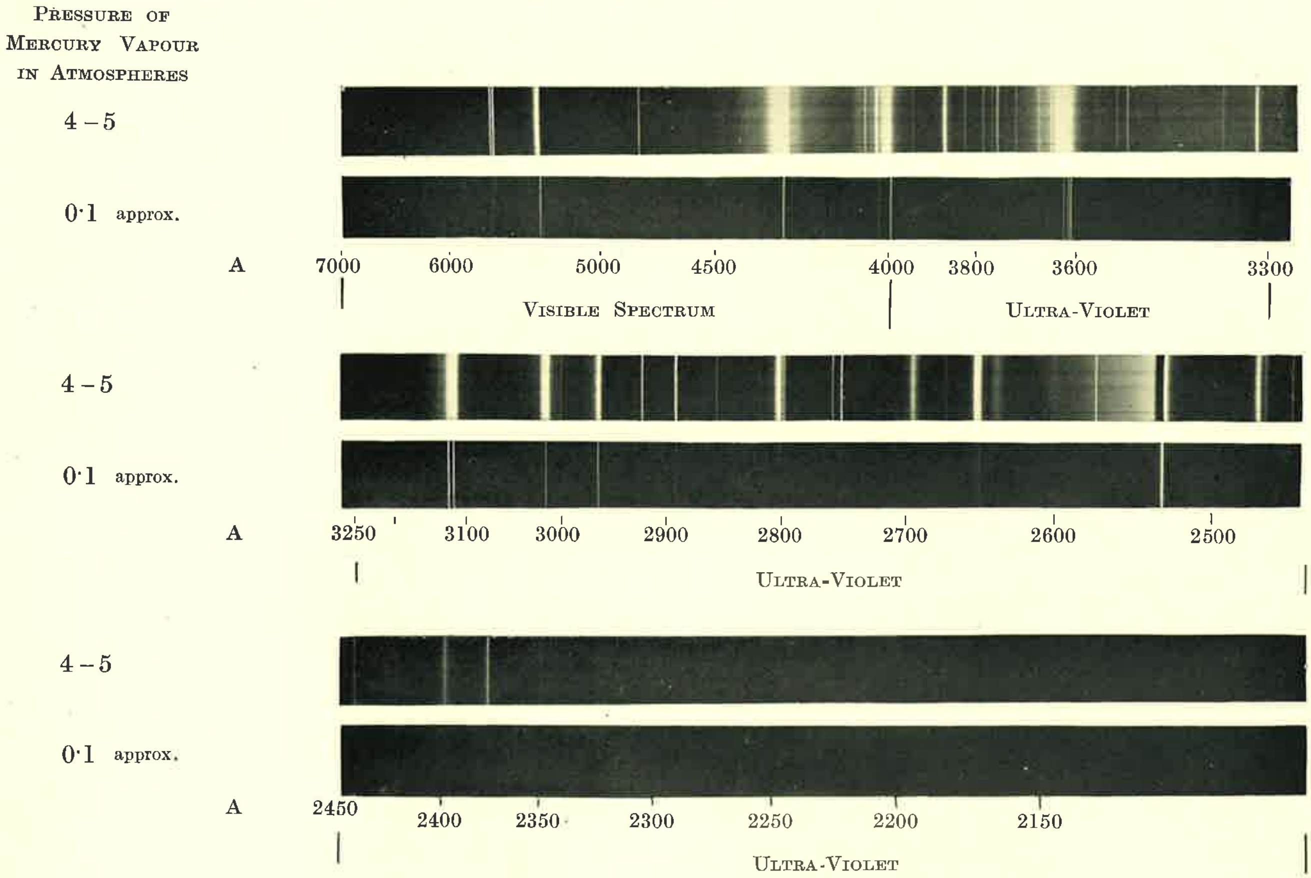


Fig. 6. Spectrograms of the Mercury Vapour Discharge at Various Pressures in Quartz Tube Lamps.

core of the discharge ; temperatures which have been stated to be of the order of 8,000° C.

An examination of the spectrogram of the high-pressure mercury lamp shown in Fig. 6. also shows that at a wavelength of about 2,537 angstrom units energy is being absorbed and re-emitted at other wavelengths. It may well be that with increased understanding of the processes which are occurring to produce such effects, means will be developed which can utilise them to a greater extent than is now possible and that the re-emission of energy may be brought about in the region of the visible spectrum. Such developments would result not only in a high effeciency, but also in a nearer approach to the lamp ideal of a continuous radiation whose spectrum reproduces that of daylight.

It may be shown that at the higher pressures of mercury vapour the position of maximum energy of the radiation moves in the direction of increasing wavelength. This has the effect of causing the high-pressure mercury discharge lamp to be redder than the low pressure lamp. This interesting effect is well brought out by the differences in colour between the blue mercury flood-lighting tube or low pressure tube used for sign work, and the yellowish-green colour of the mercury 400-watt street lighting lamp. This movement of the energy maximum towards the red end of the spectrum means that the colour of the higher pressure mercury discharge lamp in quartz will be nearer to that of daylight than its forerunner, the standard high-pressure mercury discharge lamp of the well-known form. With the pressure at which the small quartz lamps may be usefully worked, this increase in red radiation is still not very significant ; it is, however, important to us to realise that the tendency is in a helpful direction. One of the most important differences between the quartz mercury discharge lamp and the hard glass lamp is the very significant amount of energy in the ultra-violet which is transmitted by the quartz. One of the ways in which this energy may be utilised advantageously in the design of low-wattage discharge lamps will now be described.

Colour Modulation by Means of Fluourescent Substances.

E. C. C. Baly, in his book, " Spectroscopy," makes the following statement : " It is a well-known fact that many substances when submitted to the influence of light or cathode rays develop the power of emitting luminescence in the visible or ultra-violet region of the spectrum which has no connection with ordinary thermal radiation. This luminescence is observed with substances in each of the three states of gas, liquid, and solid, and in general the wavelengths of the luminescence are characteristic of the chemical composition of the excited material." Of the many substances which have been used in connection with mercury discharge lamps, the dye stuff Rhodamine is perhaps historically one of the earliest. Rhodamine has the useful property of converting some of the light from the mercury discharge lamp into light of a longer wavelength, in other words, in the orange-red portion of the spectrum. The phenomenon by which this conversion is brought about is called fluorescence. Fluorescent substances have the property of converting some of the radiation which they absorb into radiation of another wavelength, generally of lower frequency. For example, the dye stuff Rhodamine absorbs yellow-green light and emits the absorbed energy as orange-red light. The effect of a reflector coated with a suitable Rhodamine varnish is shown by projecting light from a mercury lamp by means of a reflector coated with Rhodamine on to a number of coloured objects. A similar reflector and mercury lamp without Rhodamine varnish produces an entirely different series of colours. Unfortunately, the energy which is absorbed by Rhodamine to produce such an apparently useful result lies wholly in the visible spectrum. Although the colour correction is good, from an energy point of view the overall efficiency of a lamp working in a fitting coated with Rhodamine varnish is very considerably reduced. A further difficulty deterring the practical utilisation of such organic fluorescent reflector coatings is due to the fact that Rhodamine itself is slowly decomposed under the action of ultra-violet radiation so that the efficient life of a Rhodamine coating is relatively short. Many mineral substances, however, have the property of fluorescence to a marked degree, and under suitable conditions may have a very long life.

The application of substances such as Barium Sulphide, Cadmium Zinc Sulphide, etc., to the bulbs which surround the high-pressure mercury lamp and to transparent panels in the fitting associated with such lamps is being studied by various laboratories. It would appear that material benefit will eventually result from the use of these powders in conjunction with mercury lamps, once certain practical difficulties have been overcome. A preferred method of utilising mineral powders which have the property of converting the near ultra-violet radiation into orange or red light is to surround the mercury lamp with a bulb on the inside surface of which powders have been attached by one of the well-known methods. When a mercury lamp is surrounded by a bulb on which is placed only a very thin coating, the effect with a suitable powder is to produce an increase in the total amount of light emitted by the lamp and, at the same time, to somewhat increase the percentage of red radiation. Further increases in the amount of powder produce similar effects to a less degree and a point can be reached at which an effective amount of light at the red end of the spectrum can be added without reducing the initial efficiency of the light source below that of the bare lamp. With very thick coatings of powder the efficiency of the light source is reduced, but the colour is still further improved.

It is not possible, by looking at a light source surrounded by one of these treated bulbs, to visualise exactly what the powder is contributing to the light. The contribution of the powder can, however, be shown by subjecting glass screens, suitably coated with fluorescent powders, to the light from a mercury lamp from which the visible radiation has been cut off by a suitable filter which allows only ultra-violet radiation to pass. It can be seen that there are powders available which give a large amount of light in a variety of spectral hues. Providing that the powders are of such a nature that they respond to the ultra-violet radiation from the mercury lamps and at the same time do not cut off any serious amount of visible light, they may be employed not only for colour modulation, but also specifically for increasing the efficiency of the light source.

A study of the ultra-violet spectrum from a high-pressure lamp operating in a quartz tube shows very clearly what a large percentage of the total energy is emitted below the lowest wavelength to which the human eye can respond. Available fluorescent materials enable the utilisation of some proportion of this energy particularly that of wavelengths between 2,900 and 4,000 angstrom units which is the threshold of the visible region. The energy in the more remote regions of the ultra-violet still requires harnessing to render it available as visible light. It may, therefore, be said that one of the significant directions along which progress is possible is that of the development of more efficient fluorescent materials responsive to ultra-violet at least down to a wavelength of 2,000 angstrom units.

Combinations of Quartz Lamps and Incandescent Lamps.

The development of low-wattage high-pressure mercury discharge lamps operating in quartz tubes has rendered possible the production of combinations of incandescent filament lamps and discharge tubes which do not require auxiliary gear and are of relatively simple construction. For example, owing to the very short time which the small mercury lamp requires to reach its operating pressure, it is possible to operate it in series with an incandescent tungsten filament lamp either in the same bulb or in a separate bulb. The rating of the filament and tube are such that a reasonable amount of red light can be added while the initial over-loading of the filament is of very short duration. In Fig. 7 is shown a photograph of one of these experimental combination lamps. It will be noted that the filament surrounds the discharge tube and advantage is taken in the design of thermal inter-actions between the filament and the arc. In the initial stages of the run-up where the filament is dissipating the greater proportion of the energy, the arc tube benefits by proximity to the heat source and is enabled to reach its full brightness more quickly. When this stage is reached, the thermal emission from the arc has the

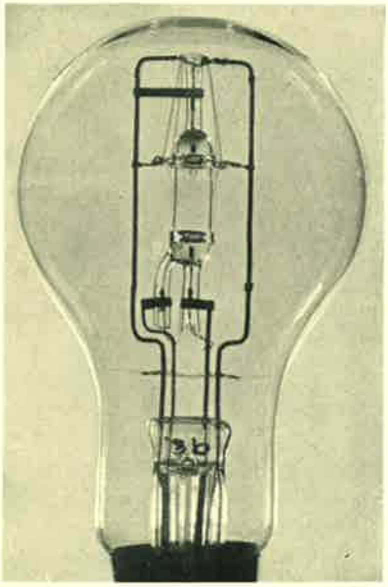


Fig. 7.

effect of enabling the filament to operate at a high temperature without requiring such a high watt dissipation as would be necessary in the absence of the arc. Such combination lamps have the advantage of simplicity, but, of course, can only be operated at efficiencies between the efficiencies of the filament and the arc tube separately.

Some Modified Forms of the High-Pressure Mercury Arc.

The normal form of the high-pressure mercury discharge lamp is that of a tubular vessel within which the arc assumes the form of a narrow pencil of light which generally has considerable length in relation to its width. Such a cylindrical pencil-like discharge is particularly suitable for floodlighting purposes and for street lighting purposes when used either vertically or horizontally. Particularly, however, where the lamp is to be used in conjunction with optical projection apparatus, a more convenient form for the discharge would be something approximating to a disc or ball of light. A modified form of light source may be obtained by operating the discharge lamp with a lower vapour pressure and reducing the gap between the electrodes, and even by altering the nature and shape of the electrodes themselves. The reduction in pressure, however, entails some sacrifice in the intrinsic brilliance of the light source. It has been found possible, by an arrangement in which two or more high-pressure mercury discharges operate together in the same vessel, to produce a composite light source which may have a variety of forms, and so produce polar curves having special values for particular purposes. For example, it is possible to produce an area of light, very suitable for lighthouse projection work, by means of two closely adjacent high-pressure arcs working within the same tube. When such lamps have passed the experimental stage it will probably be possible to utilise them with the standard type of optical system used for lighthouse work and so obviate the necessity for any re-design of the optic which might be entailed in order to utilise the ordinary high-pressure discharge lamp.

Artificially Cooled Discharge Lamps.

Some of the effects produced by increasing the pressure of mercury vapour in a discharge tube have been outlined under a previous heading. Perhaps the most interesting of these are the changes which occur in the response of the mercury atom to electrical excitation when the pressure is increased. The mercury atom may be regarded as a complex unit in which a number of electrons exist normally in equilibrium with a positive electrical charge of equal magnitude to that of the component electrons. In a discharge lamp these electrons become disturbed by collision between their parent atoms and other free electrons which have been accelerated by the electric field. As the atom regains its normal unexcited condition, it emits radiation of characteristic frequencies which correspond with the states of excitation to which its component electrons have been raised by previous collisions. At very low mercury vapour pressures a considerable proportion of the energy is emitted at a frequency corresponding with a wavelength in the ultra-violet of 2,537 angstrom units. When the vapour pressure is increased by allowing the lamp to reach a higher temperature and using an excess of mercury it is found that at a suitable pressure the whole of this ultra-violet radiation of wavelength 2,537 angstrom is re-absorbed by the mercury and re-emitted at higher wavelengths. It is thus evident that under the right conditions mercury vapour can be excited not only by the collision of high-speed electrons, but also by certain frequencies of ultra-violet radiation. This phenomenon is called photo-excitation.

From a lamp development point of view it is necessary to inquire under what conditions this phenomenon can be made to occur in a practical design of lamp and whether any material benefit may be expected from its utilisation. Experiments have shown that in order to produce very marked photo-absorption, the temperature and pressure of the mercury vapour must be higher than the values used in even the small quartz lamps already described. A mercury vapour pressure of 100 atmospheres requires a minimum temperature at the wall of the lamp of about 800° C., a temperature which is close to the maximum which quartz can satisfactorily withstand over long periods. At such a high pressure it is found that the voltage necessary to sustain an arc discharge in mercury vapour is as high as 400 volts per centimetre of the arc length. It is well known that the arc of a high-pressure mercury vapour lamp occupies less than the full diameter of the tube in which the discharge takes place and that the temperature in the constricted arc column may be several thousands of degrees centigrade.

If the quartz tube is made of relatively large diameter compared with the width of the arc column the difference in temperature between the core of the discharge and the surrounding mercury vapour will cause rapid convection currents which will tend to blow the arc against the walls of the tube. If the tube is made sufficiently narrow to prevent this effect, there will exist between the centrally disposed discharge arc and the tube walls a sheath of mercury vapour from which no visible light is emitted and which serves to some extent to insulate thermally the quartz tube from the high-temperature arc.

In general, undesirable effects due to convection currents may be prevented by the use of a tube diameter which does not exceed about three times the width of the arc stream. For very high pressure lamps this necessitates a narrow bore tube of the order of, say, 2 millimetres internal diameter. With a current of one ampere and with an arc voltage of 400 v/cm. the loading of a lamp constructed from 2 millimetre tubing will be over 10,000 watts per cubic centimetre of tube volume. When this is compared with the loading of the quartz lamps already described, *i.e.*, with loadings of up to 60 watts per cubic centimetre, it is evident that special means must be provided for preventing overheating of the quartz tube. A convenient method of attaining this result is to operate the lamp in a stream of running water and so produce the desired gradients between the high temperature arc and the outer wall of the quartz tube.

The use of water cooling thus enables the attainment of high internal pressures and consequently very compact light sources. For example, a lamp of only 25 millimetres in length and 2 mms. in internal diameter, and operated with a power input of 1,000 watts, has a brightness estimated to be of the order of 40,000 candles per square centimetre, and requires only a few seconds to reach full intensity. When this super high-pressure discharge lamp is switched into circuit, the volt drop across its terminals is quite small, but within a few seconds this voltage rises rapidly to about 1,200 volts, at which pressure equilibrium is set up between the mercury being evaporated by the intense heat and that being condensed at the wall of the tube. The central core of the discharge plays on the convex surfaces of mercury columns at each end of the tube which by a special arrangement of activated lead wires constitute the electrodes of the lamp. The simplicity of construction of this type of lamp, together with its high efficiency of 60-70 lumens per watt and extremely high brightness, should render it of great value for projection work in lighthouses, aerodrome landing lights, searchlights, and cinema projectors, etc. The necessity for the water cooling and the high-voltage transformer are factors which must be taken into account, and which serve to restrict the possible applications of these lamps at the present time. It may, however, be possible to overcome these difficulties as development proceeds.

The super high-pressure mercury discharge lamp, although still in the experimental stage, represents a distinct advance on earlier lamps from the point of view of energy distribution in the spectrum. Analysis of its radiation by means of the quartz spectograph shows that a large proportion of its energy is of a continuous nature, akin to that of heated solids, and that the sharp spectral lines due to normal excitation of the mercury atom are of greatest intensity at the higher wavelength and of the spectrum. The possibility of producing still greater improvements must depend very largely on continued study of the physics of the high-pressure electrical discharge, and possibly on the development of transparent refractories other than quartz capable of being operated at still higher temperatures.

Conclusion.

With the ever increasing part which discharge lamps are playing in electric lighting, there can be little doubt that ultimately they will be used in practically every sphere in which artificial light is required. The ultimate ideal would appear to be a vapour discharge lamp of high efficiency emitting light having a colour composition close to that of daylight. Already there are indications that such an ideal may one day be achieved.

Meanwhile with existing types of mercury discharge lamps the highest efficiencies are obtainable with the unmodified lamp, but at the present moment a nearer approach to white light is possible by using either mixtures of metals in the discharge tube, by combining the discharge tube with a tungsten filament as in the dual lamp, or by using fluorescent powders. Whether any of these methods will ultimately survive, or whether entirely new types of discharge lamp will be developed, are questions which only the future will answer.

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Railway Arches at King's Cross lighted by "Sieray" Lamps in Sussex-Sieray and Gower-Sieray Lanterns.

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West Riding Auto Company's Garage, Wakefield, lighted by "Sieray-Dual" Lamps in Dispersive Reflectors.