LOW-PRESSURE MERCURY DISCHARGE WITHIN A LUMINESCENT TUBÉ

by W. UYTERTOEVEN and G. ZECHER. 537.525.8 : 621.327.3 : 537.37

Column discharges in mercury at low pressure, due to the strong ultraviolet resonance line 2537 Å, are particularly suitable for excitation of the luminescence of zinc silicate and other phosphorescent substances. The process of this light excitation is discussed in this article, as well as the various factors which determine the efficiency. The following also are dealt with: the use of phosphorescent substances in order to improve the efficiency and colour and for the purpose of rendering alternating current discharges free of flicker.

In the discussion in a previous article 1) on the light emission in the positive column several cases were dealt with in which a considerable portion of the electrical energy supplied was transformed directly into visible light by excitation of favourably situated levels. In addition to the visible spectral lines, however, there are practically always other lines also which lie in the ultraviolet or infrared part of the spectrum, and which therefore do not contribute directly to the light flux. Attempts have been made to utilize this invisible radiation, and success has been attained in the case of the ultraviolet part by the use of luminescent substances. When these substances are exposed to radiation of certain wave lengths in the ultraviolet, they emit radiation in another region with longer wave lengths in the visible. Luminescent substances thus act as transformers of radiation. with the limitation that the wave length of the radiation is practically always increased in the transformation (Stokes' law). In this way it is possible to improve considerably the efficiency of certain discharges.

It has been found that the production of ultraviolet radiation and its transformation into visible light can take place in such a way that discharges which themselves emit almost no light can be made very efficient sources of light. As an example we shall discuss the low-pressure mercury discharge within luminescent boundary, confining our discussion to the column itself. Various factors, such as ignition and connections, which are very important when these discharges are used in lamps, will not be considered here, since they have no direct effect on the physical phenomena which occur in the column with a fluorescent wall.

Luminescent substances

The phenomenon of luminescence and the properties of various substances which exhibit this phenomenon, have been recently described in this periodical 2, 3). We shall confine ourselves here to those substances which are used as light transformers in the low-pressure positive column of the mercury discharge. We are then chiefly concerned with "impurity lumiphores" and "fluorescent glass". A typical impurity lumiphore is zinc silicate. The zinc silicate is in this case the base material, which upon being mixed with small amounts of an "activator", manganese for example, and after a certain treatment, acts as a luminescent substance. The treatment consists mainly in a crystallization by heating to a high temperature. Fig. 1 shows the emission curves for several zinc beryllium silicates activated with manganese in a low-pressure mercury discharge. The dotted line gives the light intensity as a function of wave length for the phosphorescent substance with its energy maximum at 6050 Å. At the wave length of maximum eye sensitivity the light intensity is put equal to the energy.

Fig. 1. Emission curves: energy as a function of wave length (full lines; maximum put equal to 100), for several zinc beryllium silicates activated with manganese in a low-pressure mercury discharge. The dotted line gives the light intensity as a function of wave length for the phosphorescent substance with its energy maximum at 6050 Å. At the wave length of maximum eye sensitivity the light intensity is put equal to the energy.

by the corresponding values of the relative sensitivity of the eye, as has been done for the curve with the maximum at 6050 Å (dotted line in fig. 1).

The first step in the process of light excitation is the production of ultraviolet radiation, which, in the low-pressure mercury discharge, consists mainly of the resonance line 2537 Å (partially also of the resonance line 1850 Å).

In fig. 3 is given the relative distribution of energy for a typical mercury discharge at low pressure, in which, in addition to the line 2537 Å, the intensity of which is taken as 100, several lines with longer wave lengths are also indicated. In order to obtain good efficiency in the production of the resonance line, the discharge will be made to occur preferably at a low current density. One of the results of this is that the energy taken up per cm of length is small (and therefore also the light flux produced), and the tube has a low brightness. A lamp with luminescence excited by the ultraviolet radiation of the low-pressure mercury discharge will therefore be made chiefly in relatively small units of, for instance, 25 watts. With a suitable choice of the mercury vapour pressure (i.e., the temperature), the tube diameter, and discharge current it is possible to transform about one half of the electric energy supplied per cm length of tube into radiation with a wave length of 2537 Å. If it is desired to excite luminescence by means of radiation in the near ultraviolet, for instance in the neighbourhood of 3600 Å, it is better to use a mercury discharge with high or very high pressure. For these lines as well as for the visible mercury lines, the considerations discussed in the article mentioned previously 1) are valid. According to these considerations high pressure and current density are necessary for economical production of lines of longer wave length.

A typical luminescent glass is uranium glass, in which certain groups of molecules of the added uranium compound are luminescent. In fig. 2 may be seen the relative emission curves as a function of the wave length for uranium glass irradiated with the light of a low-pressure mercury discharge.

The production of light in luminescent column discharges

The production of visible light in positive columns with fluorescent substances is a rather complicated process in which we can distinguish several successive steps. In the first place there is the production of the ultraviolet radiation in the discharge, then the absorption of this radiation by the luminescent layer, which after a longer or a shorter time emits a part of the energy absorbed as visible light. In each of these steps in the transformation of the electrical energy supplied to the discharge into visible light, there will in general be a certain loss. It has, however, been found that an extraordinarily good efficiency can be attained, which, expressed in the usual way in lumens emitted per watt supplied, may reach 100 lumens per watt. We shall now study how this high efficiency is achieved.
In order that all the ultraviolet radiation may be used, it must all be absorbed by the luminescent layer, which may therefore not be too thin. It is, however, not always possible to use a sufficiently thick layer since such a thick layer may offer difficulties by not adhering to the inner wall. It may also happen that the phosphorescent substance absorbs too much of its own radiation so that light is lost. In these cases it is possible to use a thin layer of luminescent material and, instead of ordinary glass, a fluorescent glass; the ultraviolet radiation which is not absorbed by the phosphorescent substance is then transformed into visible radiation in the glass.

Efficiency of luminescence

There are various ways of defining the efficiency in the transformation of the ultraviolet radiation absorbed by the phosphorescent substance into visible light. One may determine how many quanta of visible light are emitted per 100 quanta of ultraviolet light absorbed. If the result is 80 for instance, the "quantum efficiency" is 80 per cent. Such values actually occur, and even values up to 100 per cent.

Even when the quantum efficiency is 100 per cent, the ratio of the energy radiated as visible light to the energy absorbed as ultraviolet light, the "energy efficiency", is considerably less than unity. If for every ultraviolet quantum with the frequency $\nu_1$, one visible quantum with the frequency $\nu_2$ is produced, where $\nu_2 < \nu_1$, the energy ratio is $h\nu_2/h\nu_1 = \nu_2/\nu_1$, since according to Planck's formula the energy of a quantum of radiation with the frequency $\nu$ is $h\nu$. Since the wave length is inversely proportional to the frequency the energy efficiency is $\nu_2/\nu_1 = \lambda_1/\lambda_2$. Thus when the wave length absorbed ($\lambda_1$) is 2537 Å and the wave length emitted ($\lambda_2$) is 5550 Å the energy efficiency is $\lambda_1/\lambda_2 = 2537/5550 = 0.46$.

If it is desired to express the efficiency in lumens per watt, the position and shape of the emission curve of the energy with respect to the eye sensitivity curve must be taken into account. The highest yield of light with a given energy efficiency is obtained with a narrow emission curve which has a maximum in the neighbourhood of the wave length $\lambda = 5550$ Å of maximum eye sensitivity. The colour of the light emitted by the phosphorescent substance is then a pronounced green which may be undesirable for some purposes.

The following example in figures may give some idea of the results attainable with the phosphorescent substances now used. We assume that 50 per cent of the electrical energy used in the column is transformed into radiation of the wave length 2537 Å, that the quantum efficiency is one, and the energy efficiency is 50/100, and that for each watt radiated in the visible 200 lumens are obtained. We then find for the total efficiency of the transformation: $50 \cdot 1 \cdot 200 = 50$ lumens per watt.

Adaptation of the discharge to the luminescent substance

In principle it is possible to find for a given phosphorescent substance a discharge, the emission of which in the ultraviolet has a favourable position with respect to the absorption spectrum of the phosphorescent substance. Such a substance absorbs mainly the wave lengths in a certain region several hundred Ångström units wide, in which region the absorption has a maximum. Fig. 4 shows schemat-

---

3) In an accurate calculation it must be taken into account that the energy efficiency $\lambda_1/\lambda_2$ is not the same for all wave lengths $\lambda$ of the emission band.
low pressure with the strong line at 2537 Å is the most suitable source of radiation for the excitation of light. Phosphorescent substances in which the basic material is a sulphide, for example the green phosphorescent zinc sulphide activated with copper, are, however, best rendered phosphorescent by irradiation with ultraviolet light of long wave length (3600 Å). For this purpose the mercury discharges at high and very high pressure are the best sources of radiation, since they have very strong emission lines in the neighbourhood of 3600 Å.

In practice, however, we begin with a given discharge, and try to find a phosphorescent substance which is suitable. In doing this we may have different purposes in view: either improvement of the efficiency or improvement of the colour. In the first case the conditions which the luminescent substance must satisfy are obvious from the above discussion. The maximum in the absorption curve of the substance must lie in the neighbourhood of the maximum of the ultraviolet emission of the source of radiation, with low-pressure mercury discharges therefore in the neighbourhood of 2537 Å. The emission curve of the phosphorescent substance, which must have as high a quantum efficiency as possible, must have its maximum in the neighbourhood of maximum eye sensitivity (at λ = 5550 Å). In this way a very high efficiency is obtained, as high as 100 lumens per watt, but strongly coloured (green) sources of light are also obtained. This is not a great objection for a number of purposes (for outdoor illumination, for instance). For illuminated advertising signs attempts are even expressly made to obtain various colours. For interior illumination, however, a colour reproduction more or less true to nature is indispensable, even if it is obtained at the cost of efficiency. In this case the adaptation of the phosphorescent substance to the discharge will therefore consist in the fact that the light emission of the discharge together with that of the phosphorescent substance must give a mixed light with which the observation of colours is satisfactorily true to nature.

In fig. 5, a and b, may be seen the composition of the visible spectrum of the mercury discharge at low pressure, in fig. 5a the relative energy distribution and in fig. 5b the relative light emission. The influence of the low eye sensitivity at the extremities of the spectrum may be clearly seen upon comparing the two diagrams: with respect to energy the blue line 4538 Å is the strongest, with respect to light the green line 5461 Å is strongest.

**Block method of colour determination**

In the development of sources of light consisting of a positive column discharge with a fluorescent boundary, the so-called “block method” for the determination of colour is very useful. Since the

---

3) For the block method see Philips techn. Rev. 2, 1, 1937. The limiting wave lengths have been changed somewhat since that article was written, so that the mercury lines fall about in the middle of the blocks, which improves the accuracy of the method.
measurement of complete emission curves is a fairly elaborate procedure, these curves have been replaced by a kind of block diagrams. The whole region of the visible spectrum is divided into eight blocks limited by the following wave lengths: 4000 - 4200 - 4400 - 4600 - 5100 - 5600 - 6100 - 6600 - 7200 Å. A spectrum of the light source to be investigated is thrown on a photocell by means of a double monochromator. In the path of the light rays various diaphragms are placed, each of which passes only the wave lengths which belong in one of the eight blocks. By a suitable choice of the height of each diaphragm, the deviation of galvanometer or electrometer due to the current of the photocell may be made proportional to the light flux emitted in each block, whereby the eye sensitivity and the spectral sensitivity of the photocell are taken into account. By means of a light source with a known energy distribution, a tungsten lamp for instance, the installation may be calibrated.

In fig. 6 the block diagrams determined by this method are given for several cases. Fig. 6a represents the light emission of a low-pressure mercury discharge; it may be compared with fig. 5b. It may clearly be seen on the block diagram that the light flux is greatest in the green (5100 - 5600 Å), that there is, however, also a quite appreciable amount in the yellow region (5600 - 6100 Å) and in the blue (4200 - 4400 Å). Next to this in fig. 6b may be seen block diagrams for the radiation of two phosphorescent substances (without mercury light), namely zinc silicate (I) and zinc beryllium silicate (II).
(II), and in fig. 6c for the radiation of two phosphorescent glasses, namely uranium glass (I) and a combination of copper glass with uranium glass (II).

![Diagram of light intensity variation](image)

Fig. 8. Block diagram of the light of a mercury tube made of copper-uranium glass and containing zinc beryllium silicate.

The block diagram is very useful, particularly in judging the results of combining different luminescent substances. If one has as object the construction of a source of light which shall resemble sunlight or ordinary electric light for example, one begins by making the block diagram of these sources of light as is indicated in fig. 7. In the various experiments it is now possible in each case to find out whether the composition of the light satisfies the necessary requirements, and in which region any deficiency or excess occurs. If, for example, the dotted line of fig. 7 is compared with the diagram for zinc beryllium silicate of fig. 6b, it may be seen that the emission of the substance without the mercury spectrum resembles ordinary electric light fairly well. In this case the mercury light itself contributes only 15 per cent to the total light flux, so that the colour is practically determined by the phosphorescent substance. The combination of the light of the phosphorescent substance, glass and mercury discharge, as produced by a lamp for practical uses is finally given in fig. 8.

### Alternating current light sources rendered free of flicker

In the foregoing we have only discussed the property of luminescent substances known as

![Diagram of light variation with alternating current](image)

Fig. 10. Light variation with alternating current (50 c/s): a) mercury discharge at low pressure, b) low-pressure mercury discharge with phosphorescent cadmium silicate, c) gas-filled electric lamp (Bi-Arlita type 78 W).

"light transformation". At the same time a number of these substances may also act as "light accumulators", i.e. they luminesce not only while they are being irradiated, but they continue to emit light for some time after the irradiation has been interrupted. The phosphorescent substance is therefore able to store the energy for some time and then emit it gradually. The time during which the phosphorescent substance continues to luminesce varies very much from one substance to another. Fig. 9 gives the course of

![Diagram of light intensity variation after interruption of irradiation](image)

Fig. 9. Variation of the light intensity after interruption of the irradiation with ultraviolet light: a) for a phosphorescent silicate, b) for a phosphorescent sulphide.
the light emission after interruption of the irradiation for two types of substances: silicates (a) and sulphides (b). The silicates especially possess this property; tungstates on the other hand are practically without it. The phenomenon of phosphorescence of these substances may be used to reduce the flicker with alternating current lamps. When the direction of the current is reversed, the current is zero for a short time, and practically no atoms are excited, so that the light emission becomes zero, since the phosphorescence of the discharge itself may usually be neglected. Fig. 10a shows the variation of the light with time in a low-pressure mercury discharge. In each half period the curve has practically the form of a sine curve in which the moments when the light is zero correspond to those when the current passes through zero. This periodic variation of the light intensity may be very disturbing in certain cases, especially in interior illumination. If the variation of the light from a low-pressure mercury discharge the boundary of which is covered with a luminescing layer (a cadmium silicate) is recorded in the same way, the diagram of fig. 10b is obtained. The fluctuation in the light is now reduced to a ripple which is much smaller than the average constant value upon which it is superposed. As a measure of the irregularity one may choose the ratio of the difference between maximum and minimum to the value b of the minimum. In the case of fig. 10b the irregularity a/b defined in this way amounts to about 0.25. It has been found that under the prevailing circumstances such a value for the irregularity may be accepted without hesitation. For the sake of comparison the variation of the light is given in fig. 10c, for a gas-filled electric lamp (Bi-Arlita 78 W), for which the ratio a/b is about 0.15.

In conclusion fig. 11 gives the variation with time of the discharge current \( I_I \), to which the intensity of the line 2537 Å is practically proportional, and of the combined light flux \( F \) of mercury and luminescence light from a tube containing zinc beryllium silicate. It may be seen clearly that there is a certain phase shift between the maxima of \( I_I \) and \( F \), which facilitates the bridging over of the light minimum during the currentless period. The cause of the phase shift lies in what might be considered the reverse of the phosphorescence. Upon irradiation with a given, not too high, intensity of ultraviolet radiation, it takes some time before the phosphorescent substance reaches its full activity and the light emission reaches its maximum value, so that the light maximum lags somewhat behind the ultraviolet maximum.