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A NEW HIGH-PRESSURE MERCURY LAMP WITH FLUORESCENT BULB

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In the last decade the use of fluorescent substances has brought about a revolution in illumination engineering, the principal example of which was the low-pressure mercury lamp with fluorescent envelope (the "TL" lamp). Before the triumphal advent of this low-pressure lamp, however, the idea of applying fluorescent substances for the purposes of illumination had already materialized in the high-pressure mercury lamp. It is interesting to give thought to the differences in the problems encountered with these two kinds of lamps. Thanks to the development of new materials and methods, the high-pressure mercury lamp with fluorescent bulb has now also an opportunity to take an important place in the field of illumination, inter alia for industrial and street lighting.

The HP lamp

The principle of the electric discharge in mercury vapour of low pressure was applied several decades ago in tubes for illuminated advertising signs. For lighting purposes, however, this could not be applied because of the blue colour of the light and the very low efficiency of the light source in lumens per watt; the radiation produced by the discharge consists for about 80% of ultra-violet with a wavelength of 2537 Å, only about 5% being in the visible part of the spectrum.

About 1935 a lamp was made which was based on a discharge in mercury vapour under high pressure ¹⁾ (e.g. 5 atm or higher). This meant a great step forward in the direction of applying such discharges for lighting purposes. The high-pressure mercury lamp (HP lamp ²⁾) has a radiation spectrum as represented in *fig. 1*. A large part of

the energy of this lamp is also radiated in the ultra-violet part of the spectrum, the main wavelengths being 2537 Å and 3650 Å, but owing to the high pressure there is at the same time a continuous spectrum extending over the whole of the visible range; again due to the high pressure, the spectral lines in the visible range are also of a relatively greater intensity. The result is that quite a reasonable efficiency is obtained, viz. 35 to 40 lumens/watt. It is true that the colour of this light is still rather bluish and the colour rendering leaves much to be desired, but the high efficiency compared with the incandescent lamp made the use of these high-pressure mercury lamps so attractive that they soon found application in various cases, sometimes in combination with incandescent lamps.

Fig. 2 shows the construction of the HP lamp in its present form. The discharge takes place in a small tube of fused silica containing a certain amount of mercury together with a rare gas under a pressure of a few cm Hg. This rare gas and the provision of an auxiliary electrode enables the lamp to be started with normal mains voltage (220 V~). The heat generated by the discharge causes the mercury to evaporate and the pressure in the tube rises to a few atm (according to the type of tube). The discharge tube is mounted in a bulb of the same shape as that of an incandescent lamp

¹⁾ W. Elenbaas, Discharges in mercury vapour under high pressure (in Dutch), *De Ingenieur* 50, E83-90, 1935; C. Bol, A new mercury lamp (in Dutch), *De Ingenieur* 50, E91-92, 1935; W. de Groot The emission and absorption spectra of mercury vapour at very high pressures (up to 300 atm) (in Dutch), *De Ingenieur* 50, E92-94, 1935. See also G. Heller, The mercury vapour lamp HP 300, *Philips Techn. Rev.* 1, 129-134, 1936.

²⁾ Sometimes the HP lamps, together with the SP lamps, which are water-cooled and in which pressures of about 100 atm occur, are denoted as "super-high-pressure" mercury lamps, the name of "high-pressure" lamp then being reserved for lamps with a mercury pressure of about 1 atm (HO lamps).

and filled with nitrogen. The gas jacket thus formed round the discharge tube has a two-fold function. In the first place it protects the current leads fused in the silica, which are heated to a very high temperature, so that they would rapidly oxidize at the end where they come into contact with air. In the second place the nitrogen affords a certain thermal insulation: if the tube were exposed to the open air the thermal dissipation through convection would be so great that upon the current being

Possibilities for improving the colour rendering of the HP lamp

Considering the high efficiency and other good properties of the HP lamp, there was every inducement to investigate whether the colour rendering could not be so improved as to make these lamps suitable for more universal use. The lack of colour rendering is most noticeable with objects the colour of which is predominantly red: under the HP lamp such objects assume a brownish hue.

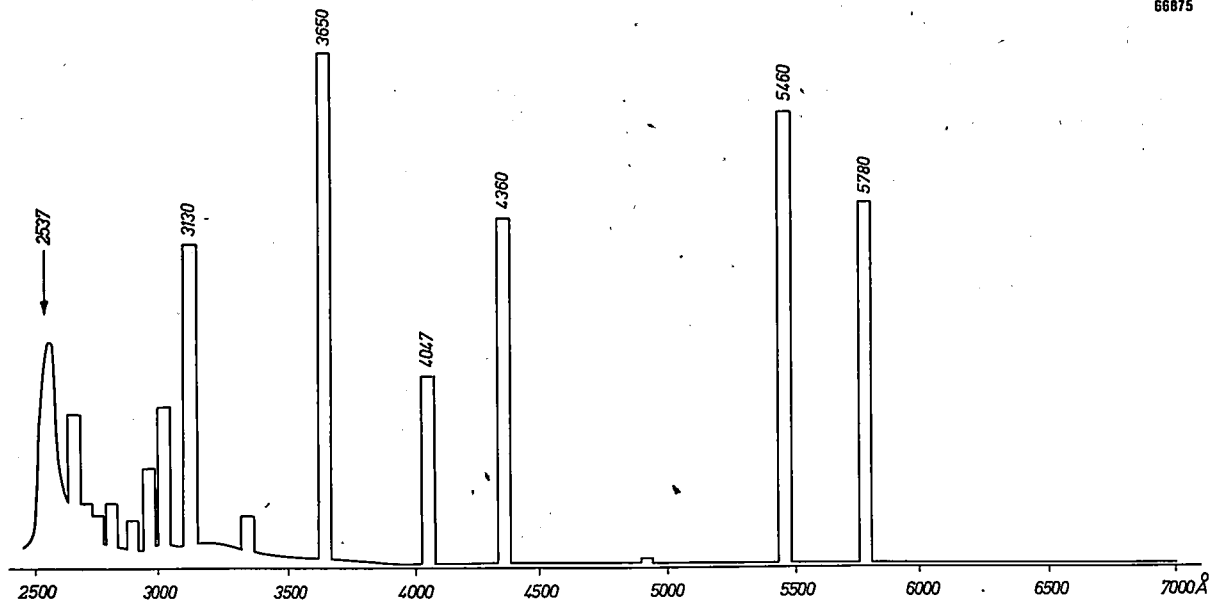


Fig. 1. The spectral energy distribution of the HP lamp (without glass bulb). The spectral lines superposed on the continuum have all been drawn relatively too low and with the same exaggerated width, such that the area covered by each line represents the energy emitted therein. About $1\frac{1}{2}$ times as much energy is radiated in the ultra-violet as in the visible part of the spectrum.

switched on the tube would only very slowly heat up and the mercury would take a long time to evaporate completely, if at all. (A more complete insulation, by evacuating the bulb — in which case the only dissipation of heat would be by radiation — is not desirable because then, in order to avoid the wall of the tube reaching too high a temperature, only a smaller power can be allowed to develop in the discharge tube.)

Some other details of the construction are explained in the subscript to fig. 2. We would only mention here — because they will be referred to again later — the strips of molybdenum, serving to carry the current through the fused silica, and the inside frosting of the bulb which hides the inside of the lamp from view and gives the lamp a pleasant appearance when it is not burning while at the same time providing for a not too great surface brightness when the lamp is alight.

This can be understood from a look at the spectrum in fig. 1. In the red, i.e. roughly between 6000 Å and 7000 Å, the mercury vapour has no spectral lines of any intensity worth mentioning, and also the continuous spectrum of the HP lamp is weak in that range. The radiation of the HP lamp therefore needs supplementing in the red.

Attempts have been made to attain this by various means: (1) By adding a little cadmium to the mercury vapour. It is true that the cadmium vapour does to a certain extent yield the desired contribution in the red, but this artifice is accompanied by a considerable lowering of the efficiency and a shortening of the life of the lamp. (2) The choke (or low power factor transformer), usually connected in series with the mercury discharge in order to stabilize it, was replaced by a filament mounted together with the discharge tube in one bulb. The incandescent light from the filament, being very rich in the red, supplemented

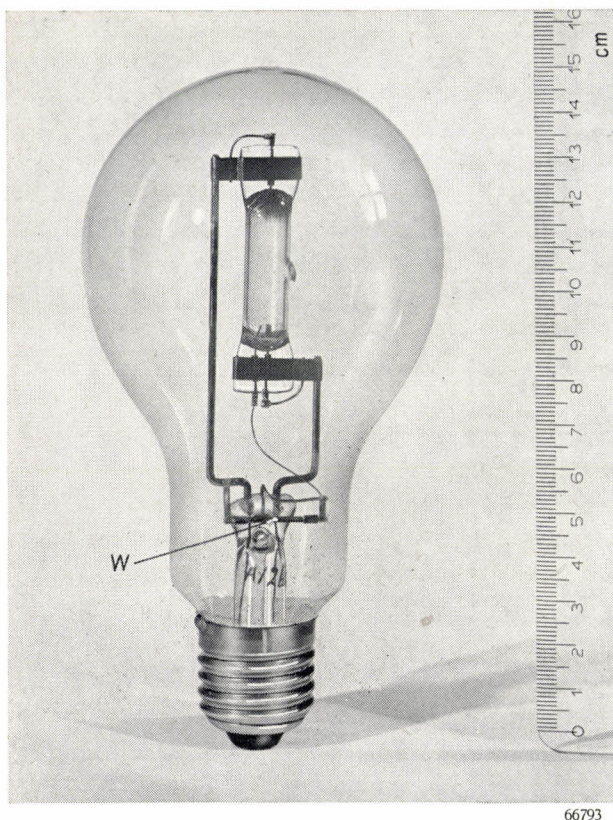


Fig. 2. The HP lamp. Inside, in the centre of the bulb, is the tube of fused silica in which the discharge takes place in mercury vapour of high pressure. The current is fed to the electrodes via leading-in strips of molybdenum (almost concealed by the supports of the discharge tube) sealed airtight in the tube. Beside the lower main electrode is an auxiliary electrode connected to the other main electrode via a current-limiting resistor *W* and serving to facilitate ignition (ignition voltage about 180 V). Usually the bulb is frosted on the inside (here it has been left clear to show the mounting inside). It is filled with nitrogen under a pressure of 50 cm Hg (in the cold state).

the radiation from the mercury discharge so as to give it a white light with good colour rendering. The contribution of light needed from the filament, however, is of such a high percentage that the efficiency of these blended-light lamps, named ML lamps, is greatly inferior (about 20 lm/W) to that of the HP lamp. (3) The most elegant solution is that whereby the otherwise useless ultra-violet radiation from the mercury vapour is converted by means of a fluorescent substance into the red radiation desired. In this way the efficiency in lumens/watt need not by any means suffer but may in principle even be made better than that of the HP lamp. This line of thought led to the construction of the HPL lamp, which is a high-pressure mercury lamp having a bulb coated on the inside with a fluorescent layer.

³⁾ E. L. J. Matthews, The blended-light lamp and other mercury lamps with improved colour rendering, *Philips Techn. Rev.* 5, 341-347, 1940. J. Funke and P. J. Oranje, The development of blended-light lamps, *Philips Techn. Rev.* 7, 34-40, 1942.

Before dealing more closely with this idea and the manner in which it was materialized, further development will be briefly outlined.

The first HPL lamps brought onto the market about 1937 were far from being ideal as regards colour rendering. In those days, however, when the art of producing fluorescent substances (phosphors) was still more or less in its infancy, we had to consider ourselves fortunate in having found a phosphor which could be excited by the radiation of both 2537 Å and 3650 Å and which, moreover, answered fairly well the other requirements set (about which more will be said later). It is to be realized that once thoughts had turned to the use of fluorescent substances it was only obvious to try to make use of them also for the low-pressure mercury lamp for converting the lost radiation of 2537 Å into visible light. Such could not be done at that moment because no phosphors were then known which satisfied the entirely different requirements for that lamp.

As is known, some time later however phosphors were also found which were suitable for the low-pressure lamp, and thus the tubular fluorescent lamps of the "TL" type made their appearance. These very soon became enormously popular, so much so in fact that the previously developed but still immature HPL lamp was relegated to the background. However, investigations with the HPL type of lamp were continued, though for a long time without any great success. It was not until in the course of last year that a phosphor was discovered which has made a decided improvement of the HPL lamp possible. The new type of HPL lamp that is now in production promises to take up a field of application of its own, side by side with the so popular "TL" lamp.

What is required of a phosphor for the HPL lamp and what is to be expected from it

As already indicated, to improve the colour rendering of the HP lamp a phosphor is needed which is excited by radiation of wavelengths in the range of 2537 and 3650 Å and which gives an emission spectrum lying mainly in the red.

Further, the phosphor has to satisfy the following requirements:

- 1) It must not absorb the visible light of the mercury discharge to any appreciable extent, so as not to affect the efficiency of the lamp. A strong selective absorption is also undesired; apart from the coloured appearance it would give the lamp while it is not burning, which effect in some cases

may be unpleasant, selective absorption might again spoil the colour rendering.

2) Although any phosphor has the tendency to lose its fluorescent power as the temperature increases, this phosphor must still give a reasonably strong fluorescence at a temperature of 150 °C to 200 °C, this being approximately the temperature reached by the bulb that is to be lined with the fluorescent layer. Of course the temperature of the bulb can be reduced somewhat by making the bulb larger, and in fact a step has been taken in that direction (the diameter of the old 120 W HPL 500 lamp was 130 mm, as compared with the 90 mm of the HP 500), but there is a limit to this because the fittings in which the HPL lamps are to be used should not be too large.

source is described by quoting the percentage of the total luminous flux supplied in each of the eight adjacent spectral "blocks" covering together the whole of the visible spectrum.

In *table I* figures are given for the HP lamp and for daylight; it should, however, be noted that these figures represent energy contributions and not contributions of luminous flux. The qualitative differences between the sources of light as considered in each block are, of course, the same in both cases, and by quoting the energies it is possible to give in the same table also the contributions in two ultra-violet blocks. Now these ultra-violet energy contributions of the HP lamp are to be imagined as being transferred to the red blocks 6100 Å - 6600 Å and 6600 Å - 7200 Å, where the radiation

Table I. Block-diagram distribution of the spectrum of the HP lamp and of average daylight. Contrary to the usual custom the relative energy contributions in the blocks are given (slightly rounded off), instead of the relative luminous flux contributions. Also the ultra-violet energy in two spectral sections is given, in the same relative measure as the visible radiation.

	< 3000 Å	3000-4000	4000	No. 1	2	3	4	5	6	7	8	7200
HP 125 W	60	80		13	24	1	2	31	26	1,5	1,5	
Average daylight	0	9		6	6	7	18	17	16	14	16	

3) Finally there is the very important requirement that the phosphor must not be subject to dissociation under the strong ultra-violet irradiation (the photo-chemical action of which is further promoted by the high temperature). Anticipating what is stated farther on in this article, it may be said here that for many substances which otherwise appeared to be suitable for our purpose this requirement proved to be the stumbling block: the photo-chemical dissociation occurring with the substances first becomes noticeable in a reduction of the content of red light in the radiation from the lamp; later the fluorescent layer often turns grey, thus absorbing visible light and causing the total luminous flux of the lamp to diminish considerably.

Supposing that a phosphor were found which ideally answers these requirements, the question is what result is to be expected from it as regards the colour rendering of the lamp. This can be calculated in a simple manner. The colour rendering of a lamp is most easily judged with the aid of the "block diagram" devised by Bouma⁴⁾. According to this method the spectral distribution of a light

from the HP lamp shows such a marked deficit. In this transference account has to be taken of the depreciation in energy taking place in any process of fluorescence: for one quantum of ultra-violet energy $h\nu_1$ (given a quantum efficiency of 100%) at most one energy quantum $h\nu_2$ of the changed wavelength can be obtained, and since a red quantum contains only about half the energy of one of our ultra-violet quanta ($\nu_2 \approx \frac{1}{2}\nu_1$) in the transference the energy has to be halved. In each of the two red blocks there is then a relative energy contribution of about 35. In reality, of course, a quantum efficiency of 100% cannot be reached, and, moreover, to ensure sufficient transmission of the visible light from the mercury discharge, the phosphor can only be applied in such a thin layer that the ultra-violet radiation is not completely absorbed. The conclusion, therefore, is that in the most favourable case possible of realization the colour rendering of daylight in the red can just about be reached⁵⁾. The improvement that can be attained appears to be indeed quite sufficient for the red colour rendering, provided — and this is the lesson

⁴⁾ P. J. Bouma, Colour reproduction in the use of different sources of "white" light, Philips Techn. Rev. 2, 1-7, 1937. See also P. M. van Alphen, A photometer for the investigation of the colour rendering of various light sources, Philips Techn. Rev. 4, 66-72, 1939.

⁵⁾ For this argument we are indebted to Dr. J. Voogd, and for the necessary connections between energy measurements in the ultra-violet and in the visible spectrum we have to thank J. Riemens.

to be learned from the foregoing — the fluorescence is utilized as far as possible to augment the red content of the radiation.

Phosphors tried out for the HPL lamp

The phosphor which until recently had always been used in HPL lamps is zinc cadmium sulphide, activated with copper, (Zn, Cd)S-Cu. The spectral energy distribution of the emission from this phosphor is represented in fig. 3, from which

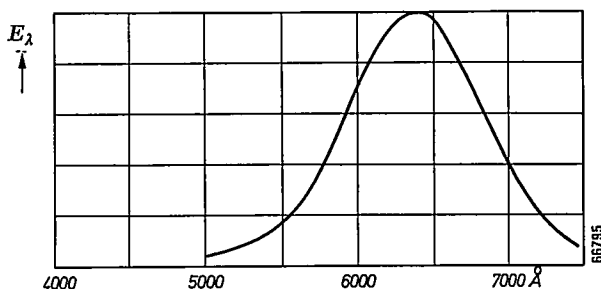


Fig. 3. Spectral energy distribution (in arbitrary units) of the emission of zinc cadmium sulphide activated with copper.

it is seen that there is a good maximum in the orange-red. Further, the "excitation spectrum" is not unfavourable; the phosphor is highly absorbent for all the ultra-violet radiation that is to be considered and it fluoresces with a reasonable quantum efficiency: upon activation with 3650 Å it is about 50% and with 2537 Å about 25%, measured at room temperature. At the working temperature (about 175 °C) these values are only slightly lower. The phosphor is also sufficiently durable during the life of the lamp. A serious drawback, however, is that this zinc-cadmium-sulphide phosphor is highly absorbent also for the blue radiation (an extension of the ultra-violet absorption band, which in itself is indispensable). Instead of a lack of red the light from the burning lamp now has a deficit in blue and is greenish in hue. Consequently under this old HPL lamp all practically white objects assume an unpleasant appearance, and this applies in particular to the human skin.

Various means have been tried in an attempt to remedy this failing of the zinc-cadmium-sulphide phosphor. Attempts were made to reduce the absorption of blue by applying the phosphor to the bulb in the form of a finer powder, but this appeared to be impossible without deteriorating the phosphor. For a long time the zinc-cadmium-sulphide phosphor used in the old HPL lamps was also replaced partly by a blue-fluorescing phosphor (ZnS-Ag), but this solution was not entirely satisfactory and

larger bulbs had to be used on account of the admixture being rather sensitive to temperature.

Thus right from the beginning there were reasons for looking for entirely different fluorescent substances suitable for correcting the colour of the light emitted by the HP lamp. This became all the more imperative with the advent of the "TL" lamp, not only because this lamp with its high efficiency and excellent colour rendering made it necessary to lay down more stringent standards, but also because it had thereby been learned that phosphors exist with a quantum efficiency up to about 80%, as compared with the 50% and 25% for the zinc-cadmium-sulphide phosphor.

Of the various phosphors which subsequently became available and which were tried out for use in the HPL lamp four will be discussed here, viz. cadmium borate, calcium phosphate, the group of halophosphates and a group of phosphors with quadrivalent manganese as activator.

Cadmium borate, with divalent manganese as activator, absorbs only the short-wave ultra-violet; thus the emission near 3650 Å is unused. The emission spectrum, however, is very favourable, as is shown by curve *a* in fig. 4, and there is no absorption of visible rays, so that with this phosphor quite acceptable lamps could be made, be it with a somewhat larger bulb because the luminescence is considerably weaker even at 150 °C. Unfortunately there was such a great decline in luminescence during the useful life of the lamp that this phosphor could not be considered for practical use.

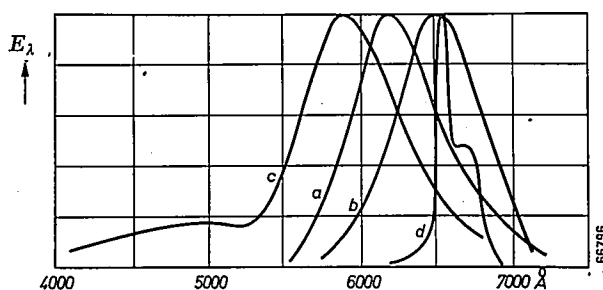


Fig. 4. Spectral energy distribution of four phosphors tried out for their suitability for use in the HPL lamp (maxima all taken to be equally high):

- a) Cadmium borate activated with divalent manganese.
- b) Calcium phosphate activated with cerium and manganese.
- c) Halophosphates activated with antimony and manganese.
- d) Magnesium titanate activated with quadrivalent manganese.

Much the same applies also to calcium phosphate (activated by cerium and manganese). This substance absorbs only the short-wave ultra-violet; in daylight it is white and it shows a beautiful red fluorescence (fig. 4*b*) with a fairly good quantum efficiency

(50%). In regard to temperature-sensitivity this phosphor is even better than cadmium borate, the efficiency remaining absolutely constant up to about 300 °C. But here again no remedy could be found for the rather rapid decline in luminescence during the useful life of the lamp.

The third kind of phosphors mentioned, the halophosphates, are of the general formula $3\text{Ca}_3(\text{PO}_4)_2\text{CaX}_2$, where X stands for chlorine or fluorine. In this case the activators are antimony and manganese. These phosphors have gained much in practical importance through their application in "TL" lamps. Essential for this application is a strong luminescence upon excitation by 2537 Å and sufficient resistance against the dissociating effect of these rays, as also against the effect of the mercury vapour, with which the fluorescent layer in "TL" lamps comes into contact. The halophosphates possess the above-mentioned properties and also retain their fluorescence at high temperatures (this is a property that is not really essential for "TL" lamps because the wall of the "TL" lamp does not reach a temperature higher than 40 °C to 50 °C); further, they are also resistant against dissociation at the high temperatures prevailing in an HPL lamp. They do not, however, answer the specific emission requirements for the HPL lamp: at the best only a spectral distribution can be obtained as drawn in fig. 4c, with a maximum at about 5900 Å. This is not sufficient for improving the red content of the radiation from the HP lamp.

Finally there are the substances containing quadrivalent manganese as activator, several of which have been thoroughly investigated in the Philips Laboratory at Eindhoven⁶⁾. All these show a deep red fluorescence. Magnesium titanate, which belongs to this group of phosphors, appeared to offer the best prospects as regards suitability under the conditions occurring in the HPL lamp. The emission spectrum is given in fig. 4d. The excitation spectrum, unfortunately, is less satisfactory, for, though the rays with wavelength 2537 Å are well absorbed, the quantum efficiency of the conversion of those short-wave rays is practically nil. Attempts were made to remedy this evil by causing the ultra-violet HP radiation to fall first upon a layer of some other suitable phosphor (e.g. cadmium borate) which absorbs only the short-wave rays and converts them into red. However this idea has not been put into practical execution because magnesium titanate also has the drawback

of its fluorescence being too sensitive to temperature: above 100 °C it diminishes rapidly.

Magnesium arsenate

Although magnesium titanate, belonging to the group of Mn^{4+} phosphors, did not answer the requirements, it was this very same group which yielded the phosphor with which the problem of the HPL lamp was ultimately solved, viz. magnesium arsenate⁷⁾.

Having already become familiar with the problems of preparing Mn^{4+} phosphors and with the characteristics of these substances, it was very soon possible, once attention had been drawn to it, to prepare this new phosphor in a form suitable for application to lighting technique.

The properties of this magnesium arsenate^{7,8)} proved to be highly favourable for its application in the HPL lamp. Its fluorescence is bright red.

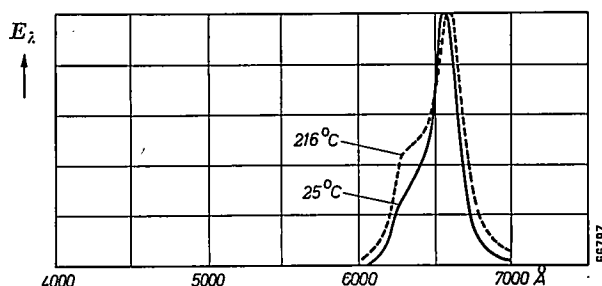


Fig. 5. Spectral energy distribution of magnesium arsenate activated with quadrivalent manganese, at 25 °C and at 216 °C (maxima taken to be equally high).

The spectral distribution of the emission (fig. 5) shows a steep peak at 6560 Å. This phosphor absorbs the whole of the ultra-violet radiation spectrum of the HPL lamp and has a quantum efficiency of about 75 % when excited either with 2537 Å or with 3650 Å (and also with intermediate wavelengths). There is a slight absorption of blue light — considering the lack of any sharp demarcation of the absorption bands of solids this absorption of some blue is inevitable if the whole of the long-wave ultra-violet is to be absorbed — but the resultant faintly yellow colour of the magnesium arsenate in daylight is not troublesome, and, contrary to the case with the old zinc-cadmium-sulphide lamps, there is no question of any green coloration of the resultant light from the HPL lamps in which this new phosphor is used. Another very favourable property of magnesium arsenate

⁷⁾ M. Travnické of Graz (Austria) brought this substance to our notice.

⁸⁾ The investigations into the properties of the new phosphor, as also the first investigation into the conditions for obtaining a high efficiency from it, were carried out in the Philips Laboratory by Dr. F. A. Kröger.

⁶⁾ F. A. Kröger, *Some Aspects of the Luminescence of Solids*, Elsevier Publ. Co., Amsterdam, 1948, in particular pp 57-106.

is the fact that it shows very little sensitivity to temperature, the quantum efficiency still being about 65% at 300 °C (*fig. 6*).

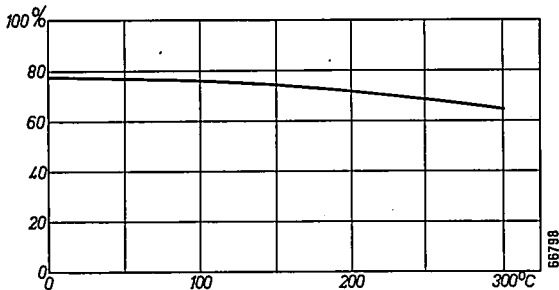


Fig. 6. The quantum efficiency of the magnesium arsenate phosphor upon excitation with 2537 Å, as a function of the temperature.

Chemical behaviour of magnesium arsenate in an HPL lamp

After this summing up of the excellent properties of magnesium arsenate it seems like an anti-climax to have to state that in the beginning this phosphor, like so many others, failed to satisfy the last requirement, namely that of durability. The red content of the light from the first HPL lamps made with magnesium arsenate declined rapidly.

Contrary, however, to the case with other phosphors which came to grief over this stumbling block, a simple means was found of improving the durability of magnesium arsenate. All that was necessary was to replace the nitrogen filling of the bulb of the HPL lamp by carbon dioxide. It is a most remarkable phenomenon that then during the first 20 to 50 burning hours the red content of the light increases, sometimes by a factor of as much as $1\frac{1}{2}$, after which it gradually decreases, but after 2000 burning hours it is still about 80% of the peak value.

Though the mechanism by which CO_2 improves the resistance of the magnesium-arsenate phosphor has not yet been fully explained, it was by fairly logical reasoning that the choice of CO_2 came to be made.

Magnesium is one of the basest metals (i.e. difficult to reduce). It was therefore probable that the decline in the fluorescence of the phosphor is not due to any separation of metal (in this case Mg), as was found to be the case with the other phosphors, but that it is to be ascribed to a reduction to a lower valency of the small amount of Mn^{4+} present (for the best yield of light a composition something like $10 \text{MgO} \cdot \text{As}_2\text{O}_5 \cdot 0.01 \text{Mn}$ is chosen). Chemical analysis confirmed the supposition that the decline in fluorescence of the phosphor is accompanied by a reduction from Mn^{4+} to Mn^{2+} .

Experiments were therefore made with a small addition of oxygen to the nitrogen filling of the bulb of the lamp. It then appeared that (at a bulb temperature of 150 °C to 200 °C) with the addition of 0.3 % to 0.5 % of O_2 and under a nitrogen pressure of 50 cm Hg there was indeed no longer any decline at all in the red content of the light.

However, with such an admixture of oxygen another difficulty arose, viz.: the extremely thin leading-in strips of molybdenum which are fused airtight in the silica for carrying the current through the "pinches" at the ends of the mercury-discharge tube (*fig. 7a*; see also *fig. 2*) tend to oxidize in an atmosphere containing O_2 , thereby expanding and after some time causing the pinches to crack. The higher the temperature at the outward extremity of the molybdenum strip, the more likely is this to occur. With the dimensions of the pinches usual in HP lamps this temperature amounts to about 500 °C, and with a partial oxygen pressure of 0.15 cm Hg (see above) the pinch cracks even after the lamp has been switched on for some tens of hours only.

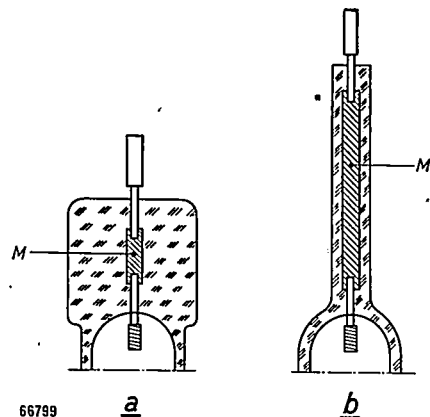


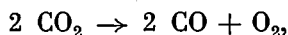
Fig. 7. Construction of the pinch of the discharge tube in the HP and HPL lamps. When the lead is being fused in, it has to be heated up to the softening temperature of the fused silica, i.e. 1600 °C to 1700 °C. Of the few metals capable of withstanding this temperature molybdenum is the most suitable. Since, however, the thermal expansion coefficient of molybdenum is much greater than that of silica, instead of a leading-in wire, use is made of a strip of molybdenum *M*, rolled out extremely thin (13μ thick), which, being readily deformable, adheres to the fused silica in spite of the differences in expansion. *a*) Pinch of normal length (drawn to approximately true size). *b*) The pinch made longer so that the outward extremity of the leading-in strip does not become so hot as in (*a*), thus reducing the rate of oxidation of the molybdenum when oxygen is added to the nitrogen filling of the bulb (the round leads are not sealed airtight in the fused silica and hence oxygen can penetrate from the outside of the tube and reach the molybdenum).

This can be remedied by making the pinch longer (*fig. 7b*). Of course oxidation then still takes place, but at a slower rate because the temperature at the danger point is lower. In this way the durability of the lamp is no longer determined by that of the

pinch construction. HPL lamps made in this manner were quite satisfactory, but their manufacture proved to be too costly because the longer pinches could not be made mechanically; furthermore, the O₂ percentage of the filling is very critical, because if it is slightly too low the yield of light from the phosphor diminishes rapidly and if it is a little on the high side then the leading-in strips oxidize too quickly.

It was then thought that perhaps in itself a partial oxygen pressure much lower than 0.15 cm Hg would suffice to maintain the light yield of the phosphor, and that the "high" filling pressure of 0.15 cm Hg, which proves to be fatal for the molybdenum strips, is only needed on account of the fact that the various metal parts in the lamp selectively "catch" the oxygen and more or less retain it ("getter" action). In that case matters might be improved by doing without the oxygen in the filling of the bulb and using instead an inert gas which, under the influence of the high temperature and possibly also under the influence of the ultra-violet radiation, continuously gives off a little oxygen, just sufficient to prevent the reduction of Mn⁴⁺, and too little to cause any serious oxidation of the molybdenum strips. CO₂ seemed to be suitable for this purpose and, indeed, it yielded the excellent results already mentioned.

Confirmation of the line of reasoning followed is found in the fact that the desired effect is obtained even with only a very low CO₂ pressure, viz. about 0.5 cm Hg. In the case of dissociation of the carbon dioxide to a degree of say 5%, which is plausible, according to the formula



the partial oxygen pressure is then no more than about 0.01 cm Hg.

With an oxygen filling the metal parts can take up only a certain amount of O₂. The larger the volume of the bulb, the smaller will be the resultant reduction of the O₂ pressure, and it may therefore be expected that then a lower initial pressure suffices in order to keep the O₂ pressure above the

minimum required for the phosphor during the desired life-time. This expectation was fully confirmed by a test whereby the O₂ volume was increased by connecting the bulb of the HPL lamp to a large reservoir via a small tube.

It appears that the CO₂ pressure is not at all critical. One can safely increase the pressure to 50 cm Hg. such as is usual for the nitrogen filling of the HP lamps. The fact that the molybdenum strips do not then oxidize too quickly is apparently due to the partial O₂ pressure not rising proportionately with the higher CO₂ pressure: the degree of dissociation of the carbon dioxide decreases with the increasing pressure, as follows qualitatively directly from the reaction equation given above (the volume on the right is 1¹/₂ times that on the left).

Construction and properties of the new HPL lamps

HPL lamps are now being made in two wattages, viz. 80 W and 125 W. *Fig. 8* shows these two lamps and, for comparison, a 150 W "Argenta" incandescent lamp. *Table II* gives the principal data for these lamps, for an HP lamp and for daylight.

As follows from the foregoing general considerations, in aiming at the maximum possible increase of the red content of the light emitted by the HP lamp one's efforts are limited by the fact that for complete absorption of the ultra-violet such thick layers of phosphor would have to be applied that the visible radiation from the mercury discharge would be reduced too much: notwithstanding the gain in the red, the total yield of light from the lamp would then be reduced. Now the thickness of the phosphor layer has been so chosen that the gain in the red and the loss over the entire visible spectrum just about compensate each other; in other words, the efficiency of the new HPL lamp is practically equal to that of the HP lamp.

The red content of the light given in the table and serving as a rough measure for the improvement reached in the colour rendering is the sum percentage of the contributions to the luminous flux in the seventh and eighth blocks. For a better

Table II. Properties of the new HPL lamp, compared with those of an HP lamp, an incandescent lamp and daylight.

	HPL 80 W	HPL 125 W	HP 125 W	150 W incand. lamp (2850 °K)	Daylight	
Luminous flux (lm)	3000	5000	5000	2000	—	
Efficiency (lm/W)	37,5	40	40	13	—	
Percentage of red	8,8	7,5	1,3	18	11	
Colour point in the colour triangle.	$\left\{ \begin{array}{l} x = \\ y = \end{array} \right.$	0,390	0,385	0,319	0,448	0,320
		0,434	0,425	0,405	0,407	0,330
Luminance (cd/cm ²)	5	8	25	3	—	
Diameter of bulb (mm)	80	90	90	80	—	

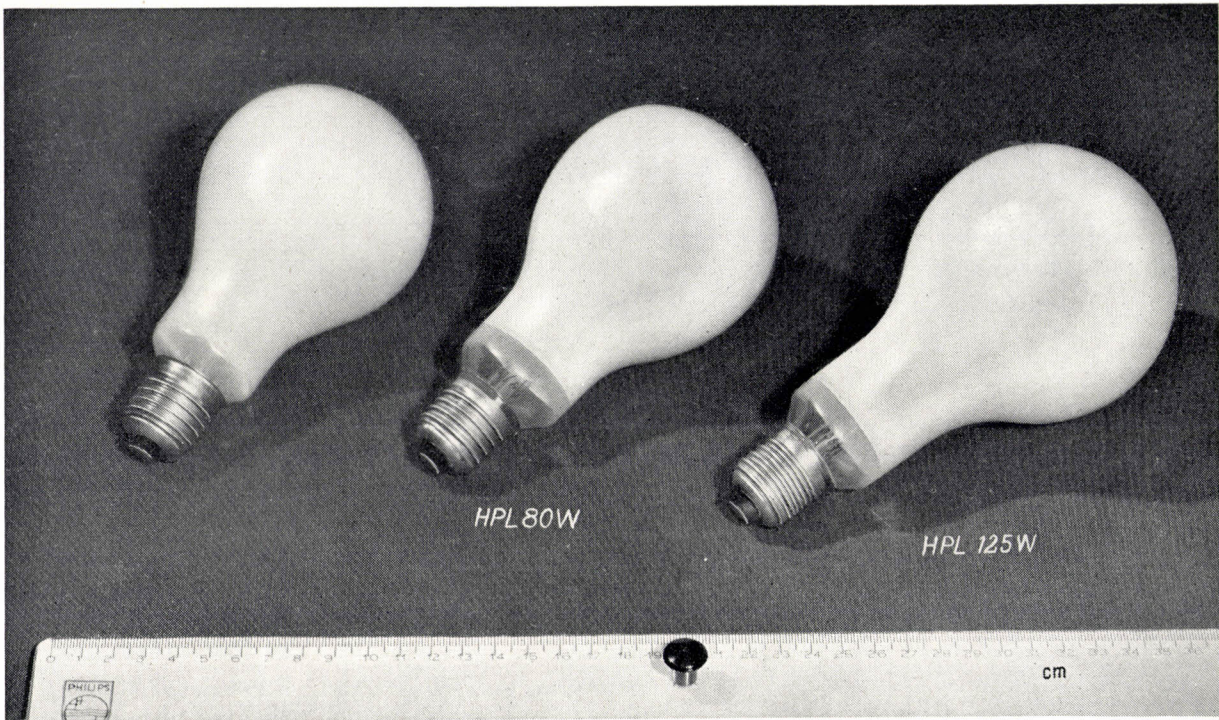


Fig. 8. The new HPL 80 W and HPL 125 W lamps coated on the inside with magnesium-arsenate phosphor. When not alight their colour is practically white. For comparison an "Argenta" 150 W incandescent lamp is also shown.

judgment of the colour rendering *table III* gives the complete block diagram distribution for the radiation of the HPL 80 W and the HPL 125 W, together with the distributions for the HP lamp and for daylight as already given in *table I* (but there expressed in luminous flux percentages) and also those for the incandescent lamp and for a "TL" lamp ("white" type).

this light. Further, with the aid of inconspicuous fittings the light from the HPL lamp can be just as easily concentrated and directed as that from a frosted or opalised incandescent lamp. For this reason in a number of cases the HPL lamp may be preferred to the "TL" lamp, the application of which for street lighting is now being tried out in various places.

Table III. Block distribution (relative luminous flux contributions) of the spectrum of the new HPL lamp, compared with that of the HP lamp, daylight, an incandescent lamp and a "TL" lamp ("white" type).

	4000	4200	4400	4600	5100	5600	6100	6600	7200
	1	2	3	4	5	6	7	8	
HPL 80 W	0,008	0,37	0,025	0,62	49,8	40,5	8,0	0,76	
HPL 125 W	0,008	0,42	0,04	0,54	47,0	44,4	7,0	0,65	
HP 125 W	0,02	0,76	0,14	1,66	55,1	41,0	1,2	0,09	
Average daylight	0,027	0,23	0,80	10,8	40,8	36,2	10,3	0,73	
150W incand. lamp (2850°K)	0,006	0,060	0,25	5,47	33,4	42,6	16,7	1,57	
"TL" 40 W ("white")	0,010	0,35	0,30	4,80	38,0	43,0	13,0	0,43	

An important field of application for the HPL lamp is the lighting of streets and squares in towns. With the high efficiency of these lamps a high level of illumination can be reached in a very economical way and the colour rendering is such that there is no longer any question of the human skin assuming an unpleasant hue under

In this connection something has to be said about the ballasts required for the HP and HPL lamps.

Lamps which are to be installed separately are usually (when a mains voltage of 220 V~ is available) connected in series with a choke (*fig. 9a*). Upon the lamp being switched on, thus while it is in the cold state, a current flows through it

which is about $1\frac{1}{2}$ times the normal working current. This starting current is strong enough — with the usual nitrogen or carbon dioxide filling of the bulb under a pressure of about 50 cm Hg — for the discharge tube to be gradually heated and the discharge to reach full strength in 3 to 4 minutes, during which the voltage across the lamp rises and the current drops. The power factor ($\cos \varphi$) of the lamp with choke is about 0.5.

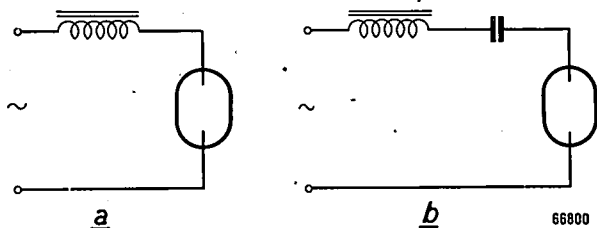


Fig. 9. As ballast for the HP and HPL lamps either a choke (a) or a combination of a choke and a capacitor (b) can be used. In the latter case the current is about just as much advanced in phase with respect to the voltage as it is lagging in the case (a). The starting current immediately after switching on the lamp is much lower in case (b) than in case (a).

This low power factor is no objection for single lamps, but in street lighting often whole rows of lamps have to be connected to one branch of the distributing network and in such a case a higher $\cos \varphi$ value is desired. This can be obtained by connecting half the number of lamps to a different ballast, viz. a combination of a choke and a capacitor (fig. 9b). The current is then about just as much advanced in phase with respect to the voltage as it is lagging in the circuit of fig. 9a. This brings the power factor for the whole installation to about 1. In the circuit of fig. 9b however the starting current is no stronger than the working current, and therefore, in order to ensure that the lamp will burn at full strength within a reasonable time after switching on, allowing also for severe frost, the

discharge tube has to be thermally more insulated, i.e. the pressure of the bulb filling has to be made lower; for such a case a carbon dioxide pressure of about 20 cm Hg is quite suitable.

For this application of the HPL lamp it is therefore very convenient that the pressure of the carbon dioxide is not at all critical for maintaining the luminescence of the magnesium arsenate phosphor.

Summary. The high-pressure mercury lamp (HP) has a very good specific light yield, viz. 35 to 40 lm/W, but the colour rendering under the light of this lamp is poor, mainly due to a deficit in the red. The colour rendering can be greatly improved by converting the useless ultra-violet radiation from the mercury discharge into red light by means of a fluorescent substance. For the HPL lamp developed on this principle the fluorescent substance first used was zinc cadmium sulphide activated with copper. Upon excitation with the ultra-violet rays this substance shows an orange-red fluorescence with a reasonable quantum efficiency, it retains its fluorescence also at the temperature of about 150°C to which it is exposed when applied to the inside of the bulb of an HP lamp, and while the lamp is alight this substance undergoes only a very gradual dissociation. A drawback however is that it absorbs the blue, so that the resultant colour rendering is nevertheless unsatisfactory. After a number of unsuccessful attempts to find more suitable phosphors, a very good solution has now been reached by employing magnesium arsenate activated with quadrivalent manganese. The quantum efficiency of this bright-red fluorescing phosphor is even appreciably higher than that of the phosphor first mentioned (viz. 75% upon excitation either with 2537 Å or with 3650 Å) and less sensitive to temperature, whilst the absorption of blue is so slight as to be practically of no effect, so that the colour rendering is quite satisfactory. At first this phosphor was not sufficiently resistant to dissociation, but this has been remedied and excellent resistance obtained by filling the bulb of the HPL lamp with carbon dioxide instead of the nitrogen commonly used for HP lamps. The action of the carbon dioxide in this respect is to be ascribed to a little oxygen being given off which prevents a reduction from quadrivalent to divalent manganese in the phosphor. This effect can also be obtained by the direct admixture of a little oxygen to the normal nitrogen filling, but then there is a prohibitively rapid oxidation of the molybdenum leading-in strips of the discharge tube. The carbon dioxide pressure can be varied between 0.5 and 50 cm Hg, thus making it possible to adjust the thermal insulation of the discharge tube according to the starting current available. This possibility is of practical importance for the application of HPL lamps for street lighting.