In the summer of 1906 there appeared in the Annalen der Physik a paper by Küch and Retschinsky on the production of light by a discharge in mercury vapour under high pressure. The discharge took place in a silica tube with two pools of mercury acting as electrodes (fig. 1). Ignition was brought about by tilting the tube, so that the electrodes were connected by a thread of liquid mercury; the breaking of the connection caused an arc to be set up. By adjusting the power fed in and the heat dissipation of the electrode spaces, Küch and Retschinsky obtained vapour pressures of several atmospheres in the tube, whereby a luminous efficiency of about 50 lumen/watt was reached. This was the first time that light had been produced with high efficiency from a gas discharge - although as yet this light source was of no immediate use for the purposes of illumination. With the low pressure gas discharges, known hitherto, it had not proved possible to produce light with efficiencies better than a few lumen/watt (see also fig. 2). On account of the high proportion of ultraviolet in their radiation, the first high-pressure mercury vapour lamps were used mainly for medical purposes, as "sun-ray lamps".

Now, fifty years after this pioneer work, it is of interest to trace the further development of the high-pressure mercury discharge. We may divide this period roughly into halves: the first half brought forth but few changes in the original lamp, while the second an intensive development took place which has led to the production of many widely differing types of lamps.

The period of intensive development started with the introduction of the oxide cathode and the addition of noble gases to the mercury vapour. The oxide cathode has been known since 1903 (Wehnelt) and had been employed in vacuum tubes, but it was not until about 1930 that the possibility of its employment in the high-pressure mercury vapour lamp became apparent. Discharges...
in mercury vapour under low pressure with additions of noble gases had been known since about 1910 (Claude and others). These two innovations made it possible to ignite the high-pressure mercury vapour lamp without the tilting operation and, with suitable geometry (combined where necessary with auxiliary electrodes or other artefacts), the lamp could be made to ignite from a mains voltage of 220 V. In this way it became practicable to use the lamp for lighting purposes, especially the lighting of streets, open spaces, factory sheds and the like, where there was a need for a light source with very high efficiency (incandescent lamps can reach only about 15 lm/W) and where, at that time, the poor colour rendering of its light was not regarded as a serious objection.

An important feature of the new lamps was that the amount of mercury introduced into the envelope was limited to that which would just be completely vaporized once the desired pressure had been reached, the vaporization taking place as the lamp warmed up. This prevented the vapour pressure rising to an excessive value should the mains voltage or ambient temperature become too high.

The first high-pressure mercury vapour lamps for lighting purposes were made of hard glass with a high softening point (of the order of 700 °C) and not of silica as used in the lamp developed by Küch and Retschinsky. The reason was not merely the high price of silica, but also the problem of the connections through the wall of the tube, a basic and recurring problem in the history of this type of lamp. The method used by Küch and Retschinsky, viz. ground conical holes in which the terminals made a tight fit, was not suitable for a commercial product and the fusing of wires into silica was still a matter of difficulty in the 1930's.

The power of one type of these high pressure mercury lamps (type HO) [MA/V]3), which were supplied from the mains via a choke coil, amounted to about 400 W and the pressure inside them to about 1 atm; the actual discharge tube was enclosed in an outer envelope. In this way the lamp was made easier to handle and, when used in the open air, the discharge tube was protected against wind, so that the warming-up process and the building-up of the mercury vapour pressure were not interfered with.

In the further development of the high-pressure mercury discharge the laboratories of the various lamp factories took diverging paths. One point was of great importance for the line of development followed by Philips: the appreciation of the fact 4) that the luminous efficiency η of a high-pressure mercury discharge, is dependent in the first instance on P, the power loading per cm of arc length, and only slightly dependent on the tube diameter and the vapour pressure once the latter has exceeded a certain value. η increases with P in the manner shown in fig. 3.

This behaviour is a consequence of the contraction of the discharge. Apart from the pressure, which remains constant throughout the tube, it is the temperature that determines excitation and ionization in the high-pressure discharge, in accordance with the equations of Boltzmann and Saha (see 4) or 2)). The temperature decreases from the axis of the tube towards the wall, owing to dissipation of heat to the surroundings. For these reasons the discharge mainly takes place in the central portion of the tube, where the temperature is of the order of 6000 °K. As a result of this contraction of the discharge, the losses are largely restricted to heat conduction losses, these being determined by the difference of temperature between the centre and the wall. If we call the conduction losses per cm length A, then a power P — A per cm of tube length leaves the discharge in the form of radiation. Of this quantity a certain fraction g is absorbed in the mercury vapour between the contracted discharge and the wall, in the tube wall itself and in the outside air (which absorbs, for example, the ozone-forming radiation

3) In this article, lamp types are designated first by the Philips code letters and then, in square brackets, by the code letters used in British territories and certain other countries.

of wavelength of 1850 Å. Hence, the measured radiation per cm of tube length, will be

\[ S = (1 - g) (P - A). \quad (1) \]

In fig. 4, S is plotted against P for a series of high-pressure mercury discharges in silica tubes. It will be seen that the points fit equation (1) very closely.

![Graph](image)

Fig. 4. Total radiation S per cm of arc length from the high-pressure mercury vapour discharge, as function of P, the power load per cm, measured on a series of silica discharge lamps. The tube diameter was 2.7 cm in all cases. The different points (+, ø, etc) in the graph indicate a sub-series of measurements on tubes differing in the quantity of mercury they contained per cm of their length. Similar series of measurements were performed on tubes with diameters of 0.92 cm and 0.33 cm, these producing roughly the same curve.

the heat conduction loss \( A = 10 \ W/cm \) being fairly constant (i.e. independent of the power \( P \), the tube diameter and the pressure) and the factor \( 1-g \) being 0.72. Consequently \( \eta \) the luminous efficiency, which is roughly speaking proportional to \( S/P \), is also to a first approximation proportional to \( (1-g) (1-A/P) \); hence, as \( P \) increases, \( \eta \) rises first rapidly and then less steeply. This agrees well with the curve obtained by measurement in fig. 3.

The following may serve to show that \( A \), the heat conduction loss from the contracted discharge per cm of tube length is largely independent of the power \( P \), the tube diameter and the pressure. If \( T \) is the temperature and \( \lambda \) the thermal conductivity, then the heat conducted away per second through an imaginary cylinder at a distance \( r \) from the axis will be:

\[ A = -2\pi r \lambda \ \frac{dT}{dr}. \quad (2) \]

The temperature of the discharge itself varies very little from one discharge to another, since \( T \) occurs only as an exponent of \( e \) in the Boltzmann equation; hence a small variation in \( T \) corresponds to a large variation of the radiation. As a consequence, the quantity \( r dT/dr \) is practically the same at corresponding points in different discharges (in tubes of diameters \( a_1 \), \( a_2 \), for example, points \( r_1 \) and \( r_2 \) are corresponding if \( r_1/a_1 = r_2/a_2 \)), since the wall temperature may be taken to be approximately the same in all cases. Further, \( \lambda \) is independent of the pressure and also independent of \( P \), since the latter can only exercise an influence on \( \lambda \) through \( T \) which, as we have seen, varies only slightly from one discharge to another. Hence \( A \) is substantially independent of the power \( P \), the tube diameter and the pressure.

From this relationship between \( \eta \) and \( P \) it followed that, for high luminous efficiency, it was advantageous to have a short arc for a given amount of power. It was also clear that very high brightnesses might be attained by increasing the power \( P \) per cm of arc length, for — assuming that the diameter of the discharge remains the same — the power radiated per unit of surface increases more than proportionally to \( P \), owing to the increase in luminous efficiency. This opened up a prospect of new applications inaccessible to the incandescent lamp whose brightness is limited to about 2000 cd/cm² by the melting point of tungsten and whose lifetime is then only some hours or tens of hours.

At first it was attempted to obtain a high value of \( P \) by arranging for the discharge to take place in the centre of a spherical hard glass vessel. However, this turned out to be impracticable in that, with the high power involved, the bulb had to be large in diameter in order to keep the wall temperature within bounds; but then the vapour pressure had to be lower, on account of the danger that the relatively large bulb might explode. This meant a decrease in the contraction of the discharge, and the desired gain in brightness was only partially realised. Moreover, at lower vapour pressures the gradient (voltage drop per cm of discharge length) is smaller, so that in order to develop a large power per cm the current has to be made much heavier; this in its turn created difficulties with regard to the electrodes and seals.

The history of the lamp then took an unexpected turn. In the Philips Laboratory at Eindhoven wires were successfully sealed in silica with the aid of an intermediate glass, thus giving seals suitable for moderate currents. A small high-pressure mercury vapour lamp was designed on this basis, the discharge taking place in a silica tube of capillary form (see fig. 5). The combined problem of wall temperature, tube diameter, pressure and danger of explosion was avoided with this design, inasmuch as the silica tube could be water-cooled. The resulting design was ideal for attaining high degrees of brightness. The pressure of mercury vapour in the capillary can be allowed to become very high indeed (of the order of 100 atm.) and this makes the discharge path, already narrow, even more constricted. The voltage gradient thus becomes very large. In consequence, the load per cm

can be made very high for a reasonable current value (about 1 A) which will not cause too much trouble with the seals and electrodes. Lamps of this type (SP) have been developed for cinema projectors amongst other purposes; brightnesses of about 50,000 cd/cm² are attained in the axis of the lamp, the diameter of the capillary being 2 mm. With experimental forms brightnesses of 180,000 cd/cm² — greater than that of the sun 7) — have been attained. A further advantage of the very high vapour pressures and current densities in super-pressure lamps is the strong continuum in the spectrum of their radiation, this resulting in light of a colour rendering that is a marked improvement on that given by high-pressure mercury vapour lamps with pressures of the order of 1 atm.

It may be mentioned that the capillary form of the original SP lamp was also of importance in regard to the design of the seals. The lamp was filled with an excess of mercury which, on account of capillarity, remained lodged as a drop at each end while the lamp was burning and which ensured a uniform and relatively low temperature at the critical regions adjoining the seals. The tungsten electrodes just protrude from the drops of mercury (fig. 5). Owing to the very high pressure inside the tube, the electrodes evaporated only slowly in spite of their high temperature.

Later there was a change to another, simpler, form of lead-in through silica, invented by Gabor 8). A molybdenum ribbon, less than 20 μ thick and a few mm wide, is fused directly into the silica. The ribbon is sufficiently ductile to accomodate the difference in the expansions of molybdenum and quartz glass. This method later allowed the making of water-cooled capillary lamps containing a precise quantity of mercury which was vaporized almost completely whilst the lamp was burning 9).

Fairly heavy currents can be passed through the silica wall by fusing in a number of molybdenum ribbons side by side. On this basis Rompe and Thouret 10) constructed spherical silica lamps of very high brightness; this, then, is the idea mentioned on the previous page, which was difficult to realize in hard glass. In the war years these lamps, known as “compact source” lamps (CS lamps) [ME], were further developed in Germany and England for searchlights. They are still being made today in various power ratings and arc-lengths for a number of special purposes.

Let us now return to the development of high-pressure mercury vapour lamps for general lighting purposes. The hard glass 400 W lamps, with vapour pressures of about 1 atm., as described earlier, had to some extent been adopted for public lighting installations. There was a demand for smaller units: 250 W and even 150 W lamps appeared, but for these wattages the advantage over the incandescent lamp in the matter of efficiency was less marked. The reason for this is that if, in view of the lower power, the arc-length is shortened in order to step up P and hence also η, in accordance with fig. 3, the total arc voltage becomes rather low in comparison with the mains voltage and there are excessive losses in the ballast and at the electrodes. One cannot avoid this by raising the voltage per cm of arc-length, since the reduction in diameter and/or increase of pressure that this would necessitate would mean high wall temperatures and the danger of explosion. One must therefore be content with a relatively long arc, a lower P and a lower η.

The problem was then attacked from a different point of view, basing design considerations on the super high pressure lamp. The use of a fused silica envelope for the latter made water-cooling possible by virtue of the low coefficient of expansion. This kind of cooling cannot of course be considered for general lighting purposes. Even without forced cooling, however, silica has the advantage over hard glass that its softening temperature is considerably higher.

It was thus possible to take the SP lamp, omit the water-cooling, and increase the internal diameter of the silica capillary slightly (to 4 mm), thereby dissipating a P of 40 - 50 W/cm (in the super-pressure lamps 400 - 1000 W/cm were dissipated). A lamp of this type 11) [HP300] [MB/U300]

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having an arc of length 18 mm and a mercury vapour pressure of about 20 atm. consumed 75 W and gave a luminous flux of 3000 lumen, so that its efficiency was 40 lm/W. The arc voltage was 230 V and the lamp was supplied from a transformer with an open-circuit voltage of 410 V. The tungsten lead-in wires were fused into the silica with various kinds of intermediate glasses. The silica tube was accommodated in an outer bulb having the same shape as an incandescent lamp.

In the further development of these lamps even more water was put into the wine by using the same principle for lamps to operate on an open-circuit voltage of 220 V. For this purpose the arc voltage had necessarily to fall to 120 V, and to this end the diameter was again increased somewhat and the pressure lowered. Moreover, the arc had to be made rather longer, because the blackening at the tube ends arising during the lifetime of the lamp caused too much loss of luminous flux. Nevertheless, as regards power load per cm and efficiency, these high pressure lamps were considerably superior to the older ones made of hard glass, so much superior in fact that even the larger types of the old lamp were largely supplanted by the high pressure lamps now developed for higher power ratings (125 W, 250 W, 400 W, and 1000 W).

The small dimensions of the high pressure quartz lamps did much to open up the terrain of interior lighting for the high-pressure mercury vapour lamp. Hard glass mercury vapour lamps using an incandescent filament as stabilising element in place of the choke had already been used in England. The high power of the mercury vapour lamp by itself produced units that were too big for practical purposes but by adding a series-connected incandescent filament to the smaller quartz lamp accommodated in the existing outer envelope, a lamp (type ML) [MBT/U] of convenient size was produced which can be connected to the mains without a ballast device 12). On account of the low efficiency of the incandescent filament, the total efficiency drops to about 20 lm/W; however the incandescent filament makes a useful contribution to the light emitted and the lamp as a whole gives quite a satisfactory colour-rendering, and can therefore be used for offices, public halls, and other utility areas requiring a high illumination level.

A further advantage offered by the quartz HP lamp was that it radiated the ultra-violet portions of the spectrum, hitherto absorbed by the walls of hard glass lamps. By giving the ML lamp just described an outer envelope that transmitted ultra-violet rays; it was possible to use it as a simple and convenient source for medical irradiation purposes (MLU lamps) [MBTR/U]. Larger units for these purposes were equipped with special lamps of the high-pressure type having no outer envelope and provided with a choke as ballast; they had power ratings of 500 and 250 W ("Biosol"). These, then, are the modern counterparts of the lamp developed by Küh and Retschinsky fifty years ago and used for the same purpose.

Also of interest is the development whereby the ultraviolet radiation emitted by the discharge tube was exploited for the production of visible light; for this purpose, the inner walls of the outer envelope were covered with fluorescent powder (HPL lamps) [MBF]. This has improved the colour rendering to such an extent that the lamps have already largely supplanted the original HP lamps for street lighting purposes. The fluorescent substances employed in these lamps have been the object of intensive research. Recently red fluorescing arsenates and germanates have been put to use 14).

The HPW lamp [MBW/U] may be regarded as the opposite to the fluorescent lamp; in this case, the mercury discharge tube is accommodated in an outer envelope that transmits no visible light but only radiation of the near ultra-violet. These lamps are used, amongst other things, for the fluorescent detection of forgeries and for special fluorescent effects on the stage, in advertising, in shop windows, and so on.

In conclusion mention may be made of a lamp type which, lying outside the mainstream of development of the high-pressure mercury vapour lamp, exploits its elongated form and particular kind of radiation. This is the photo-printing lamp. Sensitized paper, running beneath such a lamp of length somewhat greater than the paper breadth, is exposed rapidly and evenly. If a moderate paper speed is acceptable, the load per cm need only be relatively low and hence one can revert to the use of hard glass. Versions of such lamps exist in both

13) W. H. Le Maréchal and J. N. Aldington, Brit. Pat. No. 447428, 1936. Once the arc voltage has reached its full value, part of the incandescent filament is short-circuited by a bi-metallic relay.
Fig. 6. A varied collection of lamps of the high-pressure mercury vapour family. In addition to the types mentioned in the text, three other lamps are shown: the HPK lamp, i.e. a high pressure discharge tube without an outer envelope, used as a source of ultraviolet radiation of very short wavelength (2537 and 1850 Å), and the HPR [MBR/U] and HPLR [MBFR] lamps, which are provided with an internal reflector.

Fig. 7. Mercury vapour lamps which work under very high pressures. From left to right: a compact source lamp rated at 150 W; a 500 W super-pressure lamp (in reflector) for A.C. supply and water-cooling; a 900 W super-pressure lamp for forced air-cooling; a 1600 W super-pressure lamp for DC supply and water-cooling. The last three types are used for laboratory purposes, for cloud-height meters on airfields and for cinema projectors respectively.

hard glass (HOG) [MB/U] and quartz (HOK) [MB/U], and of various dimensions and power ratings.

It will thus be seen that the lamp invented by Küch and Retschinsky has given birth to a whole family of high-pressure mercury vapour lamps - suitable for all kinds of different applications. Photographs of some of the lamps are reproduced in figs. 6 and 7. Development continues in the direction of higher power ratings and higher brightness values and of special forms such as lamps having built-in reflectors, and so on.

Summary. Review of the development of different types of high-pressure mercury vapour lamps from the lamp designed by Küch and Retschinsky in 1906 and used as a “sunray lamp”. The relationship between luminous efficiency (and brightness) and the power load per cm of arc-length is discussed, this being fundamental in the design of super pressure lamps with their extremely high brightness values: up to 180000 cd/cm². There follows a discussion of the considerations that led to high pressure lamps and their derivatives, the ML [MBT/U], HPL [MBF] and HPW [MBW/U] lamps. Mention is also made of the “Biosol”, the HOK [MB/U] and HOG [MA/U] photo-printing lamps and the spherical “compact source” lamps.