RECENT IMPROVEMENTS IN SODIUM LAMPS

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Introduction

The development of sodium lamps in recent years has led to marked improvements in their luminous efficiency and to a much smaller decline in luminous flux during the life of the lamp. Better thermal insulation largely accounts for the higher efficiency; the more constant light output has been achieved by making the discharge tube from a new kind of glass, which is less susceptible to attack by sodium, and by improving its design.

Until recently the only type of sodium lamp in common use had a detachable vacuum jacket (Dewar flask) for thermal insulation (see *fig. 1a* and *b*). An advantage of this construction is that the old vacuum jacket can be used again when it becomes necessary to replace the discharge tube.

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Although this type proved satisfactory for many years, and is still widely used, it has certain practical disadvantages. The first is the increasing absorption of light by the dust and dirt accumulated on the vacuum jacket, not merely on the outside but on the inside too. The latter is due to the far from hermetic seal between lamp and vacuum jacket. Every time the lamp heats up and cools down again, air is expelled and then again drawn into the jacket, bringing dirt with it.

A second drawback is the gradual decline in the thermal insulation provided by the vacuum jacket, owing to deterioration of the vacuum. Unlike the accumulation of dirt, this trouble is not immediately perceptible, but it can seriously impair the efficiency of the lamp, whether old or new.

To avoid these difficulties, designs were introduced some years ago in which the discharge tube was hermetically sealed within the insulating

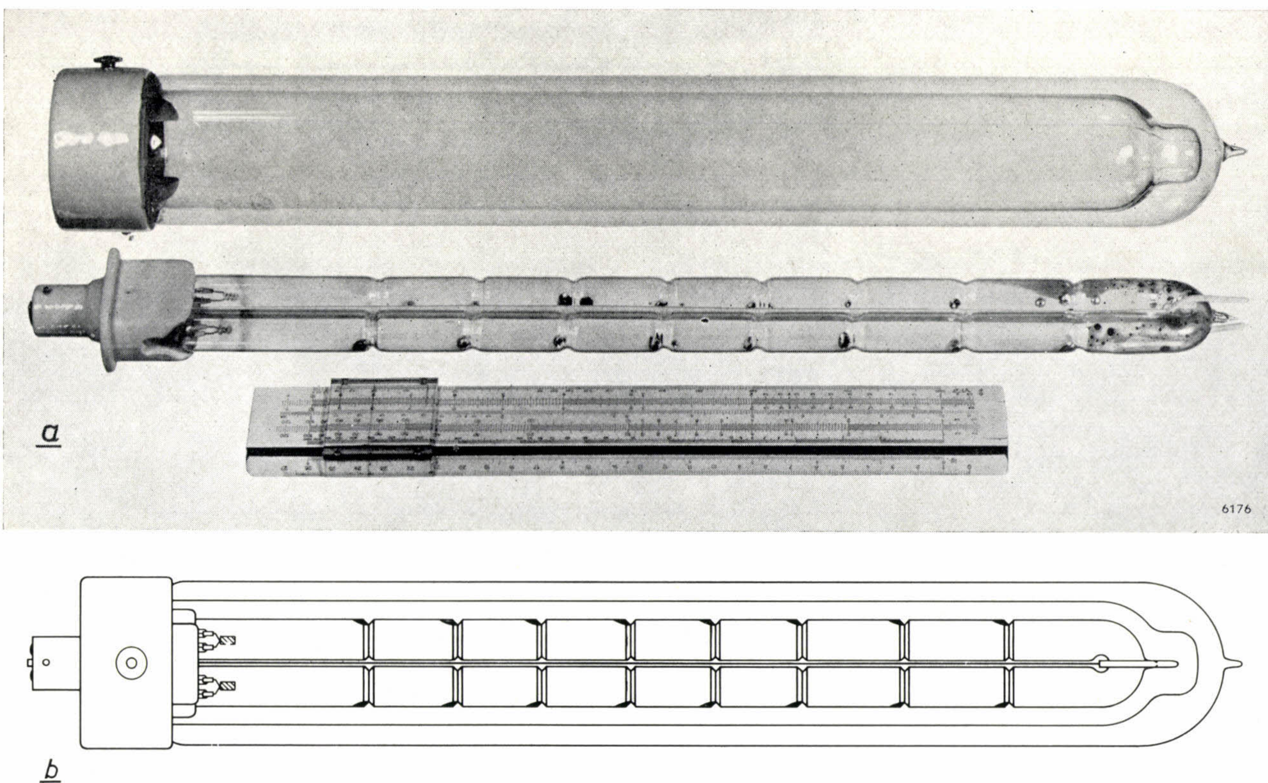

Fig. 1. *a*) Photograph and *b*) cross-section of a type SO 140 W sodium lamp. The U-shaped discharge tube is enclosed in a detachable vacuum jacket.

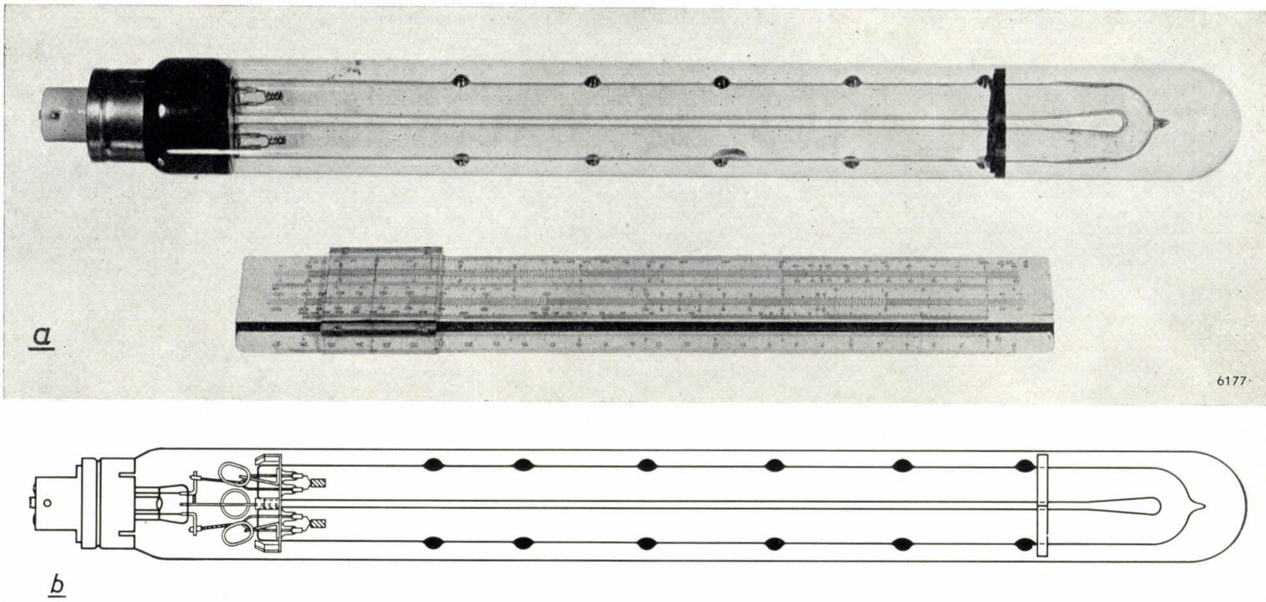

Fig. 2. *a*) Photograph and *b*) cross-section of an integral type SO 140 W sodium lamp, with single-walled non-detachable vacuum jacket. The discharge tube contains protuberances for holding the sodium in place.

jacket. This idea was by no means new, "integral" lamps of this kind having been marketed as long ago as the 'thirties [1]). It is only in recent years, however, that full benefit has been derived from the advantages of this more expensive construction, new techniques having made it possible to achieve higher efficiencies and a more constant luminous flux.

In this "integral" type of lamp, marketed by Philips in a more modern form in 1958, the separate double-walled vacuum jacket was replaced by a single-walled tubular envelope in which the discharge tube was permanently mounted. The space between discharge tube and envelope was evacuated. A modern gettering method made it possible to maintain the high vacuum throughout the life of the lamp. The discharge tube was provided with small protuberances for containing the sodium (*fig. 2a* and *b*) [2]). A range of these lamps was developed for ratings of 45, 60, 85 and 140 W. Lamps having a detachable vacuum jacket were immediately replaceable by lamps of the new type, giving a much more constant luminous flux.

In the further development of the integral sodium lamp it was found that a somewhat more complicated design offered even greater gains, both as regards efficiency and constancy of luminous flux. As a result of better thermal insulation, for example, it proved possible to achieve, and indeed exceed, the unprecedented efficiency of 100 lm/W in a sodium lamp suitable for practical use.

The improved thermal insulation was obtained by means of a separate glass "sleeve" fitted around the U-shaped discharge tube inside the evacuated bulb (*fig. 3a* and *b*). This sleeve radiates part of the heat emanating from the discharge tube back into the interior [3]).

In the lamps illustrated in fig. 2 the outer bulb also radiated energy back to the discharge tube. With the double-walled form shown in fig. 3, however, the effect is considerably greater, owing to the fact that the reflecting glass wall (of the sleeve) can get hotter than in the single-walled construction. Consequently the heat loss is smaller and the efficiency higher. This improved design is used in lamps rated for 45, 60, 85, 140 and 200 W, which were first marketed in 1960 under the type designation SOI.

Table I surveys the luminous efficiencies obtained with sodium lamps in the forms introduced in 1956, 1958 and 1960. The figures relate to 140 W lamps.

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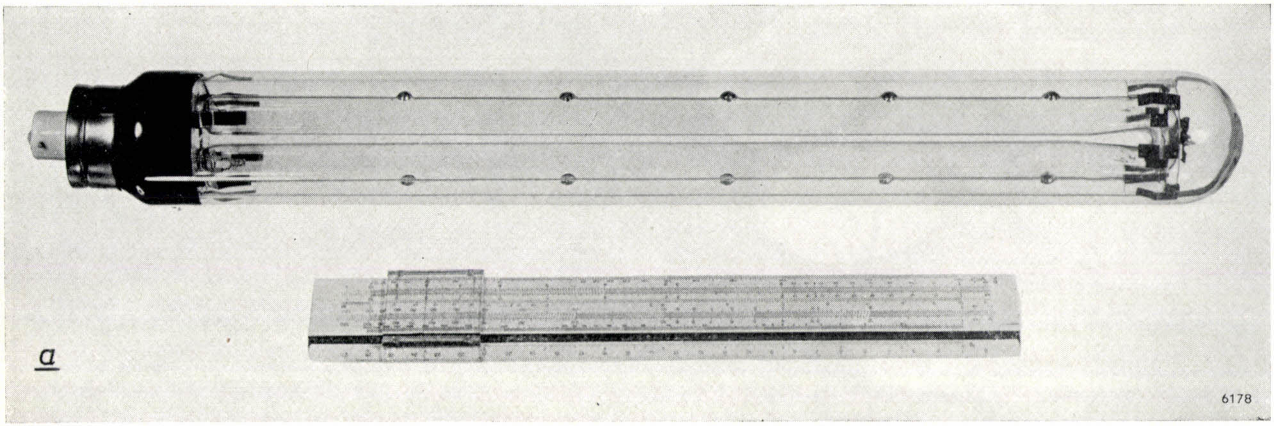
[1]) W. Uyterhoeven, Elektrische Gasentladungslampen, Springer, Berlin 1938, p. 216.

[2]) For further particulars of this type of lamp, see W. Verwey and M. H. A. van de Weijer, New sodium lamps, Communic. P-59.22 of the 14th Session of the International Commission on Illumination, Brussels 1959.

[3]) In 1955 the (British) General Electric Company brought out a sodium lamp with a narrow sleeve fitted around each limb of the U-shaped discharge tube.



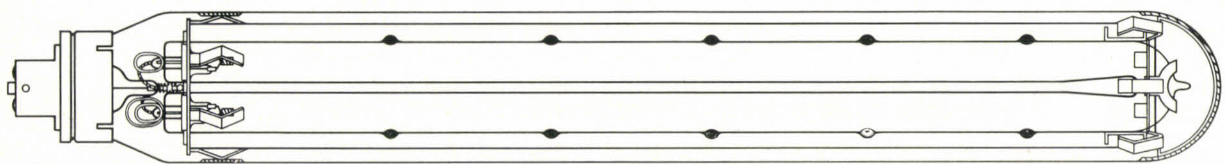


Fig. 3. *a*) Photograph and *b*) cross-section of a type SOI 140 W sodium lamp, with vacuum jacket and protuberances as in fig. 2. A sleeve for improving the thermal insulation surrounds the discharge tube.

Table I. Luminous efficiency of 140 W sodium lamps in designs of recent years.

Year	1956	1958	1960
Design	discharge tube in detachable vacuum jacket	discharge tube in single-walled vacuum jacket	discharge tube with sleeve in vacuum jacket
Luminous efficiency (lm/W)			
after 100 h	79	82	100
after 4000 h	52 *)	68	88

*) In a clean vacuum jacket.

To explain this development and give some idea of the further prospects of the sodium lamp, we must go somewhat deeper into the various factors governing the luminous flux, its decline during operation, and the life of the lamp. Principal among these factors are:

1) the thermal insulation around the discharge tube,
2) the rare gas added (for initiating and maintaining the discharge),
3) the shape and size of the discharge tube,
4) the composition of the glass of which the discharge tube is made.

Effect of thermal insulation on luminous efficiency and luminous flux

The operating principle of the sodium lamp is to excite as efficiently as possible the resonance radiation of sodium (wavelengths 589.0 and 589.6 nanometres). (1 nanometre (nm) $= 10^{-9}$ m.)

The luminous efficiency is closely dependent on the vapour pressure of the sodium. Since all sodium lamps operate with saturated sodium vapour, the vapour pressure is determined by the temperature of the discharge tube. If the vapour pressure is too low (temperature too low), the number of sodium atoms capable of being excited is too small. If the vapour pressure is too high, self-absorption predominates, i.e. the sodium atoms absorb too much of the resonance radiation themselves. There is consequently one optimum vapour pressure, and that amounts to roughly 4×10^{-3} torr (1 torr = 1 mm Hg), corresponding to a tube temperature of about 270 °C [4]).

The temperature of the discharge tube is governed on the one hand by the power consumed, and on the other by the thermal insulation. Assuming that the same tube temperature of, say, 270 °C is desirable in all forms of sodium lamp, this means that if the thermal insulation is changed the power consumption must also be changed in order to maintain the optimum temperature: improved insulation calls for less power, and vice versa. In comparing the properties of particular lamp constructions, we take each lamp at its op-

[4]) Uyterhoeven, loc. cit. p. 205. Other lamp parameters affect this optimum temperature, e.g. the pressure of the added rare gas (see p. 252 of this article). This explains why other optimum values are sometimes mentioned in the literature.

timum working point. The construction with the best thermal insulation then has the highest luminous efficiency. To obtain good thermal insulation it is necessary to take measures to counteract losses due to convection and conduction as well as the total loss due to radiation.

Convection and conduction losses depend primarily on the vacuum around the discharge tube. In *fig. 4a* and *b* it can be seen how the efficiency η and the optimum power P depend on the residual pressure p_0 in the vacuum jacket when the lamps are not exposed to wind and when they are. The graph shows clearly that the vacuum inside the jacket has to meet high requirements. It is maintained by a barium film deposited on the inside of the outer bulb. Practically all the gases gradually released during operation are removed by chemical combination with the barium. The film is of course deposited at a position where it does not obstruct the emission of light.

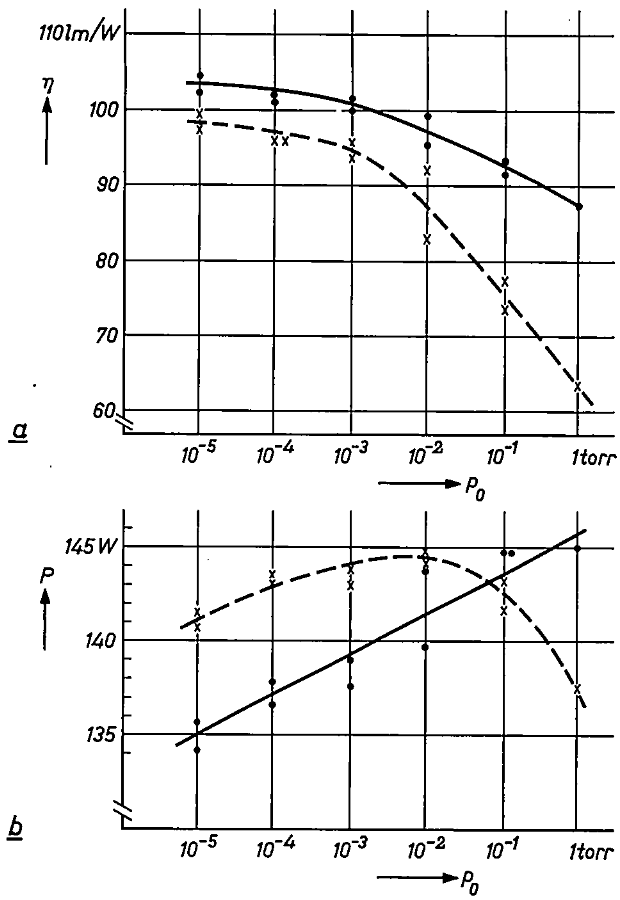


Fig. 4. *a*) Luminous efficiency η, and *b*) optimum power consumption P, of a sodium lamp (type SOI 140 W), as a function of the pressure p_0 of the gas (argon) in the outer bulb. The solid curves relate to operation out of the wind, the broken curves to exposure to wind.

The radiation losses can be limited in two ways:

a) Thermal energy radiated by the discharge tube is absorbed by a surrounding jacket. This consequently gets hot and radiates heat back to the discharge tube. The sleeves mentioned work largely along the same lines.

b) Thermal energy radiated by the discharge tube is directly reflected by the surrounding jacket. As we shall see, the discharge tube radiates mainly in the infrared, with a peak at about 5 μ. Since glass reflects only about 14% of radiation at these wavelengths, it is necessary in this case to coat the glass with some substance which is an effective reflector of infrared rays.

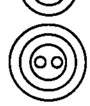
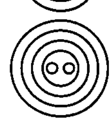
Both methods are discussed below.

Limitation of radiation losses by means of sleeves

The function of the sleeves, then, depends mainly on absorption and to a slight extent on the reflection of infrared radiation. The hot sleeve radiates outwards as well as inwards. The outward radiation can in turn be intercepted by a second sleeve around the first, and so on. Radiation losses can thus be progressively reduced by increasing the number of sleeves. In each case, however, the reduction becomes successively smaller, whereas the absorption of light (2.5% to 3% per sleeve) becomes more and more of a nuisance. These effects are illustrated in *Table II*.

The table clearly demonstrates that, as mentioned above, an improvement in insulation is accompanied by a smaller optimum power loading. As a result of this effect the luminous flux decreases more steeply than it would be increased by the greater efficiency if the power were constant. The

Table II. Influence of the number of sleeves, under optimum load (P_{opt}), on the luminous flux Φ_{la} and the luminous efficiency η_{la} of the lamp (including sleeves) and on the luminous flux Φ_t and efficiency η_t of the discharge tube. The figures relate to a U-shaped discharge tube having an inside diameter of 12 mm and an arc length of 666 mm.

Cross-section	number of sleeves	P_{opt}	lamp		disch. tube alone	
		W	Φ_{la} lm	η_{la} lm/W	Φ_t lm	η_t lm/W
	0	127	11300	89	11600	91.5
	1	96	9400	98	9900	103
	2	80	8150	102	8800	110
	3	70	7200	103	8000	114

sleeves thus improve the efficiency but reduce the luminous flux, and at the same time they make the lamp larger and more fragile. For these reasons no more than one sleeve is used in present-day sodium lamps.

Limitation of radiation losses by means of an infrared-reflective coating

For further improvement of the thermal insulation better results can be expected from the second method mentioned, i.e. the application of a coating around the discharge tube for effectively reflecting the infrared rays. A coating of this kind, applied to the sleeve or to the inside of the outer envelope, must of course readily transmit the sodium light.

The radiant power emitted in the infrared by the discharge tube is roughly equivalent to that from a black body having a temperature of about 545 °K (270 °C). At this temperature the spectral distribution of the radiant power from a black body is as shown in *fig. 5*. The coating to be applied must therefore be an especially good reflector at wavelengths of about 5 μ.

In about 1930 investigations were made at Philips into the usefulness of metallic layers as

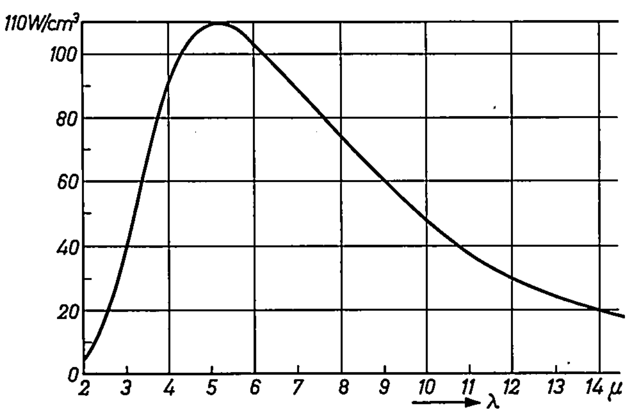


Fig. 5. Spectral distribution of the radiant power from a black body at 545 °K. The power in watts per square centimetre of radiating surface and per centimetre wavelength interval is plotted against the wavelength.

infrared reflectors for sodium lamps [5]). This work has been continued by Kauer of Philips Zentrallaboratorium GmbH, Aachen, and by Van Alphen of Philips Research Laboratories, Eindhoven. Without going into the theory, we shall mention here some of the results of the study made of metallic and metal-oxide layers.

1) *Metallic layers. Fig. 6* shows the reflection coefficient of a layer of gold at a wavelength of 5.29 μ

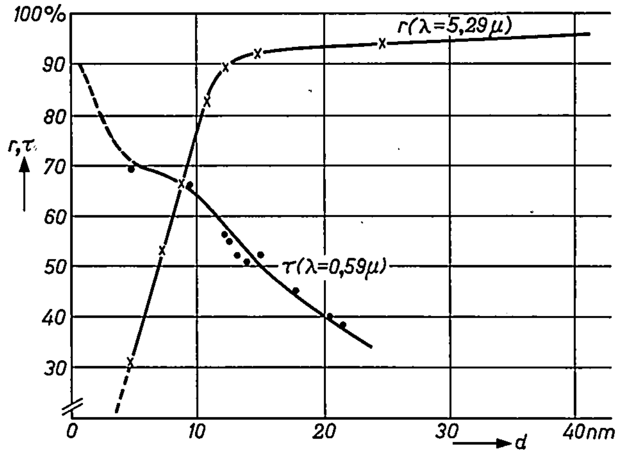


Fig. 6. The reflection coefficient r of plane gold layers at a wavelength $\lambda = 5.29$ μ, and the transmission coefficient τ at $\lambda = 0.59$ μ (sodium light), both as a function of the thickness d of the layers.

and the transmission coefficient at a wavelength of 0.59 μ (sodium light), as functions of the thickness of the layer.

To decide on the thickness of the layer it is necessary to strike the most favourable compromise between the infrared reflection and the transmission of light. For this purpose a series of sodium lamps were made, differing only in the thickness of the layer of gold on the sleeve in each lamp. The lamps thus differed in their thermal insulation and hence in their optimum power loading. *Fig. 7* shows how the optimum power, the maximum luminous efficiency and the total luminous flux vary as functions of the thickness of the gold layer.

The variation of the luminous efficiency can be explained broadly as follows. At thicknesses less than 4 nm the reflection in the infrared is practically zero, although the layer already absorbs some light. Even layers as thin as this, therefore, reduce the efficiency. Between 5 and 15 nm there is a marked increase in infrared reflection. In spite of the accompanying increase in the absorption of light, the efficiency nevertheless rises with increasing thickness up to a maximum which, in this case, had the high value of 125 lm/W at 15 nm. In layers thicker than 15 nm the reflection coefficient shows no further rise of any significance and the increasing absorption of light predominates, as a result of which the efficiency declines.

Thus, although the application of a gold layer of the proper thickness can raise the luminous efficiency from about 100 to 125 lumens per watt, the gain is accompanied by a severe decline in light output, namely from about 14 000 to some 4000 lumens. That explains why lamps of this kind have not been put on the market. Efforts are still being

[5]) Austrian patent number 134 018, granted in 1933 in the name of W. de Groot.

made, however, to improve the transmission of light by coating the gold layer with another substance to reduce its reflection of light.

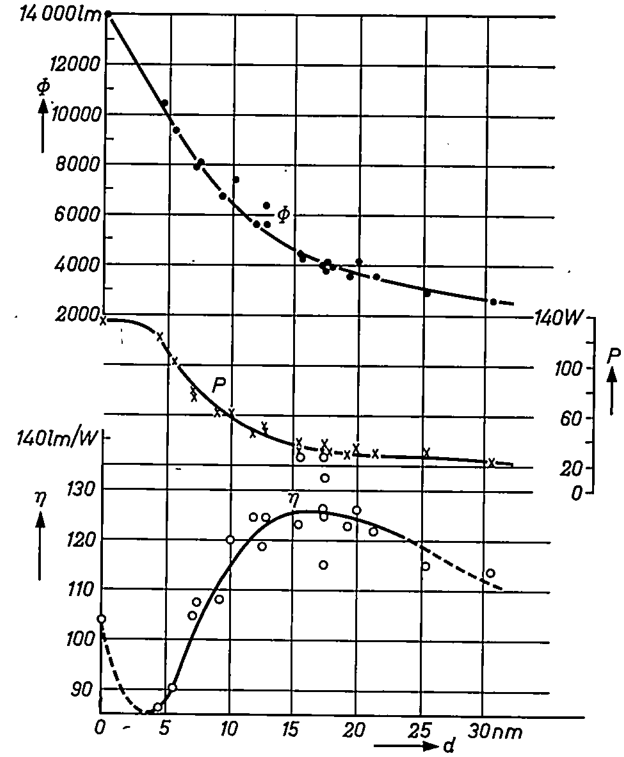


Fig. 7. Luminous flux Φ, lamp power P and efficiency η under optimum loading, as functions of the thickness d of a gold layer coated on the sleeve of a series of otherwise normal SOI 140 W sodium lamps (diameter of discharge tube 15 mm, arc length 820 mm, sleeve diameter 50 mm, outer bulb diameter 60 mm).

2) *Metal-oxide layers.* From the classical electron theory of metals it was already known that substances containing a fairly high concentration of free charge carriers would be good infrared reflectors. Substances exhibiting the required property were therefore to be expected amongst the semiconductors, provided that the concentration of free charge carriers could be made sufficiently large.

Investigations have been carried out on thin layers of metal oxides (on glass) which were known to combine transparency with a fairly high electrical conductivity [6]). The reflection coefficient is then dependent on the electrical conductivity as well as on the wavelength of the radiation. *Fig. 8* shows the reflection coefficient r of a layer of stannic oxide (SnO_2) at a wavelength of 5 μ, as a function of conductivity, together with the absorption coefficient a of the layer for sodium light.

A comparison of these curves for stannic-oxide layers with those for gold layers (fig. 6) shows that the light transmission of the stannic-oxide layers is markedly superior. It has thus proved possible with lamps of the type just described, but in which the sleeve is coated with stannic oxide instead of gold, to achieve the equally high efficiency of 125 lm/W [7]) with the considerably higher light output of about 8800 lumens (power consumption 70 W). A lamp of the same size, containing a gold layer, gives an equal efficiency with a light output of no more than 4400 lm (power consumption 35 W). It therefore looks as if the transparent semiconductor coatings offer better practical prospects than the metal layers, which are more reflective but absorb more light.

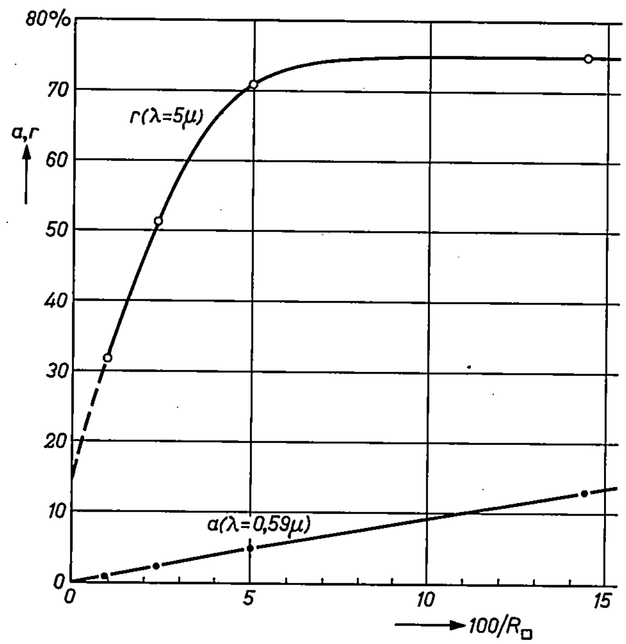


Fig. 8. Reflection coefficient r at $\lambda = 5\,\mu$ and absorption coefficient a for sodium light, as functions of the conductivity of stannic-oxide layers. The abscissa is $100/R_\square$, where $R_\square$ is the "resistance in ohms per square".

Finally it should be noted that the gain in efficiency obtained by using an infrared reflector always involves a lower lumen output, even if the infrared reflector were to transmit light for 100 %. This appears from *fig. 9a*, in which the measured luminous flux is corrected for the light absorption in the reflector (in this case a layer of gold). For this purpose separate measurements had previously been made of the light transmission of sleeves coated with gold layers of different thicknesses (fig. 9*b*).

[6]) This property makes such layers useful for other purposes, e.g. in electroluminescent panels; see Philips tech. Rev. **19**, 1-11, 1957/58.

[7]) In larger lamps, rated for 200 W, efficiencies as high as 140 lm/W have been reached.

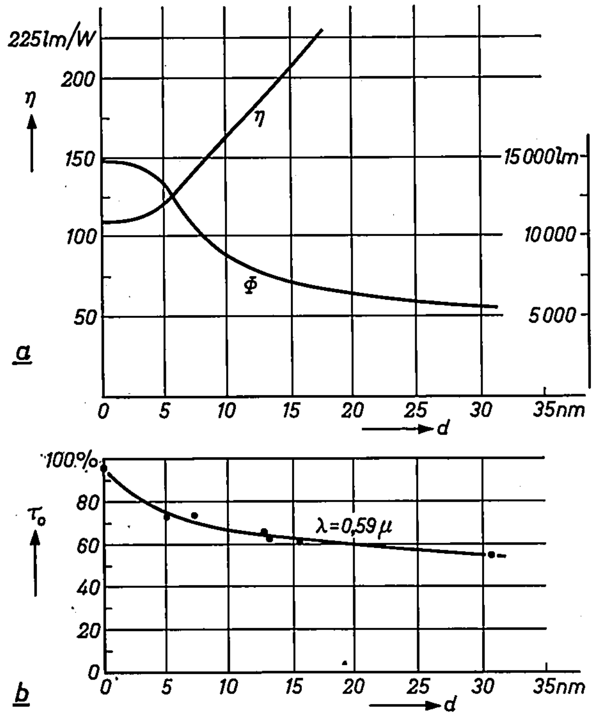


Fig. 9. *a*) Luminous flux Φ and efficiency η of a sodium lamp with a layer of gold coated on the sleeve, after correction for the absorption of light in the gold layer. The curves are derived from fig. 7 and fig. 9*b*.
b) Sodium-light transmission coefficient τ_0 of sleeve coated with gold layer, as a function of layer thickness *d*. The curve differs from that in fig. 6, which relates to a plane layer (single reflection), whereas the above curve relates to a sleeve, in which the light undergoes multiple reflections.

Influence of rare-gas pressure on luminous efficiency

The rare gas, which serves to initiate and maintain the discharge in sodium lamps, is given a pressure of about 10 torr. Under optimum power loading (temperature about 270 °C) the vapour pressure of the sodium is of the order of only 10^{-3} torr. In that case, then, there are roughly 10^4 times as many rare-gas atoms as sodium atoms present in the gas mixture. It is therefore evident that the kind of rare gas used and its pressure will have a considerable influence on the properties of the lamp. We shall confine ourselves here to mentioning some established relations between rare-gas pressure and certain properties of the lamp, such as luminous efficiency and power consumption.

The rare gas nowadays used in sodium lamps is neon, with a small admixture of argon and/or xenon to lower the ignition voltage. The effect of the pressure of a mixture of neon and argon on luminous efficiency has been investigated quantitatively by measurements on a type SOI 140 W lamp in the pressure range from 1 to 15 torr. The measurements showed that as the rare-gas pressure is decreased the maximum efficiency of the lamp increases fairly steeply: lamps with 15 torr reached 94 lm/W, lamps with 1 torr 114 lm/W. A striking circumstance is that the lamp, when operated at maximum efficiency, consumes less power at low rare-gas pressures than at high. This means that the optimum temperature of the discharge tube must also differ in these two cases, being lower at low powers than at high [8]).

We see, then, that if the rare-gas pressure is reduced, the sodium-vapour pressure — which is of course governed by the temperature of the discharge tube — must also be reduced in order to obtain maximum efficiency.

Fig. 10 illustrates how the luminous efficiency, the power consumed, the arc voltage and the lamp current vary with the rare-gas pressure under optimum loading conditions. The luminous flux Φ is also represented, and it can be seen that Φ in this case rises with increasing luminous efficiency, in

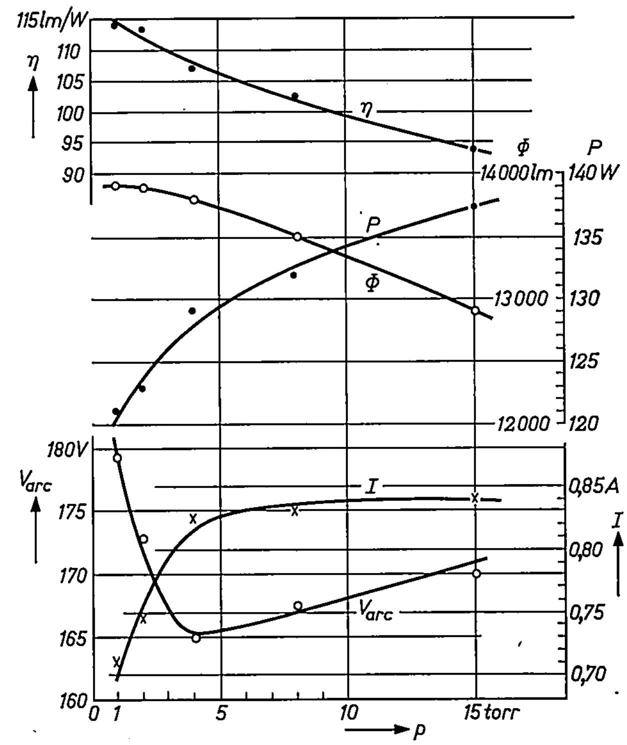


Fig. 10. Luminous flux Φ, lamp power P, efficiency η, arc voltage V_{arc} and lamp current I of an optimally loaded sodium lamp, type SOI 140 W, in dependence on the rare-gas pressure p (neon plus 1% argon).

[8]) We have not yet confirmed this by direct measurements, but the conclusion is reasonable, especially considering that the lowest power loading gives the highest efficiency, so that a smaller fraction of this low power is converted into heat.

spite of the lower power needed for optimum loading [9]).

The improvement in luminous efficiency which, as shown by these experiments, can be achieved by lowering the rare-gas pressure is unfortunately possible only within strict limits. It will presently be made clear why the pressure of the filling cannot be arbitrarily low.

Effect of arc length on luminous efficiency

If only the length of a sodium discharge is varied and the current is kept constant, the efficiency increases as the arc is made longer. This familiar effect is due to the fact that the electrode losses are relatively less significant in a long arc than in a short one. *Table III* shows how various properties of the lamp vary as functions of arc length. As we shall presently see, it is particularly important to take this effect into account when there is any reason to make the lamp shorter.

Table III. Arc voltage V_{arc}, power consumption P and luminous efficiency η of a sodium discharge tube as functions of arc length. Diameter of the tube 12 mm, current 0.6 A.

Arc length mm	V_{arc} V	P W	η lm/W
280	82	45.5	80.7
405	109	61.2	89.7
615	156	85.6	98.0

9) First the optimum power loading was determined at every pressure by plotting efficiency versus lamp current (*fig. 11*)

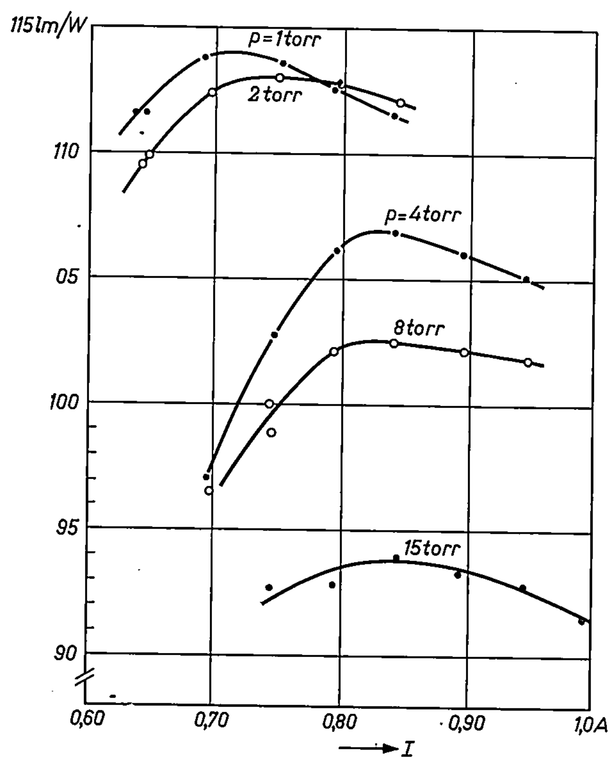


Fig. 11. Efficiency of SOI 140 W sodium lamps as a function of lamp current I, with the pressure p of the rare-gas filling (Ne + 1% A) as parameter. The maxima of the curves correspond to optimum loading conditions.

Sodium migration

Decline in light output as a consequence of sodium migration

Owing to the relatively high pressure of the rare gas in the lamp, each droplet of sodium only supplies sufficient vapour pressure for its own immediate surroundings. For this reason it has always been customary to distribute a fairly large surplus of sodium uniformly in drops over the whole surface of the discharge tube. Usually, however, the even distribution is not maintained. This is due to various causes, the main one being the differences in temperature along the wall of the tube, as a result of which the sodium tends to distil from hot to cold spots. A consequence of this migration is that the average vapour pressure of the sodium diminishes during the life of the lamp from its original, optimum value. Ultimately, all the sodium accumulates at the coldest spot in the lamp, and the vapour pressure drops to a minimum. A state may be reached where large parts of the discharge tube have hardly any sodium vapour, all the liquid sodium having accumulated at one point. The emission of sodium light from these parts is then virtually zero [10]).

Limitation of sodium migration by protuberances in the discharge tube

Sodium migration can be substantially reduced by applying the sodium droplets, during the manufacture of the lamp, to defined points along the tube that remain relatively cold. The points in question may be small protuberances in the tube wall, sufficient to hold a sodium droplet. This principle has been adopted by Philips in their more recent types of sodium lamps (figs 2 and 3).

A different method has been used in the "Linear Sodium Lamp", recently brought on to the market by the A.E.I. Lamp and Lighting Co. The tube wall in this lamp contains a number of depressions, at which positions the cross-section of the tube is not circular and has relatively cold spots where the sodium, once applied, is held in place [11]).

Suppression of sodium migration by the appropriate choice of rare-gas pressure

If for some reason or other there is a deficiency of sodium vapour in a part of the discharge tube,

10) Uyterhoeven, loc. cit. p. 251.

11) R. F. Weston, High-output sodium lamps, Electrical Times **135**, 719-722, 1959.

the discharge at that part is sustained almost entirely by the rare gas. At that part the voltage gradient is usually greater than in areas where the sodium participates properly in the discharge. Owing to the steeper gradient the part deficient in sodium consumes more power per unit length. Because of this the region where the sodium is lacking gets hotter than those well supplied with sodium, and this tends to encourage further migration. The migration thus has a cumulative character and the temperature equilibrium that initially existed becomes unstable.

It is possible, however, to choose the rare-gas filling in such a way that the power dissipated per unit length is lower in the parts deficient in sodium than in the parts well supplied. Contrary to the case just mentioned, the deficient parts then heat up less than the other parts, and sodium migrates back to where a shortage existed. The temperature equilibrium in such a tube is stable. The two cases are represented schematically in *fig. 12a* and *b*.

This effect, in dependence on the rare-gas pressure, has been studied quantitatively on lamps containing neon plus 1% argon. The state where no sodium vapour takes part in the discharge was investigated by measuring, at room temperature and without giving the lamp a chance to get hot, the voltage gradient of the column and the power dissipated per centimetre length of column. The data thus obtained relate to the low-sodium discharge (rare-gas characteristic) [12]. The lamp was then allowed

[12]) A discharge tube containing no sodium was investigated to ascertain whether the rare-gas characteristics differed at 20 °C and 270 °C. This proved not to be the case.

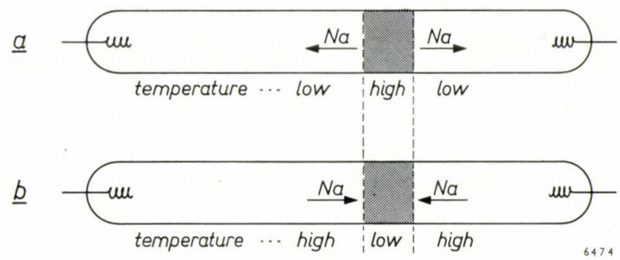


Fig. 12. Diagrammatic representation of sodium migration, (*a*) cumulative, (*b*) reduced. The shading in both cases denotes a zone deficient in sodium.
a) Classical case of relatively high rare-gas pressure. The low-sodium zone is hotter than the adjacent zones, which tends to promote migration.
b) When the rare-gas pressure is kept within specific limits, the low-sodium zone remains colder than the adjacent zones, which reduces or even eliminates migration.

to heat up, and measurements were made of the discharge characteristic in the mixture of rare gas and sodium vapour. The arc voltage and the power consumption were determined in dependence on the rare-gas pressure for both the cold and the hot lamp.

The results of measurements on type SOI 140 W lamps are presented in *fig. 13a* and *b*. It can be seen from fig. 13*a* that at all rare-gas pressures the r.m.s. value of the arc voltage is higher in the pure rare gas than when sodium vapour is also present. Fig. 13*b* shows that there is a range of pressures in which, notwithstanding the higher arc voltage, the power consumed is lower than in the mixture of rare gas and sodium vapour. This is due to the fact that the wave-forms of the voltage in the two discharges are different (see the oscillograms in *fig. 14a* and *b*), so that the form factor — and hence the power factor a — is greater when the discharge

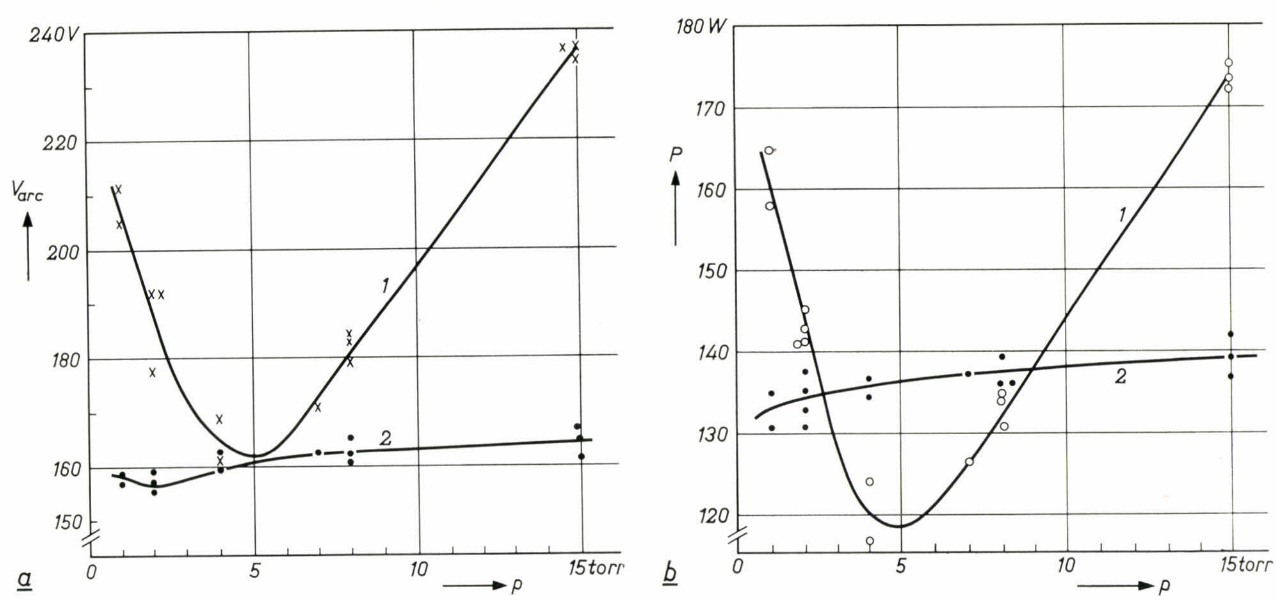


Fig. 13. *a*) Arc voltage V_{arc} (r.m.s. value) and *b*) lamp power P as a function of the pressure p of the rare-gas filling (Ne + 1% A); curves *1* without and curves *2* with sodium vapour. Measured on a standard SOI 140 W sodium lamp.

takes place in a mixture of rare gas and sodium vapour than when no sodium vapour is present. The values measured on the above-mentioned lamps were $\alpha = 0.83$ for the discharge in rare gas alone, and $\alpha = 0.94$ for the discharge in rare gas with sodium vapour.

In the region from 3 to 8 torr it is reasonable, in view of the temperature differences caused, to expect self-stabilization of the sodium distribution. In this way, then, the decline in light output due to sodium migration is effectively reduced.

For simplicity we have disregarded here the effect of the rare-gas pressure on the optimum working point of the lamp. In fact, as indicated, the lamp currents for maximum efficiency must be smaller at lower rare-gas pressures. This has no influence, however, on the effect described, the pressure region concerned remaining virtually unchanged.

A life test on type SOI 140 W lamps, with rare-gas pressures of 6 and 9 torr, confirmed the stabilizing effect of the lower pressure. The measured efficiencies are collected in *Table IV*. After 5000 hours, marked migration was observed in the lamps with 9 torr, whereas in the lamps with 6 torr hardly any sodium was found outside the original points.

a

b

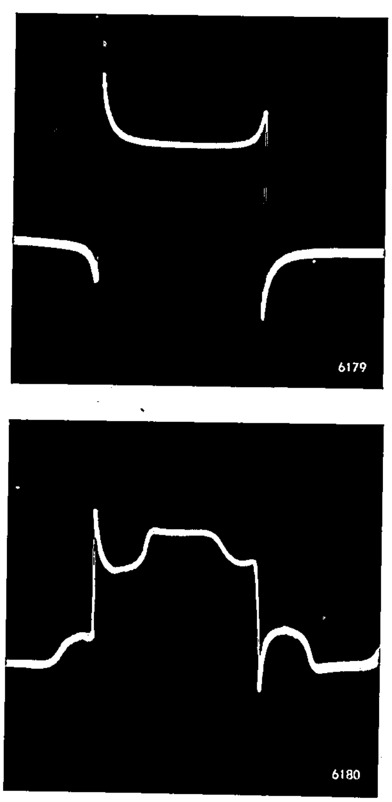


Fig. 14. Oscillograms of the arc voltage of a discharge in rare gas (Ne + 1% A, pressure 8 torr), *a*) without, *b*) with sodium vapour. Measured on a standard sodium lamp type SOI 140 W, lamp current 0.9 A. The difference in wave-form explains the smaller form factor in *a*) than in *b*).

Table IV. Efficiency of type SOI 140 W sodium lamps, during a life test with rare-gas pressures of 9 and 6 torr (Ne + 0.5% A).

Rare-gas pressure	efficiency in lm/W, measured after					
	100 h	1000 h	2000 h	3000 h	4000 h	5000 h
9 torr	97.7	94.6	91.9	88.2	81.7	81.4
6 torr	102.7	97.9	96.0	94.6	95.8	93.9

Decline in light output owing to glass discolouration

Sodium is chemically an extremely aggressive substance, particularly in vapour form, and quickly attacks all ordinary kinds of glass. The surface layer of the glass exposed to sodium vapour takes up a large quantity of sodium, and as a result turns brown. In certain cases concentrations of 2.1×10^{22} sodium atoms per cm^3 have been found in the brown layer; this implies that the average distance between the sodium atoms in the layer is less than twice that in metallic sodium [13]).

The discolouration of the glass obviously entails considerable absorption of light. Moreover, due to the uptake of sodium the composition of the glass changes and so too therefore does the coefficient of expansion; the consequent stresses may become so high as to crack the glass, prematurely ending the life of the lamp.

To avoid these effects, special kinds of glass have been developed to withstand the influence of sodium vapour under the conditions prevailing in a sodium lamp, without any significant discolouration. However, a serious drawback of these non-discolouring types of glass is the marked extent to which, in general, they adsorb argon.

Life of the gas filling

As stated, the rare-gas filling in present-day sodium lamps is neon with small admixtures of argon or xenon, or both. These admixtures, which are essential for lowering the ignition voltage [14]), steadily diminish in concentration during the life of the lamp, owing to adsorption, particularly at the glass wall. The gas filling will finally consist of almost entirely pure neon, resulting in such a high ignition voltage that the lamp can no longer be started by the available open-circuit voltage. The lamp is then said to have reached the end of its "gas life" (as opposed, for example, to the "cathode life").

[13]) J. W. Wheeldon, Absorption of sodium and argon by glass, Brit. J. appl. Phys. **10**, 295-298, 1959.

[14]) F. M. Penning, Über Ionisation durch metastabile Atome, Naturwiss. **15**, 818, 1927; Über den Einfluss sehr geringer Beimischungen auf die Zündspannung der Edelgase, Z. Phys. **46**, 335-348, 1927/28.

The rate at which the glass wall adsorbs rare gases depends primarily on the following factors:
1) the pressure of the rare gas,
2) the voltage gradient in the column,
3) the composition of the glass used for the discharge tube.

When the lamp is burning, ions are formed not only from the sodium but also from the rare gas, in particular from the argon, which has a lower ionization voltage than neon. These (positive) rare-gas ions are attracted to the negatively charged glass wall, which they strike with a certain energy. If the energy upon impact is high enough, the ions — possibly after recombination with electrons — are trapped in the wall. The energy at which the ions impinge upon the wall increases with the field strength, i.e. with the voltage gradient in the column, and also with the free path, i.e. with decreasing rare-gas pressure. Whether the wall in fact continues to hold the ions depends further on the structure of the glass.

The rare-gas pressure needed for the lamp to attain a specific life is plotted in *fig. 15* as a function of the voltage gradient in the column, for two different compositions of glass. The lamps in question were experimental types filled with neon plus 0.5% argon. The curves show that the gas life is longest when the gas pressure is relatively high and the gradient in the column small; the composition of the glass is seen to have a considerable influence.

Of course it is a simple matter to employ a high gas pressure, but, as we have seen, this leads to low efficiency and a marked decline in light output during the life of the lamp. Both reasons are in fact a strong argument for a low pressure.

A low voltage gradient in the column can be obtained by using a wide discharge tube. If the sodium lamp is to have the correct operating temperature the choice of a wider tube must be associated with a higher current, i.e. with a lower lamp voltage at a specified power loading; in other words the lamp must be made shorter. A lower lamp voltage, however, entails relatively higher electrode losses and hence a lower efficiency (see Table III). The scope for lowering the voltage gradient is thus restricted.

The crux of the problem of achieving a satisfactory gas life is therefore the composition of the glass.

As remarked above, those types of glass that are not turned brown by sodium vapour generally have the disadvantage of strongly adsorbing rare gases. Recently, however, types of glass have been developed that show relatively favourable properties in both respects [15]). With glass of this kind it has

[15]) Due in particular to the work of C. M. La Grouw, Glass Development Centre, Eindhoven.

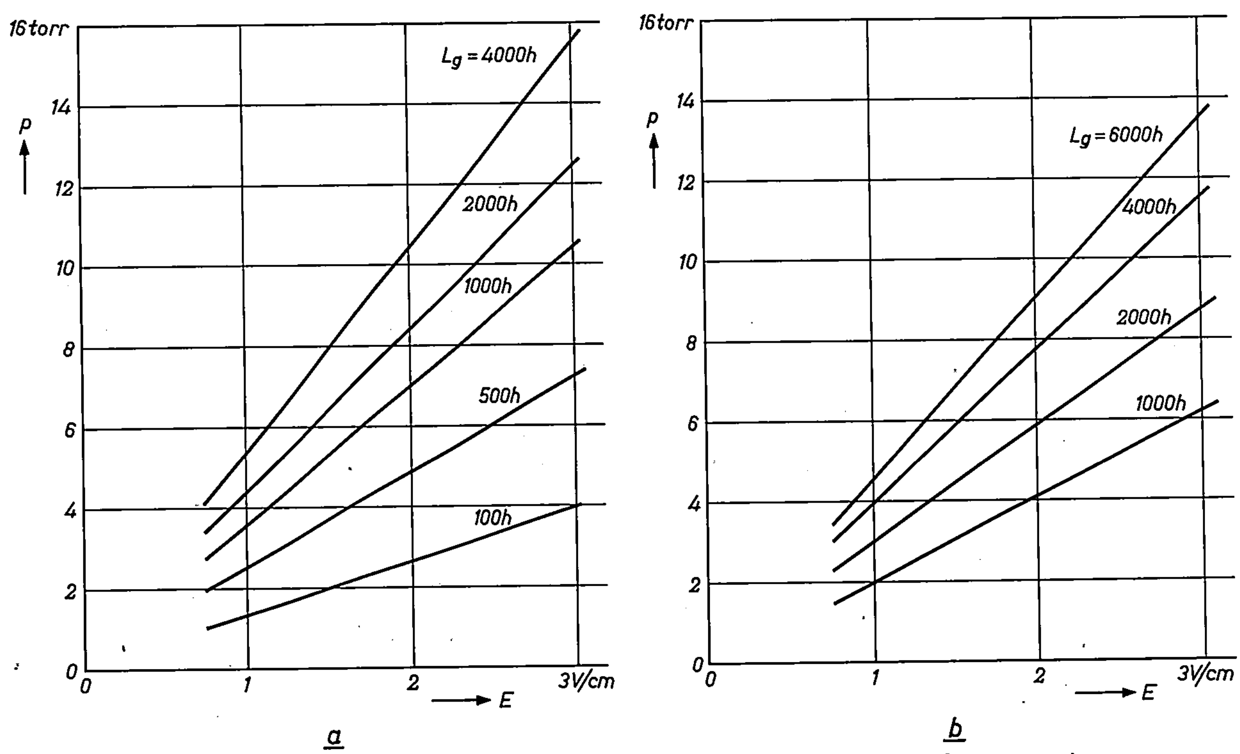


Fig. 15. The lowest rare-gas pressure p (Ne + 0.5% A) needed for a sodium lamp to attain a specific "gas life" L_g, as a function of the voltage gradient E in the column. The lines b relate to a better type of glass (adsorbing less argon) than lines a.

proved possible to reduce the pressure of the neon-argon mixture to 8 torr for a gradient of 1.8 V/cm in the column, ensuring a gas life of at least 6000 hours.

Future prospects

We shall now briefly examine the further evolution of sodium lamps that may be expected in the not too distant future.

Thermal insulation

From what has been said in the foregoing, it will be evident that there is still ample scope for refinements in the use of infrared-reflecting layers. It is by no means unlikely that advances in this direction will make it possible to produce sodium lamps giving an efficiency of 150 lm/W or even more. These lamps will be bulky, however, since if the thermal insulation is improved the optimum temperature of the lamp can only be maintained by reducing the power loading of the discharge tube per unit surface area.

Another potential development, running parallel with this, is therefore the construction of sodium lamps that combine a high lumen output with a relatively small size. The thermal insulation of such lamps would have to be deliberately poor in order to make a high power rating possible. For instance, a type SOI 140 W discharge tube, without an insulating jacket, has been found to give a luminous flux of more than 19 000 lm at 300 W, representing an efficiency of scarcely 60 lm/W. By means of a jacket offering very good thermal insulation and light transmission, the efficiency of the same discharge tube might be raised to perhaps 200 lm/W; the power consumed would then be only 35 W and the light output 7000 lumens. These widely divergent possibilities are probably both of importance, since lamps with the emphasis on efficiency can be developed at the same time as others with the emphasis on light output.

Rare-gas pressure

The use of lower filling pressures than have hitherto been feasible may lead to a further increase in efficiency, together with a luminous flux that will remain practically constant throughout the life of the lamp. These advantages might be achieved with a neon-argon pressure of 5 or even 4 torr. Such low pressures are not yet feasible because of the too rapid adsorption of argon by the glass in its present composition. It may be assumed, however, that the last word has not yet been said on the development of types of glass that are not turned brown by sodium vapour whilst at the same time adsorbing little rare gas.

If the filling pressure could be reduced to about 2 or 3 torr, the quantity of sodium used per lamp could also be considerably reduced, so that only a very small surplus of liquid sodium would be needed at the working temperature (just as the surplus of fluid mercury is very small in tubular fluorescent lamps). The present protuberances in the discharge tube (figs 2 and 3) could then be dispensed with, without the risk of any troublesome migration.

If, instead of a mixture of rare gases, one pure rare gas were to be used, it would already be possible to operate with a very low filling pressure, with all its attendant benefits. True, the lamps would then have a very high ignition voltage, but with a suitable ballast this need be no insuperable obstacle. The length to which one could go in this direction is limited by the life of the cathode, which is shortened when the filling pressure is reduced.

Use of other rare gases

After a thorough study has been made of the properties of gas discharges in mixtures of rare gases and sodium vapour, it may well be concluded that other rare gases offer more advantages as a filling than the classical neon. In cases of poor thermal insulation, for example, helium has proved to result in a higher efficiency than neon.

Renewed fundamental research into the sodium discharge should narrow the gap that still exists between the efficiency achieved in practice and the maximum efficiency theoretically possible, which is in the region of 450 lm/W. Notwithstanding the results achieved, the width of that gap makes it plain that we still have a long way to go.

Summary. Recent improvements in the sodium lamp concern in particular the luminous efficiency. With a lamp suitable for practical use the unprecedented efficiency of 100 lm/W has now been reached and even surpassed.

The author discusses the background of these advances and of others expected in the future, with particular reference to the influence of thermal insulation, rare-gas pressure and glass composition.

The use of infrared-reflecting layers on the glass — especially of transparent semiconductors, such as stannic oxide — is likely to result in considerably higher efficiencies, possibly up to 150 lm/W, though at the expense of making the lamps bulkier.

A promising trend is the development of types of glass that are not turned brown by sodium vapour and also adsorb little argon. Further progress in this field should lead to rare-gas pressures low enough for the light output of sodium lamps to remain almost constant throughout their life. The present protuberances in the discharge tube, which serve to hold the liquid sodium, can then be dispensed with.

Apart from the development of lamps of extremely high efficiency, lamps of lower efficiency but with smaller dimensions and a high light output are also to be expected.