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THE SODIUM LAMP

FROM LABORATORY EXPERIMENT TO STREET LIGHTING

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Summary. A short survey is given of the technical problems encountered in the development of discharge lamps using sodium vapour. The development led a) to a low tension arc for direct current and b) to a positive column lamp for alternating current. The latter has meanwhile almost entirely superseded the direct current lamp. Following a technical description of the lamps, the properties of their light are discussed as well as the possibilities of application which follow from these properties.

Since street lighting is the most important application, the circuits and installation of sodium lamps for street lighting are gone into in some detail, while finally some results are given of investigations on the visibility on roads lighted with sodium light.

Introduction

When one considers the fact that the light from a discharge in sodium vapour consists chiefly of radiations of a single wave length (5890/5896 Å), and moreover that the sensitivity of the eye for this wavelength, is very great being 76.5 per cent of the maximum value [1]), it is understandable that attempts have been made for some time to apply such a discharge in the construction of a practical high efficiency source of light.

Innumerable difficulties and problems had to be solved before sodium lamps were developed to such a point that they could be installed in large numbers for street lighting; only when this stage had been reached was it possible to form a satisfactory opinion about the utility of sodium light, and the influence of its unusual composition on visual acuity.

Development of the lamp

Since the vapour pressure of sodium at room temperature is so low that no discharge can occur, the lamp is provided not only with sodium but also with a rare gas filling. This latter gas makes ignition possible, while in addition the rare gas discharge heats the glass wall, so that after some time the pressure of the sodium vapour becomes sufficiently high to cause the sodium light radiation to predominate. Two problems immediately arose, namely that of the heat insulation, which is necessary in order to raise the lamp to the correct temperature with the least possible energy, and which must ensue that this temperature is not too greatly affected by the temperature of the surroundings, and that of the kind of glass: the "ordinary" kinds of glass are strongly attacked by sodium vapour at these temperatures (250 - 280° C). They become brown or black in a short time and then absorb very much light.

The first problem was solved in this laboratory by surrounding the lamp with a removable double-walled evacuated glass container. The contents of such a container can easily be brought to a given temperature and kept at that temperature, since, of the three forms of dissipation of heat, radiation, conduction and convection, the last two are practically ineffective here. Another system which is also used, that of mounting the lamp permanently in an evacuated outer bulb, makes a somewhat simpler construction. A disadvantage of latter system is the fact that the lamp must always be replaced as a whole, while the removable vacuum glass can always be used again. Moreover, the circulation of air between the vacuum glass and the lamp promotes uniformity in the temperature distribution.

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[1]) Characteristics of the eye with special reference to road lighting, Philips techn. Rev. 1, 102, 1936.
The representation of colour sensations in a colour space-diagram or colour triangle, Philips techn. Rev. 2, 39, 1937.

Since the reaction with the glass appeared to consist in the reduction of the silicates present in it, silicon-free glass or glass poor in silicon, borate glass among others, was used at first. Since, however, this glass is very difficult to work with, due to the short transition interval in softening, we changed over to an ordinary glass which was protected from attack by a thin layer of borate glass. This glass was easily workable and almost entirely unattacked.

The solution of these two main difficulties made possible the construction of an efficient sodium lamp.

Further development was carried out in two different directions: that of the low tension arc, where the distance between the electrodes is small and the working voltage low (10 - 30 volts), the lamp being usually bulb-shaped, and that of the positive column discharge with a greater distance between the electrodes, a higher voltage (100 volts or more) and straight or bent tube-shaped lamps. We shall not go into the fundamental differences between the two forms of discharge. The low tension arc is in many respects comparable with the discharge in a rectifying valve [2]); the positive column discharge with the discharge in neon advertising signs. The low tension sodium arc here described (*fig. 1*) has been able to hold its own only in the case of direct current installations mainly because its length of life with alternating current was not sufficiently long.

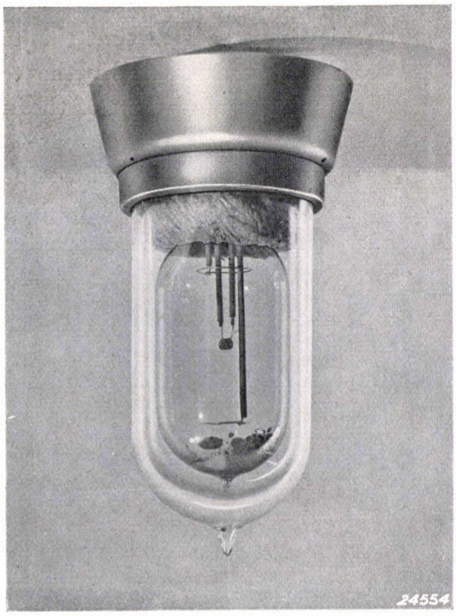

Fig. 1. Latest model of the low tension arc for direct current. Heat insulation by means of a removable vacuum glass.

[2]) Physical principles of gasfilled hot-cathode rectifiers, Philips techn. Rev. **2**, 122, 1937.

In order to make use of direct current mains of the order of 220 volts a number of lamps were connected in series with a common series resistance.

The positive column lamp is now generally used with alternating current. In order to be able to include the connections for both electrodes in one cap the tube is bent in the form of a single or a double U (*fig. 2*). One of the problems encountered in the development of both types of lamps is that of the distribution of temperatures. In order to obtain a sufficiently high vapour pressure (about 10^{-5} atm) the temperature of the coldest part of the lamp must be about 250 - 280° C, while the rest of the walls of the tube may not be much hotter because of possible attack on the glass. A fairly uniform temperature of the walls is thus required. The method of sealing in, usual in the manufacture of electric light bulbs (see *fig. 3a*), (in which the lead-in wires are previously fastened into a glass foot which is fused into the bulb), is less suitable for sodium lamps since it is difficult to keep the place where the foot is fused into the neck of the bulb at the right temperature, while in addition the place where the connection wires are sealed in (the "pinch") becomes very hot, so that there is the danger that the glass along the wires will crack. Therefore, a special method of construction has been developed for sodium lamps (fig. 3*b*), in which the sealing-in wires are sealed in directly in the neck of the bulb (so-called reversed pinch). Especially in the case of the U-shaped positive column lamps has this method of sealing in proved effective. Both pinches are formed at

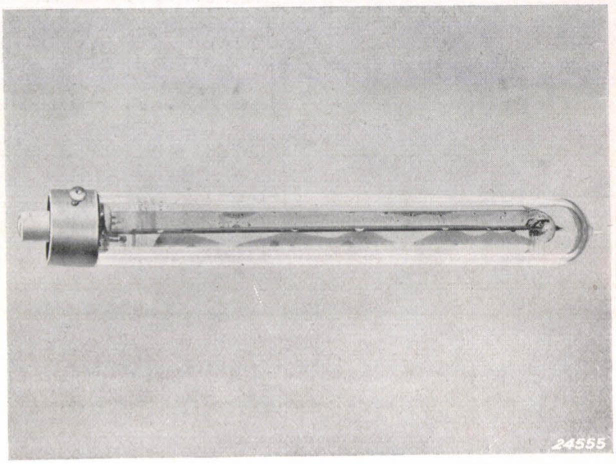

Fig. 2. Latest model of a positive column lamp for alternating current with vacuum glass. Tube bent in U shape. Running voltage 170 volts; current 0.6 A. Hot cathodes heated by the discharge.

the same time mechanically. For low tension arc lamps the construction shown in fig. 3*c* is also used, in which the space around the foot is isolated from the discharge by means of a chrome iron plate.

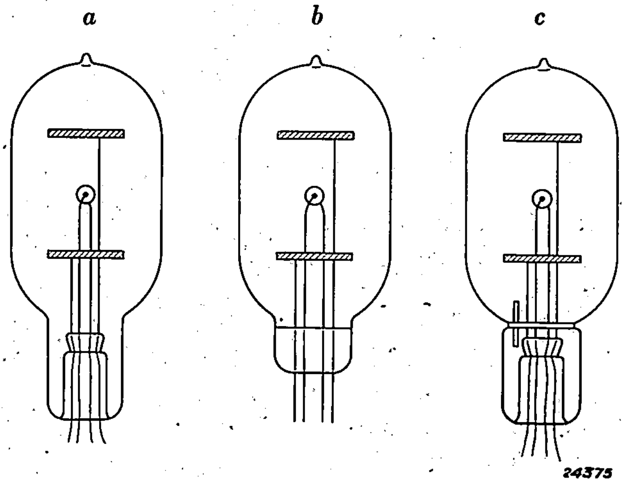

Fig. 3. a) Normal sealing in. The space around the foot is at too low a temperature so that when used as a sodium lamp the sodium condenses at this spot.
b) Leading-in wires attached directly to the neck of the bulb. The harmful cold space is here avoided.
c) Like a) but with a partition between the discharge space and the space around the foot. The condensation of Na vapour around the foot can also be avoided in this way.

In the low tension arc lamp the electrode system consists of a cathode in the centre of the discharge space, and two ring-shaped anodes situated about 2 cm above and below the cathode.

The cathode, which is wound in a spiral, is heated by current from a separate transformer. Its electron emission is large due to a film of alkaline earth oxides deposited upon it.

The positive column lamp, which is fed with alternating current, as already mentioned, has at each end of the tube one electrode which is wound in a spiral like the cathode of the low tension arc lamp. The function of this electrode is more complicated, however, since it must serve not only as cathode (in the negative phase) but also as anode (in the positive phase). Especially under the latter circumstance the heat to which the electrode is subjected due to the discharge is so great that a special heating current transformer is unnecessary.

A problem which must receive particular attention in the case of the positive column discharge is that of the distribution of the sodium. In order to obtain a uniform light from all parts of the lamp, it is necessary that the same concentration of sodium vapour be present in all parts of the bulb (or tube). The uniformity of distribution is threatened by different effects, such as one-directional movement of the ions due to a direct current component and differences in temperature. The influence of such effects is particularly great since the diffusion which seeks to promote uniformity is very weak in the case of sodium vapour in a gaseous atmosphere. With low tension arcs this fault is less serious due to the symmetrical construction of the lamp with the discharge in the centre. With positive column lamps the non-uniformity of the distribution of the sodium may cause some parts of the lamp to give less light than others; in extreme cases only the radiation of the rare gas remains in these parts. Little by little the causes of the non-uniformity have been successfully overcome, in the first place by providing for an even temperature distribution, and in the second place by keeping the transport of ions within definite limits (both the electrodes of the alternating current tube should be prepared in exactly the same way; since the conductivity is then the same in both directions, practically no direct current component occurs).

The problem of the dependence on temperature was found to be especially important in connection with the practical application. We have already seen that the temperature must be about 250 - 280° C. At a higher temperature and pressure the intensity of the light is found to increase only very slightly, and then to decrease again. Since more energy must be supplied for the higher temperature, the efficiency (lumen per watt) thus decreases. *Fig. 4* gives the light intensity as a

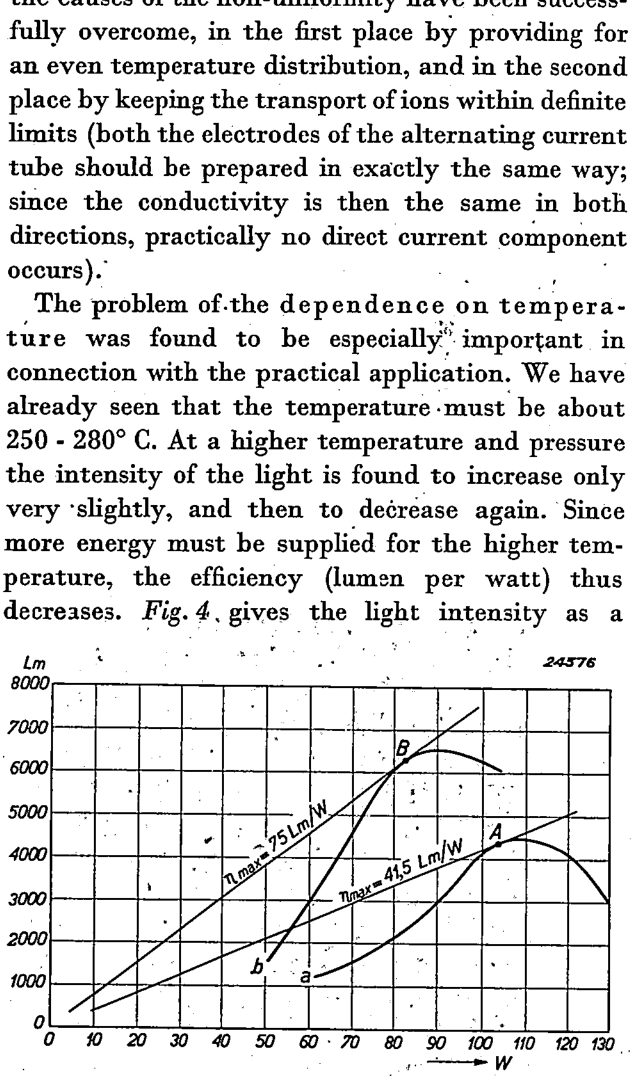

Fig. 4. Intensity of light (lumens) as a function of the power. a) Low tension arc on direct current. b) positive column lamp on alternating current. The curves do not represent average values but were measured on two individual lamps.

function of the energy input for two given lamps:

a) for a low tension arc lamp on direct current,
b) for a positive column lamp on alternating current.

The tangents to the curves from 0 give the points *A* and *B* where the lamps have their maximum efficiency. In practice it was found advantageous to let the lamps work in the horizontal portion of the characteristic: the variations in the energy supplied (mains voltage variations!) as well as variations in the external temperature then have only little influence on the intensity of the light.

The properties of sodium light

As the above-mentioned problems and difficulties were more and more already overcome, and the lamps reached the stage of practical application, the study of the properties of this new kind of light was also begun. Considering that results of several of these studies have already been described in this periodical, a brief outline will be sufficient here.

The monochromatic character and the favourable spectral position of the sodium lines in relation to the curve for the sensitivity of the eye have been pointed out in the introduction.

With the first experimental installations it was remarkable how sharply small objects could be seen by sodium light. It is therefore understandable that the first physiological-optical investigations were concerned with the acuity of vision [4]). In connection with the monochromatic nature of the light and the consequent lack of chromatic aberration, and also from earlier experiments by Ives an important difference from ordinary electric light was to be expected. The acuity of vision with sodium light was actually found to be considerably greater. It is remarkable that the magnitude of this difference was found to depend upon the nature of the test objects used.

In the case of speed of perception [3]) also, which is closely related to acuity of vision, important differences between sodium light and ordinary electric light were found.

Upon continuation of this study it became clearer and clearer that the improved acuity of vision, although one of the most striking phenomena, is certainly not the only factor which determines vision with different coloured light, and that especial attention must be devoted to still another side of the problem, namely that of contrasts [4]). In the beginning it proved very difficult to confirm by means of laboratory experiments the general impression of the better contrasts on a road lighted by sodium light. The differences in sensitivity to contrast were too slight to explain the striking phenomena; nor did the measurement of coefficients of reflection for the various kinds of light show any important differences. A critical study of the concept of brightness and the Purkinje effect led us by way of the concept of subjective brightness [5]) to that of richness in contrast [4]). Along these lines it could be shown how the greater contrasts with sodium light are to a large degree related to a shifting of the curve for the sensitivity of the eye which is strongest at just the brightness occurring on a well-lighted road.

Since all these characteristics of the eye can be influenced very strongly by glare [6]), it was interesting to make comparisons between the different kinds of light in this respect also. The result was that for simultaneous glare no important differences could be shown, but that sodium light presents appreciable advantages with respect to successive glare as well as with respect to disturbing effects. The low brightness of the sodium lamp (compared with that of the mercury lamp for instance) was found to be important in this connection.

Little is yet known about the psychological effects of this new kind of light; in general it may be said that on country roads the yellow colour makes a restful impression on the great majority of road users. Experiments carried out in workshops and offices showed that the fatigue phenomena were equally great for white light and sodium light.

The range of application

Simultaneously with the physiological-optical study the investigation of the possibility of application was carried out. Although this problem was often attacked by intuition and by the method of trial and error, we may now conclude directly from the results mentioned in the previous section as to the conditions under which sodium light may be used to advantage.

Because of its monochromatic character we can employ sodium light only where the reproduction of colour is of no importance [7]). Its use in living rooms, shops, streets in the centre of cities, etc. is therefore immediately eliminated.

Moreover, in cases where very low intensities are

3) Visual acuity and speed of vision in road lighting, Philips techn. Rev. 1, 215, 1936, other literature is cited in this article.

4) The perception of brightness contrasts in road lighting, Philips techn. Rev. 1, 166, 1936.

5) The definitions of brightness and apparent brightness and their importance in road lighting and photometry, Philips techn. Rev. 1, 142, 1936.

6) The problem of glare in highway lighting, Philips techn. Rev., 1 225, 1936.

7) The perception of colour, Philips techn. Rev. 1, 283, 1936. Colour reproduction in the use of different sources of "white" light, Philips techn. Rev. 2, 1, 1937.

usual, as for example in mines, sodium light cannot be used, since in these cases the Purkinje effect has an unfavourable influence on vision.

The use of sodium light will offer particular advantage in those cases in which acuity of vision is very important, such as the inspection of articles for fine cracks, or when quickness of perception plays a part (on tennis courts for example) [8]). When, as in the case of the lighting of country roads, the levels of brightness are of such a nature that in addition to these advantages that of the great richness in contrast becomes important, the sodium lamp will often be the most suitable source of illumination. Wherever glare must be avoided or kept at a minimum, the sodium lamp with its low brightness, its slight successive glare and its relatively pleasant colour offers great advantages.

Further there is a long series of applications in which special use is made of the pronounced yellow colour of the light. The advantages of this colour may be manifested in very different ways:

1. Aesthetic effects may be obtained when the light is used as flood lighting for buildings, as part of festival illuminations, illumination of groups of trees, etc.
2. Certain objects such as advertising signs, signals, etc., can be given a very striking appearence by means of sodium light; its use for boundary lights of aerodromes belongs to this category.
3. In various special cases small contrasts become much clearer in sodium light, because the differences in coefficient of reflection may be greater than with illumination by white light. This applies particularly to various cases of the testing of materials.

Sodium light is already being used in the photographic studio [9]).

Finally sodium light will often be used for purely economic reasons in cases where large areas must be lighted (shunting yards) or where for special reasons road lighting of a very high intensity must be used (traffic tunnels in the daytime). Sodium light in such cases presents entirely new possibilities, since illumination with ordinary electric lamps is often extremely expensive.

Circuit and electrical characteristics of sodium lamps [10])

In the low tension arc lamps used with direct current the two anodes are connected to each other so that the lamp has three connections: one positive terminal and the two ends of the heated cathode as negative terminals. *Fig. 5* gives a complete diagram of a number of lamps connected in series. For heating the cathode each lamp has a separate heating current transformer T which is fed with alternating current. In addition there is a cut-out cartridge S in parallel with each lamp, which breaks down when the lamp does not work, and thus keeps the circuit closed. Since in such a circuit the direct voltage applied is at first distributed unevenly over the various lamps so that the lamps may light one after another, the ignition voltage required per lamp may be considerably lower than that for one single lamp (this is about 30 volts). Consequently only about 10 per cent of the total voltage need be lost in a series resistance, which often takes the form of an iron wire in an atmosphere of hydrogen. This series resistance keeps the current constant in spite of variations in the mains voltage or changes in the

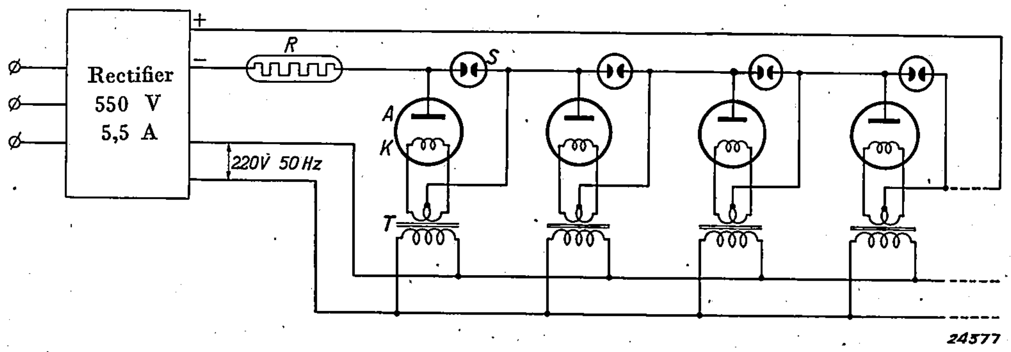

Fig. 5. Diagram of a series installation with low tension arc lamps. A anodes, K cathodes, T heating current transformers, R iron wire resistance, S short-circuiting cartridge.

[8]) Sodium lighting of tennis courts, Philips techn. Rev. **1**, 252, 1936.

[9]) The "Philora" sodium lamp and its importance to photography, Philips techn. Rev. **2**, 24, 1937.

[10]) Alternating-current circuits for discharge lamps, Philips techn. Rev. **2**, 103, 1937.

load resulting from the falling out of lamps. Some of the objections connected with supply by direct current are the necessity of installing whole groups at the same time, the four-conductor system (see fig. 5), the relatively high sensitivity to variations in temperature and the occurrence of radio interferences which may, however, be suppressed by installing filters [11]).

We are giving herewith some data of a direct current installation (first street lighting with sodium lamps, June 1931, Beek - Geleen, Holland).

Total direct voltage: 500 volts.
Voltage across the series resistance (average): 50 volts.
Sum of the voltages of the individual lamps: 450 volts.
Number of lamps: 30
Current 5.5 A.
Consumption of lamp including heating current transformer: 102 W
Total consumption: 3.1 kW.
Luminous flux per lamp: 4000 lumens
Efficiency, gross: 38.5 lm/W.

The positive column lamp used with alternating current offered wider possibilities. In this lamp two hot cathodes are used for electrodes. These electrodes are raised and kept to the proper temperature by the discharge itself, and function as both cathode and anode alternately. A separate heating current transformer is therefore not provided. The current is limited by a transformer of special design. *Fig. 6* shows such a combination

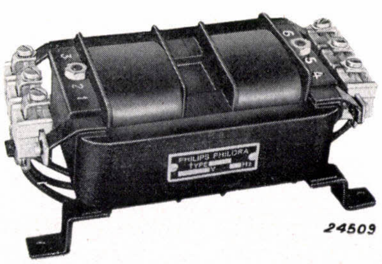

Fig. 6. Leakage flux transformer.

which is called a leakage flux transformer. The self-inductance of this transformer causes a phase shift between current and mains voltage which may be eliminated by the introduction of a correcting condenser across the mains terminals.

The A.C. lamps may be installed quite independently of each other. The following table (*table I*) gives some data of the lamps in use at the present time:

11) High-frequency oscillations in sodium lamps, Philips techn. Rev. **1**, 87, 1936.

Table I

Type	Power incl. losses in current limiting device	Current through lamp	Running voltage	Luminous flux	Efficiency
50 W	65 W	0.6 A	80 V	2 550 lm	39.3 lm/W
65 W	80 W	0.6 A	110 V	3 780 lm	47.3 lm/W
100 W	105 W	0.6 A	165 V	6 100 lm	58.1 lm/W
150 W	165 W	0.9 A	165 V	9 600 lm	58.2 lm/W

As may be seen the first three types take the same current. Because the current supplied by the leakage flux transformer due to its high impedance depends only slightly on the voltage of the lamp used, these types can be used with the same transformer.

Fig. 7 shows how the light flux increases as a function of the time elapsing after switching on.

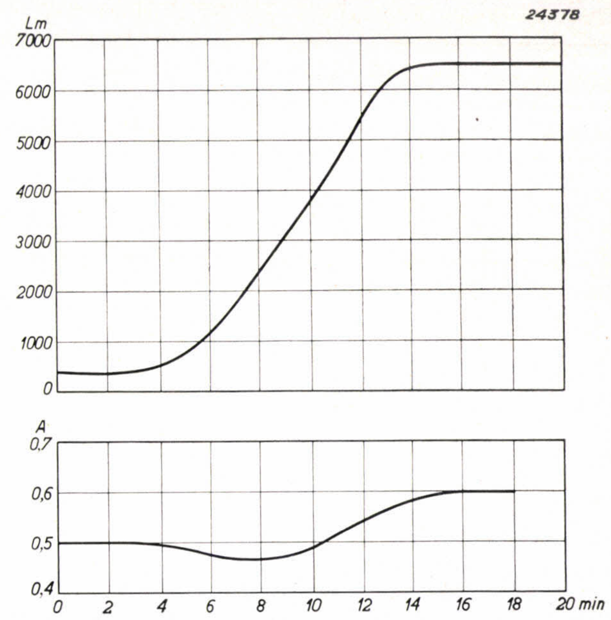

Fig. 7. Luminous flux (lumens) and lamp current (amperes) as a function of the time elapsed after switching on for a U-shaped lamp of 100 W on a transformer for 470 volts and 0.6 A.

The changes in light flux with variations in the mains voltage may be seen in *fig. 8*. For the sake of comparison the corresponding curve for an incandescent electric lamp is also shown.

We conclude this section with a few remarks about the life of sodium lamps, particularly of A.C. lamps.

While with ordinary electric lamps the length of life is chiefly determined by the rate at which the filament evaporates, and therefore has a value which may be foretold with fair accuracy, the length of life of sodium lamps depends upon a number of factors whose influence it is more difficult to discover. Evaporation of the electrodes and the material deposited upon them occurs here also, but the available reserve is so great that the length of life of the lamp is not generally influenced by this factor. After several thousand

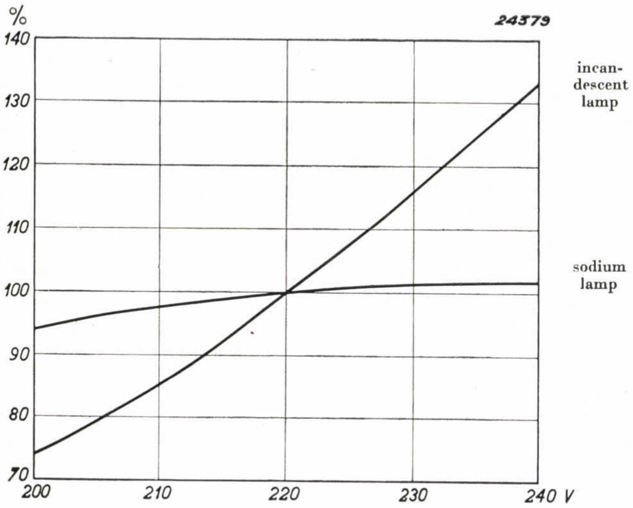

Fig. 8. Light flux of a sodium lamp and of an incandescent electric lamp for different mains voltages in per cent of the value reached at the nominal mains voltage of 220 volts. The sodium lamp is very insensitive to voltage variations.

hours, however, symptoms of age appear, which to a great extent may be ascribed to a less uniform distribution of the sodium. This may result in certain parts of the tube giving too little light. Local brown coloration of the glass may also result, while an abnormal accumulation of molten sodium in the neighbourhood of the electrodes may lead to cracking at the point of sealing in. On the average an A.C. sodium lamp lives 2 500 hours.

The installation of sodium lamps from the standpoint of lighting technology

We shall not go too deeply into this subject, and shall only discuss those points in which sodium illumination differs fundamentally from illumination by means of incandescent electric light.

These differences are due chiefly to the special form, dimensions and light distribution curve of the sodium lamp. Because of these differences special measures must often be taken in order to satisfy the general requirements of street lighting, such as the greatest possible uniformity, sufficiently high brightness of the road surface, little glare and good visibility.

If we consider the distribution of light from a sodium lamp (*fig. 9*), we see that the best position for the lamp is horizontal and perpendicular to the direction of the road. The greatest part of the light radiated downward then falls on the surface of the road and its immediate surroundings. In order to obtain illumination directly under the lamp the two arms of the U must lie in a horizontal plane.

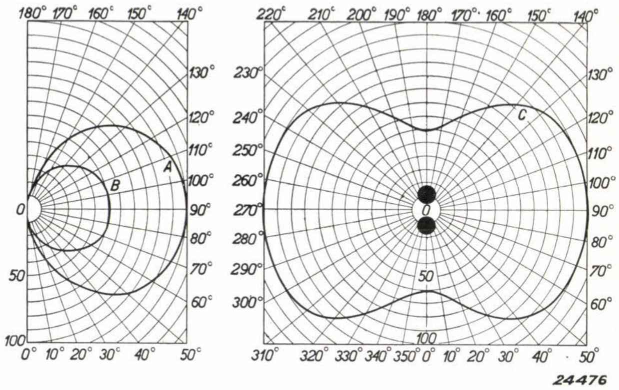

Fig. 9. Distribution of the light of a U-shaped sodium lamp in three different planes. *A*) plane through the axis of the lamp and perpendicular to that of the U-tube. *B*) plane through the axis of the lamp and coinciding with that of the U-tube. *C*) plane perpendicular to the axis of the lamp.

On the other hand for road lighting where it is desired to distribute the light more or less evenly over the whole surface of the road, it is better to place the two arms one above the other.

The part which serves chiefly to reflect the light radiated in an upward direction may be very simple in this case. In *fig. 10* may be seen a reflector, white-enamelled on the inner side and of such a shape that light rays which fall within an angle of 20° to the road surface are intercepted. Direct perception of the lamp at a greater distance

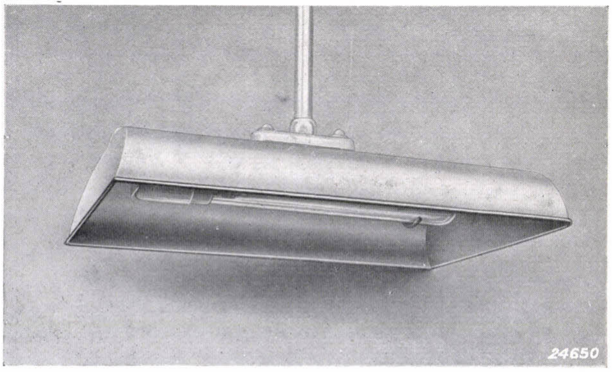

Fig. 10. Simple holder for sodium lamps.

is hereby impossible, so that glare is practically eliminated. Because of the fact that the vertical dimension of the light source is so small (about one inch) it is possible to cut it off sharply and yet retain a wide angle of radiation.

With existing installations the height of the light is usually 25 to 30 feet with a distance between the standards of 100 to 120 feet. Using lamps of about 100 W a good illumination is obtained with this arrangement.

In certain cases (workshops where machines, cranes, etc. are used) the fact that the intensity of the light pulsates 100 times a second may cause stroboscopic effects. If this must be avoided two lamps may be placed in one holder, and their transformers may be so connected that the lamp currents are 90° out of phase with each other. The total light flux is then never zero, and the difficulty mentioned is thus avoided.

Appraisal of the result achieved

When sodium lamps have been employed in a lighting installation, especially for the lighting of a country road, after taking into due account practical experience as well as results arrived at through theoretical considerations it is interesting afterwards to find out to what degree the result achieved may be considered satisfactory. The appraisal of the result may be carried out in very different ways.

One method which may give very misleading results when injudiciously applicated, is to stand on the road and look. In general more attention is paid to the light sources than to the road, more to the total amount of light entering the field of vision than to the correct distribution of brightness, more to the impressiveness of the installation than to the visibility on the road. It is much better to drive along the road and to notice how the lighting influences the ease of driving and the feeling of security. The objection to this method is that it is difficult to express the result in figures. As has been explained in another place in this periodical [12]), this goal can be reached with the help of a visibility meter, an instrument by means of which the weakest contrast still observable on the lighted road can be established in a simple way: the weaker this contrast the more successful the lighting system.

In *table II* are collected the average values of the weakest recognizable contrast for a number of different installations.

Table II.

No. of installations	Kind of light	Type	Power kW/mile	Weakest recognizable contrast (average)
14	Sodium	A	5.3	0.20
5	Mercury (and mixed light)	A	9.0	0.22
4	Mercury	V	15	0.395
5	Incandescent electric light	V	10	0.31

The letter *A* here indicates that a well-shielded light source was used, the letter *V*, that this was not the case. The great influence of glare due to insufficiently shielded sources of light may be seen: in spite of the high power installed the visibility is very low. With sodium lamp installations an excellent visibility is attained with a small power.

[12]) How can one judge the efficiency of road lighting?, Philips techn. Rev., 1, 349, 1936.