NEW AEI DESIGN EMPLOYING CRESCENT-SHAPED ARC TUBES FOR GREATER LOADING

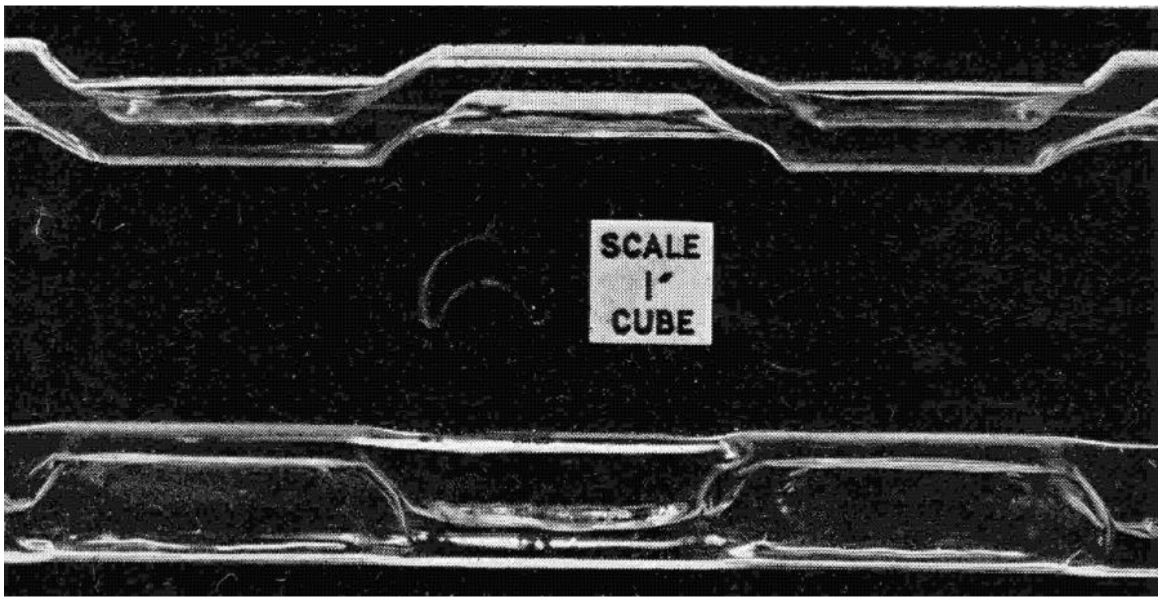

Fig. 1 (Heading illustration) Section of arc tube of AEI's new linear-sodium lamp with crescent-shaped cross-section. The sectional view illustrates the metal retaining capillary action of the small-radius lobes of the crescent

High Output Sodium Lamps

by R.F. Weston *

PARAMETERS related to the design of sodium vapour discharge lamps have been the subject of extensive investigation in the western hemisphere since the first commercial lamps were marketed in the early 1930's. Whilst fundamental understanding of the mechanism by which light is produced from the sodium discharge has been provided from the research work of many physicists over the past century,[1,2,3] the subject remains one of great technical complexity. This is because many of the design factors are interlinked one with another in relation to the performance characteristics of the lamp.

In the post-war years a rapid expansion of sodium lighting of traffic highways has stimulated increased research and development activity in the study of these factors in order to assist the design of more efficient forms of this type of light source. An illustration of the success resulting from this work over the past 20 years is afforded in the table below, in which the light output and life expectancy of 140 W lamps (Dewar flask type) publicised in 1938 is compared with the equivalent values quoted in 1958.

Table l. - Output and life expectancy of sodium lamps

	1938	1958
Initial lumens per watt ...	71.5*	73.0†
Lumens per watt at 1,250 h	57	
Lumens per watt at 2,000 h		65
Average life	2,500	4,000

* Measured at zero hours. † Measured at 100 hours.

In the last, two or three years improved forms of sodium lamp offering further service advantages have been introduced both in this country and in Western Europe. Some of these improvements have been introduced without changing the dimensions or electrical characteristics of the long-established 45, 60, 85 and 140 W lamp range of separate arc tubes and Dewar flasks. Examples of this type of development include lamps having arc tubes made from glasses more resistant than hitherto to sodium vapour attack;[4] lamps having arc tubes in which are moulded ribs or dimples, designed to retain the metallic sodium in correct position even when the lamp is operated at an appreciable angle to the horizontal plane. Other new introductions represent more radical departures from past convention, such as the range of integral jacket lamps in which the vacuum flask is sealed permanently around the arc tube to give a complete unit assembly.[5]

Linear Designs

Assessment of the results achieved by the use of modified materials and constructions, such as those briefly referred to above, have recently led to the conception of an entirely new design of lamp incorporating a linear arc tube instead of the previously standardised "U" form. Three such lamps are shown in Fig. 3; their normal ratings would be 100, 150 and 200 W respectively. It will be noted that they closely resemble tubular fluorescent lamps in appearance. Their mode of electrical operation is also similar to that of the tubular fluorescent lamp, but their efficiencies are some 25% greater than those of similarly rated Dewar type sodium lamps. Before reviewing in more detail the constructional features of these new lamps, it may be helpful to consider the various technical factors which have led to their conception.

Sodium Vapour Pressure

In order to obtain the maximum efficiency of conversion of the electrical input to the arc discharge into light of the 5890 / 5896 Å wavelength, namely, the characteristic yellow light of the lamps, the vapour pressure of sodium must be in the order of 0.9 microns of mercury, which corresponds to a metal temperature of approximately 230°C. Any appreciable deviation from this pressure results in a very undesirable loss in the lamp efficiency.

Any efficient design of lamp must therefore support a metal temperature of 230°C when the total energy dissipated by the lamp is equal to the rated electrical input.

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It can be shown that current density within the arc discharge, the surface area of the arc tube, and the volume in which the arc is contained, affect the efficiency of a sodium lamp, as shown in Figs. 2(a), 2(b) and 2(c), whilst Fig. 2(d) shows the variation of the total emitted light from a given lamp plotted against current density. All four curves are based on a metal temperature of 230°C.

From the curves of Figs. 2(a) and 2(d) it will be seen that if a very low current density, high efficiency lamp is to be designed, the total lumens obtained from a given size of source will be very low. It is estimated that the arc tube of a 12,000 lumen lamp with 40 W input (300 lm / W) would be in the order of 1 in. diameter and some 16 ft long. The arc tube would be required to support a minimum sodium temperature of 230°C, and as nearly 65% of the input power would be radiated as light, only 14 W would be available to give the temperature required. Such a lamp is obviously impractical.

Thermal Insulation

For practical low current density lamps the maximum efficiency is set by the thermal insulation which can be achieved consistent with good light transmission. Lamps of 80 lm / W are obtainabe. [5] As an alternative to low current density, lamp efficiencies can be improved by increasing the arc tube surface area and decreasing the volume of the lamp as shown in Figs. 2(b) and 2(c). It will be noticed that surface area and volume changes are most effective above 0.5 amps / sq cm for sodium lamps, whereafter any increase in current will have only a minor effect upon efficiency.

The obvious way of obtaining surface area and volume changes is to distort the arc tube cross section from circular to a more advantageous shape which has large surface area and small cross section. Much work has been done in this field on mercury vapour lamps by the GE Company in America in the development of their "Power Groove" fluorescent tubes. Fig. 4 illustrates some cross sections which immediately suggest themselves some which have been proved capable of giving efficiencies in the order of 120 lm / W or more with a sodium lamp. Final choice is, however, influenced by other factors such as manufacturing possibilities, materials and stability in service which may favour shapes giving somewhat lower efficiencies.

A third factor which affects the efficiency of a sodium lamp is the volt/amp electrical characteristic. The reason for this lies in the fact that the electrode losses in the lamp will largely be determined by lamp current and are virtually unaffected by lamp voltage drop.

The electrodes, and the energy dissipated by them, will play little part in the light output of the lamp, whilst the energy in the positive column between the electrodes can be regarded as useful energy. We can therefore write:

E varies with AX+B

where E is lamp efficiency

A the dissipation/unit length of positive column

X the length of positive column

and B represents electrode losses.

A relatively high-voltage, low-current lamp is thereby indicated for maximum efficiency, but this may not be very practical because of control gear cost if high voltages are required to operate it.

Gas Filling

At normal ambient temperatures sodium metal is solid and its vapour pressure is so low that a gas filling must be provided to aid lamp starting. The gas carries the arc discharge until the lamp has heated up sufficiently to raise the vapour pressure of the sodium to a point where it can play its part in the conductivity of the discharge and in so doing provide the useful light output of the lamp. When the pressure of the gas filling of the lamp is low it is possible for the glass of the arc tube to absorb gas sufficiently to effect operation during life.

The gas absorption characteristic of the glass of the arc tube therefore sets the minimum pressure of gas filling, whilst the maximum pressure is usually set by striking voltage requirements. With any practical lamp design it is generally possible to fulfil gas requirements by the use of neon with small additions of argon, xenon or helium.

Sodium Metal Movement

In order that the gas filling shall not interfere with the efficiency of the lamp, it is required that the volt drop of the arc due to the gas alone shall be higher than the volt

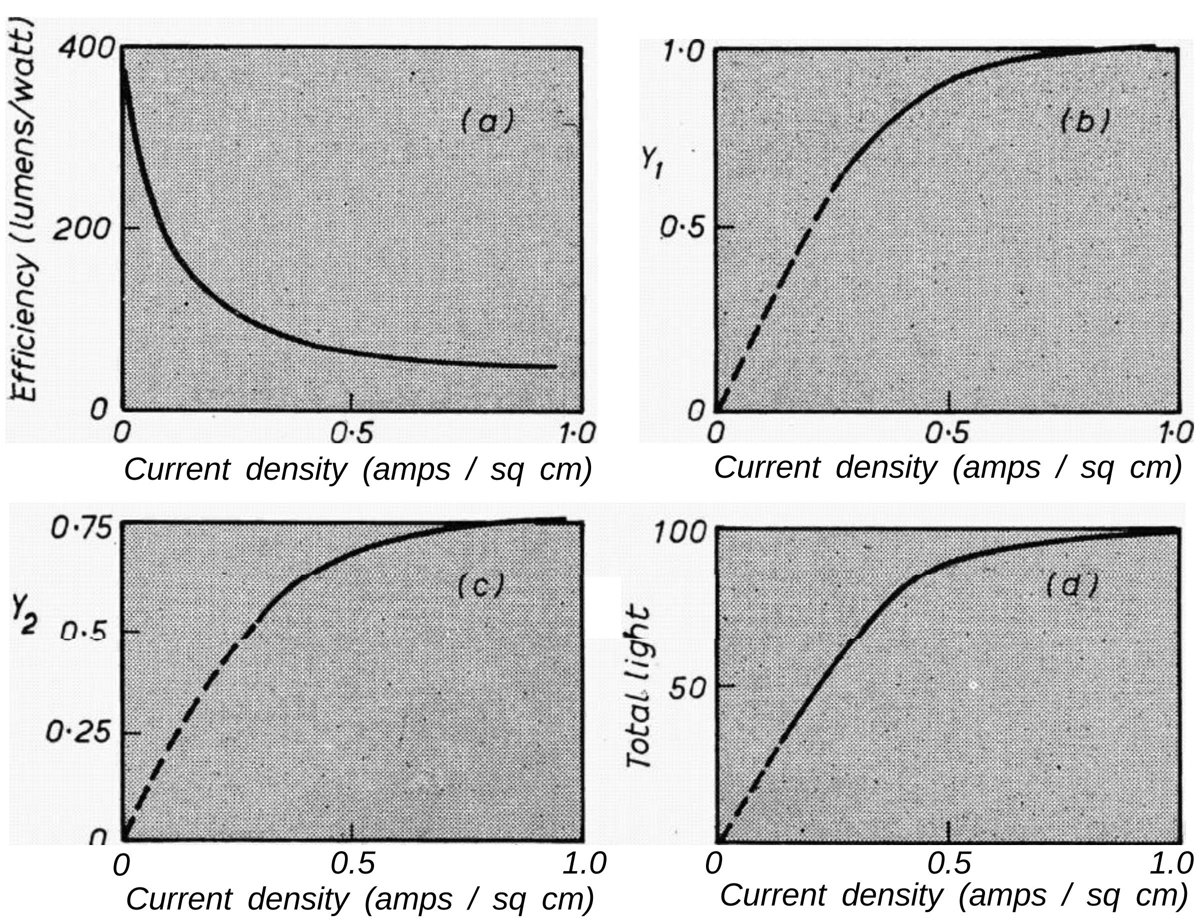

Fig. 2. Electrical Characteristics of sodium lamps. Diagram (a) shows how lamp efficiency varies with current density in the discharge. Efficiency of the lamp is reduced as the arc discharge becomes saturated with sodium atoms excited to the 2.1V level. In (b) is shown how efficiency may be raised by increasing the arc-tube surface area; the curve depicts the effect of current density on a factor Y_1 which, when multiplied by percentage surface area, will give the percentage efficiency increase desired. Curve (c) illutstrates that efficiency may also be raised by decreasing arc-tube volume; the curve shows the effect of current density on a factor Y_2 which, when multiplied by the percentage volume decrease, will give the percentage efficiency increase secured. Curve (d) indicates the variation of light output of any given size of lamp with current density in the discharge

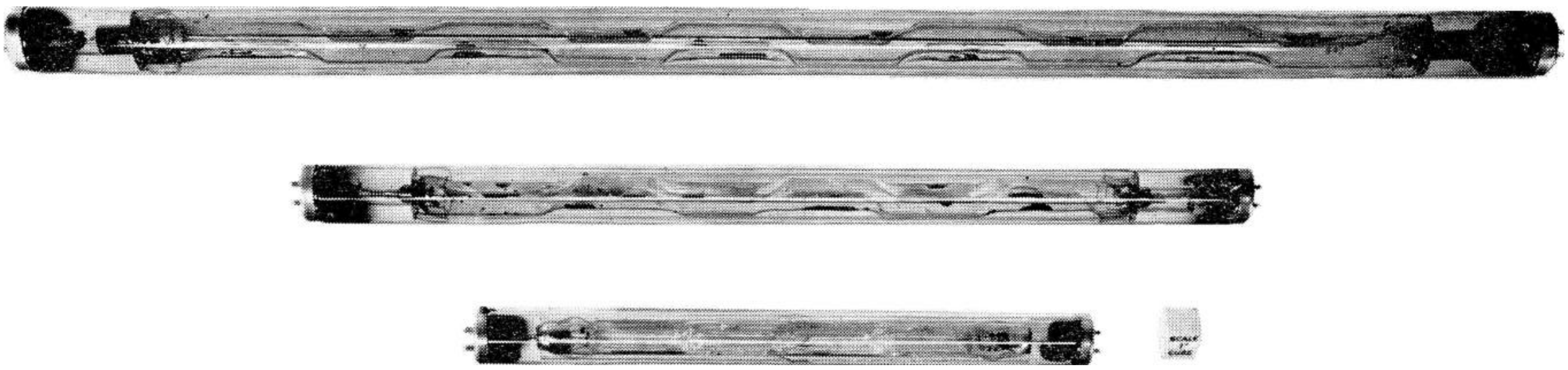

Fig. 3. Prototype linear arc tube sodium lamps of 100, 150 and 200W rating

drop obtained when the sodium is present. As a result of this requirement any part of the arc tube, which for any reason becomes devoid of sodium, will run hotter than the remainder. The generation of such a hot spot along the length of the lamp will result in sodium being progressively distilled away from that spot which will, therefore, increase axially in size with time. Sodium vapour diffusion back into the hot spot has proved to be insufficient to compensate for the loss by distillation, and the lack of sodium in the hot spot results in a considerable reduction in the light output from the lamp.

In order to control the effects of both mechanical movement and migratory distillation of sodium metal, it is necessary to provide definite cool areas or pockets in which the liquid sodium will preferentially reside. The cool areas must run at 230°C but the remainder of the arc tube should preferably be maintained at a higher temperature.

Glass Discolouration

It is general practice to manufacture sodium lamp arc tubes from soda lime glass, which is lined on its inside by a second glass designed to be specially resistant to chemical attack by sodium vapour. Much research and development has been carried out in order to produce glasses which are completely free from discolouration resulting, from chemical attack during lamp life, glass discolouration being very undesirable because its reduction of light transmission through the arc tube wall reduces lamp efficiency. The successful development of sodium resistant glasses, which do not discolour throughout an extremely long life,[4,5] virtually eliminate this factor from lumen maintenance considerations. Any new design of sodium lamp should be based on the use of these glasses.

Electrode Life

As a result of widespread research and development work on the design of long-life electrodes for low-pressure discharge lamps, there now exists a variety of electrode designs from which a choice may be made. The present type of sodium lamp electrode is suited to high-voltage cold-starting requirements, under which condition it is capable of giving excellent results, but if low-voltage operation is required, it is preferable to use electrodes of the type established in tubular fluorescent lamp design when the circuitry and control gear associated with these lamps may be used.

Basis for New Lamp Design

Examination of the curves in Fig. 2 indicates that relatively high current densities can be used in conjunction with large surface areas and small volume in order to obtain maximum efficiency. No apparent limit is set by the curves, Figs. 2(b), 2(c), to efficiency gain obtainable, but in practice there are limits as explained below.

When the current density of the arc exceeds a certain value restriction of the arc takes place thereby invalidating the normal current density, surface area and volume relationships. Experimental evidence indicates that 0.2 amps of total arc current per mm of the minor axis of the arc cross-section, as shown in Fig. 4(e), is a limiting figure required to avoid constriction.

The dimension of the major axis of cross-section as shown in Fig. 4(e) largely determines the surface area of the arc tube, hence the lamp efficiency and heat dissipation properties, or arc tube loading. It will be seen that, whilst the lamp current proposed sets an objective minor axis dimension, knowledge of the heat conversion characteristics of the type of lamp construction envisaged determine the major dimension, hence the efficiency of the arc discharge. Arc tube loadings at present achievable, therefore, dictate the amount of distortion from the circular cross-section which can be used to improve lamp efficiency.

Cross-sections

Practical investigation of the various cross-sectional shapes in Fig. 4 shows that in some cases the shape required can be formed by application of a pressure pad to a suitably heated glass tube; in other cases air pressure inside the glass tube is required in conjunction with outside moulds to achieve the required shape. Tests reveal that the shape of Fig. 4(b) can be formed by pressure alone. A reasonably consistent cross-sectional area is obtained from tubing subject to a 10% diameter tolerance by setting mould depth with reference to a 90° angle trough into which the tube is placed for moulding. In order to obtain good resistance to mechanical sodium movement and thermal migration this shape was changed

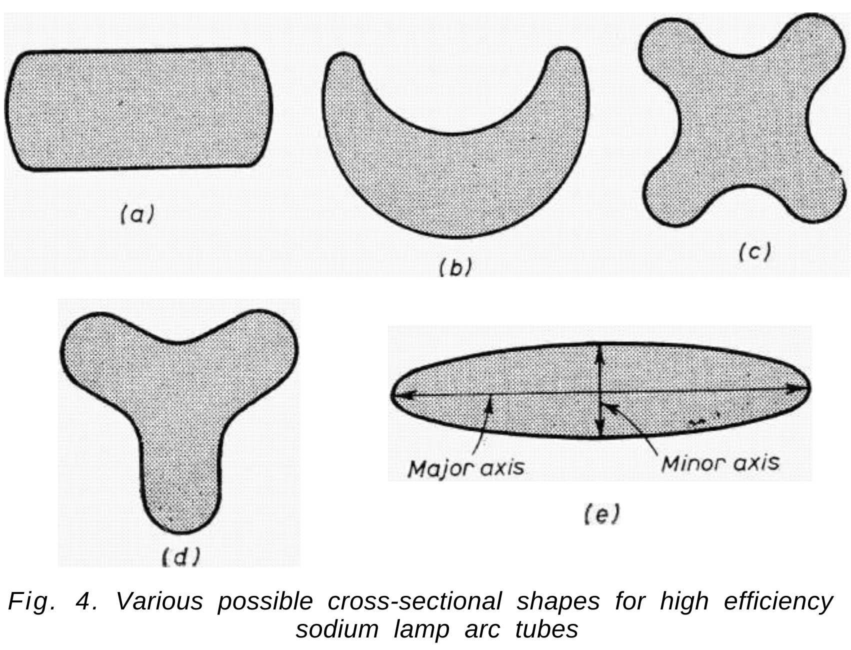

Fig. 4. Various possible cross-sectional shapes for high efficiency sodium lamp arc tubes

Table 2. - General characteristics of sodium lamps of the new design

Arc tube loading	0.215 W / sq. cm
Arc tube loading	0.233 W / mm of arc length
Arc current	1.60 amps
Current density	0.8 amps / sq cm
Efficiency of positive column only	115 lm / W
Electrode losses for 1.6 mm arc ...	20 to 25 W
Arc voltage gradient	6.25 mm / volt

from Fig, 4(b) to the shape of Fig. 5 (depicted pictorially in Fig. l), sodium being effectively retained in the region of, the small radii by capillary attraction against the application of mechanical forces to remove it and also against the effects of thermal migration, because the capillaries are maintained cooler than other parts of the arc tube which are closer to the arc stream. In order to prevent undue metal movement along the capillaries it was found best to limit the axial length of crescent formation to a maximum of some 2½ times the diameter of the tubing used, this being accomplished by alternate formation from opposite sides,[7] as shown in Fig. 1.

Lamps have been constructed from crescent grooved tube of various diameters and groove depths in order to ascertain the relationship between major and minor cross-section dimensions and arc-tube loading. Such arc tubes

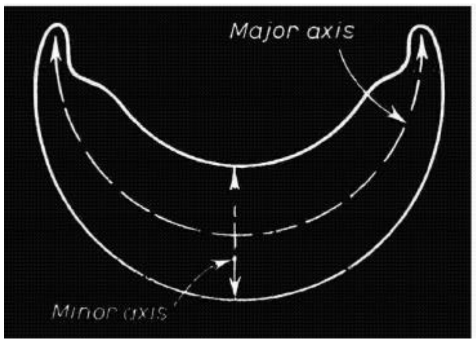

Fig. 5. The crescent-shape cross section finally developed for the new AEI linear arc tube sodium lamp. Liquid metal resides in the regions of smallest radius by virtue of capillary action

were mounted within loose glass sleeves and the whole assembly sealed into tubular outer jackets similar in dimension to l½ in. diameter tubular fluorescent lamps, the outer jacket being exhausted to a high degree of vacuum to prevent heat loss from the arc tube by conduction or convection. The loose glass sleeve between arc tube and outer jacket serves to further restrict heat loss as it absorbs a large part of the infra-red radiation from the arc tube and re-radiates half outwards and half back inwards.

The most promising lamps have been produced from nominal 1 in, diameter tubing, the construction of which is illustrated in Fig. 1. These lamps exhibit the general characteristics shown in Table 2. From the above figures it can be estimated that the types of lamps shown in Table 3 could be of interest for practical sodium lighting applications.

Table 3.-Data of four sizes of sodium lamp of the new design

Lamp power, watts	100	150	200	250
Lamp arc drop, volts	70	102	136	170
Lamp current, amps	1.6	1.6	1.6	1.6
Initial or 100 hr efficiency, lm/W	80	92	100	102
Overall length, inches / mm ...	18/457	28/711	36/914	44/1118
Outside diameter, mm max. ...	40	40	40	40
Arc length, mm	322	535	750	965
Arc diameter	26 mm or 1" nominal			
Light output at 100 hours, lumens	8,000	13,800	20,000	25,500

Lamps have been made up and tested to the general specifications given in the tables. These show that the lumen maintenance achieved should enable the final efficiency of lamps of 200 W and upwards to be as high as the initial efficiency of any lamp at present on the market. Evidence from these tests also shows that cathode conditions and sodium location in this form of lamp are such that it can be relied on to give a survival performance equal to that of present types.

The control gear requirements for lamps of this type are readily fulfilled since tests show that the following striking voltages are obtained in a thermal relay circuit with series inductance, as is normal practice for fluorescent lamp operation :

Lamp watts ...	100	150	200	250
Striking volts ...	180	240	300	360

These values are maintained throughout the life of the lamp and provide a sufficient margin in excess of lamp voltage to give good stability during operation. The use of a thermal relay ensures the positive restarting of hot lamps after short duration power failures. These lamps may be operated on the "instant start" type of circuit when slightly higher control gear voltages and cathode heating are preferable for absolute dependability.

The gas filling used in the lamps ensures that during the run-up period the maximum deviation from normal operating voltage is very small. The lamps have a steep negative resistance/current characteristic and greater stability can be obtained if desirable by designing the control gear so that it tends to give a constant lamp current characteristic with varying input voltage.

Conclusions

The prime function of the sodium lamp has proved to be street lighting, where its usefulness may be measured in terms of the product of efficiency and life. The linear sodium lamps described should prove to have a number of advantages over existing types amongst which are the following:

1.-A 25% gain in efficiency.

2.-Lower voltage control gear requirement for a given wattage.

3.-A more convenient light source shape for many applications.

4.-Robust construction and compact dimensions for storage and handling.

5.-The high lumen output is well suited to new schemes of street lighting, calling for higher road lighting intensities or greater economy.

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