# High-Pressure Sodium Discharge Arc Lamps

By W. C. Louden and K. Schmidt

THE potential of sodium and other metallic atoms for use in light production was examined by Dushman[1] and others.[2] These results stimulated work by Fonda and Young[3] and in 1932 they demonstrated low-pressure sodium lamps in several installations. The lamps were characterized by their monochromatic yellow color and had an efficacy of 30 to 70 lumens per watt. Highway lighting installations were the principal use for these early lamps as application to other use was limited for esthetic considerations.

Commercial history of high-pressure discharge arc lamps began in the early 1920's with the development of mercury lamps. Developments in the mercury lamp since Elenbaas,[4] by Noel[5] and others,[6] have resulted in a generally accepted light source that has replaced the low-pressure sodium lamp in almost all the old installations. However, the low-pressure sodium lamp still finds wide application in European countries where development work has continued. Efficacies of over 120 lumens per watt are now common through improvements in techniques and innovations in arc-tube designs. The lamps are popular in those countries that pay a premium for electrical power.

The low-pressure lamp operates with a sodium pressure of several microns. Special arc-tube glasses and glazes have been developed to resist the corrosive chemical characteristics of the sodium. Higher sodium pressures achieved by increasing arc-tube temperatures cannot be attained in conventional glass or quartz arc tubes as rapid chemical action darkens the arc tube. This reduces the efficacy and eventually causes failure of the lamp. Therefore, all commercially available sodium lamps, even with recent innovations and increased efficacy, have a characteristic yellow color with the associated poor color rendition.

Schmidt[7, 8] has studied high-pressure discharges through the vapors of alkali metals, sodium, potassium, rubidium and cesium, and discovered that sodium provides the highest efficacy in a light source with a good color rendition. The high-pressure sodium discharge is enclosed in an arc-tube envelope of high-temperature, alkali-vapor-resisting, high-density, polycrystalline alumina. Nelson[9] and Rigden[10] have since made similar studies and have substantiated these findings. Operation of the high-pressure sodium discharge differs from that of the high-pressure mercury-metallic-iodide discharge[11] in that the discharge is wall stabilized with high-volume loading, the sodium pressure is higher by a factor of several hundred, and it is primarily the sodium atoms that are excited. The iodide lamp operates constricted and, convection determined, the sodium pressure is ordinarily a few torr; it uses mercury as well as metal iodides, and atoms of all the metals and mercury are excited. The low-pressure sodium lamp in comparison has high electron temperature and low gas temperature with low-volume loading. The sodium pressure in the arc is several microns compared to 200 mm (200 torr) in the high-pressure sodium lamp.

## Physical Construction

A 400-watt high-pressure sodium discharge arc tube is shown in Fig. 1. The arc tube, *B*, is sintered, high-density polycrystalline alumina manufactured by a process[12] that promotes controlled grain growth. The alumina tubes produced by this process are translucent and have a total transmission of light in the visible region greater than 90 per cent. The translucent alumina is highly resistant to alkali vapor at high temperatures. As a comparison, a high-pressure sodium arc operating in a conventional quartz arc tube would cause chemical darkening of the quartz by forming sodium silicate in less than an hour of operation. The translucent alumina shows no attack even after 10,000 hours of operation. Subassemblies

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*A* and *C*, consisting of metal end caps and standard electrode structures, are sealed to the alumina tube. A metal tube, *D*, on one end of the structure serves as a means for exhausting and for dosing the arc tube with an amalgam of sodium and mercury. This tube is sealed off after processing is completed. The final lamp structure, similar in outward appearance to other high-pressure discharge lamps, is shown in Fig. 2. The translucent alumina arc tube is supported by a metal framework in an evacuated outer glass jacket. As in the mercury-metallic-iodide lamp, evacuation of the outer jacket serves to increase lamp efficacy by reducing conduction heat losses from the arc tube.

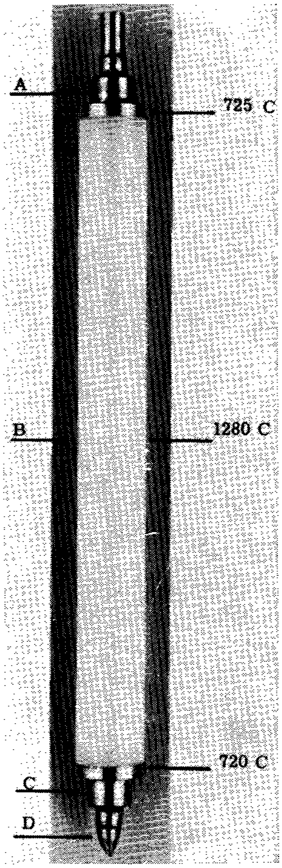


*Figure 1. The 400-watt high-pressure sodium discharge arc tube and operating outside-wall and seal temperatures. B—translucent alumina arc tube; A and C—metal end-cap subassemblies; D—closed exhaust tube.*

## Discharge Mechanism

In the low-pressure sodium lamp almost all the energy is radiated in the sodium *D*-lines. Since they are located in the yellow portion of the eye-sensitivity curve, very high efficacies can be obtained but the color rendition of the source is poor. As the sodium vapor pressure is increased, a great percentage of the total radiation is emitted on either side of the *D*-lines and the line radiation becomes imprisoned or self-reversed. As a result, the source loses its characteristic monochromatic yellow color to become golden white with a significant amount of energy in the red. Mercury is added to the sodium in the discharge tube and acts only as a buffer gas. Little radiation of mercury lines is apparent in the visible region. Mercury raises the voltage gradient of the arc, permitting higher efficacies in the current range of 2.5 to 5.0 amperes.

Stable operation of the discharge is maintained with a reservoir of liquid sodium amalgam located in the exhaust appendage. By a careful balance of heat flow the appendage temperature is held constant; thus the sodium and mercury pressure in the discharge is constant.

The discharge is operated wall stabilized with an

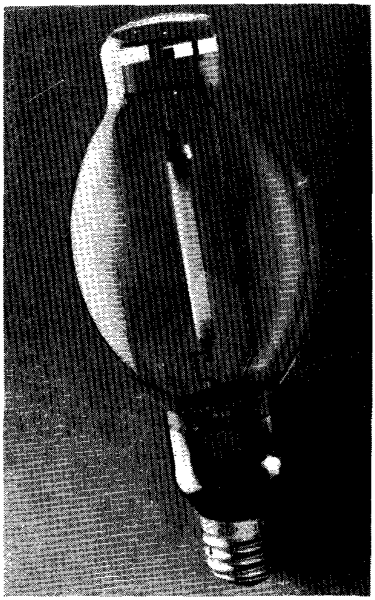

*Figure 2. Complete 400-watt high-pressure sodium discharge lamp assembly.*

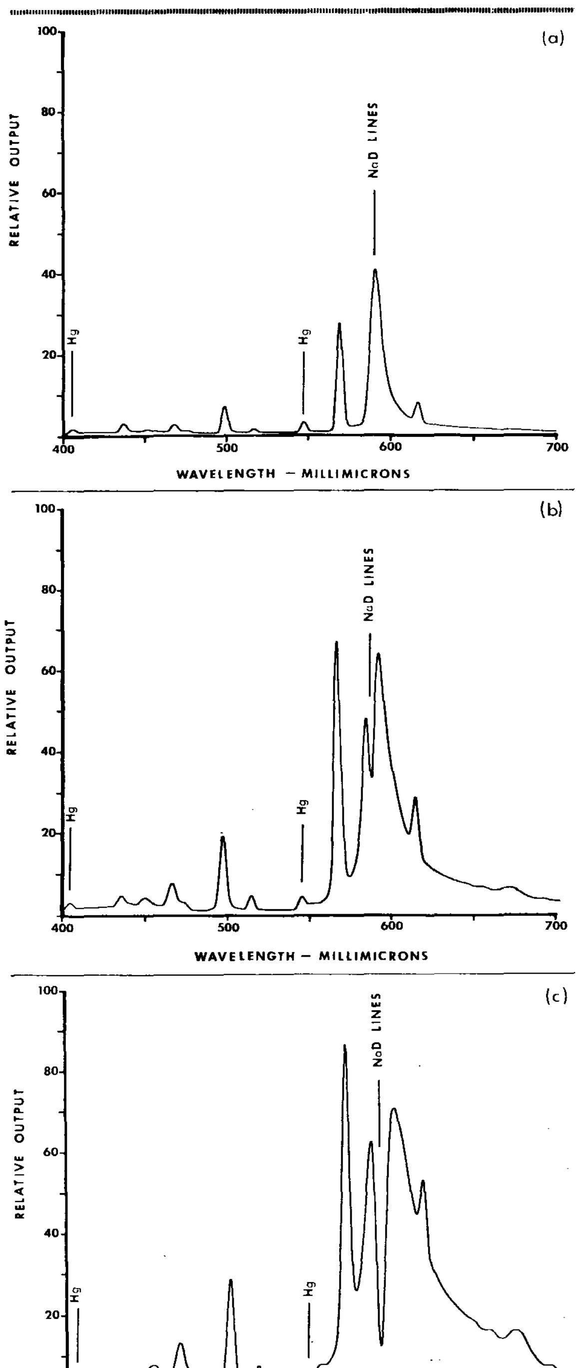


*Figure 3. High-pressure sodium discharge lamp spectral distribution: (a) 3.0 amperes, 68.5 volts and 185 watts; (b) 4.4 amperes, 105 volts and 400 watts; (c) 5.0 amperes, 143 volts and 620 watts.*

arc length of 70 mm between electrode tips. The tube diameter, 7 mm, is small enough for the positive column to be stabilized only by heat conduction to the wall. Convection disturbances in the arc chamber are negligible.

## Design Characteristics

The scope of this paper has been limited to a discussion of the measurements made on a representative sample of the high-pressure sodium discharge lamp. The reader is referred to Reference 8 for further details concerning the discharge and its characteristics. The variation of design parameters has not been included as investigation of all variables has not been completed.

The spectral-energy distribution[13] of a 400-watt lamp operated at three different wattage inputs is shown in Figs. 3a, b and c. Since the discharge characteristics depend on the temperature of the liquid amalgam, a change in energy input results in a change of the amalgam temperature. The effect of temperature and vapor pressure can be seen on the energy distribution. As the wattage increases (pressure increases) the line wing broadening becomes more apparent. The lamp color changes from a light yellow at 185 watts to a golden white at 400 to 620 watts. The golden-white color may be obtained in any wattage, however, by varying the length and holding other parameters constant.

The operating temperatures of the 400-watt arc tube are indicated in Fig. 1. High-pressure mercury arc tubes generally operate with a center bulb-wall temperature of 700 to 800 C and a seal temperature of 400 to 500 C. By virtue of the high-density translucent alumina the center arc tube wall can be operated at 1280 C, and proprietary seal design allows operation of the seals at 720 to 725 C. The wall loading of this lamp is 22 watts per square centimeter if electrode losses are deducted.

## Electrical Characteristics

The electrical-characteristic curves for the 400-watt sodium lamp are illustrated in Figs. 4 and 5. The operating points for the three energy distributions in Fig. 3 are indicated by the circles on the volt-ampere characteristics. These curves represent the measurable characteristics of a typical lamp operated on an adjustable choke ballast. As mentioned under "Discharge Mechanism," the reservoir of liquid sodium amalgam in the appendage is maintained at a constant temperature. However, in making characteristic measurements on a finished lamp the appendage temperature will vary and adjust itself to a different value dependent upon the ballast conditions. Therefore it would appear that the volt-ampere characteristic has a positive slope when actually the characteristic is negative at any single dynamic operating

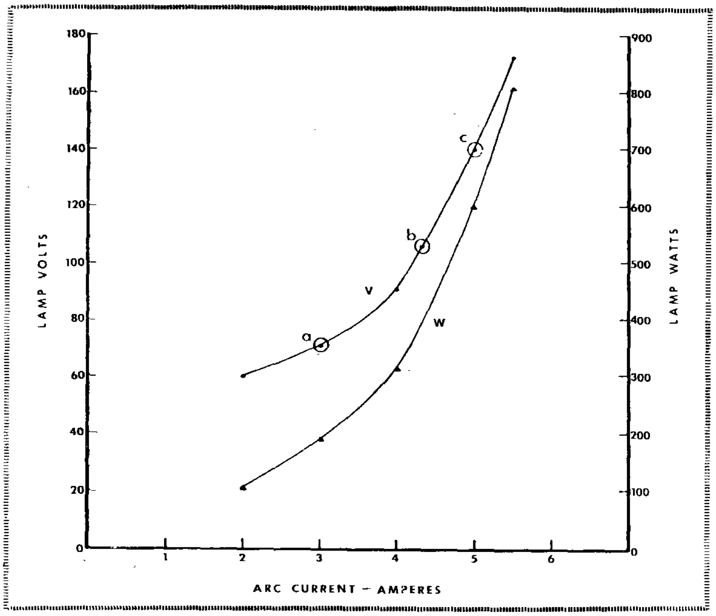


*Figure 4. Lamp volts and lamp watts as a function of arc current for a 400-watt high-pressure sodium lamp.*

point where sodium and mercury pressure is constant.

The electrical parameters of the 400-watt design point have been chosen to obtain maximum efficacy with the objective color. The maximum of the efficacy curve appears not to occur at the design point as this characteristic also is the combined effect of both the increase in loading and the increase in sodium and mercury pressure.

The red factor, an arbitrary measure of the red segment of the visible spectrum, is measured with a filter that has a transmission characteristic as illustrated in Fig. 6. As demonstrated by the spectral distribution curves, the higher-wattage operation increases the line wing broadening and therefore the red factor increases.

Operating curves of lamp voltage and current at the rated 400-watt input are shown in the oscillogram, Fig. 7. Line voltage, indicated by the sine wave, is 240 volts. The lamp voltage curve indicates that the re-ignition voltage required to sustain the arc is somewhat more pronounced than that which normally occurs in a standard mercury discharge arc.

## Starting Voltage

Xenon at 20-torr pressure is used as the starting gas to raise the temperature of the sodium and mercury to a vapor pressure that will cause excitation of the sodium atoms. The combination of this gas pressure and the small-diameter arc tube results in a starting voltage of 1800 volts peak. A compact auxiliary starting circuit that provides 2500 volts peak has been designed for use with a series inductive ballast. A peak starting current of 3 amperes with a pulse width of 1 microsecond is delivered by the starting circuit to insure that a hot spot develops on the electrodes.

Restarting of the lamp requires two to three min-

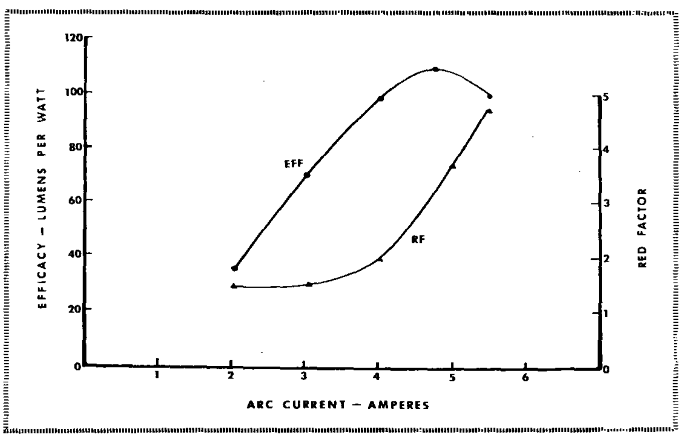


*Figure 5. Lamp efficacy and red factor as a function of arc current for a 400-watt high-pressure sodium lamp.*

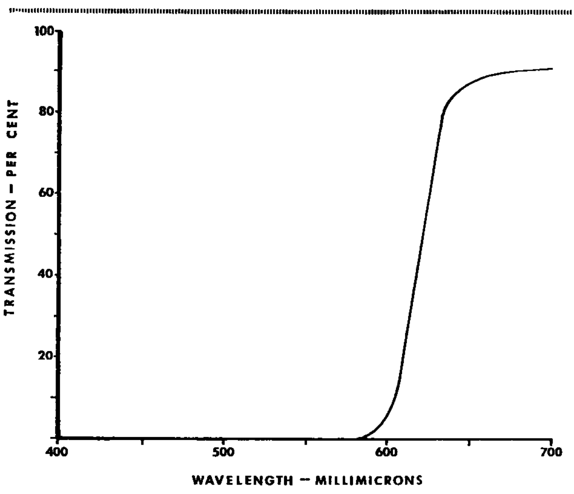


*Figure 6. Transmission characteristic of CS2-61 filter used to measure lamp red factor.*

utes cool-down time for re-ignition and two minutes to re-establish operating temperatures. The short re-ignition time, compared to that of standard mercury lamps, is a result of the lower vapor pressure of sodium at any given temperature and the high starting voltage generated by the auxiliary starting circuit.

## Lamp Life and Maintenance

With initial efficacy in excess of 100 lumens per watt, 10,000-hour lumen maintenance has been measured on laboratory test lamps at over 90 per cent. Median life at the present time is in the 3000- to 6000-hour range. From an engineering viewpoint it is reasonable to expect that this can be increased as techniques for constructing the lamps are improved. Both life and maintenance can be expected to equal and possibly exceed those of the present mercury types, which use quartz arc tubes. This results from the use of sintered translucent alumina for the arc tube. Unlike quartz, it is not only free from chemical reactions with sodium but also shows no depreciation in transmission with lamp life due to devitrification or other similar effects.

## Applications

High luminous efficacy with acceptable color combined with a small, high-brightness source and low ultraviolet radiation makes the high-pressure sodium discharge lamp attractive as a lighting source. Since the cost of light generally is inversely proportional to lamp efficacy, other factors remaining constant, the new lamp shows promise of wide acceptance in new outdoor installations such as street lighting, floodlighting and area lighting. Indoors it will be used in high-bay industrial installations and eventually on other commercial applications. More complete coverage of lighting applications will ensue as a line of 100- to 1000-watt lamp sizes is introduced. The small high-brightness translucent alumina arc tube allows an increase in precision of refractor and reflector design and therefore greater control of light. Low ultraviolet radiation may permit the use of lower-cost plastics in refractor design.

A trial installation of 25 400-watt lamps used to illuminate an 87,000-square-foot parking lot and its entranceways is pictured in Fig. 8. The lamps are mounted in modified 1000-watt mercury luminaires on 30-foot poles spaced 85 feet apart on a diagonal grid layout. The lighting level is 4.5 footcandles—more than twice the level of the average well-lighted parking lot. The new light source combines, for the first time, efficacy of over 100 lumens per watt with good color rendition. Laboratory tests enable us to predict with confidence further improvements in efficacy and life. The impact of the high-pressure sodium discharge arc lamp on lighting technology and lighting applications is foreseen to equal that of the fluorescent lamp.


## Acknowledgments

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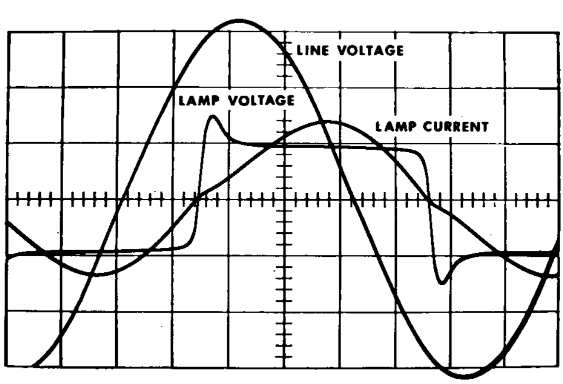


*Figure 7. Oscillogram of line voltage, lamp voltage and lamp current at 60 cps for a 400-watt high-pressure sodium lamp. Line voltage is 240 volts, 100 volts/cm; lamp current, 4.5 amperes, 5.0 amperes/cm.*

*Figure 8. Parking-lot installation of 25 400-watt high-pressure sodium discharge lamps.*


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## DISCUSSION

M. L. QUIN:* The authors have predicted that the impact of this light source development on lighting could equal that of the fluorescent lamp. Time will tell if there need be any reservations regarding color. As for my own observations, the present lamp color is intriguing. With any further improvement, the lighting cycle from point source to linear source and back again would seem insured.

One question I have pertains to thermal characteristics. The authors state that low ultraviolet radiation may permit the use of lower-cost plastics in refractors. It should be pointed out that clear thermoplastics having high heat resistance are even more costly than light-stable resins in current use. If high-pressure sodium arc-tube temperatures are operated in excess of 1200 C, it would follow that outer jacket temperatures could range considerably higher than mercury lamps of equal wattage. It would be helpful to luminaire designers if the authors could cite comparisons in outer jacket temperatures for the two types of lamps.

Regarding lamp sizes, the authors mentioned a line of 100- to 1000-watt lamps. One could conclude from the paper that a 400-watt size will be a future design rating. My only comment is a plea that any progression of sizes will consider lamp lumens with lamp applications rather than simply adopting the present mercury wattage progression.

W. E. THOURET:** The authors close their important paper with an interesting prediction; they say that high-pressure sodium vapor lamps may have an impact on lighting technology equal to that of the fluorescent lamp.

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The facts presented in the paper seem to justify this prediction. This is clear particularly to those specialists who have been familiar for a long time with the characteristics of alkali vapor discharges. It was known to them that a new tube material capable of withstanding alkali vapor under high-pressure conditions would lead to a group of new light sources with superior properties. The authors should be congratulated on this achievement.

My questions are the following:

1. Why is xenon used as a starting gas instead of krypton or argon? It would be interesting to learn more about the reasons for using xenon which seems at least partially to be responsible for the high ignition voltage.

2. It is stated that the small tube diameter also contributes to the high starting voltage. What would be the consequences of an increased tube diameter?

3. Figs. 3 and 5 indicate that the described 400-watt lamp operates at about the optimum pressure for efficacy and has a red factor of under 3. For good color rendition in the red region a red factor of 10 to 12 is considered necessary. Have the authors investigated the obtainable increase of the red factor by increasing vapor pressure or wattage per unit arc length? What sacrifices in efficacy have to be made in order to obtain better red color rendition? Has the color rendition index of the described 400-watt lamp been determined?

4. The method of sealing the metal end caps to the alumina tube is described only by the statement that it is proprietary. We believe that no harm would be done to commercial interests if the authors would state what metal is used for the end caps, what sealing medium is used and whether the end caps are sealed internally or externally to the tube or flatly against the tube end surfaces.

5. Could the authors say what is understood under "stand-

ard electrode structures"? Do they mean thoria-activated, thorium-activated, alkaline earth-activated or pure tungsten electrodes?

6. Have the authors determined the absorption of the "Lucalox" material through comparison of the lamp efficacy with that of an equally dimensioned lamp make of clear synthetic sapphire? Such quantitative information would allow conclusions about efficacy improvements to be expected in the future from improvement of the tube material with respect to absorption and diffusion characteristics.

7. Have the authors investigated the possibilities of improving the color rendition of the sodium high-pressure arc by adding other alkali or other metal vapors besides mercury?

M. C. Unglert:* In this paper the authors discuss a really exciting light source. Some additional information might be helpful in the evaluation of this new lamp type.

1. Curves are provided for voltage *vs* current and efficacy *vs* current for constant cold-spot temperature. The paper mentions that electrical parameters were chosen. What parameters were chosen for the test lamps cited?

2. 90 per cent maintenance at 10,000 hours is indeed excellent; what type of electrodes were used in these lamps?

3. Why was xenon chosen as the starting gas rather than argon, which is used in many discharge lamps?

4. There have been rumors of lamps such as this with efficacies of 150 lumens per watt. Would the authors care to comment on this point?

W. C. Louden and K. Schmidt:** We thank the discussers for their comments.

In answer to Mr. Quin's question concerning the outer jacket temperature of the high-pressure sodium lamp compared to that of a mercury lamp of equal wattage: The operating temperature of the outer jacket is limited by the type of glass used. Since the type of glass in the jacket is the same for both the high-pressure sodium lamp and the mercury lamp, operating temperatures have been adjusted to be the same by careful design of the jacket shape. The final jacket design is somewhat smaller even though the arc-tube temperature is in excess of 1200 C. The high-pressure sodium arc tube is smaller than the mercury arc tube and the outer jacket is evacuated as opposed to gas-filled for the mercury lamp. The net result is that a more compact outer jacket may be used which operates at the same temperature as the mercury lamp.

Regarding lamp sizes: The 400-watt size is the initial design rating. Consideration will be given to a progression of lamp sizes from this initial size both up and down, based on lumen steps for lamp applications.

Mr. Thouret questions the use of xenon as a starting gas instead of krypton or argon. Xenon is used since maximum efficacy is obtained with this gas. Other gases will lower the starting voltage slightly, but a significant decrease in efficacy results.

The consequences of increasing the arc-tube diameter to reduce the starting voltage would be an efficacy loss for equal arc currents, which would outweigh a slight decrease in starting voltage.

The high-pressure sodium lamp operates at optimum efficacy with a red factor of about 3. The red factor used here is measured with a CS2-61 filter. Using the same filter, a clear mercury lamp would measure 0.4, an improved-color mercury lamp 2.0, and a mercury-metallic-iodide lamp 0.6; therefore it is apparent that this lamp has more red than existing sources.

Details of the mechanical structure of the lamp were considered not to be of general interest and were therefore omitted from the paper. They are of a proprietary nature.

The "standard electrode structures" are the same as those used for a 400-watt high-pressure mercury lamp.

Under "Physical Construction" it is stated that the total transmission in the visible region of the translucent alumina is greater than 90 per cent; therefore it is to be expected that future improvements in arc-tube materials would result in less than 10 per cent increase in efficacy.

Among the alkali metals that have been considered as possibilities for further improvement of the color rendition of the high-pressure sodium lamp is cesium. However, because of its low ionization potential and the relatively high pressure required a serious drop in efficacy results.

Mr. Unglert questions the electrical parameters chosen for the test lamp cited in the paper. The golden white color at optimum efficacy of over 100 lumens per watt may be obtained over a range of lamp currents and lamp voltages. The design current and voltage chosen for the 400-watt lamp is 4.4 amperes and 105 volts.

Efficacies of 150 lumens per watt have been measured on experimental laboratory lamps. This is possible in the laboratory by optimizing all lamp parameters, such as current, sodium-vapor pressure, starting gas and starting gas pressure. More development work is necessary to arrive at a commercially feasible lamp with this high an efficacy.

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## Gold Medal Nominations Due January 1

General Secretary Arthur S. Tylor invites all IES Members to submit nominations for the 1966 Gold Medal award for "meritorious achievement which has conspicuously furthered the profession, art or knowledge of illuminating engineering." Nominations must be received at IES Headquarters, 345 East 47th St., New York, N. Y. 10017, by January 1. Nominees need not be Members of the Society or citizens of the United States.