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TECHNICAL REPORT

ELECTRIC LIGHT SOURCES STATE OF THE ART - 1987

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U. Amlong	DDR
P. Baxter	Australia
D. Blanc	France
A. Bouwknecht	Netherlands (Radiation Sources)
H. Csapody	Hungary
L. Di Fraia	Italy
D. Dimitrov	Bulgaria
M. Gandolfo	Spain
W. Gungl	U.S.A. (Light Sources)
J. Hormio	Finland
A. Jack	Netherlands (Secretary)
J. Juntunen	Finland
T. Kanoh	Japan
K. Karlsson	Finland
W. Mathis	Switzerland
Y. Matsushima	Japan
A. Mendel	Canada
M. Neumannova	Czechoslovakia
D. Nikolov	Bulgaria
D. Platt	Britain
M. Plaza	Spain
H. Prochazka	Austria
M. San Martin	Spain
B. Schalin	Finland (Electronic Devices)
D. Seeger	FRG (Standardization)
J. Sullivan	R.S.A.
M. Urculo	Spain
M. van de Weijer	Netherlands (Chairman)
F. Whittaker	Britain

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Electric light sources - State of the art-1987*Summary*

This quadrennial report covers the period 1982 to 1986. It describes the state of the art with respect to light sources, radiation sources and electronic devices used in connection with such sources. Standardization of light sources, radiation sources and electronic devices is also covered. The application of light sources and radiation sources is briefly summarized in table form.

Stand des Wissens der elektrischen Lichtquellen-1987*Zusammenfassung*

Dieser Vierjahresbericht umfaßt die Periode 1982 bis 1986 und beschreibt den neuesten Stand des Wissens auf dem Gebiet der Lichtquellen, Strahlungsquellen und elektronischen Hilfsgeräten, die im Zusammenhang mit diesen Quellen benutzt werden. Die Normung von Lichtquellen, Strahlungsquellen und elektronischen Hilfsgeräten wird auch behandelt. Die Anwendung von Lichtquellen und Strahlungsquellen wird knapp in Form von Tabellen dargestellt.

L'état de l'art des sources lumineuses électriques-1987*Résumé*

Ce rapport quadriennal couvre le période de 1982 jusqu'à 1986 et décrit l'état de l'art à l'égard des sources lumineuses, sources de radiation et appareils électroniques utilisés en combinaison avec ces sources. En outre, ce rapport décrit la normalisation de sources lumineuses, sources de radiation et appareils électroniques. Dans une table on peut trouver un résumé de l'application des sources lumineuses et des sources de radiation.

ELECTRIC LIGHT SOURCES

PART I - TRENDS IN THE DEVELOPMENT OF INCANDESCENT LIGHT SOURCES

1. Introduction

The incandescent lamp is the oldest of the major electric light source families. The viability of this source over the years is a consequence of its many advantages and relatively few disadvantages. Simplicity, low cost construction, and excellent colour rendition are major attributes of this class of light source.

1.1. General Service Incandescent Lamp

The general service lamp, a major subdivision of the incandescent lamp family, is made of three parts. These include a mount incorporating a tungsten filament, a soft glass (generally soda lime glass) bulb and an inert filling gas. Because of the simplicity of construction, these lamps can be made at high speeds yielding a good source of illumination at a low cost. A typical lamp is shown in Figure 1.

1.1.1. New Developments in General Service Lamps

Of recent years, with emphasis on energy savings due to cost of generating electricity, the disadvantages of the general service lamps, such as low efficacy (90 % of energy is dissipated as infrared radiation) and short life has resulted in major efforts to replace this light source with more efficient arc discharge sources. Even so or as a consequence, development studies have been underway to increase both efficacy and life of the incandescent source.
1, 2, 3.

The incandescent lamp (general service lamp) is in a general passive state. One area of change is the substitution of powder coated bulbs in place of hydrofluoric acid etching. The motivating force for this change is environmental consideration. An improved electrostatic coating method has been developed⁴. This coating method has yielded a small increase in transmission (+ 1 %) and a reduction of peak luminance by a factor of 3. A survey of decorative lamps has been published⁵.

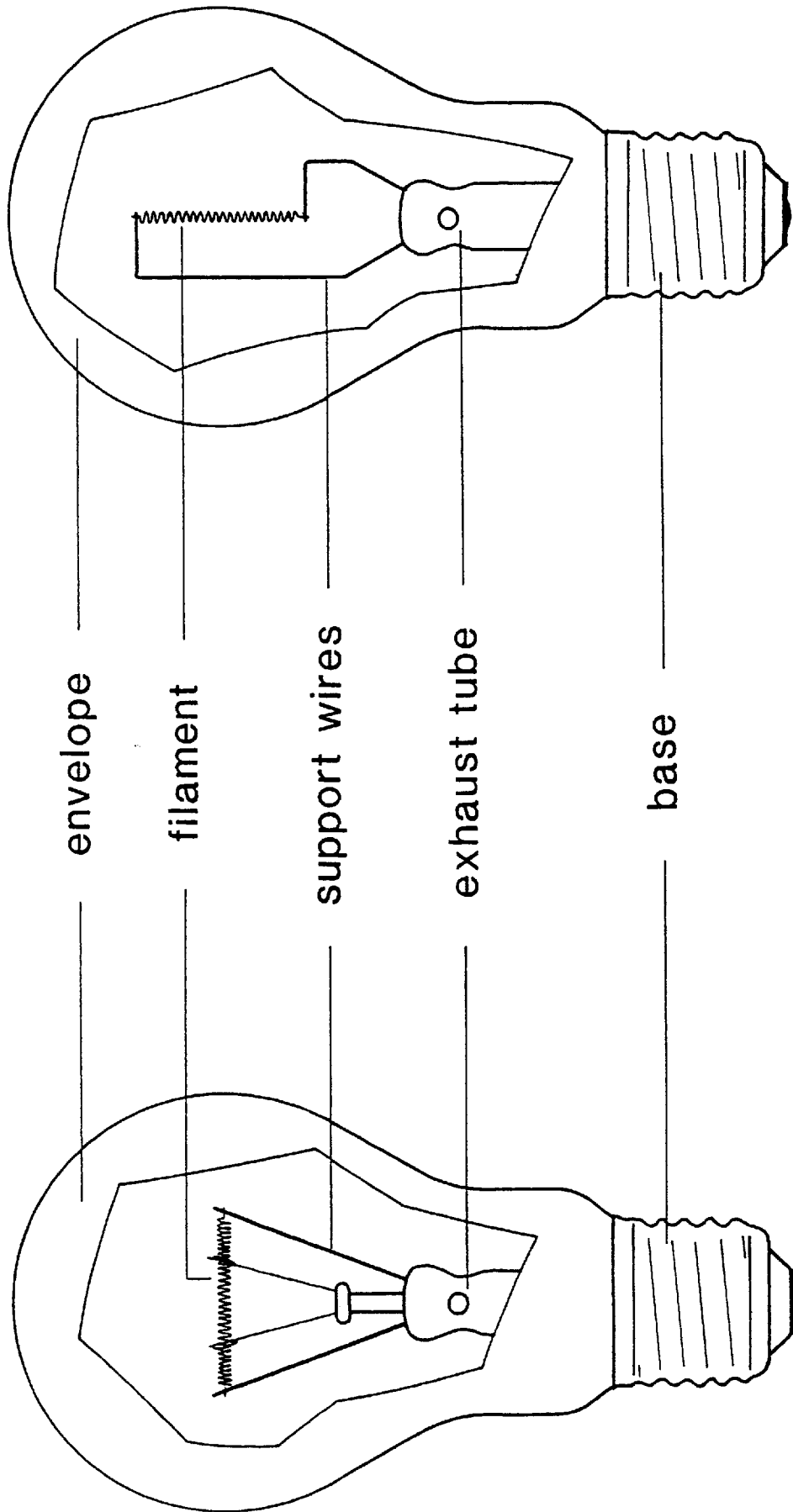


Fig. 1 Typical incandescent lamp showing coil mount structure

A number of experimental studies have been reported characterizing the tungsten used in incandescent filaments. Papers have been presented discussing the role of potassium concentration on properties of tungsten as a filament^{6, 12}. Other studies have dealt with a study of properties (thermal, electrical, luminous, etc.) of tungsten filaments⁸. The transport of tungsten from a filament through an inert gas has been an object of study⁹. Effort has been directed to the economic study of lamps relative to their life and performance¹⁰.

1.1.2. Classic Wedge Base Lamp (Motor Car) Developments

Xenon gas filled 2 W and 3 W wedge base lamps have been developed for automobile dashboard application¹¹. They have been developed to fill a demand for smaller and brighter sources. In comparison to the conventional vacuum lamp, they yield a higher efficacy, 10 lm/W compared to 6.7 lm/W and an increased colour temperature - 2690 K as compared to 2420 K and a smaller diameter 6.5 mm compared to 10 mm.

1.2. Tungsten Halogen Incandescent Lamp

The tungsten halogen lamp is a second major subdivision of the incandescent family. Again, the construction of this lamp is relatively simple but a number of significant differences exists between the general service lamp and the tungsten halogen lamp.

The light generating element is a tungsten filament; the enclosing envelope is fabricated from either a hard glass or a fused silica (quartz). The third element, the filling gas, includes a halogen compound. The halogen compound most frequently incorporates either bromine or iodine. Typical lamps are presented as Figure 2.

1.2.1. New Developments in Tungsten Halogen Lamps

The tungsten halogen lamp continues to experience change¹³. Studies are continuing on the use of fluorine to facilitate tungsten transport¹⁴. Passivation layers to protect against fluorine attack of quartz have been investigated.

Other studies of tungsten halogen lamps have been concerned with tungsten transport processes^{15, 16, 17, 18}, with the morphological changes of the tungsten and associated hot spot formation¹⁹ and with the identification of resultant tungsten compounds in the wall region of the halogen lamp²⁰.

The reactions and transport of molybdenum with halogen and oxygen has been the object of another study²¹.

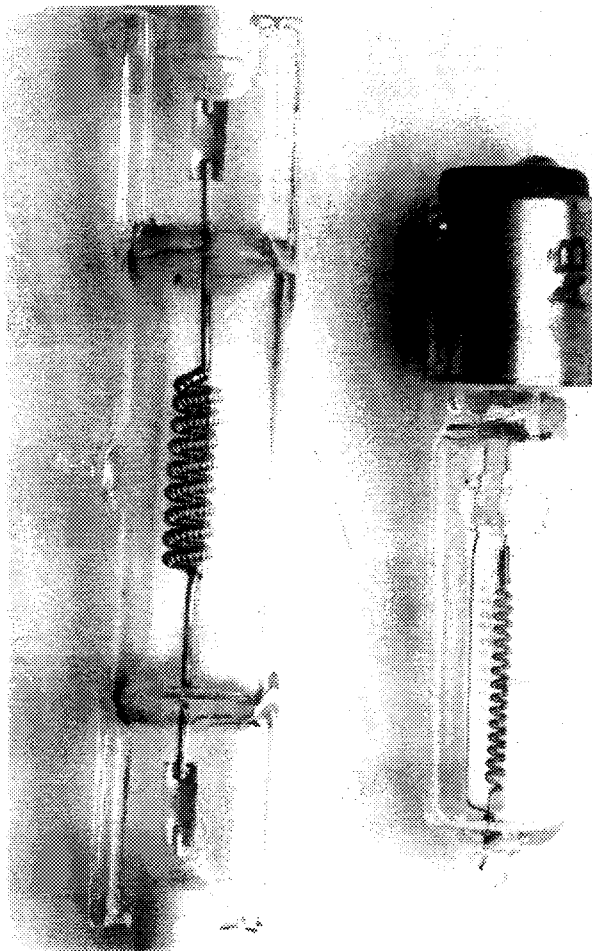


Figure 2. Typical Tungsten Halogen Lamp

Getters to control oxygen in tungsten halogen lamps continue to be a prime interest^{22, 23}. The performance characteristics of tungsten halogen lamps operating at 2865 K has been investigated²⁴.

The design of PAR type tungsten halogen lamps has been accomplished. This design was made possible by the development of a long life low wattage capsule²⁵. This technology has been extended to general service tungsten halogen lamps by enclosure of the capsule in a small jacket. Single ended lamps have been mounted in small dichroic reflectors in order to reduce thermal (IR) radiation and increase the colour temperature of the beam²⁶. The technology of reflecting infrared radiation back onto the tungsten filament of a tungsten halogen lamp is continuing to be exploited^{27, 28, 29, 30}. The reflecting films in one design incorporate interlayers of titanium dioxide (TiO₂) and silicon dioxide (SiO₂)^{31, 32, 33, 34}. A series of infrared reflective film lamps have been introduced to the market place^{35, 36, 37}. These are 65 W, 85 W and 130 W. The luminous efficacy has been increased by about 15 % as a consequence of a 30-40 % reduction of escaping infrared radiation in the range of 0.78-2.5 microns. A new mini lamp has been developed using bromine as the active halogen gas³⁸.

The use of a 100 KHz switched mode power supply for dimming of tungsten halogen lamps has been reported³⁹.

1.2.2. New Developments in Tungsten Halogen Automotive Lamps

Dual filament (C6/C6 asymmetrical configuration) hard glass tungsten halogen lamps for automobile headlights have been developed^{40, 41}. These lamps satisfy the requirements of the asymmetrical light distribution for the passing beam. They have an effective luminous flux approximately 10 % higher than obtained by a C8/C8 filament configuration.

Automotive headlamps have been designed for the US market incorporating a tungsten halogen hard glass (alumino silicate) capsule mounted in an aluminized PAR hard glass bulb. The lens is cemented to the reflector. Evolution of this source has seen the PAR reflector made of aluminum deposited on plastic. These lamps are presently designed with replaceable capsules. Efforts are directed to size reduction, one approach being the use of multi-sources.

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PART II - TRENDS IN THE DEVELOPMENT OF LOW PRESSURE DISCHARGE LIGHT SOURCES

2. Introduction

The family of low pressure arc discharge light sources consists of two major light sources. These are the fluorescent lamp, a low pressure mercury discharge encapsulated in a UV sensitive phosphor coated glass envelope, and the low pressure sodium lamp, a low pressure sodium discharge encapsulated in a glass envelope.

2.1. Fluorescent Lamp

The fluorescent lamp is an arc discharge through a mixture of mercury and a rare gas, generally argon. The mercury gas, the active gas, has an operating pressure of the order of $6-10 \times 10^{-3}$ torr. The rare gas, a buffer gas has an operating pressure of the order of 3 torr. The conducting species of the discharge are electrons and mercury ions. In addition the discharge yields a number of excited mercury atoms. These excited atoms yield a copious quantity of photons of 253.7 and 185 nm UV radiation. These are resonant radiations from the mercury atom. The phosphor on the inner wall of the encapsulating glass tube is in turn excited by these UV photons and fluoresces in the visible spectrum. The phosphors used in these light sources are designed to yield white light for a general source of illumination. The photon conversion efficiency of phosphor exceeds 90% making the fluorescent lamp a high efficiency source of visible radiation.

The fluorescent lamp as shown in Figure 3 is designed as a cylindrical tube with a large aspect ratio. The diameter of the tube is of the order of 16-40 mm with lengths ranging from 13.5 - 250 cm. The surface area of these sources may be quite large, up to 3000 cm^2 . Due to the large surface area, the surface brightness of the source is relatively low (8.2×10^3 candela/meter²) even though the overall efficacy is quite high (of the order of 80 lm/W).

2.1.1. Fluorescent Lamp Phosphor Development

During the past quadrennium trends in fluorescent lamps have been evident in two areas, namely energy efficient lamps and compact source lamps. Energy efficient sources have been developed by the application of high efficacy narrow band phosphors. The phosphor improvements reported include rare earth activated chlorophosphates, halo-boro-phosphates, silica phosphates, yttrium oxide, rare earth activated borates and europium activated alkaline with aluminates¹⁻⁷. Lamps have been designed using rare earth phosphors in which luminous efficacy varied from 97-80 lm/W and the General Colour Rendering Index varied from 87-81 over the correlated colour temperature range of 3000 - 6500 K⁸.

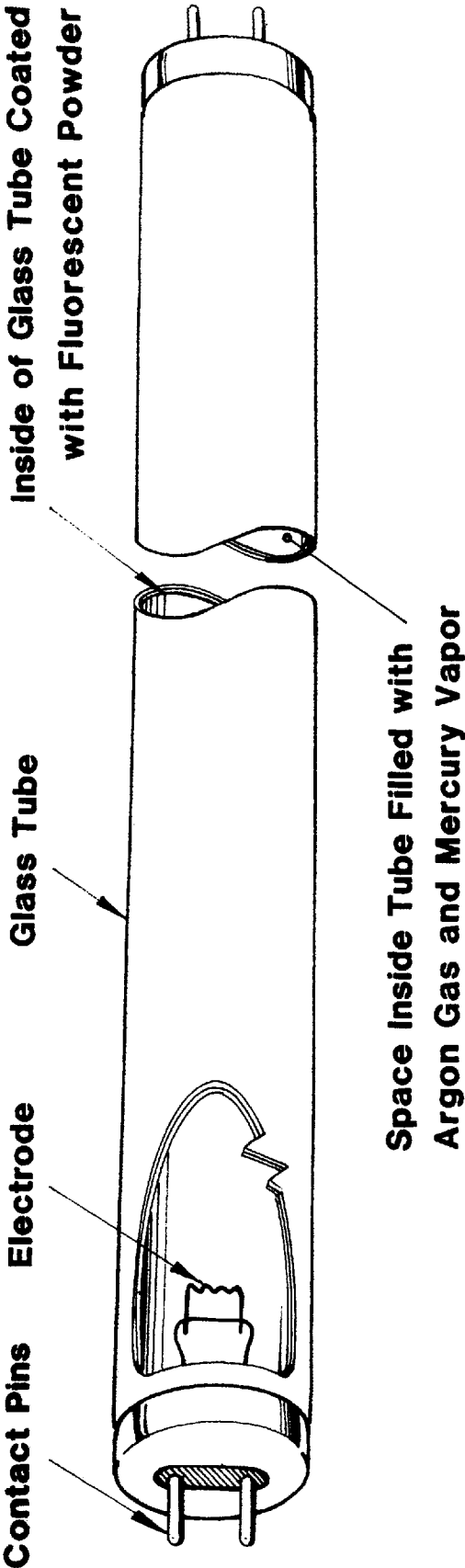


Figure 3

TYPICAL FLUORESCENT LAMP
SHOWING ELECTRODE MOUNT STRUCTURE

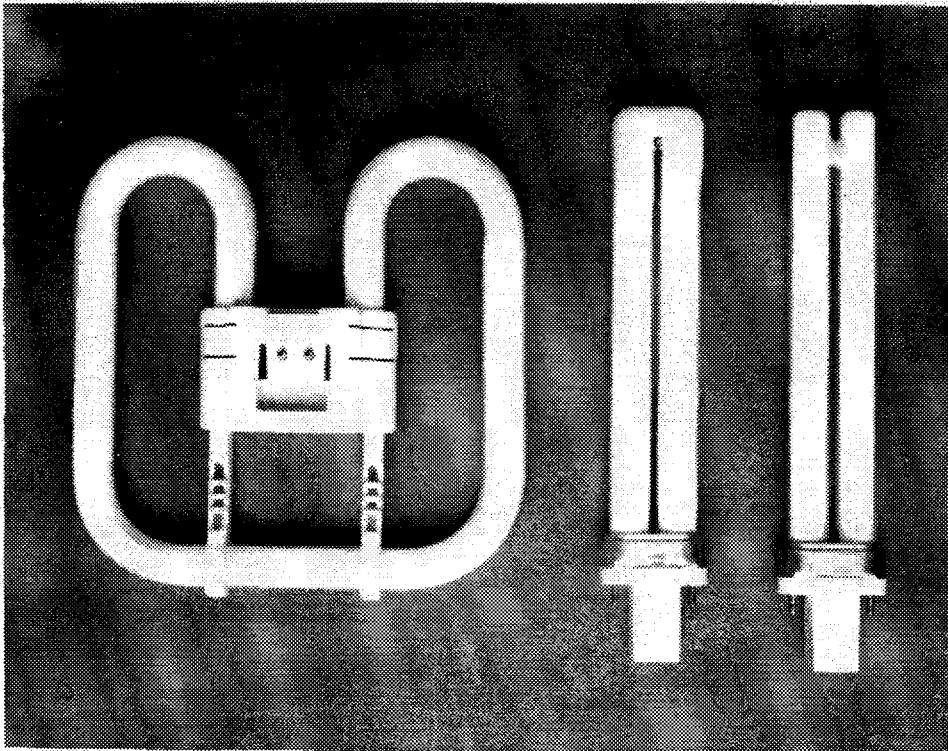


Figure 4 Typical Compact Fluorescent Lamps
(D Shape and U Shapes)

A barium chloroapatite phosphate⁹ was discovered, a blue emitting phosphor, exhibiting improved stability resulting in a three band type fluorescent lamp with a reduced colour shift. A green emitting silicate phosphate has been developed yielding an efficacy of 132 lm/W¹⁰.

Phosphor-lamp studies have been made to improve colour rendition^{12,21}.

2.1.2. Fluorescent Lamp Discharge Development

Studies have been undertaken toward optimization of fluorescent lamps and their operating system^{13,14}. Others^{15,16} have studied the improvement of lamp operating parameters through reduction of lamp diameter. Studies of recombination structures mounted within the plasma volume have been continued^{17,18}.

Others have investigated the improvement of lamp efficacy through alteration of the natural isotopic distribution of mercury in the lamp¹⁹.

2.1.3. New Fluorescent Lamp Designs

Energy saving lamps have been developed to reduce the cost of lighting. One such innovation consists of a lamp in which a switch is incorporated to disconnect heater power to the filament of a normally heated filament²⁰.

The European T-8 (26 mm diameter) lamp concept has been introduced in the USA by the design of a lamp ballast system yielding the highest efficacy of any equivalent fluorescent system (over 100 lm/W), with an acceptable colour rendering index (75), and long life (15000 hrs.)²².

2.1.4. Compact Fluorescent Lamp Development

A second area of change in fluorescent lighting is the continuing trend toward compact fluorescent lamps²³⁻³¹. There are two main types: Those with an integrated ballast and those with a separate ballast. Self-ballasted compact source lamps with an integrated ballast are being widely accepted. They are available in both cool white and incandescent colour³¹⁻³⁵, with a colour rendering index of 85 and luminous efficacy of about 50 lm/W. The use of amalgams for control of the mercury vapor pressure in self ballasted compact fluorescent lamps has been extensively examined. Efficacy increases of 13 % have been reported with the use of a bismuth-indium-tin amalgam³⁶⁻⁴⁰. Amalgams have been avoided in a design in which two open ended discharge tubes are mounted within an outer jacket, so that the atmospheric composition is controlled by the cold spot temperature within the outer bulb. Significant improvements in luminous efficacy are reported for such lamps⁴¹⁻⁴⁴.

Luminous efficacy improvements of compact fluorescent lamps are being realized by the incorporation of an electronic ballast. These ballasts are integrated into the lamp structure⁴⁵⁻⁴⁷, and result in reduced overall weight of the light generating package. Non integrated compact fluorescent lamps have luminous efficacies of up to 80 lm/W. Lamps consisting of a pair of 10 mm tubes bent in the shape of a D, bent in the shape of an U or joined with a glass bridge to form an U have been introduced. Typical dual leg compact lamps and a D lamp are shown in Figure 4. Further, lamps consisting of a pair of U tubes, either bent or joined with a glass bridge as noted above, and joined again with a glass bridge to realize a further reduction in overall length, have been introduced. Typical 4-leg compact lamps are shown in Figure 5.

2.1.5. Compact Fluorescent Lamp Experimental Studies

Modeling of compact lamps has been carried out using general fluorescent theory⁴⁸. Experimental studies of parameters influencing luminous flux and luminous flux efficacy have been reported^{28, 49}. Discussion of lamp voltage limitations are presented. The interaction of a mercury discharge with a glass envelope having a high sodium content continues to command attention⁵⁰.

2.1.6. Fluorescent Lamp behaviour on specific electronic circuits

Evaluation of dimming of 26 mm diameter lamps was reported⁵¹. Operation of lamps at high frequencies is continuing to be studied⁵²⁻⁵⁶.

Starting studies of lamps at low and high frequency were reported⁵⁷.

2.2. Low Pressure Sodium Lamp

The low pressure sodium lamp is the second member of this family. As the name suggests this lamp consists of an arc discharge through a vapour of sodium/rare gas. In this case the conductive species are electrons and sodium ions. The sodium gas operates at a vapor pressure of approximately 3×10^{-3} torr. The rare gas acting as a buffer gas is at a pressure of a few torr.

This discharge ionizes atoms of sodium in developing a discharge. In addition, the discharge generates a copious supply of excited sodium yielding radiation in the sodium D doublet at 589.0 and 589.6 nm - resonant radiation. Due to the low energy of the excitation of these resonant lines this lamp operates with a high efficiency of generation of visible radiation. These radiations are in the yellow region of the spectrum with essentially no radiation elsewhere.

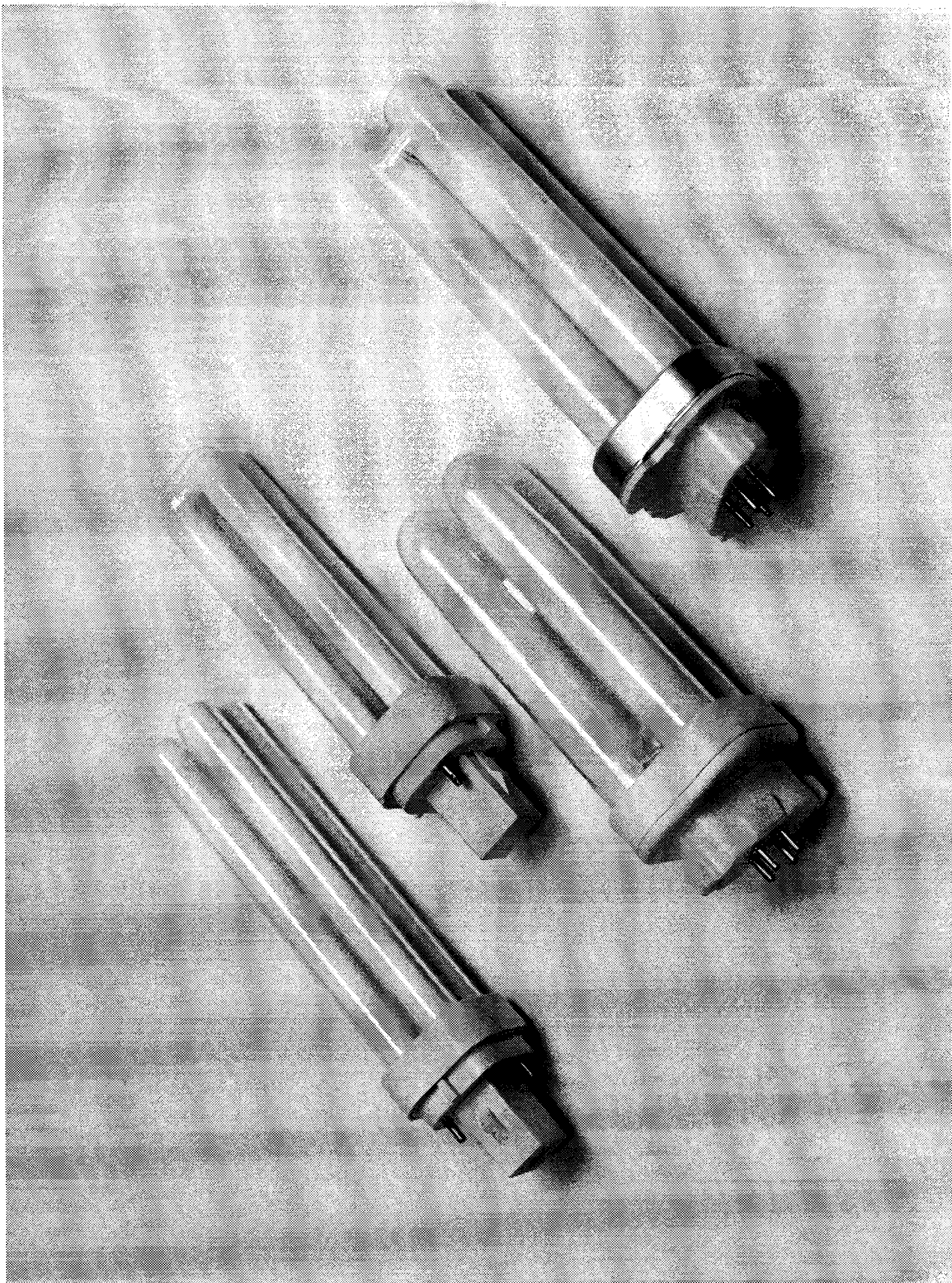


Figure 5 Typical 4-leg Compact Fluorescent Lamps

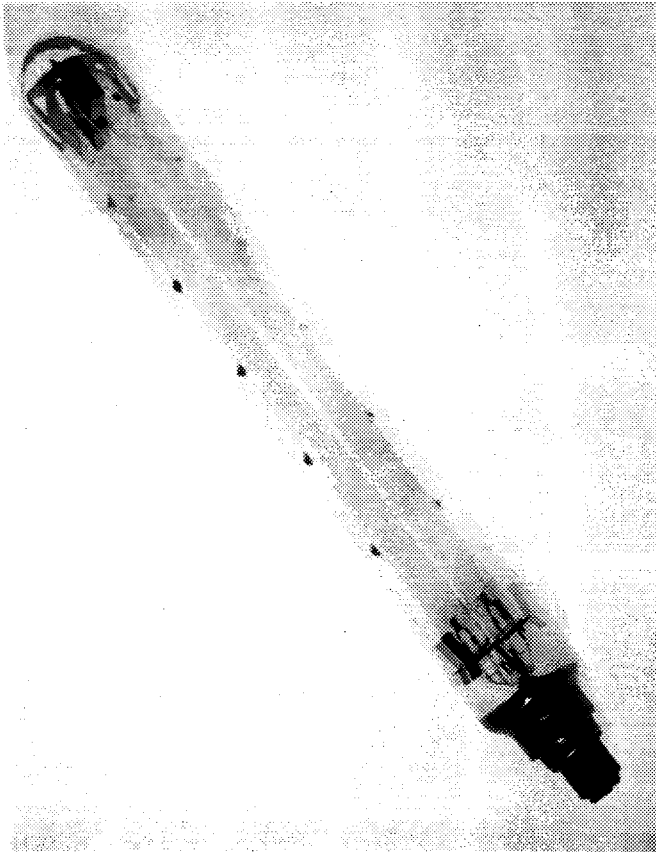


Figure 6. Typical Low Pressure Sodium Lamp

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These sources are tubular in shape with a large aspect ratio as shown in Figure 6. Further, due to the reactivity of sodium a special borate glass is required to contain the discharge. This lamp has the highest efficacy of any of the common commercial light sources with values between 100 and over 200 lm/W.

Due to the limited spectrum, two narrow lines in the yellow region of the visible spectrum, application has been in areas where colour rendering is not important - such as roads, road tunnels, marshalling yards, parking spaces, etc.

2.2.1. Low Pressure Sodium Lamp Development

The major trend in low pressure sodium lamp technology continues to be directed toward increased efficacy by improvement of the heat conservation. The improvement of indium oxide envelope coating by optimization of the tin dopant has made possible the development of 200 lm/W light source⁵⁸. Other reflective coating studies have been reported⁵⁹.

A successful dimming of low pressure sodium lamps through increasing the frequency of operation of an inductively ballasted lamp has been reported⁶⁰. Studies of high frequency operation have been reported⁶¹.

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PART III: TRENDS IN THE DEVELOPMENT OF HIGH INTENSITY DISCHARGE LIGHT SOURCES

3. Introduction

The High Intensity Discharge (HID) group of light sources encompasses three families of lamps, namely high pressure mercury, metal halide and high pressure sodium. Typical examples of each are shown in Figure 7. These lamps have an operating pressure in the range of 1-10 atmospheres - the medium pressure range. The lamps consist of an arc tube enclosing a discharge which is mounted within an outer envelope of soda-lime glass, hard glass or even quartz to conserve heat. Lamps in this group operate in the range of 50 watts upward to 3000 watts.

3.1. High Pressure Mercury Lamps

The discharge tube of the mercury lamp is fabricated from fused quartz incorporating molybdenum foils for electrical feed throughs. It contains a mixture of mercury and argon gases. Prior to ignition of the discharge, the mercury is in the condensed state such that it exhibits a vapor pressure of only a few microns. The discharge is initiated as a low pressure mercury discharge at a few thousand Pa pressure due to the argon fill. As the discharge increases the envelope temperature to its equilibrium value of about 1100 K, the operating pressure increases to a few bar. The discharge is carried by electrons and mercury ions. In addition, excitation of mercury neutrals and their subsequent return to the ground state results in the transfer of electrical energy into radiant energy. The more important radiant energies of this lamp are in the visible, namely 579, 577, 546, 436 and 405 nm. The discharge does generate ultraviolet radiation particularly the near ultraviolet. By the use of special phosphors this energy is converted to visible radiation, primarily in the red part of the spectrum, to improve the colour rendition of the lamp. The radiation from the mercury discharge is notable for the absence of any red radiation. High pressure mercury lamps generate visible radiation with an efficacy of 50-60 lm/W.

3.1.1. Developments in High Pressure Mercury Lamps

Based on the literature of "high intensity discharge" light sources, little if any development is taking place in the area of the high pressure mercury discharge. The only studies reported during the last quadrennium concerned start-up characteristics of the source¹. Thus one must conclude that this light source is becoming less important, although the self-ballasted lamp continues to be a dominant source in developing countries, which value the combination of long life and the avoidance of an auxiliary ballast.

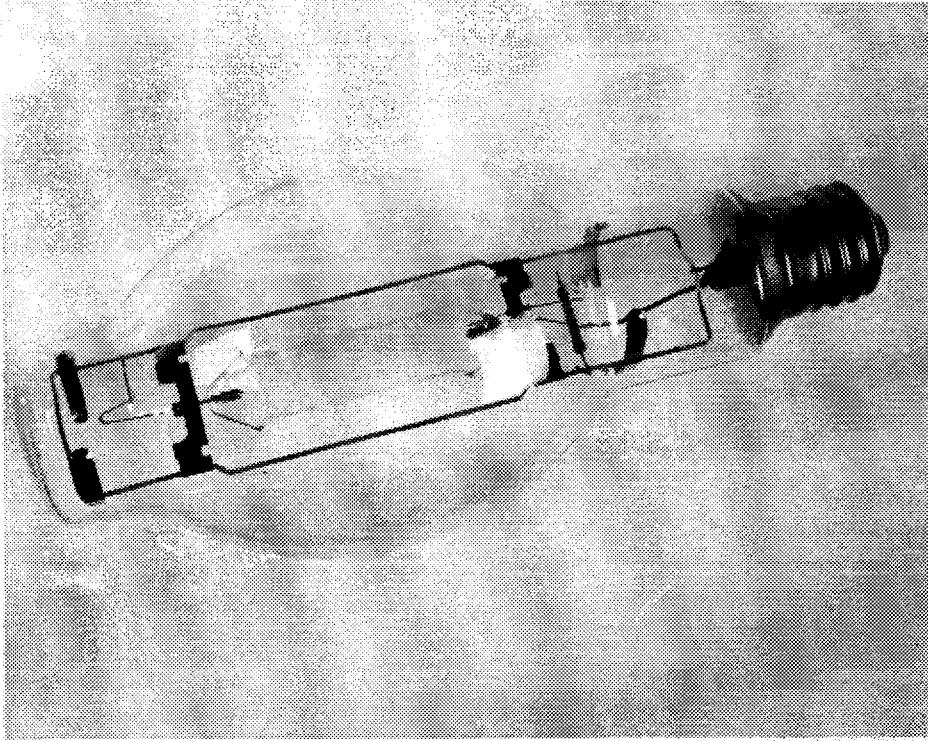


Figure 7a. Typical High Pressure Mercury Lamp

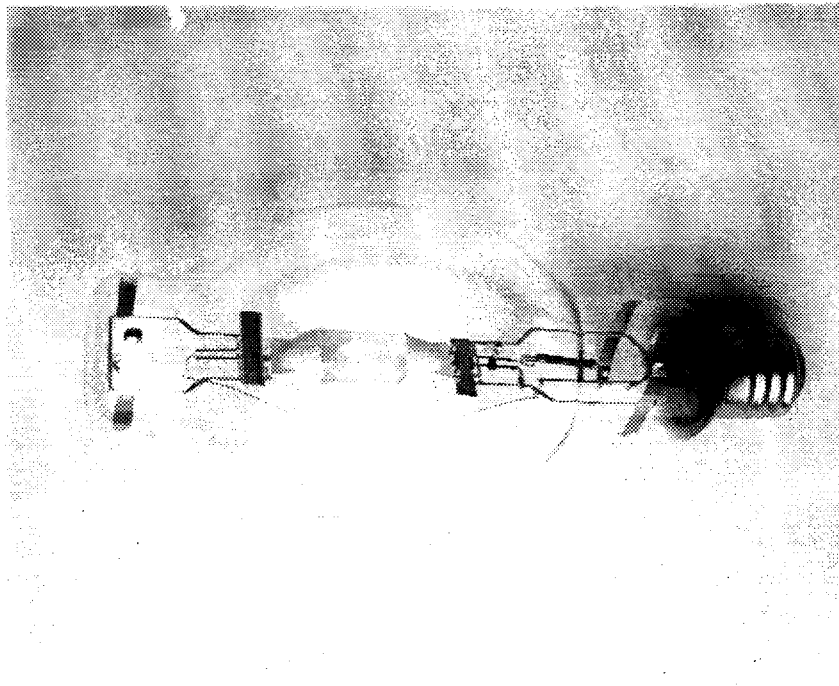
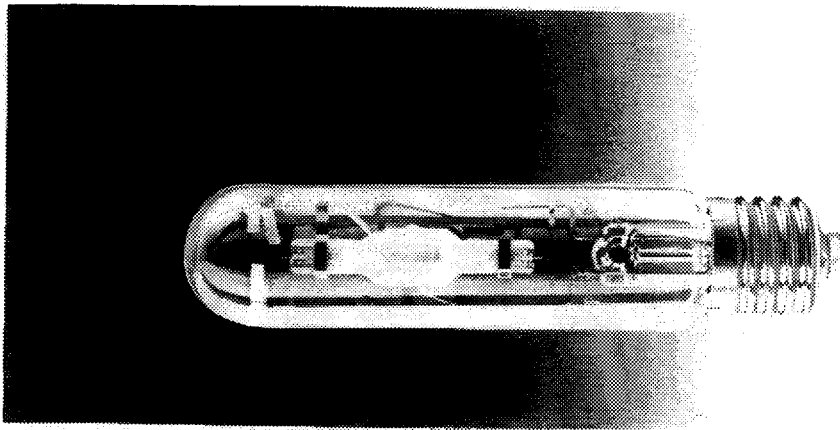


Figure 7b. Typical Metal Halide Lamps

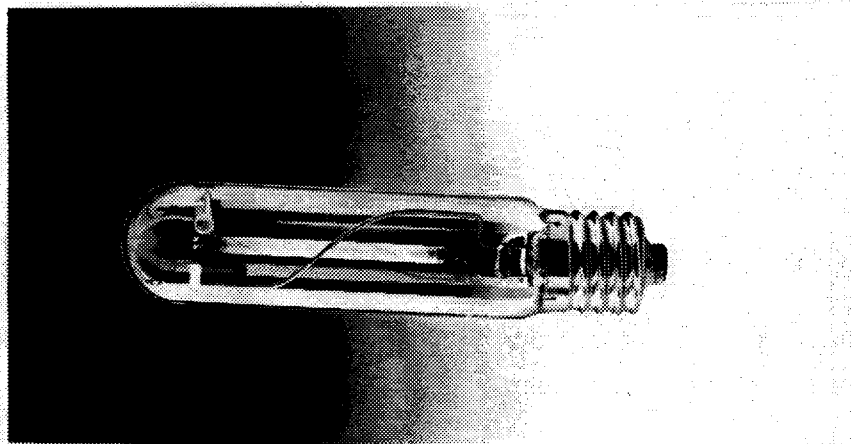
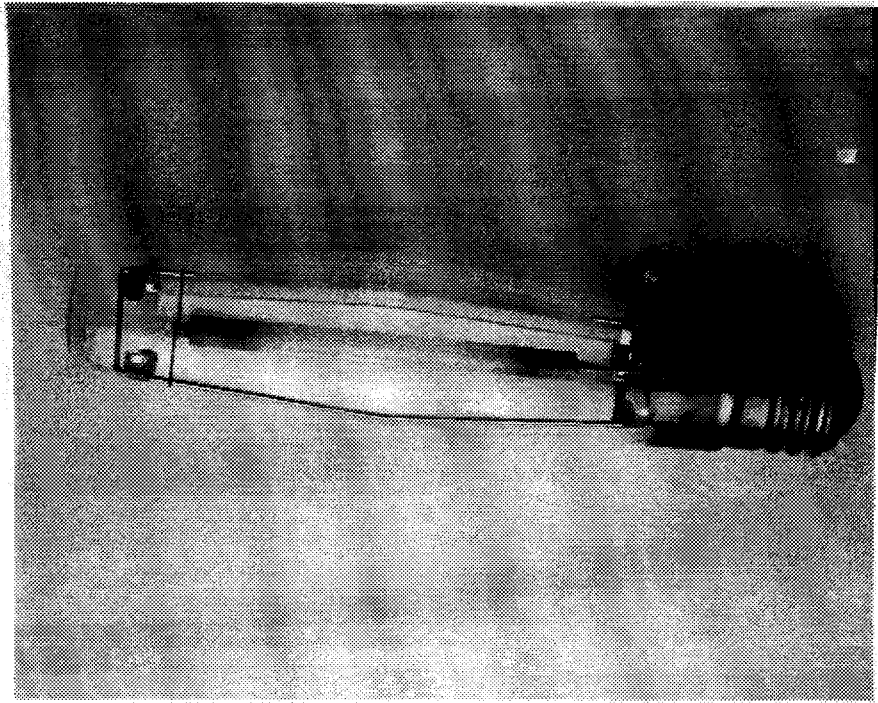
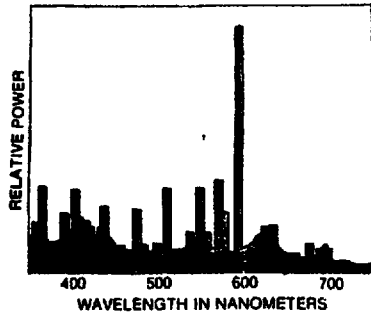


Figure 7c. Typical High Pressure Sodium Lamps



Sodium Scandium Iodide

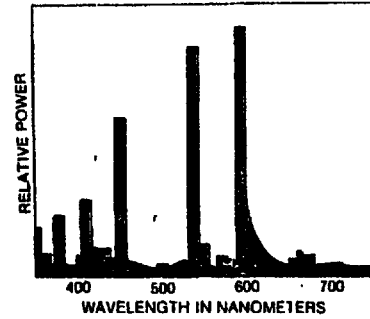
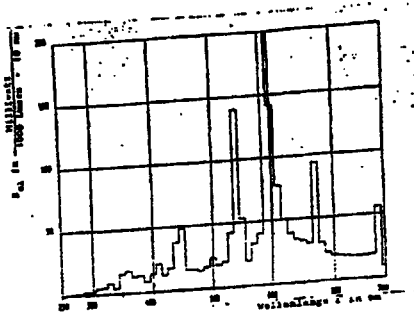
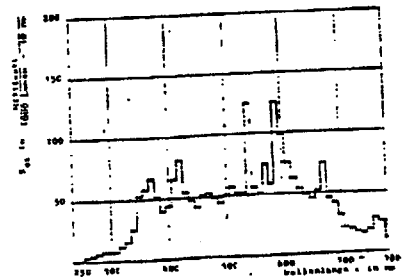
Sodium, Thallium, Indium
IodidesDysprosium, Holmium, Thulmum
Sodium, Thallium, IodidesIndium, Tin, Sodium, Thallium
Lithium Iodides

Figure 8. Spectrum of Typical Metal Halide Lamps

3.2. Metal Halide Lamps

The metal halide lamp discharge is enclosed within a quartz arc tube using molybdenum foil electrical feed throughs. The envelope contains metal halides (generally metal iodides), mercury and a rare gas, (generally argon). As with the mercury lamp, the metal halide lamp is ignited as a low pressure mercury discharge. As the quartz arc tube temperature increases the mercury pressure increases. Subsequently, the metal halides vaporize. The halides become dissociated and supply metal atoms to the discharge. These atoms become ionized supplying electrons and ions to the discharge. In addition, excitation of the metal atoms results in the subsequent emission of a photon of radiation as the excited atoms return to the ground state. Due to the number of differing metal halides in the discharge, generally a minimum of three, the radiation emitted by the source may be sufficiently dense to appear as a continuum yielding a balanced emission over the visible range.

For general lighting there are a number of metal halide formulations in use. These include sodium, scandium, mercury plus iodine; sodium, thallium, indium, mercury plus iodine; dysprosium, holmium, thullium, sodium, thallium, mercury plus iodine and bromine; indium, tin, sodium, thallium, lithium, mercury plus iodine and bromine. Spectra for each of these formulations are shown in Figure 8. These lamps generate visible radiation at an efficacy of 80-125 lm/W. Main problems in this lamp type are colour instability and lumen-maintenance throughout lamp-life.

Again, phosphors may be coated on the enclosing outer envelope which will convert some of the ultraviolet radiation to visible radiation particularly in the red region mainly to give improved color rendition of the source. This phosphor radiation does not significantly enhance the efficacy of the source.

3.2.1. Developments in Metal Halide Lamps

In contrast to the mercury lamp, numerous recent papers are to be found discussing developments in metal halide lamps. One significant trend in metal halide light sources has been of developmental studies of low wattage metal halide lamps. These studies have involved single ended lamps studying energy balance, double ended lamps evaluating performance²⁻⁶, studies of performance under D.C. operation⁷, and acoustic resonance⁸. New methods of manufacturing these lamps to reduce residual contamination have been studied⁹. Means for improving the performance of the sodium-scandium lamp are continuing to be evaluated¹⁰⁻¹³. New metal halide lamp chemistry designs are being studied¹⁴⁻²⁰.

The development of a new phosphor compositional ratio²¹ yielding 3000 K colour temperatures has been reported²¹. The effect of changes in outer jacket configuration on lamp operation has been evaluated²², while renewed interest is found in the study of electrode temperature distribution.

3.2.2. Lamp on special Circuitry

Interaction of lamp with auxiliary equipment continues to be of importance²³⁻²⁸. Restarting of lamps is becoming of increased interest²⁷.

3.2.3. Fundamental Studies of Metal Halide Lamps

Studies of the physics and chemistry of these metal halide lamps to yield improved performance are continuing²⁸⁻³⁷. New studies have been made of tin halide lamps³⁸. Renewed interest has surfaced on the application of microwave operation of metal halide lamps³⁹.

3.3. High Pressure Sodium Lamp

The high pressure sodium lamp arc tube is made of sintered alumina powder incorporating niobium electrical feedthroughs. (The alumina is required in place of fused silica because of the high reactivity of sodium with fused silica). The lamp dopants include sodium, mercury and a rare gas, most often xenon. The arc is initiated as a low pressure discharge. With increasing wall temperature the sodium pressure increases as sodium is vaporized. Upon reaching stable operation, the discharge consists essentially of electrons and sodium ions. Again, the radiating species are primarily excited sodium atoms which emit photons of visible radiation (primarily) as the atoms fall to the ground state. The major radiation is due to the sodium D doublet at 589 and 590 nm. Other lines at 615, 568, 567, 515, 498, 466, 449 nm become important at the higher sodium vapor pressure. As the discharge plasma is optically thick for a number of atomic lines, these lines saturate effectively developing a continuous visible spectrum. A typical spectrum is shown in Figure 9.

3.3.1. Developments of High Pressure Sodium Lamp

The high pressure sodium lamp technology continues to be developed. The number of studies reported appears to be stabilizing indicative of product maturization.

Development of a new generation of lamps has been the subject of two studies⁴⁰⁻⁴¹. There is a continuing emphasis on improvement of the colour of this lamp⁴²⁻⁴⁵. Other lamp developments have been directed to low wattage lamps⁴⁶⁻⁴⁷.

In the effort to obtain a better understanding of lamp operations, studies of factors influencing the efficacy of the high pressure sodium discharge have been undertaken by several authors⁴⁸⁻⁵⁰. Also a new computer lamp design program has been developed⁵¹. Studies of lamp operation as influenced by dopants, geometry, and such factors are continuing⁵²⁻⁵⁷, while ballast lamp systems studies are evaluated⁵⁸.

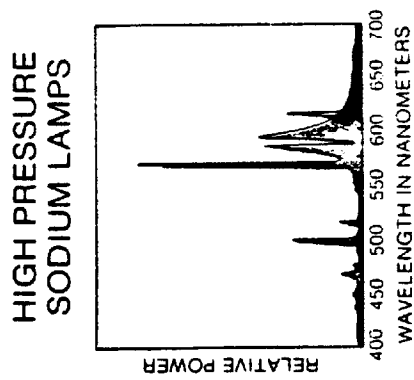


Figure 9. Spectrum of A Typical High Pressure Sodium Lamp

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