An Iodine Incandescent Lamp with Virtually 100 Per Cent Lumen Maintenance

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This paper will describe the theory and operation of a new type of incandescent lamp which employs iodine in a regenerative process in which evoporated tungsten (W) is redeposited on the filament, resulting in approximately 100 per cent lumen maintenance and increased life. While the concept of using a halogen such as chlorine (Cl_2), bromine (Br_2) or iodine (I_2) in a lamp to prevent blackening is not novel, the difficulties associated with the regenerative process have previously precluded its practice. For the first time these difficulties have been overcome and a practical lamp employing iodine in a regenerative cycle can be produced.

A SURVEY of the patent literature indicates that in 1882 a patent (No. 254,780) was issued for the inclusion of a small quantity of Cl_2 in a carbon filament vacuum lamp. Since then, a series of patents have appeared covering the use of I_2, Br_2, Cl_2 and mixtures thereof in both incandescent and discharge lamps. It is interesting to note that early patents proposed that the halogen reduced blackening during operation by reacting with the evaporated W to form a more transparent halide layer on the bulb wall. In 1923, a patent (No. 1,552,128) was issued for the inclusion of an alkali halide which supposedly reacted with impurities such as Ni and Fe on the bulb wall to form transparent halides, and reacted with the evaporated W, returning it to the filament in a regenerative cycle.

Our present efforts were initiated during the developmental work on the tubular quartz heat lamp. Small quantities of I_2, added to the usual Ar filling gas, were found to be very efficacious in preventing blackening during normal and over-voltage operation. This work led to the discovery of the necessity for correlating certain critical relationships in order to achieve successful operation of the regenerative cycle.

Iodine Cycle

In general, I_2 is being used in an incandescent lamp to prevent blackening and enhance life by redepositing evaporated W on the filament. During normal operation of an incandescent lamp, W is transferred from the filament to the wall by normal evaporation and diffusion or via the water cycle.[1] I atoms produced by the pyrolysis of molecular I_2 in the vicinity of the filament diffuse to the wall and under the proper conditions react with the adsorbed W, forming a voltatile WI_2 which diffuses to the filament. The WI_2 is decomposed on the filament, resulting in the deposition of the W on the filament and the production of I atoms which then diffuse to the wall to repeat the cycle.

Consequently, the iodine cycle depends on the reaction:

$$W + 2I \rightleftharpoons WI_2$$

where the forward reaction predominates at the wall while the reverse reaction predominates at the higher temperatures of the filament. WI_2 may also be formed in the gas phase as a result of a reaction between W(g) and I atoms (or I_2) with an inert gas molecule removing the excess energy. The relative amounts of WI_2 formed in the gas phase and on the wall are not known. Thermodynamic considerations indicate that the WI_2 is decomposed on filament rather than in the gas phase in the vicinity of the filament. The surface decomposition of the WI_2 is attested experimnetally by the success of the I_2 cycle in coiled-coil filament lamps.

The iodine cycle has been extensively studied in the developmental lamp shown in Fig. 1. This particular lamp is a nominal 500-watt, 120-volt tubular, quartz lamp, 10 mm in diameter and 95 mm in length, containing 600 mm of Ar and approximately 1 μ mole of I_2 which, if the I_2 were completely vaporized at room temperature, would give a partial pressure of approximately 4.5 mm. The filament operated at 3000K and the wall temperature was approximately 600C. This developmental lamp contains a coiled W filament, spiral W supports, a

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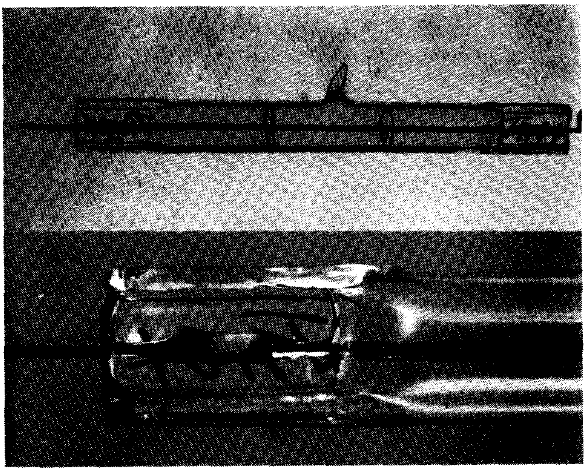

Figure 1. A 500-watt quartz iodine lamp and an enlargment of the pinch seal.

W inner lead welded to Mo foil and an Mo outer lead. With the successful operation of the I_2 cycle, the developmental lamps showed no blackening during operation, *i.e.,* with a filament temperature of approximately 3000K, and most lamps had 100 per cent of initial lumens at the end of life. A typical lamp at burnout is shown in Fig. 2. Since W was being returned to the filament, the life was increased and consequently a higher filament temperature was possible at the same life in the absence of I_2.

The remarkable efficacy of the I_2 cycle in removing adsorbed W from the surface of a quartz bulb is shown in Fig. 3. The top photograph shows a lamp that was blackened by operating the filament at a high temperature under vacuum. The lamp was then filled with the desired I_2-Ar mixture and sealed off. Below, is the same lamp after 60 seconds of normal operation. The W was almost completely removed from the wall in 30 seconds.

Wall Temperature Requirements

It has been found that the I_2 cycle will operate successfully with the bulb wall temperature in the range of approximately 250-1200C. Ordinarily, the reaction between W (solid) and I_2 requires a temperature of 700C.[4] The fact that the cycle does operate with the wall temperature considerably below 700C indicates that the reaction occurs between W and I atoms (as opposed to molecular I_2), produced by the pyrolysis of molecular I_2 near the filament. The reaction between the adsorbed W and I atoms is primarily dependent on the availability of I atoms at the wall, while wall temperature is relatively unimportant. The lower limit of the bulb wall temperature is determined by the desorption of the WI_2. If the bulb wall temperature is below this limit, a brown deposit of WI_2 is formed and the cycle is interrupted, resulting in subsequent blackening. The upper limit is determined by the stability of the WI_2 molecule on the wall. At high temperatures, the reverse reaction, $WI_2 \rightarrow W + 2I$ will be favored and the W will not be removed from the wall. This fact is important in considering the attack of the supports and leads by the atomic I with the formation of WI_2. In the developmental lamp shown, the supports operated at a considerably higher temperature than the wall and as a consequence, the iodine did not transfer W from the support to the filament. If this undesirable condition did exist, not only would the supports be attacked and eventually destroyed but excessive W would be deposited on the filament, resulting in whisker growth and the shorting of adjacent filament turns.

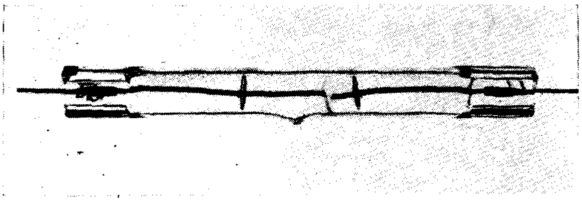

Figure 2. A 500-watt quartz iodine lamp at the end of life—870 hours at 26 lumens per watt.

Filament Temperature Requiremnts

The minimum filament temperature required for the decomposition of the WI_2 is indicated by an examination of one of the W supports from a developmental lamp, shown in Fig. 4. During normal operation of the lamp, W was deposited on the support near the filament and a certain distance from the filament. The point at which the deposition of

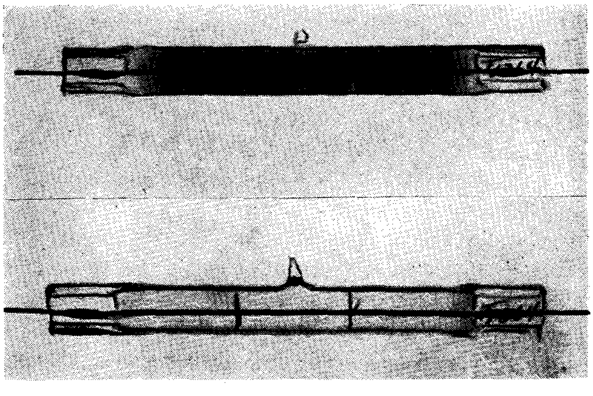

Figure 3. Removal of evaporated W from the bulb wall by iodine cycle. Lamp at top—blackened under vacuum prior to filling; at bottom—same lamp after 60 seconds of normal operation.

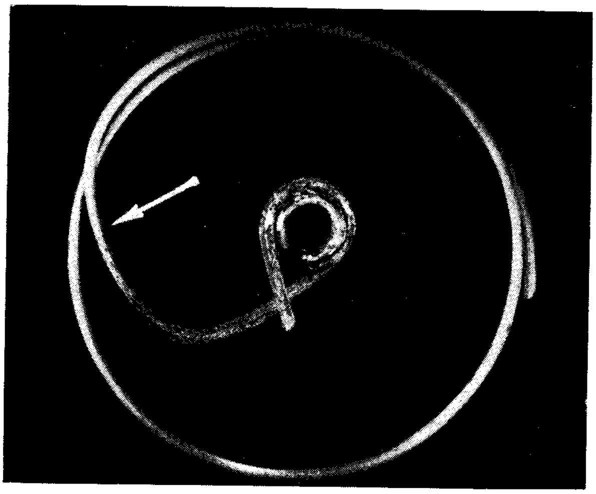

Figure 4. Deposition of W on a support by iodine cycle. Arrow indicates point at which deposition ceased.

W ceased, indicated by the arrow in Fig. 4, was determined by microscopic examination. The temperature of this point on the support was determined in several identical lamps with an optical pyrometer. The average temperature obtained, assumed to be equivalent to the minimum filament temperature required, was well below 2000C, which was substantially below the normal operating temperature of incandescent lamp filaments. However, if the I_2 cycle were to be used in discharge lamps to return evaporated or sputtered metal to the electrodes, this temperature limit could be of very considerable importance.

Iodine Concentration

A priori, the I_2 concentration should be minimized due to the strong absorption of visible radiation by the I_2 Aside from this consideration, there appeared to be no upper limit for the successful operation of the cycle. The lower limit was difficult to establish due to the presence of varying trace quantities of metallic impurities in the developmental lamps which formed stable iodides in the cooler sections (corners) of the lamp, resulting in a depletion of the I_2 concentration. The concentration of I_2 studied was in the range 0.01 to 1.0 μ moles/cc. with 0.2-0.3 μ moles/cc. employed in the majority of lamps. This concentration, which imparted a distinct pink color to a lamp when the I_2 was vaporized at slightly elevated temperatures ($>$50C), was sufficiently low so that there was no measurable loss of visible radiation by adsorption and sufficiently high so that the usual trace quantities of impurities encountered did not appreciably deplete the I_2 concentration by the formation of stable iodides.

Inert Gas

While evaporated W could be returned to the filament by the I_2 cycle in a vacuum lamp, an inert gas such as Ar, Kr or Xe (600-6000 mm.) was employed in the developmental lamps to prevent arcing and also to decrease the rate of evaporation of W. It was found that if the rate of return of W to the filament were large, whisker formation, pronounced crystal growth on the filament surface and preferential deposition of W on the cooler areas of the filament in the vicinity of the supports and leads was observed. Consequently, it was desirable to minimize the rate of transfer of W to obtain maximum life. While most of the developmental lamps were filled with 600 mm of Ar, there was a tendency for the lamps to arc at the end of life. Due to the high current surge during the arc, the Mo foil in the pinch seal frequently ruptured and the lamp exploded. This situation was rectified either by an external fuse or by increasing the Ar pressure. With an increase in Ar pressure, there was also a considerable increase in life at the same efficiency. These small diameter tubular lamps operate inside the so-called Langmuir sheath[2] where heat loss is due solely to conduction and is independent of pressure in this range. Consequently, an increase in inert gas pressure resulted in an increase in life by decreasing the rate of evaporation of W from the filament while the wattage, filament temperature and efficiency remained constant.

The I_2 cycle can also operate under certain conditions in the presence of N_2 which is important in certain lamp construction where close spacings present arcing problems. No evidence has been found for compound formation between the N_2 and I_2 (or I), *e.g.*, NI_3, during operation of these developmental lamps.

Difficulties

(1) In small diameter tubular lamps (6-12 mm o.d.) of the 500-watt variety, a thermal diffusion separation[3] of the I_2 and inert gas occurred when the lamp was operated vertically or even several degrees off a horizontal position, resulting in the heavier gas, *i.e.*, the I_2 being concentrated at the bottom of the lamp and the lighter inert gas at the top. This thermal diffusion separation depleted the I_2 concentration at the top of the lamp and blackening resulted. In small diameter 500-watt lamps, the separation which, in general, was a function of temperature gradient and length was unfortunately efficient and necessitated horizontal operation. However, in larger diameter 500-watt lamps (20-35 mm o.d.) turbulent convection currents were operative and promoted remixing so that the sep-

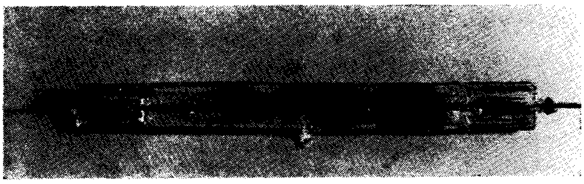

Figure 5. Blackening due to small quantities of impurities in horizontally-operated lamp.

aration did not occur and the lamps could be operated in any position.

(2) It has been found that small quantities of certain materials, *e.g.,* Al, Ni and Hg, interfered with the successful operation of the I_2 cycle and blackening resulted even in the presence of sufficient I_2. This blackening, shown in Fig. 5, occurred on specific areas of the bulb wall. While blackening of this type usually occurred early in life with no apparent effect on life, it has been observed to occur at any time during life. While the exact cause of this type of blackening has not been established, it is believed to be the result of an accumulation of impurities and a specific surface condition of the bulb wall in certain areas.

(3) Due to the highly reactive nature of the I_2 vapor at elevated temperatures, it was not possible to employ any of the usual getters in the developmental lamps to remove H_2O vapor or H_2 present initially or released from the quartz during operation. Either the I_2 and the getter reacted to form a stable iodide in the cooler areas of the lamp, resulting in a depletion of the I_2 and subsequent blackening, or else the getter material interfered with the formation of WI_2 on the bulb wall, resulting in blackening in the presence of sufficient I_2. While the I_2 cycle operated successfully in the presence of the H_2O cycle,[1] resulting in a clean lamp throughout life, the life of the lamp was considerably shortened due to H_2O cycle activity. Consequently, it was necessary to minimize the H_2O cycle activity by a good bake-out of the lamp prior to filling and then employing thoroughly dried I_2 and inert gas to insure long life.

Design Features

Lamps made to operate with the iodine cycle have not only shown an extremely high lumen maintenance, but also have other outstanding features which are direct results of meeting the essential requirements for successful operation. As previously indicated, a minimum bulb wall temperature of about 250C is required for reliable performance. This fact dicated the use of either Pyrex, quartz or Vycor as a bulb and lamps were made to operate successfully in each of these materials. All lamps discussed in this paper were made from tubular quartz or Vycor because of their higher melting points and very good resistance to thermal shock. If a bulb wall temperature of approximately 250C or greater is to be maintained, the filament must be located comparatively close to the bulb wall. A tubular bulb allows us to achieve this temperature without large variations between temperatures at the hottest and coolest portion of the bulb on which the cycle is functioning. The tubular construction also shows other advantages when the lamp is mounted in a luminaire.[5]

Interference with the iodine cycle caused by metals other than tungsten necessitated making lamps without filament supports or with supports of tungsten, and also indicated that the portion of the lead projecting into the lamp must be tungsten. The basic construction of an iodine lamp is shown in Fig. 1. The leads are two piece molybdenum-tungsten and the supports are tungsten wire. This design meets the temperature and material requirements and also permits an increase in operating voltages because of the double-ended construction. By increasing the length of the coil, a 10,500-watt argon-filled iodine lamp which successfully operates on 2400 volts has been made.

Fig. 6 shows some of the developmental lighting lamps that have been made in which the iodine cycle functions properly. From top to bottom, these lamps are rated at 45-, 100-, 150-, 200-, 500- and 1500-watts. They range in length from $1\frac{5}{8}$ to 10 inches, and from $\frac{5}{16}$ to $\frac{1}{2}$ an inch in diameter. Operating voltage for the group is 120 volts or less, with the exception of the 1500-watt lamp which operates at 277 volts. One obvious advantage of this

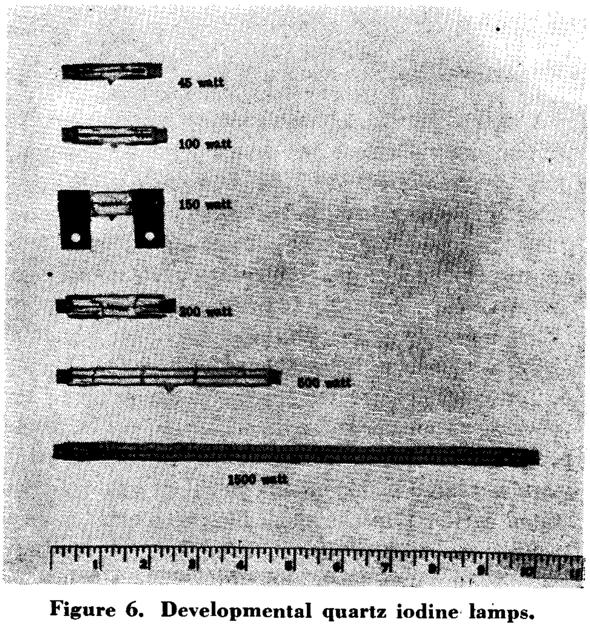

Figure 6. Developmental quartz iodine lamps.

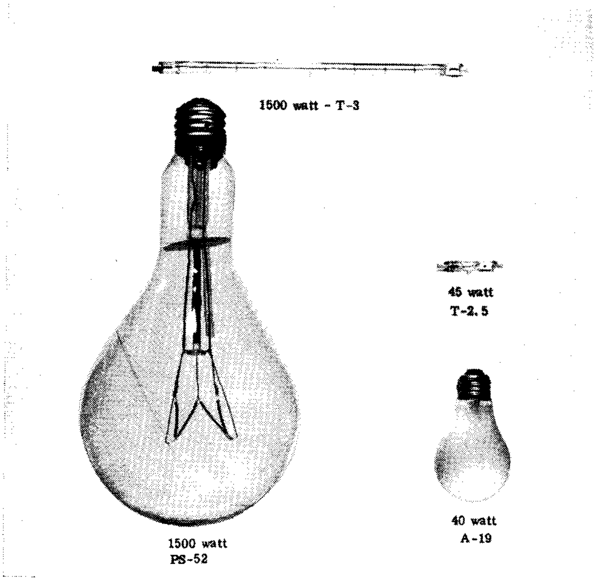

Figure 7. Size comparison of quartz iodine lamps with standard lamps of equal or near-equal wattage.

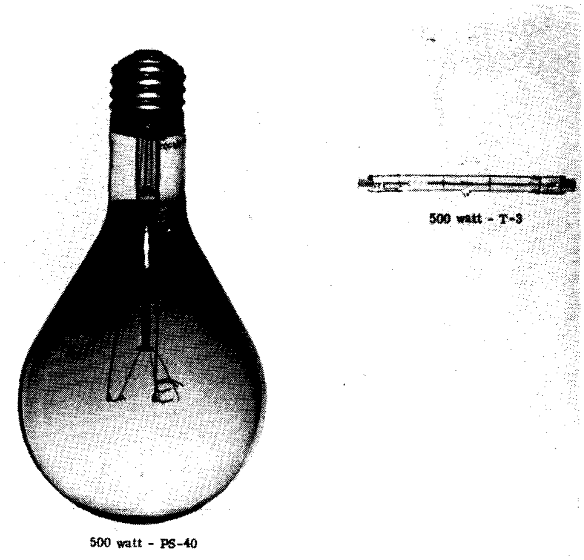

Figure 8. 500-watt standard lamp and 500-watt quartz iodine lamp after failure.

design is the size reduction it has achieved. In Fig. 7, a comparison of the size of the 45- and 1500-watt iodine lamps is made with that of standard 40- and 1500-watt lamps. The volume of the 45-watt lamp is 1.4 per cent of that of the 40-watt A19 and the 1500-watt volume is .55 per cent of that of the PS52 lamp. The remarkable size reduction is further evidenced by the fact that all of the lamps shown in Fig. 6, which represent a combined total of 2495 watts, occupy less volume than a 25-watt household lamp. Smaller size also means better positioning of the light source in a reflector or luminaire, enabling us to obtain beam patterns heretofore unobtainable.[5]

Operating Characteristics

A unique and favorable characteristic of the tubular lamp is that its lumen output and watts for a given filament are independent of fill gas pressure from a few hundred millimeters to as high a pressure as the bulb will contain. As is commonly known, in the general lighting lamp thermal losses are due to convection currents and conduction. Convection currents passing over the filament reduce its operating temperature and lower its lumen output, while increasing its watts. The effect of convection currents is changed with changes in fill gas pressure, thus, initial lumen and watts rating in a standard lamp is dependent on fill pressure. It was stated earlier that the small diameter bulb contains the fill gas within the so-called Langmuir sheath during lamp operation and convection currents are non-existent. Thermal losses are then due only to conduction and these losses are independent of gas pressure above a few hundred millimeters. Another favorable result of placing the filament in a small diameter bulb is that of obtaining a higher operating pressure than is obtained in the standard lamp for the same fill pressure. A standard 1000-hour, 500-watt, 19.8-lumen per watt lamp is filled with 600 millimeters of gas and operates at approximately 800 millimeters. The 500-watt filament, when placed in an iodine lamp of the tubular design which is filled with 600 millimeters of gas, will operate at approximately 1800 millimeters. An increase in operating pressure, plus the complete absence of convection currents, enables us to increase the efficacy of the filament to 21 lumens per watt and obtain a 2000-hour life. One more example of gain in efficiency is shown in the comparison of a 1500-watt, 275-volt lamp and a 1500-watt, 277-volt iodine lamp. The standard lamp operates at 17.5 lumens per watt for 1000 hours, while the iodine lamp operates at 22 lumens per watt for 2000 hours.

Lumen maintenance, by far the outstanding feature of this lamp, has ranged from 96-101 per cent on constant voltage lamps at 99 per cent life. These figures are quite remarkable when compared with those of the 500-watt general lighting lamp, whose lumen maintenance is 86 per cent at 70 per cent design life, and the 1500-watt lamp, whose lumen maintenance is 78 per cent at 70 per cent design life. Although figures are not available, it can be seen that the comparison would be even more astounding if the standard lamps were rated at 99 per cent design life. Fig. 8 shows a 500-watt stand-

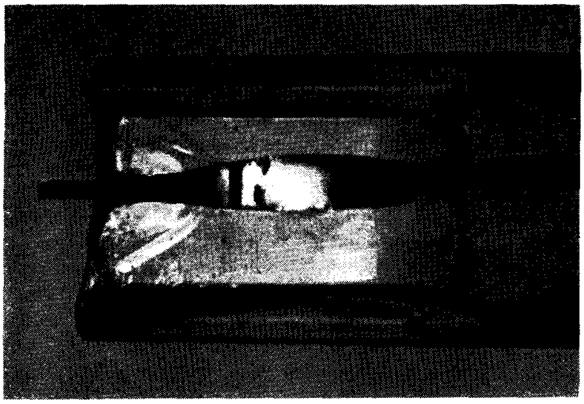

Figure 9. Typical failure pattern on overheated seals. Seal has not yet failed.

ard lamp and a 500-watt iodine lamp after burnout. The percentage of lumen maintenance quoted for the iodine lamp has been measured on all constant voltage lamps, regardless of wattage.

The iodine lamp as designed, in comparison with a presently-made incandescent lamp of equal wattage, offers an incandescent light source that is drastically reduced in size, with ratings independent of fill gas pressure. Its total lumen output can be increased while maintaining equal life, it can be operated at higher voltages and it maintains 96-101 per cent lumen output until burnout.

Operating Limitations

As is true in other lamps, precautions must be taken with the iodine lamp if it is to give the expected service. We have said that wall temperatures below approximately 250C were too low for reliable cycle operation; therefore, these lamps cannot be operated in a cooling atmosphere. Operation under water or in stiff drafts without a protective covering is not feasible. However, the lamps do perform satisfactorily under normal conditions and applications since the wall temperatures are high enough (500-600C) to maintain adequately the specified minimum. One other temperature limit which it has been necessary to specify is that of the seal. This limitation applies to the developmental lamp construction and is not necessarily a feature of all iodine lamps. Fig. 9 shows the type of failure occurring with overheated seals. Temperatures in excess of 350C, measured on the quarts directly over the center of the molybdenum foil, are detrimental to lamp life. If operated above this figure, oxidation of the foil is rapid enough to puncture the seal and leakage occurs. Lamps placed in evacuated chambers or chambers containing a non-oxygen gas have only the current carrying capacity of the foil as a limitation.

Gas separation, which has been fully explained, was found to be quite pronounced in the longer lamps. The 500-watt and the 1500-watt lamps must not be positioned more than four degrees from a horizontal plane if sufficient iodine is to remain in the high end of the lamp for efficient cycle operation. In the lower wattage lamps the gas separation is not so apparent and these lamps have been operated successfully in a vertical position.

The last precaution that we must indicate is one that is no new, nor limited to the iodine lamp. A fact that many of us may not be aware of is that all high-wattage, argon-filled incandescent lamps are internally fused to protect them against arcing. The common cause of arcing is the failure of the filament at or near the peak of inrush current when the lamp is energized. If not arrested, the arc may cause rupture of the bulb. As presently made, the iodine lamps do not contain an internal fuse and therefore the high-wattage lamps must be externally fused to protect against this type of failure.

Applications

A discussion of the iodine lamp would not be complete without mention of possible or actual applications. It should be noted, however, that these lamps are in a developmental stage and are not presently mass produced. A broad answer to the question of what applications are the lamps suited for is that they can be used in any application that now uses incandescent lamps so long as the required conditions of temperature and position are met. Some specific possible applications would be street lighting, floodlighting of outdoor areas, display window lighting, and illumination for movie making and television. Miniaturization is a prime factor in these applications. To date, four types of iodine lamps are being used in actual applications; only one type has developed to the point of supplying lamps in small quantities. The 45- and 200-watt lamps are being tested for possible use in runway illumination and the 1500-watt lamp is being used to successfully grow algae in underwater and space travel research. The 150-watt lamp has been flight tested and is being used as a wing tip marker on high speed aircraft. While there are many possible applications, the ones mentioned are those in which this lamp may find initial usage; small size and nearly constant lumen output are features which we feel certain will guide it into numerous others.

Acknowledgement

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DISCUSSION

W. G. Matheson:* The work reported in this paper deals with results obtained using tubular envelopes. Should one assume that no work has been done on globular envelopes or that the results obtained were unsatisfactory? The necessity of external fusing is not desirable. Also, the precise positioning with respect to the horizontal involves new fixture designs. In fact, it is likely to require extensive fixture replacement with a new design in order to accommodate the proper fuse protection and a satisfactory light distribution pattern.

The authors have indicated a high degree of success in controlling the redeposition of the evaporated tungsten on the filament. We have made tests which indicate that this control is critical due to bulb and filament temperature variations.

A. W. Weeks:** I would anticipate considerable difficulty in controlling the exacting manufacturing processes required, but undoubtedly these can be met. The following questions have occurred to me:

Is it possible to ''coil up'' the longer tubular lamps, such as the 1500-watt, so that spotlighting applications would be furthered?

Under the paragraph ''Application,'' the authors say that requirements of temperature and positioning must be met. They then say that the 150-watt lamp has been flight-tested as a wing tip marker. This application does not seem to meet requirements of temperature and positioning.

G. A. Freeman:† The accomplishment of a practical lamp with 100 per cent lumen maintenance, as described in this paper, is indeed a milestone of lamp improvement. The function of the reaction between halogen gases, iodine, chlorine, etc., with tungsten to remove tungsten blackening from a lamp bulb is not new, but to control it for practical use *is* new.

This is interesting particularly to lamp development engineers who have experimented with iodine or chlorine in the gas filling of incandescent lamps and then set it aside after finding out the requirements for successful operation. The authors have been quite conscientious in pointing out the problems.

Most experimenters have considered the more conventional forms of incandescent lamps where ordinary lamp leads are chemically attacked by the iodine vapor and the minimum temperature requirement of 250C-300C is difficult to achieve. Potential gain in intrinsic quality was not enough incentive to overcome practical limitations.

The tubular quartz lamp with only tungsten parts appears to meet the requirements with fewer practical limitations. Whether the gain in intrinsic quality comes at too high a penalty in light source shape, in limited operating position and in production cost and dependability where trace quantities of impurities would be ruinous remains to be seen. The authors are to be commended on their development which appears to have attained the necessary degree of practicality.

E. G. Zubler and F. A. Mosby:* In reply to Mr. Matheson we have found that the iodine cycle does not function satisfactorily in globular envelopes such as the standard ''A'' bulb shape. There are two reasons for this. First, temperature variations are such that the cycle does not operate on all portions of the bulb, and second, manufacturing methods for the usual ''A''-shaped lamp do not permit all tungsten parts internally. Also, the fact that a minimum wall temperature of 250C is required would prohibit its use in present standard sockets.

In answer to Mr. Weeks' question, there has been no attempt to coil up the 1500-watt lamp since a shorter lamp could be obtained by using a coiled-coil filament. The 500 and 1500-watt lamps are not now offered with coiled-coil filaments because of support problems.

As stated in the paper, the lower wattage lamps are not restricted to a horizontal burning position and the 150-watt lamp falls in this group. Temperature specifications for the wing tip application are above the 350C seal limit. However, the aircraft manufacturer and his customers are fully aware of the seal limitation and still choose to use the iodine lamp because they have found no other which will perform as well.

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Annual Index to IE

The Index to 1959, to be published as Section II of the January 1960 issue of Illuminating Engineering, includes subject and author indexes and, in addition, business addresses, where available, for IES officers and committee personnel for 1957-1958 and 1958-1959.