BRIGHT LIGHT SOURCES

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(1) Introductory

The remarkable advances which have been made in recent years in the development of electric discharge lamps have tended to overshadow, at least as far as the published literature is concerned, developments of equal note in the field of incandescent tungsten filament lamps. This is unfortunate, as the electric discharge lamp is supplementary to and is not likely to supplant the incandescent lamp. Nowhere is this more true than in regard to the class of lamps which form the subject of the present paper and which, because they are designed primarily for use with optical projection systems, may be termed bright light sources.

In the initial stages of the evolution of the electric lamp it was only to be expected that the dominating influence should be concern for the means by which the light was produced, rather than with the form of the source and the relation of that form to the duty which the lamp was required to perform. Thus among early lamps the carbon arc was inherently a small light source of approximately spherical form, while the first tungsten filament lamp consisted of a long thin wire incandescing within an exhausted glass bulb. Entirely different in character and in physical size were the first discharge lamps, such as those due to Moore and Cooper Hewitt, where light was emitted at low brightness from glass tubes several feet in length. In each case the means by which the light was produced governed the adaptability of the source and limited its field of usefulness. Gradually, however, it was found possible to exercise an increasing measure of control over the functional aspects of lamp design and without sacrifice of essential features to relate the size, shape, and brightness of the source to the purpose for which it was intended. At the present time, therefore, and to some extent for the above reasons there is a large variety of lamps of both the incandescent filament and the electric discharge types which have been specifically designed as bright light sources and in the design of which some of the earlier restrictions on the shape and size of the source have been largely overcome.

(2) Requirements for a Light Source

Ideally a lamp should be designed specifically for the fulfilment of its required functions. While this may appear an obvious truism, experience shows that design requirements for the lamp itself frequently conflict with those of the purpose for which the lamp is intended. For some applications the characteristics considered most essential may be debatable, but certain principles have been established both theoretically and by experience which have acted in recent years as determining factors in the development of lamps for particular purposes. It has been shown, for example, that there are advantages in using sources of large area and low brightness for general illumination purposes, and that the tubular fluorescent lamp fulfils these requirements in an admirable manner. In a somewhat different category fall the requirements for street lighting where some degree of optical projection appears necessary as economic considerations demand the illumination of large areas from comparatively few points. To this end sources of high light output and fairly high brightness such as the high-pressure mercury vapour lamp appear desirable, at least for many of the lanterns which were in use in the immediate pre-war years.

In a third category come lamps designed specifically for use with optical projection systems where, in general, sources of small size and the highest possible brightness are required.

The developments which have taken place in this field are perhaps not so generally well known. They include improvements in tungsten filament projectors of established design, the production of novel designs of higher brightness, and the introduction of highly specialised lamps employing groups of filaments closely associated together. In the field of electric discharge lamps progress has been equally marked, and the high brightness high-pressure mercury lamp is now proving of value for a variety of projection purposes.

(3) Tungsten Filament Projector Lamps

With the highest melting point (c. 3,655 deg. K) of any metal, tungsten has proved to be a unique material for producing filaments for electric lamps. In the smallest lamps the glowing wire may be no more than 0.01 mm. in diameter, while a 100-ampere projector lamp requires wire nearly 200 times this size. In all cases, however, the tungsten filament must be so constituted and constructed that it maintains its designed form during the life of the lamp. While this is a useful characteristic in any electric lamp it is an essential one in the case of a projector lamp, where the filament may be arranged in a very compact form, and where its various convolutions may be closely adjacent. Progress in the metallurgy of tungsten has resulted in the production of tungsten wire of such stability that after it has received appropriate heat treatment a single coil 200 mm. long containing 2 metres of wire will show negligible sag throughout a life of at least 200 hours while operating at 3,000 deg. K, although the distance between adjacent filament supports may be as much as 15 to 20 mm. (See Figure 1.)

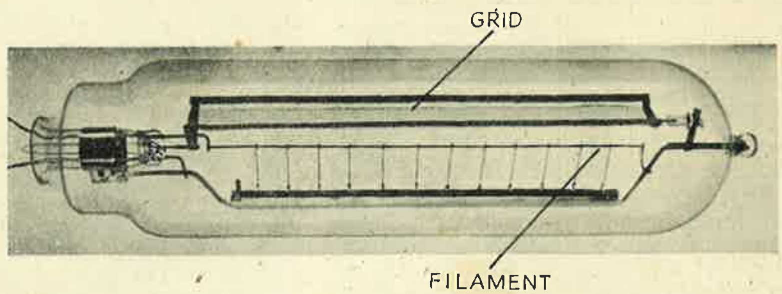


Fig. 1. 230-volt, 2000-watt horizon lamp.

In order to study various designs of high brightness tungsten filament projector lamps in more detail it is proposed to subdivide this section under a number of headings as follows:—

(A) General Considerations and Characteristics of Tungsten Filaments in Vacuo and in Gas.

(B) Lamps Employing Single Wound Helices.

(C) Lamps Employing Double Wound Helices.

(D) Multi-Filament Lamps.

(E) Symmetrical Sources.

In each case one or two typical

examples will be selected to illustrate the various factors under discussion.

(A) General Considerations and Characteristics of Tungsten Filaments in Vacuo and in Gas.

The properties of straight tungsten wire operating in vacuo form the subject of an exhaustive study by Jones and Langmuir published in the *G.E. Review*, 1927. 30, 310. It was shown for wires of a length sufficient to have their characteristics unaltered by the cooling effects of the electrodes or supports that:—

Efficiency varies as (volts) $^{1.87}$
Current varies as (volts) $^{0.64}$
for temperatures around 2,500 deg. K.

The extent to which these conclusions may be influenced by the cooling effect of the surrounding gas and of the electrodes is indicated by the following experiments. A tungsten filament 1 mm. in diameter and 30 mm. long was mounted axially within a tubular glass bulb 64 mm. in diameter. It was carried by electrodes consisting of 2.5 mm. in diameter nickel wire. The bulb was exhausted and the filament and electrodes were degassed and processed in the known manner. The exhaust stem was sealed off and the lamp after capping was aged for several hours to stabilise the filament. A series of measurements of luminous output and filament brightness were then carried out, with the results shown in Table I.

TABLE I.
Characteristics of a Straight Tungsten Filament Operating in Vacuo.
Approximate Filament Dimensions
30 mm. × 1 mm.

Volts.	Amps.	Lumens.	Efficiency. (L/W)	Centre Brightness Stilbs.	Temperature Deg. K.
1.75	31.4	128	2.33	112	2310
2.0	33.9	236	3.48	195	2430
2.25	36.3	398	4.86	325	2560
2.5	38.8	650	6.7	484	2670

An identical lamp was then constructed, but after the exhaust process pure nitrogen was introduced into the bulb at a pressure of 600 mm. After a suitable ageing treatment the characteristics of the filament operating in the inert gas were determined exactly as above (see Table II.).

TABLE II.
Characteristics of the same Tungsten Filament Operating in 600 mm. Pressure of Nitrogen

Volts.	Amps.	Lumens.	Efficiency (L/W)	Centre Brightness Stilbs.	Temperature Deg. K.
1.75	34.4	76	1.26	65	—
2.0	36.6	152	2.08	122	2330
2.25	39.0	275	3.13	232	2475
2.5	41.2	460	4.47	363	2590
2.75	43.1	700	5.9	525	2690
3.0	45.3	1025	7.54	735	2790
3.25	47.1	1370	8.97	969	2885

Not only were the values of the various functions altered, but their relationships were modified by the gas filling, as illustrated graphically in Figure 2. The values of brightness given in both Tables I. and II. were determined at the centre of the filament, i.e., at the position of maximum brightness. Due to the increased energy losses the efficiency and brightness of the filament for the same input voltage are less in the case of the gas-filled lamp than in the case where the same filament is operating in vacuo. The presence of the gas, however, reduces the rate at which tungsten evaporates from the filament, and therefore makes allowable a higher filament temperature for a given life. It was shown by Langmuir that by coiling the filament and so reducing the effective area exposed to gas convection and conduction losses the gain in allowable temperature can be made to more than offset the gas losses, and hence for a given life a gas-filled coiled filament lamp may be operated at a higher efficiency than would be possible with the same filament operating in vacuo. It will be appreciated that the life of the filament, which is governed by the rate at which evaporation occurs, is a function of its maximum temperature, while the efficiency of the lamp is a function of the average temperature of the filament. It is, therefore, important in the design of any lamp, and particularly in the design of a lamp having a comparatively short, thick filament, such as a low voltage projector lamp, to investigate the brightness distribution and hence the temperature gradients along the filament length. Typical data determined for the special straight wire lamps mentioned above are given graphically in Figure 3.

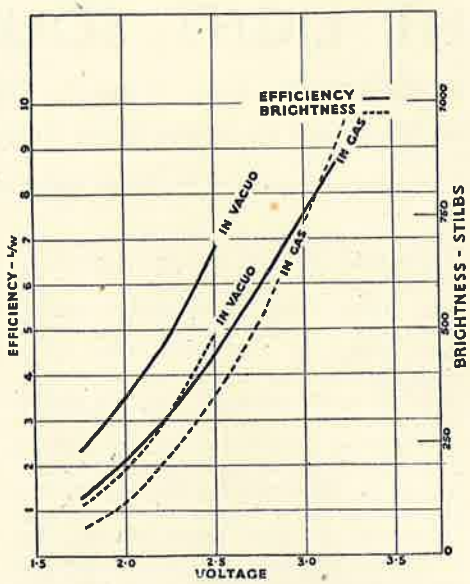


Fig. 2.

It will be seen that the filament brightness and, therefore, the filament temperature, rises steeply from each electrode to a point about the centre of the filament. In the case of the vacuum lamp the peak brightness coincides with the mid-point between the electrodes, but in the case of the gas-filled lamp the mid-point is somewhat below the zone of maximum brightness due to the effect of convection currents. These high temperature convection currents along a sheath surrounding the filament reduce the energy losses from the upper regions of the filament as compared with the lower regions, and therefore the zone of maximum temperature is shifted slightly in an upward direction.

The data given above show the effect of end cooling on a straight tungsten filament. A similar effect is produced, although generally to a less extent at each point at which a filament support is introduced. The cooling effect is produced whether the filament is in the form of a straight wire or in the form a coil. It will, therefore, be appreciated that the effect of introducing supports, which are essential in all but certain low-voltage lamps for maintaining the location and rigidity of the filament,

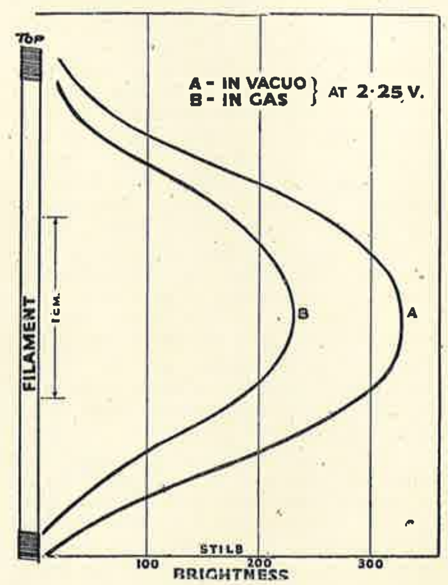


Fig. 3.

is to increase the temperature gradients along the filament length and so to increase the maximum temperature of the filament operating at some specified overall efficiency. We therefore reach the conclusion that anything which favours a reduction in the number of points at which it is necessary to support the filament is advantageous, as is also any feature of design which acts in the direction of reducing gradients in temperature along the filament length. It follows, therefore, that while electrodes and supports must be adequate to fulfil their respective functions it is desirable that their heat capacity should be kept to a minimum. Other factors which influence filament temperature gradients will be mentioned in a later section.

(B) Lamps employing single wound helices.

(i) *Lamps with straight single coiled filaments*:

Certain types of tungsten wire coils will, after a suitable heat treatment, develop a single crystal structure. The conditions necessary to bring about this desirable result have been studied for many years, and improvements in the properties and behaviour of tungsten coils under high temperature conditions are still being effected. All such improvements which act in the direction of reducing the liability of filaments to distort or sag under gravity have an influence on the design of projector lamps. It will have been noted from the previous section that the minimum number of supports is desirable in any lamp, and, therefore, if the length of a self-supporting section of a filament coil can be increased by an improved technique this fact can be made use of to decrease the number of filament supports for a given length of wire. As a measure of the present position, and in respect to a type of tungsten wire which develops a single crystal structure and which has proved very effective in a wide range of projector lamp designs, it may be shown that a single helix carrying 30 amperes at 40 volts does not require any intermediate support, even when operating at an efficiency of 30 L/W. With thinner wires a filament carrying 3 amperes at 30 volts may be made self-supporting and sufficiently rigid for ordinary purposes when designed for operation at 30 L/W. The above examples are for filaments of sufficient stability to remain substantially in their original positions relative to any associated optical axis throughout the life of the lamp. The simplest type of projector lamp therefore consists of a single helix of tungsten mounted between rigid electrodes and in general such lamps are designed for voltages up to 24 volts. The excitor lamp illustrated in Figure 4 is a typical example. Data for a range of lamps are given in Table III.

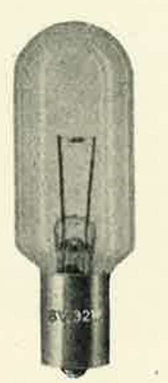


Fig. 4. 8-volt, 32-watt exciter lamp.

TABLE III.
Exciter Lamps.

Volts.	Watts.	Amps.	Diameter (mm.)	Overall Length (mm.)	L.C.L. (mm.)	Life Hours.	Average Filament Brightness.
8	32	4	25	75	44	100	1700
8.5	34	4	25	75	44	100	1800
10	50	5	25	75	41 or 44	100	1900
10	75	7.5	25	75	41 or 44	100	2300

Lamps of this type are designed primarily for sound track actuation in film projectors, or for other purposes where a high-brightness spot of light is required. The average filament brightness for these lamps is given in column 8, Table III. It follows, for the reasons given in section 1, that a zone of maximum filament temperature, and therefore of maximum filament brightness will occur at the centre of the filament coil. For this reason it is found that the highest rate of evaporation of the filament occurs on the centre turns, and it is at the mid point that filament failure ultimately occurs. The current density on the centre turns therefore increases during life, producing an increased centre brightness, although there may be an overall decrease in the horizontal candle power and lumen output. These complex, but inter-related, phenomena are due to evaporation from the filament taking place in the preferential manner described above. The thinning of the filament in the centre zone and the increased temperature gradients resulting therefrom produce an overall increase in filament resistance, thereby reducing the lamp wattage for a given constant voltage of operation. The total luminous output from the lamp will also be decreased further during life by the deposition of tungsten from the filament on to the bulb walls. It is apparent that the magnitude of these effects will be reduced as the total length of wire in the filament is increased. The higher the voltage of the lamp the less will be the maximum temperature of the filament for a given efficiency. Beyond a certain increase in filament length or lamp voltage, however, the addition of a filament support becomes necessary, and in its simplest form this support generally consists of a loop of thin molybdenum or tungsten wire placed centrally between the electrodes carrying the filament. Its purpose is to hold the filament coil rigid against sag under gravity and against distortion due to chance shocks or vibration. Besides fulfilling this necessary function, however, it has the effect of cooling the filament at and about the point of contact, and therefore increases the proportion of energy used in non-light producing processes.

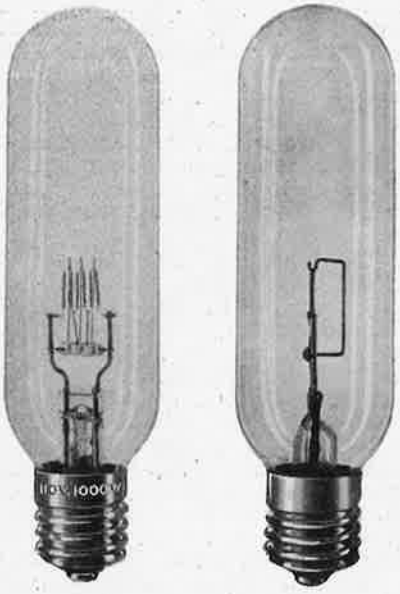
Before leaving the subject of straight helix lamps, there are two further points of general interest. Both are related to the temperature gradients which result from the cooling effect of the electrode. For certain purposes electric lamps require to be operated at a specified temperature, say 2360 deg. K or 2848 deg. K. Particularly in low-voltage lamps, but to some extent in all lamps, it will have been appreciated from the foregoing section that considerable temperature variations exist along the length of the filament. While a lamp can therefore be calibrated to colour-match another source operating at a given colour temperature, the energy distribution can at the best be only an approximation to that corresponding with the desired temperature.

A reduction in these temperature gradients would result in a more economical production of light as a given maximum temperature (corresponding with a given life) would be achieved at a higher average efficiency of the source. To enable this desirable result to be realised it would be necessary to provide a filament wire which had a gradually decreasing diameter towards the supports or the electrodes, the rate of change of the diameter being calculated to offset the cooling effects exactly. Such suggestions have been made, but appear unlikely of practical achievement. Another means which suggests itself, particularly in the case of gas-filled lamps, would be to continuously vary the pitch of the filament helix between each support, using a closer wound coil near the supports than at the middle of the filament. In this way the relative energy losses in the gas could be made to compensate at least to some extent for the conduction losses at the supports. This latter suggestion may be something more than an interesting speculation.

(ii.) *Flat Grid Filament Lamps.*

In order of increasing complexity, the next type of lamp to be considered is the flat grid projector, in which a single coil of wire is bent into a monoplanar grid. This is illustrated in Figure 5.

An interesting feature in the design of this class of lamp is the method used to support the filament. In order to reduce thermal losses the filament coil is produced with a number of equidistant spaces about which the



Front view. Side view.
Fig. 5. Monoplanar grid class A1 projector lamp, 110-volt, 1000-watt.

filament is bent and supported. The molybdenum supporting loops therefore engage only the filament wire itself and not the coiled portion. Data for a range of these A1 projector lamps is given below, together with average brightness values for typical designs. (See Table IV.)

TABLE IV.
A1 Flat Grid Projector Lamp.

Volts.	Watts.	Diameter (mm.)	Overall Length (mm.)	L.C.L. (mm.)	Life, Hours.	Average Filament Brightness. 100-115v.	Average Filament Brightness. 200-250v.
100-115 and 200-250	100	25	125	75	100	300	175
	200	32	125	75	100	500	—
	250	32	125	75	100	650	400
	300	32	125	75	100	700	—
	500	64	125	75	100	750	500
	1000	64	230	120	100	1000	800

The values of brightness given in columns 7 and 8 are considerably lower than those quoted for the exciter lamps, and this follows for two reasons:—

(a) The designed efficiency for a given life is in many cases lower, due to the smaller current consumption.

(b) The average brightness takes account not only of the space between adjacent turns of the filament helix but also of the space between the various segments which make up the filament grid.

The average brightness values therefore depend not only on the filament temperature, but on the ratio of the projected area of the incandescent tungsten wire and the space which it occupies. While in many cases it is useful and desirable to design a lamp of this type in such a way that the area of the filament grid is a minimum for the particular wattage to be dissipated, this is not an invariable rule. For certain purposes and types of optical apparatus there may be a minimum filament area requirement which is necessary to ensure adequate flashing of the optical system, or to give the required divergence of a beam of light from the apparatus. In all cases, however, it is desirable to design the individual segments so that the desired area is occupied by the incandescent filament in as even a manner as possible, the object being to reduce to a minimum brightness gradients within the filament area.

(iii.) *Lamps with Biplane Filament Arrangement.*

A development of considerable importance was the introduction of the biplane filament arrangement. The object of this design was to increase the average brightness of the filament by increasing the ratio of incandescent filament wire to total space occupied. It was achieved by arranging alternate segments of the filament coil in two planes and staggered relative to each other in such a way that when the filament is projected the spaces between adjacent coils in the front plane are occupied by alternate coils in the back plane. (See Figure 6.)

The biplane filament therefore allows of a given wattage to be dissipated in approximately half the filament area that is generally possible with monoplane filaments. Some typical brightness values for lamps of identical wattage and output are given in the table below—

TABLE V.

Volts.	Watts.	Average Filament Brightness. Stilbs. Monoplane Filament.	Average Filament Brightness. Stilbs. Biplane Filament.
110	500	750	2000
220	1000	800	1600

While the values given in the table above are for typical lamp designs which illustrate the relative average brightness of monoplane and biplane lamps of the same output they must not be taken as necessarily representing the practice of all lampmakers.

While this principle finds its most effective use in lamps of relatively high voltage, for example, lamps designed for 100-130 or 200-250 volt mains, it has also been applied in modified form to comparatively low-voltage lamps. For example, in certain types of low-voltage projectors the filament segments are arranged in three planes in such a way that when projected the filament segments appear to be touching. (See Figure 7.)

Lamps of the biplane type require for their manufacture and assembly a very high degree of precision as well as tungsten coils of considerable stability. Obviously, if the design were such that

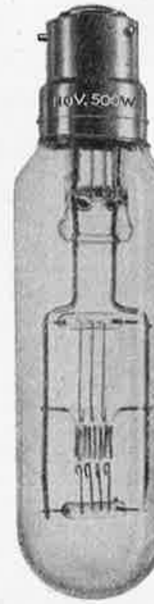
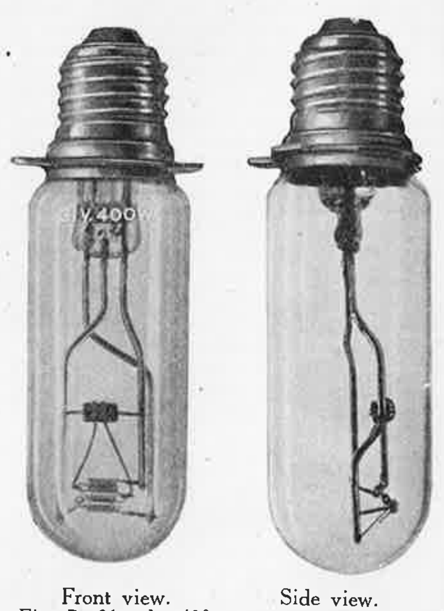


Fig. 6. Biplanar filament, 110-volt, 500-watt.



Front view. Side view.
Fig. 7. 31-volt, 400 watt projector lamp.

adjacent filament segments came into contact the lamp would fail, due to arcing and local over-running of the filament.

(C) Lamps Employing Double Wound Helices.

The principal advantage of the double wound helix or coiled coil filament as used in projector lamps lies in the fact that such a filament arrangement enables the requisite amount of tungsten wire to be contained in a smaller space than is conveniently possible with a single wound helix. The fact also that the coiled coil filament of certain types of low-voltage projector lamps has an approximately spherical form leads to the more efficient use of optical systems employing deep parabolic mirrors. These desirable results can moreover be achieved with the minimum of supports and the maximum simplicity of construction. It is of interest to study a little more closely the effect of the coiled coil filament structure on temperature and brightness gradients. In a large single helix of even pitch the adjacent turns of the filament lie parallel to one another through all parts of a complete convolution: such temperature gradients as exist therefore are due largely to the cooling effects of the electrodes and supports. The inside of each turn is brighter than the outside, but this is due to internal reflections. When, however, such a single coil filament is wound on a secondary mandrel to produce the coiled coil formation, the parallelism of adjacent turns of the primary coil is immediately disturbed. (See Figure 8.) It will be seen from this figure that at the points of contact of the primary turns with the secondary mandrel the convolutions of the primary coil are nearer together than the original pitch distance, while on the outside of the secondary coil the distance between adjacent turns is greater than the primary pitch. This point is significant not only from the geometrical aspect, which necessitates a coil design such that the distance between the nearest point of adjacent turns is adequate to preclude the possibility of turns touching, but because when the lamp is in operation the closest parts of the filament turns will tend to operate at a higher temperature and therefore higher brightness than those parts of the filament coil which have a greater spacing between them. (See Figure 9.)

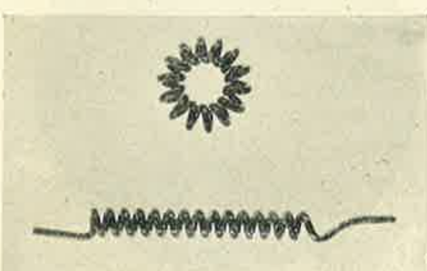


Fig. 8. Primary coil before and after bending into coiled coil formation.

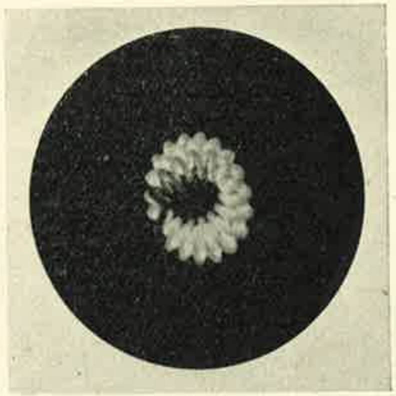


Fig. 9. End view of coiled coil filament in operation, showing end cooling effects and effect of internal reflections.

(i) *Low Voltage Coiled Coil Projector Lamps.*

Taking account of the above considerations it is still found possible to design the coiled coil filament in such a way that the projected image of the filament is virtually filled with the primary coil, as shown in the enlarged photograph Figure 10, which shows the filament arrangement and electrodes of a 24-volt 1,000-watt lamp. In voltages up to 24 or at higher voltages in certain special cases the unsupported coiled coil filament may be used for projector type lamps from about 24 watts up to 2,500 watts, and it is probable that this range could be extended if the need arose. A common feature of the whole range of such lamps is that in general the ratio of the filament breadth to the the filament length does not vary by more than 50 per cent. in either direction. Data for a series of typical lamps is given in Table VI.

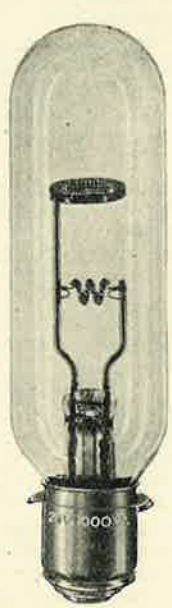


Fig. 10. 24-volt, 1000-watt coiled coil projector lamp.

Due to the concentrated filament of these low-voltage lamps and the fact that for many purposes it is desirable to operate them close to condensing lenses or mirrors, they are generally designed to be mounted in relatively narrow tubular bulbs. In some cases the filament may even be offset from the axis of the bulb in order to increase the angle of embrace of an associated optical system. When lamps of this type are in operation the convection currents set up in the gaseous atmosphere within the bulb take the form of a narrow central stream which carries upwards tungsten continuously evaporated from the filament. It will have been appreciated from an earlier section that gradual evaporation of tungsten occurs during the life of the lamp: it is therefore normal for bulb blackening to occur. In a well-designed projector lamp account is taken of this fact and the design is such that the blackening causes the minimum obscuration of the bulb surface over the solid angle subtended by the optical system employed therewith.

TABLE VI.
Low Voltage Coiled Coil Projector Lamps.

Volts.	Watts.	Diameter (mm.)	Overall Length (mm.)	L.C.L. (mm.)	Life Hours.	Average Filament Brightn'ss Stilbs.
12	150	38	150	55	100	1250
12	250	38	150	55	100	1450
12	600	64	230	84	100	2300
24	150	38	150	55	100	1000
24	250	38	150	55	100	1150
24	400	64	230	84	100	1550
24	600	64	230	84	100	1650
24	1000	64	230	84	100	1850

Various devices have been used to minimise the effect of this evaporation, which by darkening the bulb in the neighbourhood of the filament impairs the efficiency of the lamp. The use of a narrow tubular bulb is perhaps the most important, as its effect is to cause condensation of the tungsten in the form of a black or dark brown deposit in the upper regions of the bulb. It has been found that any object which causes a change in direction of the convection stream will receive a deposit of tungsten. A useful development which prevents much of the tungsten from reaching the bulb at all is the inclusion of a thin disc of nickel at such a distance above the filament as permits it to operate at a red heat. Such a disc will collect during the life of the lamp a substantial proportion of the evaporated tungsten. It is a device of particular value where the highest possible candle-power maintenance is necessary. An interesting application of the collector shield principle was its application to the so-called horizon lamp shown in Figure 1. In this case a grid of nickel gauze is mounted above the line of the filament to intercept evaporated tungsten. It therefore acts as a filter although its action cannot be compared with that of a physical filter as the tungsten is presumably deposited from the vapour phase.

(ii) Higher Voltage Coiled Coil Projector Lamps.

Of equal interest is the type of lamp in which the use of a coiled coil filament enables a compact light source to be produced suitable for higher voltages than those hitherto described under this section. In this case the filament segments, which may be only two or three in number, are complete in themselves and are welded or otherwise attached to rigid electrodes which serve as the supports as well as the current carrying leads. Such lamps are, of course, developments from the coiled coil general lighting service lamps in that the stability of the filament on which the success of the lamp depends has been made of such an order as to allow of self-supporting sections up to 50 to 60 volts to be used. In one design, in order to prevent the interference of objectional gas currents the electrode connections to the filaments are so arranged that the minimum potential difference occurs between adjacent ends. It will be appreciated that if two parallel coils are seriesed from the same end the potential drop of each filament taken singly will be doubled over the gas space of perhaps only one or two millimetres at the opposite ends of the filament where they are connected to the electrodes. By seriesing two such filaments by a conducting member connected to alternate ends the potential gradient across the electrode gap is limited to that across one filament segment.

In the case of very high power lamps where the optical requirements would appear to be best satisfied by a coiled coil filament construction, it has been found convenient to build up the filament from a number of self-supporting sections. For example, a 100-volt 5 kw. lamp has been constructed by seriesing five 20-volt 1 kw. coiled coil filaments, and the arrangement can be made such that no further supporting means are necessary. Such a design lends itself to the highest possible utilisation by reducing to a minimum the obscuration due to the supports..

(D) Multi-Filament Lamps.

In all the types of tungsten filament projector lamps so far described the current is carried by a single conductor coiled and arranged in a variety of ways according to the requirements of the particular design. It thus follows that for a given voltage a lamp of higher wattage will require a heavier tungsten wire than a lamp of lower wattage. Certain advantages accrue from this fact. Notably, that the increased wire diameter leads to improved mechanical stability and to an increase in the life of the filament designed for a given efficiency. In general, the latter advantage is given to the user in the form of an increased efficiency for a given life. There is, however, a corresponding disadvantage in that the employment of a single conductor to form the filament of a projector lamp offers some degree of restriction on the shape, size, and form of the filament unit which can be achieved, having in mind the considerations outlined in preceding sections. With the biplane lamp described in B (iii) above this disadvantage is reduced by arranging alternate filament sections in parallel planes in such a way that when the complete unit is viewed from a direction at right angles to the planes of the filament grid the spaces between adjacent coils in the front plane are largely filled by alternate coils in the back plane. The various coil segments are part of a continuous helix and therefore operate in series with each other. It is an essential feature of all lamps of this type that sufficient clearance is allowed between the various coils to prevent the possibility of a short circuit occurring, either initially or under the specified conditions of use. If short circuiting does occur an arc will probably be formed, and in any case the lamp will fail prematurely.

Another consideration which affects the design of all gas-filled tungsten filament lamps is the clearance necessary between high potential points of the filament which are required to operate in close proximity to each other. The actual clearances which are used are a function of the filament temperature, the nature and pressure of the gas-filling, and the potential difference which will exist between adjacent points of the filament structure when the lamp is in operation. The presence of minute surface impurities on the filament may also increase its emission locally and contribute to flash over unless suitable precautions are taken both in the design and manufacture of all types of gasfilled lamps.

With these considerations in mind, about a year ago the author evolved a new design of filament structure for low-voltage projector lamps which has certain advantages over the types hitherto described.

In the new lamp two or more filament segments are mounted electrically and mechanically in parallel.

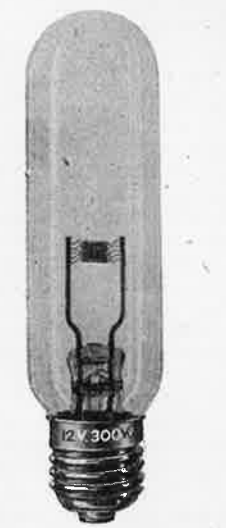


Fig. 11. 12-volt, 300-watt "solid source" projector lamp.

Adjacent segments are placed in physical contact with each other so allowing of a grid formation of maximum compactness, and to this arrangement the description "solid source" has been applied. See Figure 11, which is a photograph of a typical lamp.

In the development of this lamp it was shown that the restriction against allowing individual filament units to lie in contact with each other need not apply, providing that contact was established at equi-potential points. The principle was first investigated during the development of a multi-filament lamp in which 20 filaments were supported by a single conducting member arranged to intercept each filament at the mid-potential point. It was later shown that no

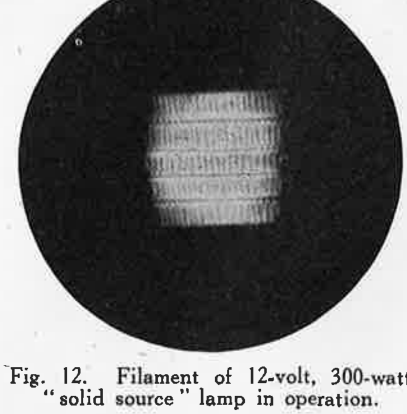


Fig. 12. Filament of 12-volt, 300-watt "solid source" lamp in operation.

support was necessary if the filaments were suitably designed and were placed in contact along their entire length. (See Figure 12.) This discovery led to the quantitative investigation of the effect of such an arrangement of parallel filaments on life, efficiency, candle power distribution, and maintenance. While in practice it is considered impossible to prevent the occurrence of some circulating current it has been established that with accurately made filaments the effect of this is negligible. It has been established that for many purposes the solid source lamp offers marked advantages over other types of projector lamp, particularly in the improved ratio of the horizontal candle power to the total luminous output and the increased average brightness of the filament unit and the increased brightness uniformity which can be attained thereby. Some comparative figures are given in Table VII.

Polar curves for a typical solid source lamp of 12 volts 250 watts rating, designed for 100 hours life, and for a 12 volt 250 watt coiled coil projector lamp of similar designed life, are shown in Figure 13.

It will be seen that in the direction of use the solid source gives some 50 per cent. more flux than the lamp with coiled coil filament formation as a result of the decreased emission of light in unwanted directions. There is some evidence that the use of the closely packed filament units in the solid source lamp leads to a reduction in the amount of energy dissipated by convection and conduction in the surrounding gas.

TABLE VII.

COMPARATIVE DATA FOR COILED COIL FILAMENT CONSTRUCTION AND SOLID SOURCE CONSTRUCTION.

Volts.	Watts.	Ratio of H.C.P. to Lumens.	
		Coiled Coil.	Solid Source.
12	150	.097	.125
12	250	.093	.142
24	250	.088	.128
24	300	—	.133
24	350	.088	—

This is a not unexpected result, and it to some extent offsets any reduction in efficiency, due to the reduced wire diameter required for the individual filaments of the group as compared with that required for a single filament designed for the same wattage dissipation.

These effects are illustrated graphically in Figure 14, in which the average brightness and the luminous efficiency are compared for a series of lamps in which one, two, three filaments, etc., are mounted in solid source formation, all the lamps being measured at the same voltage. It will be seen that with increase in the number of coils forming the filament the efficiency increases, together with a more than proportionate increase in the average brightness.

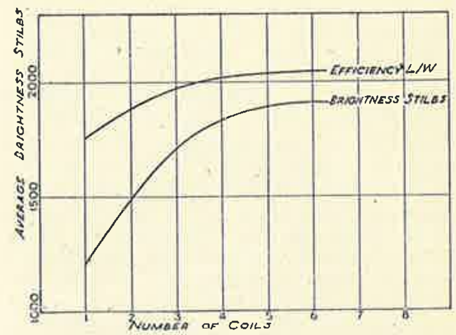


Fig 14. Variation of average filament brightness with number of filament coils arranged in solid source formation.

The solid source arrangement lends itself to close control of filament shape, which for a given output may be rectangular or square, and within limits may be designed for different areas without sacrificing the essential feature of a high degree of uniformity of brightness over the whole area. The optimum size of filament for a given wattage and efficiency is a function of the relationship between the horizontal candle power and the brightness. As the total filament area is reduced the brightness will increase up to a maximum and then begin to decrease. This apparent anomaly is due to the particular way in which the projected area of a solid source filament group can be modified. For a given single coil filament the pitch of the helix can be altered between about 115 per cent. and 190 per cent. of the wire diameter without introducing difficulties. If therefore filaments are produced on a constant mandrel diameter a change in

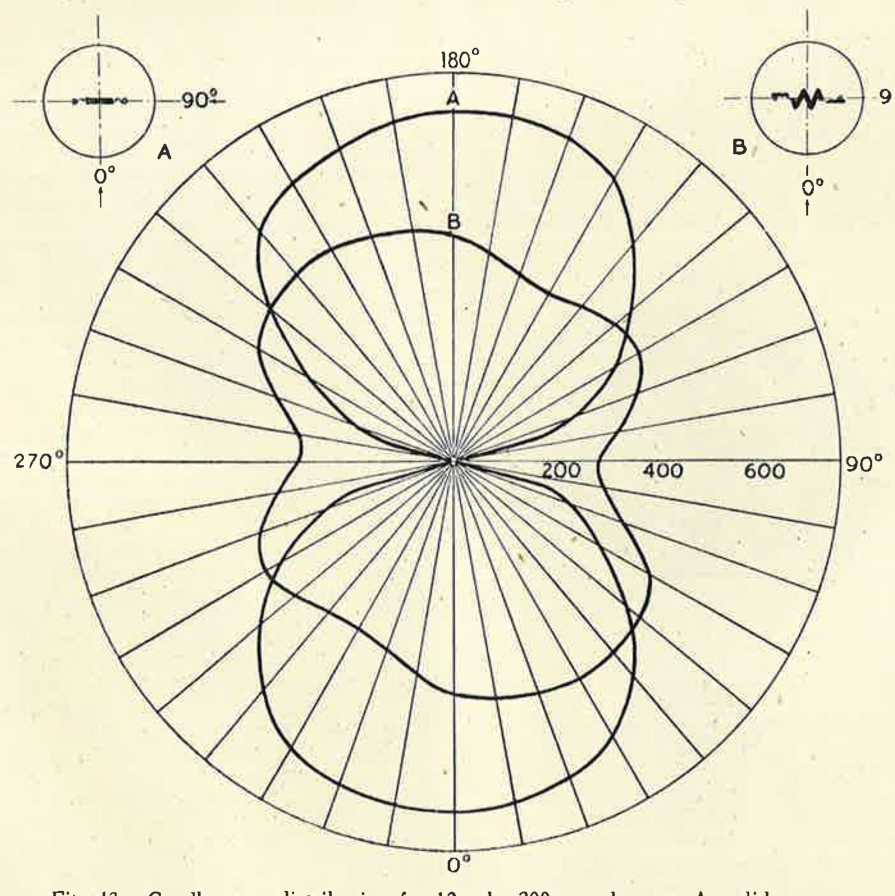


Fig. 13. Candlepower distribution for 12-volt, 200-watt lamps. A, solid source. B, coiled coil.

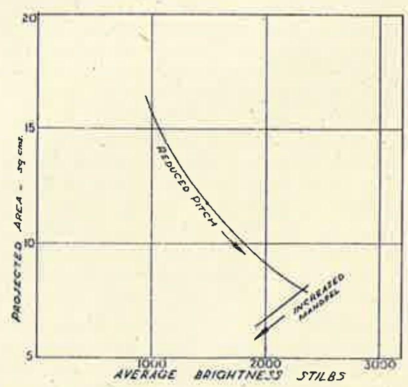


Fig. 15. Variation of brightness with area, for 12-volt, 72-watt filaments operating at 21 L/w.; consisting of two 12-volt, 36-watt coils in parallel.

pitch will produce an approximately proportionate change in average filament brightness. Beyond a certain point, given above as a pitch ratio of approximately 115 per cent., further reductions in the projected area of the filament in the direction of use can only be made by an increase in the diameter of the mandrel on which the filament is wound. The effect of this is to increase the emission of light in non-effective directions and therefore to produce a net decrease in the average brightness for a given wattage and efficiency. This interesting effect is illustrated in Figure 15.

Apart from these general considerations of lamp design which resulted in the evolution of the solid source there are certain additional features which, while generally applicable, are particularly useful in connection with these new lamps.

The Use of Internal Mirrors.

In considering the inter-relation of projector lamp design with that of the design of the optical system to be used therewith, it is in general axiomatic that the utilisation of the light must be a maximum. This desirable result may be achieved in two ways:—

(a) By designing the bright light source to give the maximum light flux within the effective solid angle of collection of the optical system.

(b) By re-directing the flux issuing from the source in a direction away from the optical system so that it is ultimately collected thereby.

The principles underlying the first of these requirements have been discussed above. The second form the subject of the present section. It has long been the practice in slide projectors and similar instruments to fit a mirror on the side of the lamp remote from the condensing lens, the object of which is to re-direct non-effective light back in the condenser. In the case of an open grid type of filament a correctly adjusted mirror will produce an image of the filament interlacing the filament itself and in the same plane. This principle finds its most effective use when the mirror is made integral with the lamp bulb. The mirror may be formed on the outer surface of the lamp bulb by any of the well-known silvering processes. In the opinion of the author it is, however, preferable to develop the mirror on the inside surface of the bulb, which in general should therefore have a spherical form. The reason for this preference will be understood by reference to Figure 16.

It will be seen that by accurate location of the filament unit relative to the optical centre of the mirror a filament image can be formed in any desired position. For example, if the filament unit itself is

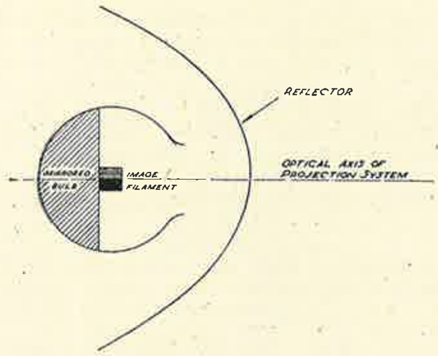


Fig. 16.

in the form of a rectangle the major side of which has twice the length of the minor side, by arranging that this rectangle lies to one side of and touching the mirror axis the filament image and the filament itself will merge together to form a square of light which can be most efficiently utilised by the optical system proper. Careful design of this type will enable an increase in beam flux to be obtained of the order of 175 per cent. of that produced with a similar filament operating at the centre of a clear bulb without a mirror. The spherical mirror on the bulb surface may approach, but should not exceed, a hemisphere. It may be formed by the evaporation of aluminium in vacuo, and mirrors of this type have a very high reflectivity and stability. A lamp embodying these principles is shown in Figure 17.

It will be seen that a group of filaments in solid source formation is arranged normal to the mirror axis and offset from it in such a way that an image of the filament group occurs

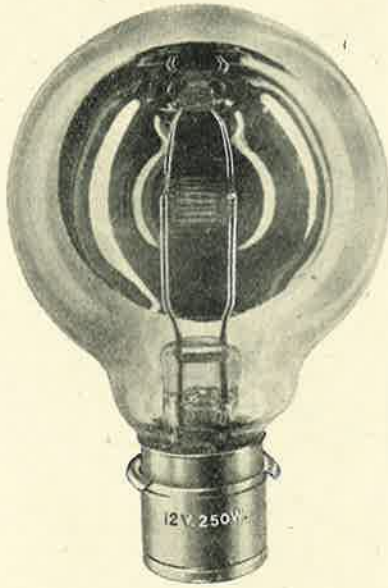


Fig. 17. 12-volt, 250-watt solid source lamp, showing reflected image of filament group.

adjacent to the filaments themselves. The complete unit formed by the filaments and their mirror images are bisected by a line through the axis of the mirror. When used in conjunction with a deep parabolic reflector the arrangement gives a very high utilisation of the total light emitted by the lamp.

A development of a somewhat different nature was finalised in the U.S.A. about 1938. It consisted of a lamp in which the bulb was made in the form of a parabolic mirror, the front glass of which consisted of a refractor unit. It was originally developed as a complete headlamp for the motor industry with the object of producing a standardised type of beam to conform to certain agreements reached in that country. It is outside the scope of the present paper to discuss this sealed beam headlamp in any detail. It is, however, a very interesting example of lamp-making technique.

(E) Symmetrical Sources

All the types of high-brightness tungsten filament lamps so far described are designed to be used with substantially unidirectional optical systems. In such systems, while the lamp and associated optical gear are designed to give the maximum possible utilisation of the flux, this flux is ultimately emitted in a single desired direction, as, for example, in the form of a searchlight beam or in the form of a beam from a projector lamp. According to the nature of the optical system employed and the size of the source, as well as to the use or otherwise of dispersing systems in the light beam itself the solid angle over which the flux is emitted may be varied very considerably. There is, however, in general, a definite directional characteristic which may be described as the optical axis of the complete arrangement.

An important group of bright light sources, however, belong to a class designed to emit their flux as uniformly as possible through 360 deg. around the axis of the lamp. Such sources find extensive use in lighthouses, airway beacons, and for the production of general floodlighting effects. They have been the subject of a considerable amount of development work, not only in regard to the lamps themselves, but also in regard to the optical systems associated therewith. The simplest example of a lamp of this type is what is known as a bunch filament or class " B " projector lamp. It consists of a grid filament not dissimilar to that employed for the flat grid A1 projector, except that the filament is mounted in such a way as to lie on the surface of a cylinder. A typical lamp is shown in

Figure 18, and some data for a range of these low power floodlights is given in Table VIII.

The design of lamp shown in Figure 18 allows of a relatively uniform

TABLE VIII.

B1 Floodlight Projector Lamps.

Volts.	Watts.	Diameter. (mm.)	Overall Length (mm.)	L.C.L. (mm.)	Life Hours.
110–	100	80	115	75	800
210	250	95	125	75	800
230–	500	130	180	115	800
250	1000	130	180	115	800

light distribution over at least 180 deg. of arc, and in some cases up to 270 deg. Over the remaining angle the light flux is largely supplied by segments of the filament unit on the remote side of the lamp axis. There is, therefore, some falling off in candle power in this direction. This is inevitable, as it is essential for the electrodes to have a certain minimum

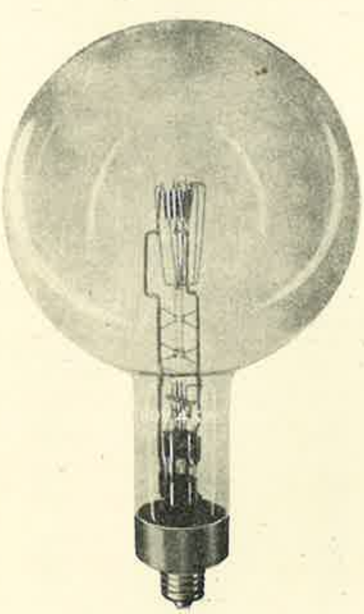


Fig 18. 80-volt, 4-kw. bunch filament projector lamp.

spacing to prevent the possibility of flash-over occurring. While for many purposes the flux distribution of this simple form of all-round source is entirely satisfactory, there are cases in which a modified distribution of light is desirable. Various designs have been produced, the object of which is to give an improved light distribution through 360 deg. Of these, three types will be described by way of example. It must be understood, however, that no attempt is being made to catalogue all the types of tungsten filament projector lamps which, while not without intrinsic merit, generally represent modifications of the basic types which are described.

(i) Parallel Filament Arrangement.

(ii) Cruciform Filament.

(iii) Diffusing Medium.

The improved filament arrangements which are to be described are generally employed in lamps of higher wattage than the range of B1 floodlighting lamps mentioned above, and this results from two principle considerations. The first is that the optical systems with which these lamps are employed are generally of much greater accuracy than the more simple units used with the smaller lamps, and can therefore utilise lamps of improved light distribution. Secondly, the larger the lamp the more generally feasible is it to introduce constructional methods, which in low-power lamps would be extremely complicated, and in some cases cumbersome. The various methods will therefore be described in terms of lamps of 3 to 5 kw. rating, although this by no means represents the range over which the principles employed are normally applied.

(i) Parallel Filament Arrangement. In this construction the requirement of a symmetrical filament covering the surface of a cylinder and the requirement of giving the maximum possible inter-electrode spacing are brought together by the use of two filaments each dissipating half the total wattage and each covering 180 deg. of the surface of a cylinder. In very high power lamps this device has been extended to give a balanced loading on three-phase supplies by arranging three filament segments each occupying 120 deg. of arc, the points of union of the three filaments being brought out to three terminals on the lamp base. Another method of achieving the same result is to arrange a series of filaments in parallel planes around the surface of a cylinder. In this case each individual filament may be designed to dissipate only a small proportion of the total wattage of the lamp. While such an arrangement has valuable properties for special purposes it is necessarily of greater complexity and therefore of less mechanical rigidity than arrangements in which the number of individual filament units is kept to the absolute minimum.

(ii) Cruciform Filament. Among the most elegant methods for producing a substantially symmetrical light source the cruciform filament holds a high place. It consists of two monoplanar grid filaments arranged to bisect one another at right angles. This construction lends itself to a rigid supporting arrangement for each of the intersecting grids and allows of considerable latitude in the height/width ratio of each grid as the electrodes are at the maximum distance apart. A photograph of a typical 80 volt 3 kw. lamp is shown in Figure 19. It will be

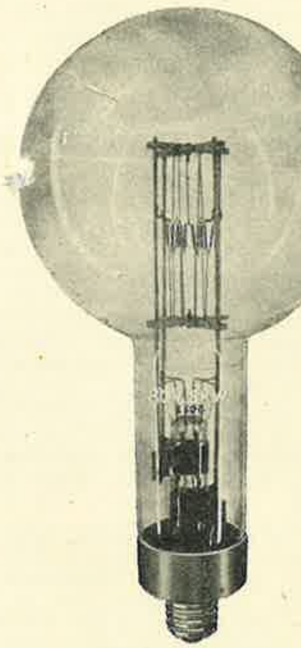


Fig. 19. 80-volt, 3-kw. cruciform filament lamp.

noticed from this illustration, which is of a lamp designed for cap down burning, that the filament unit is positioned below the centre of the spherical portion of the bulb. Such an arrangement gives an increased candle-power maintenance over the solid angle of collection of the associated lens or mirror system within which the lamp is designed to operate, as the tungsten carried upwards in the convection stream during the life of the lamp is deposited on the upper regions of the bulb which lie outside the effective angle of collection of the optical system. While the cruciform arrangement is advantageous from the point of view of lamp design it still leaves something to be desired from the point of view of symmetry of light distribution through 360 deg. in a plane at right angles to the lamp axis. It is obvious from a consideration of the arrangement that the polar curve of light distribution in the plane of use will rise to a maximum in the four positions at which each filament is normal to the angle of test. For many purposes, however, the disadvantage of such variations in light flux are offset by the general attractiveness of the design. In some cases, however, a greater measure of brightness uniformity is desirable combined with a larger light source than can be achieved with any degree of uniformity with a tungsten grid filament formation. For such purposes an experimental arrangement has been produced which is described below under the heading Diffusing Medium.

(iii) Diffusing Medium. In this arrangement any suitable filament formation is arranged within a diffusing refractory cylinder of high transmission. By this means the surface of the cylinder may become the virtual source providing that the degree of diffusion is sufficiently high. With increased diffusivity the apparent size of the source is materially increased and of course its average brightness is proportionately reduced. With proper design it can be arranged that the convection stream from the filament carries the evaporated tungsten through the cylinder, causing it to deposit on the upper regions of the bulb. The effect is therefore to provide the equivalent of a light source mounted in a diffusing bulb of much smaller dimensions than could be obtained by means other than those described.

The lamp with diffusing cylinder has perhaps only a limited field of usefulness, as there is necessarily a certain loss of efficiency due to absorption at the surface of the diffusing medium. It is, however, an interesting development, as the brightness uniformity can be made higher than that possible with the unscreened tungsten filament, or higher than can be produced with a discharge lamp source of comparable size.

Conclusion

It is to be hoped that in this general survey of tungsten filament projector lamps enough detail has been given to enable the trend of recent developments to be appreciated. Some of these developments have occurred concurrently with advances in bright light sources of the discharge type and it is hoped to present a further paper on this subject in the not too distant future.

APPENDIX

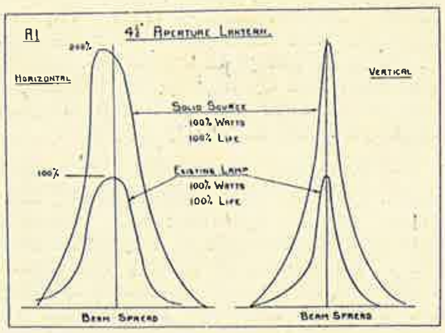
I am indebted to the Director of Scientific Research, Admiralty, for permission to include some comparative performance data on high-brightness tungsten filament lamps operating in precision signalling lanterns. It must be understood that this data shows the results of the effective combination of lamps and optical projection systems.

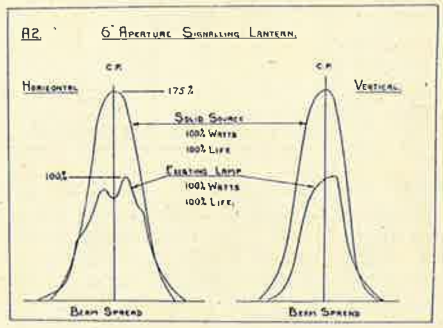
The lamps used for these tests were developed in collaboration with the Admiralty, and embody some of the principles discussed in the preceding sections.

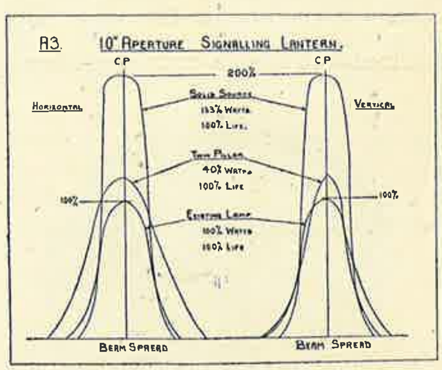
In the case of the solid source lamps it is of interest to note that this development emerged from considerations of a somewhat cognate problem put up by the Admiralty. Once the underlying principle of the solid source lamp had been established the further development work was greatly facilitated by the keen interest paid by the Admiralty to its application to a variety of lamp types which were of importance in their own development work.

Only comparative results are given, and they indicate the magnitude of the gain which results from functional lamp design in relation to the optical system.

'A' refers to a lamp with an internal aluminised mirror. Corresponding beam curves are shown in Figs. A1, A2, and A3 respectively.







Relative Performance of High Precision Signalling Lanterns with Existing Lamps and with certain of the Lamps Described in This Paper.

Lantern.	Lamp.	% Watts.	% Life.	% P.C.P.	Beam Spread at 50% P.C.P.
4½ in.	Existing	100	100	100	100
	Solid Source 'A'	100	100	200	150
6 in.	Existing	100	100	100	100
	Twin Pillar 'A'	100	100	175	100
10 in.	Existing	100	100	100	100
	Twin Pillar 'A'	40	100	100	150
	Solid Source	133	100	200	100

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