MONOGRAPHS
OF THE
QUEKETT MICROSCOPICAL CLUB

ILLUMINANTS
AND
ILLUMINATION
FOR
MICROSCOPICAL WORK

by
F. E. J. OCKENDEN
M.I.E.E., F.INST.P.

London

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The Quekett Microscopical Club

ROOMS OF THE ROYAL SOCIETY
BURLINGTON HOUSE, PICCADILLY, LONDON

AN INTRODUCTORY NOTE

This Club was founded in 1865 for the purpose of affording to experienced microscopists, as well as to students, regular and frequent opportunities of discussing these special subjects in which they are mutually interested, and also for promoting Field Excursions to the well-known collecting districts around the metropolis. From the commencement in 1865 until the present time members living in home counties have enjoyed these advantages of membership.

In other parts of the country it was soon found that the possibilities of discussing problems with other members by letter, the posting of the *Journal* of the Club regularly, and the knowledge that a warm welcome awaited one at headquarters when visiting London, made membership desirable.

Further, the authoritative nature of Quekett publications, especially the regular publication of the *Journal of the Quekett Microscopical Club*, has gained for the Club an important membership in many parts of the world.

A fraternity of members, willing to exchange experiences in all branches of microscopical interest, is the most valuable asset of the Club, but the lending library of several thousand books on all subjects related to the microscope, and the many thousands of unique microscopical preparations available on loan are also to be noted.

There is no entrance fee, and the Annual Subscription is £1. 1*s*. 0*d*., dating from 1 January.

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The Ordinary Meetings are held at 6.30 p.m. on the SECOND Tuesday in each month, except July, August and September. Business commences at 6.30 o'clock and finishes by 8.30 p.m.

The meetings on the FOURTH Tuesday in each month are for conversation and for the exhibition of objects, from 6 to 8.30 p.m. In July, August and September these informal meetings are held on both the second and fourth Tuesdays in each month.

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JULY 1947

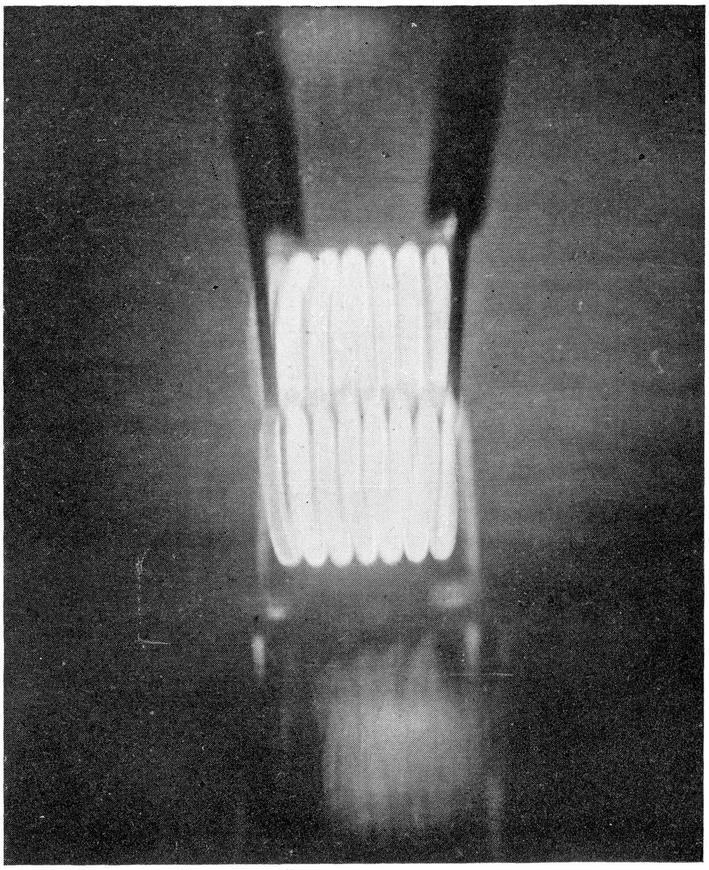

Fig. 1. Doubling apparent size of filament by using spherical mirror to form real image just above actual filament. Cf. Pl. 2, fig. 1.

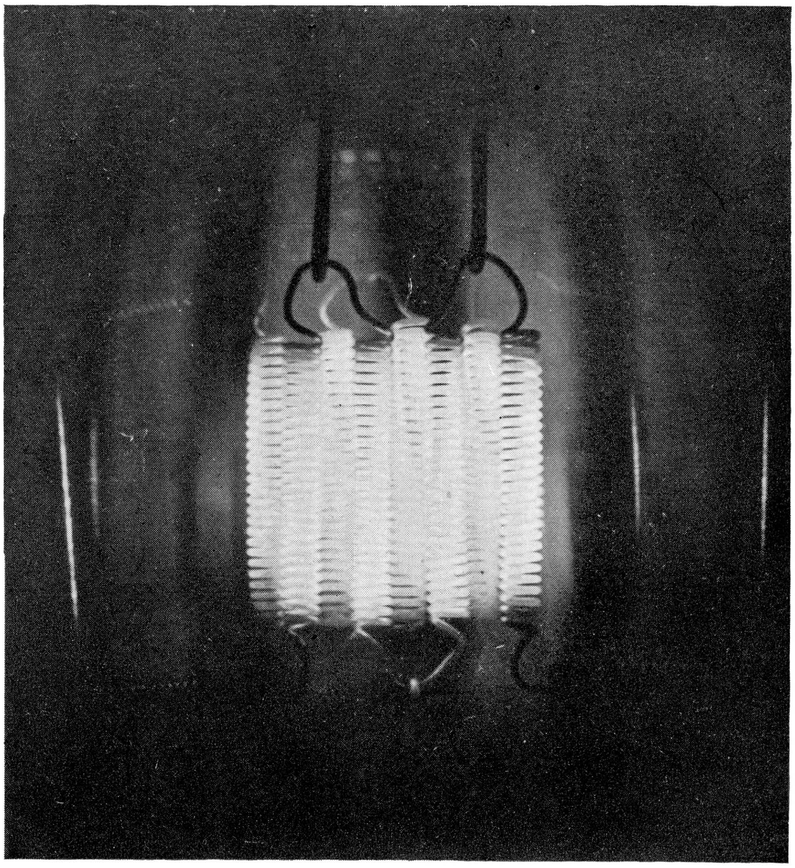

Fig. 2. Filling in gap between narrow spiral filaments by similar method. Cf. Pl. 2, fig. 3.

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Illuminants and Illumination for Microscopical Work

By F. E. J. OCKENDEN, M.I.E.E., F.Inst.P.

(Plates 1–3)

The degree of attention which the average microscopist needs to pay to his illuminating technique is decided, very largely, by the type of subject in which he is most interested. Even the simplest low-power investigation is rendered easier, and more attractive, if accompanied by some appreciation of the theory of illumination, whilst high-power resolution (particularly with deep colour filters) demands his closest possible attention. For projection, either on a small scale, as for photo-micrography, or on one adequate for the entertainment of a large audience, high-efficiency illuminants combined with condensing systems of the maximum possible aperture are almost essential if pleasing results are to be obtained.

Before discussing light sources in detail, it may be helpful to consider some of the terms and definitions used in connexion with them. Of these, the simplest and best known is the:

Candle (symbol I), the standard of luminous intensity, originally a carefully constructed wax candle burning a given number of grains per hour. The present International Candle, although based on the original concept, is actually maintained by comparison with specially designed electric lamps run under very closely controlled conditions.

Flux (symbol F). The light emitted from a light source is treated as an entity, the luminous flux. The unit is the *lumen*, which is the amount of light falling on a surface area of 1 sq.ft., when it is uniformly illuminated, at a distance of 1 ft., by a source having an intensity of 1 candle in every direction. The total number of square feet which can be so illuminated is equal to the area of the surface of a sphere of 1 ft. radius surrounding the source, i.e. 4π; it follows that the total flux emission from a source of intensity 1 candle is 4π lumens (approximately $12\frac{1}{2}$).

Foot-candle (f.c.). This is a special case of the more general unit of illumination, *lumens per unit area* (symbol E), but it is very widely used. It is the light falling on any surface, when it is evenly illuminated, at a distance of 1 ft., by a source having an intensity of 1 candle. When this surface has an area of 1 sq.ft., the luminous flux falling on it will, of course, be 1 lumen.

Since the area of a sphere surrounding a light source increases as the square of its radius, it follows that the illumination on any surface lit by a lamp of intensity I candles at a distance D ft. is I/D^2 f.c., and the luminous flux falling on it is I/D^2 lumens per sq.ft.

Brightness (symbol B). The unit of brightness is the *candle per unit area*,* and here we leave the concept of a uniformly emitting point source, and consider the light radiated from a uniform source of finite area. This, for example, may be either the luminous surface of a flame, or a diffusing reflector such as a white screen illuminated externally. The size of the unit chosen depends mainly on the type of radiating surface under consideration. When the brightness is high, as in the case of the filament of a tungsten lamp, the usual unit is the square millimetre, for illuminants of lower brightness the square centimetre,† and for reflecting surfaces, the square metre or square foot is commonly employed. Assuming the latter, a uniformly diffusing surface, which has a brightness of 1 candle per sq.ft., radiates or reflects π lumens from every square foot. It follows, from consideration of the definition of illumination given above, that a uniformly diffusing surface reflecting the whole of the light falling upon it will have a brightness of 1 candle per sq.ft. when the illumination falling upon it is π f.c., that is, a flux of 3·14 lumens.

It should be noted that only in the case of a perfectly white reflecting surface does the degree of illumination give any indication of the apparent brightness. For all other conditions, the brightness will also depend on the reflexion factor which may vary from 80% in the case of clean white blotting paper to less than 1% for black velvet. The minimum brightness regarded as necessary for a cinema screen is about 2 candles per sq.ft. and to attain this on a screen having a reflexion factor of 70% implies that at least 9 lumens must fall on every square foot of it. The great value of this method of assessing illuminating power when using optical projection systems will be seen later.

Directional and 'mean spherical' candle-power. Although it is often convenient to state the output of a lamp in terms of candle-power or lumens it is evident that, except in special cases, the value of these quantities is by no means the same for varying directions of illumination. Thus the average electric bulb has but little light emission when viewed from the top, and the amount emitted from the side often depends on the relative position of the filament, whether, for instance, it is seen side or end on. It is therefore often necessary to consider the 'directional' candle-power (Walsh, 1926; Grieveson, 1935), and a polar curve showing the light distribution in a horizontal plane round a typical projection lamp is shown in Text-fig. 1. The form of lamp concerned is that in which the illuminant is a short flat sheet of incandescent material and is therefore representative equally of a 'ribbon' filament lamp, a headlight lamp in which the filament is wound in a short straight spiral, special lamps in which a series of spirals mounted in the same plane form an incandescent grid, or even the flame of a simple flat-wick oil lamp.

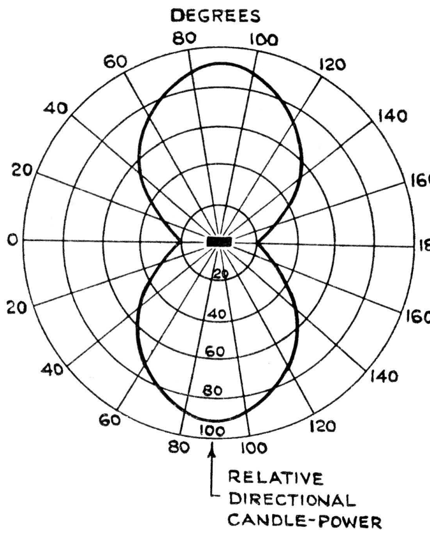
It will be seen that the maximum light emission is in a direction at right angles to the plane of the emitting surface, becoming less as the latter is viewed

* Or lumens per unit solid angle, per unit area.

† 1 candle per sq.cm. = 1 stilb.

'end on'. This is due to the fundamental law that the emission from a diffuse radiating surface is proportional to the cosine of the angle between the direction of illuminating angle and the normal to the surface, so that if I is the emission at right angles to the radiating surface, that at any other angle θ is equal to $I \cos \theta$. In practice the effect of this law is to make the brightness of a flat radiating surface appear the same at all angles. As, however, the apparent area is reduced by foreshortening when viewed obliquely it follows that the light falls off in the same ratio, becoming zero in the case of an infinitely thin radiant seen edge on. In most cases, however, particularly those of a lamp flame or spirally coiled filament, the thickness is considerable and so the zero point of illumination is never quite reached. Curves of light distribution similar to that shown in the figure, but differing in their proportions, are obtained if the distribution through the vertical plane is measured, the total obscuration due to lamp caps and filament supports being, for simplicity, ignored.

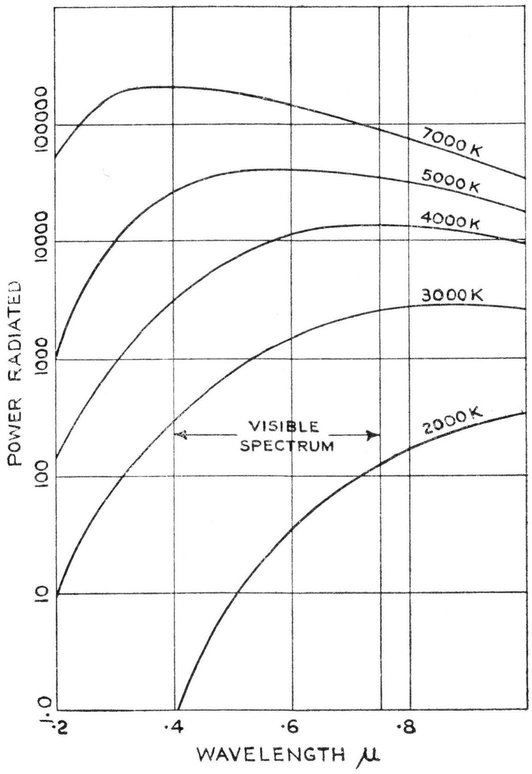
An alternative definition of the power of a lamp, which takes into consideration all the possible measurements shown in the polar curves, is its 'Mean Spherical Candle-power', which is the average value of all of them. To take such a series for every lamp would be exceedingly laborious, and it is usual to standardize one or more lamps by careful measurement and then to enclose one of them in a whitened cubical or spherical chamber. The total light reflected on to a translucent window in the chamber wall is measured (the direct light being screened by an internal shield), and this is then compared with the illumination produced, under similar conditions, by the lamps to be tested, only one measurement being then required for each test. The directional candle-power of any light source, and hence the number of lumens available in any given solid angle, such as that subtended by the lamp condenser, is often of importance in microscopical work, and some knowledge of the appropriate polar curve can be of considerable help in arranging a lighting system to the maximum advantage. The mean spherical candle-power, on the other hand, is rarely of any interest except in matters concerning general illumination.



Text-fig. 1. Polar curve for flat filament lamp. The numbers 0–100 refer to the relative candle-power at differing illuminating angles.

Colour temperature. The apparent colour of a body heated to incandescence varies with the temperature, hence the well-known expressions 'red' and 'white' hot. The actual distribution of the spectral energy in the continuous spectrum of an ideal radiating body, generally known as a 'black body' or full radiator, can be predicted by the application of the Planck and Wien laws if the temperature of the body is known. The higher the temperature the greater the proportion of high- to low-frequency radiation, and this is equally true whether the whole range of wave-lengths radiated is considered or only that portion to which the human eye is sensitive. Text-fig 2 shows the relative distribution in a portion of the spectrum given by an incandescent body between the temperatures of 2000 and 7000° K. (° K. = ° C. + 273).

It will be seen that, at 2000° K., the colour temperature of an oil flame, the ratio of red (0·7μ) to violet (0·4μ), is about 100 to 1, and at 3000° K., the temperature of a large tungsten filament lamp, this ratio is improved to about 10 to 1. At the temperature of a high-intensity carbon arc, nearly 5000° K., the two colours are emitted in about equal proportions, whilst at yet higher temperatures the high-frequency (blue and violet) radiation preponderates over the low. Such temperatures are, however, unattainable by all ordinary artificial means.



Text-fig. 2. Relative power radiated/wave-length in μ, for 'black bodies' at temperatures between 2000° and 7000° K.

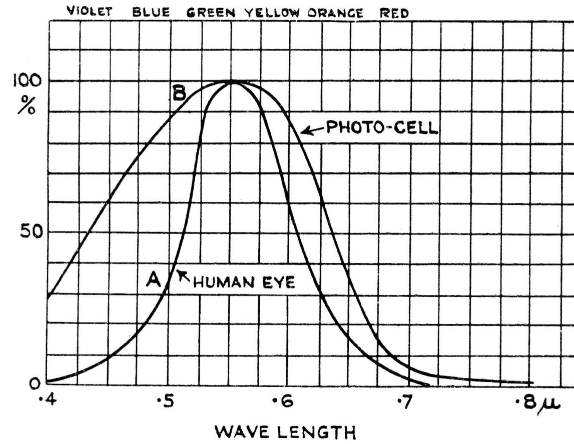
It follows that the colour temperature of a glowing body can be estimated if the proportions of the radiation at differing wave-lengths are known. This fact provides a ready means of ascertaining the approximate* temperature of all high-powered illuminants, even that of the sun itself. It will also be apparent that if, by any auxiliary device, such as a colour filter, the ratio of, for example, red to blue is altered, the effect is to modify the apparent colour temperature. A well-known example in nature is the filtering action of fine dust and moisture particles in the upper atmosphere, whereby the 'blue sky' effect is produced. The colour temperature of the clear sky is thus made to appear as high as 25,000° K. A similar effect is of course produced whenever a blue glass is placed in front of a lamp flame, but the total illumination then available will depend on the amount of selected radiation available in the original emission. It is for this reason that the use of deep colour filters is only satisfactory when high-temperature illuminants are employed.

The eye. Although not directly connected with the subject of colour temperature, a few comments on the spectral sensitivity of the human eye may appropriately be inserted at this point. Numerous tests have been made from time to time to ascertain the relative sensitivity of the eye to radiation of

* In the case of illuminants behaving strictly as 'black-body' radiators, that is, without selective emission in any part of the spectrum, the actual and colour temperatures are identical. Carbon and tungsten conform very closely to this condition over the visible spectrum, but such is not necessarily the case with all incandescent materials and never with gases.

differing wave-length, one of the earliest being that by König and Dieterici in 1893. The shape of the curve connecting wave-length with visual response depends to some degree on the intensity of the illumination, the so-called Purkinje effect, whereby the optimum sensitivity tends to shift towards the blue at very low (threshold) values, but for normal levels and for all but colour-blind individuals, the average sensitivity is represented, fairly closely, by the curve *A* shown in Text-fig. 3.

This curve is obtained by measuring the amount of power, at wave-lengths varying from 0·4 to 0·7μ, required to give equal brightness for each colour. It will be seen that the maximum lies between the range blue-green to yellow, with a marked peak in the yellow-green. The response to both the red and blue ends of the spectral range is comparatively low, and, to deep red and violet, very low indeed (about 1/20th of that for the yellow-green).



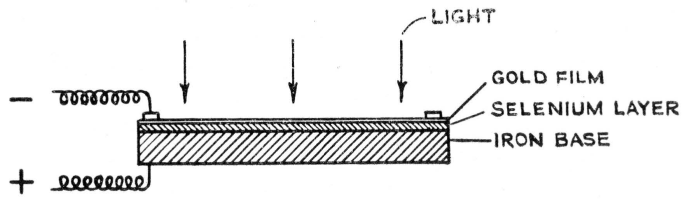
Text-fig. 3. *A*. Relative response of normal eye to equal amounts of radiant energy between 0·4 and 0·7μ. *B*. Ditto for selenium (barrier layer) photo-electric cell.

The high sensitivity for green combined with the large proportion of this radiation normally available combines to make the use of this wave-length (0·55μ) extremely popular. Not only is the green filter an exceedingly comfortable one to use for prolonged periods, but the relatively short wave-length transmitted helps to procure the maximum possible resolution for an objective of given aperture.

That this property is possessed to a yet higher degree by blue light is well known, and frequent attempts have been made to produce a filter which will pass light of the shortest possible wave-length, and yet have sufficient luminosity to make visual observation possible. The difficulties involved will be appreciated by combining curve *A* of Text-fig. 3 with that for tungsten at 3000° K. of Text-fig. 2. It will be seen that the radiation in the blue-violet is only about 1/15th of the total which, together with the low spectral response of the eye to this wave-length, gives a total reduction factor of about 1/200, and this must be yet further modified by the transmission factor of the screen itself (probably some 70%). Thus, efficient blue-violet illumination is unlikely to be obtained without a reduction in the brilliance of the illuminant by some 300 times. Where a better result appears to have been attained, with other than 'arc' light sources, spectroscopic analysis will usually reveal that this is due to the transmission of an appreciable proportion of green light by the filter employed.

The comparatively poor response of the eye to orange and red is generally of little importance in microscopical work, since the average artificial illuminant is particularly rich in these colours. They are, in any case, but little used except occasionally as a means of obtaining colour contrast with blue or green stained specimens.

Photo-electric cells. Two forms of light-sensitive cell have been developed in recent years, the vacuum type and the selenium or 'barrier layer' pattern (Preston 1936; Van Geel 1946). Of these only the latter is sufficiently powerful to operate directly an electrical indicator and thus form the basis of a simple portable light meter. Such cells, which may be either circular or rectangular, consist of a thin iron base (Text-fig. 4) on which is spread a layer of amorphous selenium. This is subsequently transformed into the crystalline variety by suitable heat treatment.



Text-fig. 4. Construction of photo-electric cell (barrier layer pattern).

Electrical contact with the upper surface of this layer, which constitutes the light-absorbing component, is made by means of an exceedingly thin, semi-transparent layer of gold, deposited either by direct evaporation or by cathode dispersion. The back of the iron plate forms one terminal, and a ring of low melting-point alloy (Wood's metal) encircling the gold layer the other.

A cell having an effective diameter of 60 mm. will give an electrical output of 10^{-7} watts per foot candle (10^{-5} amp. into 1000 ohms). The light flux on the cell in this case amounts to about 0·03 lumen, and since 1 lumen of green light is equivalent to 0·0016 W., the electrical conversion efficiency is of the order of 1/5th of 1%. A considerable proportion of the conversion losses are due to the relative opacity of the gold film. Owing, however, to the well-known tendency of such films to transmit most freely in the region of the green wave band, this also gives the response curve of the cell (*B* in Text-fig. 3) a general resemblance to that for the human eye, and thus has enabled considerable use to be made of this form of cell for photometric purposes.

It will be seen that, taking the sensitivity to yellow-green as the point of equality, the response to both the blue and the red is relatively too high. This sensitivity for blue makes the cell valuable for use as a photographic exposure meter, but the corresponding sensitivity for red makes it necessary to take into careful consideration both the type of plate and, in photo-micrographic work, the colour of the subject and filter when estimating the exposure. Filters are available whereby the response curve may be made to approach that of the eye more closely, but this is only accomplished by reducing the electrical output of the cell for a given illumination by some 60%.

Illuminants. Although many illustrations of old microscopes show some form of candle or simple 'torch' lamp as the source of light, there is little doubt that the earliest and most convenient source of illumination was ordinary daylight, and from the point of view of both colour and convenience, this has still much to recommend it. The chief objection to its use is its variability. The illumination due to the open lightly clouded sky may, on a bright day, be as much as 5000 f.c., on a dull day 1000 f.c., and on a very dull day 100 f.c. These values are all well above the minimum of 50 f.c. regarded as the least in which fine work can be carried out (Illuminating Engineering Soc. 1945), and would appear adequate for all purposes. The light, however, is derived from a very large area, of which only a small fraction can be introduced into the optical system of the microscope, and it is thus common experience that daylight is only satisfactory when employed for low magnifications and on bright days. The use of daylight has, however, the advantage of obviating the difficulties usually found when trying to obtain a uniform field with large objects, when artificial illumination is employed.

An exception is the use of direct sunlight, with a heliostat to make the beam static so far as the observer is concerned. In this case the effective area is very small and the intensity exceedingly high. In this country the number of hours during which a clear unclouded sun is available is, even in the summer months, very limited, but in the tropics its use, combined with deep monochromatic light filters, offers special advantages, since both the intensity and the colour temperature (some 6000° K.) are much higher than anything else available.

It will be apparent from the general considerations discussed earlier that the efficiency of artificial light sources is governed by three factors: their area, their brightness in candles per unit area, and their spectral distribution. Both the candle and the oil lamp have too low an intrinsic brightness to be suitable for any but simple observational work, though the extra 'air' contact round the extremities of the oil flame tend to raise the temperature and hence the brightness of these portions. The fact that the edge of the flame is a more satisfactory source of light than the flat, despite the greater area and therefore lumen output of the latter, is well known.

An improvement on the oil flame, and one sufficiently powerful to be suitable for high-power research where no electrical supply exists, is the acetylene burner. The origin of the light, incandescent carbon particles, is the same as for oil, but the higher temperature of the burning gas gives these a colour temperature of some 2360° K., about the same as that of a vacuum pattern electric lamp. The area of the flame on the flat side is considerable, some 25 sq.mm. for a 7-litre burner, and the constancy of the lumen output is such as to permit the use of a flame of this type as a photometric standard. As with the oil flame, the temperature at the edges is slightly greater than that at the centre, but even the latter is sufficient to permit the flat of the flame to be used for all but the highest magnification, or for wide-aperture dark-ground illumination.

The only remaining light sources of practical use other than the electrical are the lime and thorium disks heated in an oxy-hydrogen or similar flame. Thorium has the peculiarity of giving a somewhat selective radiation in the green wave band, and this tends to enhance its visual efficiency, but the apparatus required for the operation of the requisite burners is so cumbersome, and in some respects dangerous, that such illuminants have now been discarded in favour of the incandescent tungsten filament.

Electric (*tungsten filament*) *lamps*. These depend for their operation on the heating of a tungsten wire by the passage of an electric current. The melting-point of tungsten, 3655° K., is higher than that of any known substance (except carbon), and at this temperature the intrinsic brightness is 57·4 candles/sq.mm. Surface evaporation occurs, however, considerably below the melting-point, and the amount which can be tolerated decides the permissible working temperature. It is controlled by three factors: the presence of an inert gas surrounding the filament and thus, to some extent, inhibiting the evaporation by physical means, the massiveness of the filament employed, and the effective life expected from the lamp under operating conditions.

The use of an inert gas filling, though originally covered by patents, is now common for all reputable makes of lamp whether for domestic or projection purposes. The efficiency of the filling is materially increased if the filament is made as compact as possible. This has been put into effect, in the case of domestic lamps, by the 'coiled coil' construction in which the filament wire (necessarily exceedingly fine when it has to be connected to a circuit of 240 V. or more) is first made up in the form of a long thin spiral which is again wound into a close unit offering a minimum of external surface from which free evaporation can take place. The use of this type of lamp, either enclosed within a frosted bulb or mounted behind a ground-glass screen, gives an even and brilliant light which is unequalled for visual work. The use of lamps operating at a lower voltage than that usually available on a.c. house mains involves the interposition of a small transformer by which the 'input' voltage, usually 240, is stepped down to a lower value, either 6 or 12 V. and, when serious microscopical work is contemplated, whether amateur or professional, the provision of such a unit is highly recommended. The cost does not exceed that of a medium-power objective, and little engineering skill is required for its installation. Such a transformer should be of the 'separately wound' as distinct from the auto-connected pattern, so that there is no electrical connexion whatever between the low-voltage supply and the mains. The 'fool-proof' low-pressure supply thus provided is suitable for the operation of high- or low-intensity lamps of all sizes, warm stages, or any other small devices involving lighting or heating. The operation of such apparatus by direct connexion through a resistance to the mains is strongly deprecated. The method is wasteful in regard to power, and introduces fire and shock hazards which should be intolerable in both the average biological laboratory, and the living room of the amateur worker.

With a low-voltage supply it is possible to operate lamps, having relatively thick filaments, at the highest possible temperatures and thus attain, in ratings of 100 W. or less, the intrinsic brightness and spectral distribution which are otherwise only practicable with lamps of several thousand watts capacity.

As stated earlier, the working temperature of a filament is decided by the permissible evaporation, the effect of this is twofold. The loss of metal involved gradually reduces the thickness of the wire, thus weakening it, until, eventually, fracture occurs; this is obviously minimized if the initial diameter is as great as possible. A further and consequential effect is the blackening of the glass envelope by the condensation of the tungsten vapour on the inner walls. This is usually accelerated by the fact that the efficiency of any condenser system suitable for deep screen or projection work depends on the angular aperture or 'pick up' of the system. Like all high-aperture optical devices the working distance of such a system tends to be small, and hence it will not work in a satisfactory manner unless brought close to the lamp filament. This means that, however large the watt dissipation, the filament must be mounted in a bulb, usually cylindrical, which is very small compared with that of an ordinary lamp of the same capacity. A great deal of attention has been paid to the design of these bulbs, particularly to the flow of the convection currents in the gas filling, with a view to ensuring that the coolest part of the glass, on which the circulating vapour will be condensed, is at a point remote from that through which the filament is viewed. Even so, the rate of blackening is comparatively rapid and, when used at the rated voltage, an effective life of 100 hr. is the usual target.

For the amateur, however, this life may be greatly increased if one or two low-voltage taps in the transformer are available. Thus a transformer nominally rated at 6 V. may conveniently have additional terminals rated at 5, 4, and even 3 V. The life of a lamp when connected to the 5 V. tapping is increased two- to threefold and that on the 4 V. tapping is almost unlimited. It is but rarely that the maximum light obtainable on the 6 V. tap is required, most observational and preliminary photographic or projection work being amply covered by one of the lower ratings, and the convenience offered by this facility makes the small extra expense involved by its provision well worth while.

It may here be timely to point out that a frequent cause of lamp failure is the fracture of the filament near the point of support, as the result of frequent switching on and off. Owing to the temperature resistance characteristic of tungsten, or any other metal, the current rush when switching on the cold filament is very large. As a result, the centre of the filament, which depends almost entirely on radiation for the dissipation of the energy so released, attains its final temperature exceedingly quickly. The ends of the filament, which are attached to supports of large heat capacity, remain cold for a longer period. Thus the centre, expanding rapidly as it heats up, has to buckle against the relatively cold and brittle ends. This source of failure can be minimized by arranging the control circuit so that the lamp is never switched on immediately to full heat, use being made of the taps mentioned above. An even better practice is so to arrange the controls that the filament is rarely completely switched out, but is merely transferred from yellow to the working brilliance required; indeed, the life of the lamp when connected to the lowest tapping is so great, and its watt consumption so small, that it does not really matter if it is never switched off at all.

Where photographic work is carried out, and a knowledge of the lamp output becomes of importance as the basis for the estimation of exposure, the use of some form of indicating instrument to show the electrical input into the lamp is often worth while. Two methods of measurement are in general use: the provision of a voltmeter connected directly across the lamp terminals, and the measurement of the current flowing through the filament using an ammeter. Strictly speaking, the former method is the more correct, since the luminous output of a lamp at normal brilliancy varies with the fourth power of the voltage as compared with the seventh power of the current. Despite this, however, the use of an ammeter is actually more satisfactory, since, unless special provision is made for the voltmeter leads, the former measurement will include the voltage drop in the lamp connexions, and this, where currents of from 5 to 20 amp. are concerned, may be a serious proportion of the total. A current measurement is immune from this objection, and has the further advantage that in the case of a filament which has become thin due to long use, the light output from it will, for a given current, become somewhat larger, so offsetting to some extent the blackening of the bulb which will almost certainly have taken place.

Projection lamps. These vary in type from the simple motor-car headlight lamps rated at some 24 W. to the multiple filament patterns having ratings of from 50 to 500 W., or the ribbon filament type in which the spiral construction is avoided altogether.

The first mentioned is a lamp of considerable general usefulness and has the advantage that replacements are obtainable at almost any garage or motor dealer. The filament of a 12 V. lamp consists of a short spiral about 10 mm. long and $\frac{1}{2}$ mm. in diameter. The main objection to its use is the relatively large ratio between these two dimensions which makes it similar in appearance to the conventional 'edge' of a lamp flame in the field of a medium-power objective. The colour temperature is high (some 2700° K.), but the life tends to be short unless the lamp is somewhat under run for general use. They are available with either centre pin, small bayonet or Edison screw fixing and are convenient for mounting in small adjustable lanterns of the 'projector' pattern in which the bulb is viewed 'end on' with a fitting for either a ground-glass screen or a condensing lens in the front.

An improvement on the foregoing is a small 6 V. 8 amp. projection lamp, shown in Pl. 2, fig. 1, in which the filament is concentrated into a spiral about 2 mm. wide and 3 mm. long. The extra width is of great value where the full aperture of a high-power system has to be adequately filled, and the length is sufficient to enable advantage to be taken of the doubling effect of a spherical reflector whereby a source of light apparently 3 mm. square may be obtained. The effect is shown in Pl. 1, fig. 1.

A further development of this class of lamp (Manders, 1946; Shillaber, 1944) is that in which the unit consists of from two to eight filaments, each dissipating up to 100 W. The simplest arrangement comprises two to four spirals mounted in one plane with a spacing between them equal to the filament width (Pl. 2, fig. 3). A reflector can then be employed to fill in the gaps so as to make the incandescent surface appear continuous; the result is shown in Pl. 1, fig. 2. In the more elaborate constructions, eight filaments are mounted in two planes, one slightly behind the other, and 'staggered' so

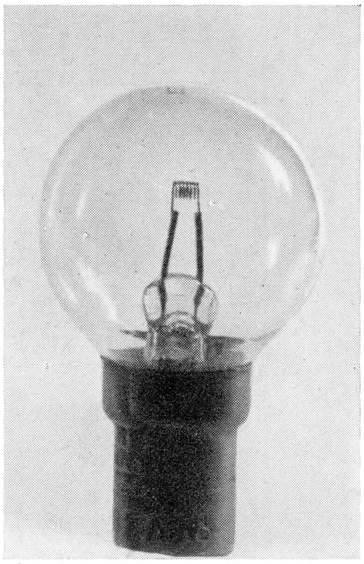


Fig. 1. 6 V. 8 amp. spiral-filament lamp. × ⅔.

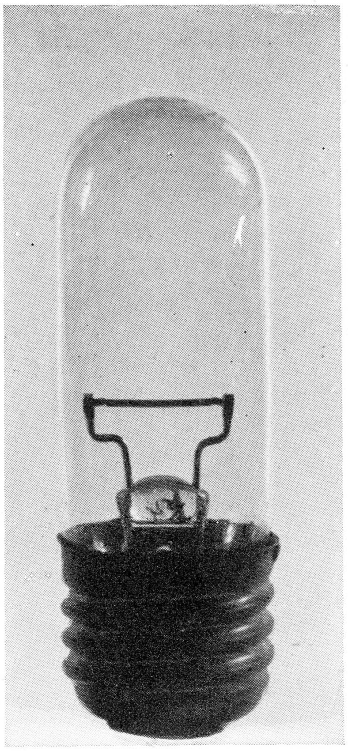


Fig. 2. 6 V. 9 amp. ribbon-filament lamp. × ⅔.

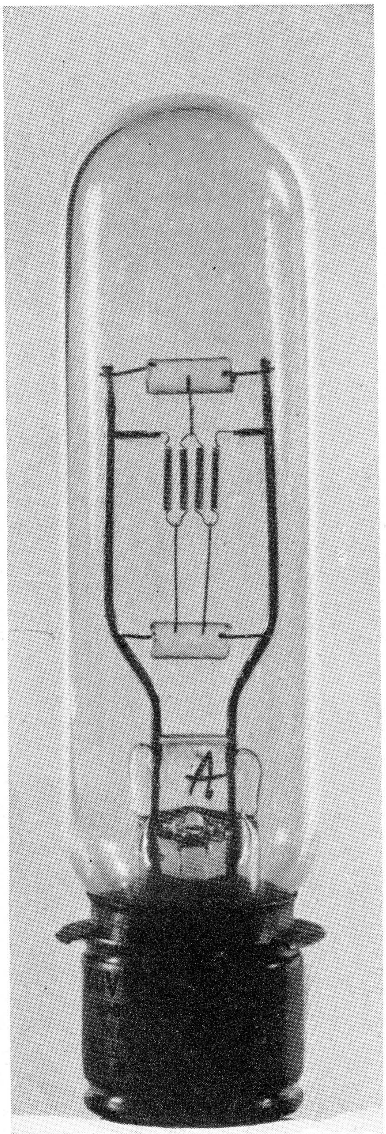


Fig. 3. 50 V. 5 amp. four-coil, grid-filament lamp. × ⅔.

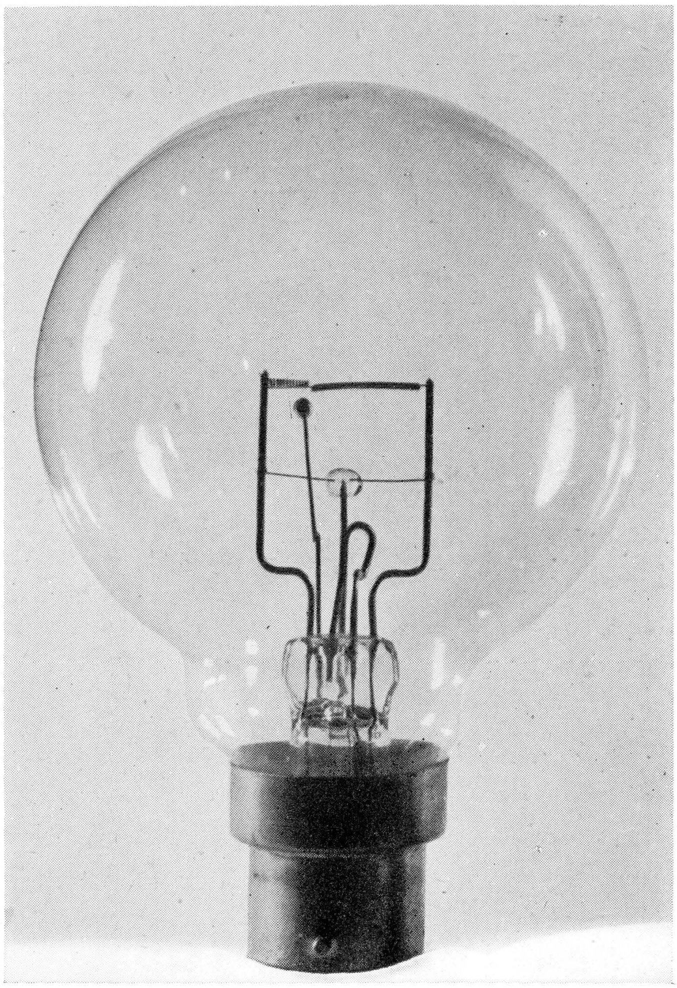


Fig. 4. 100 c.p. Pointolite lamp. × ⅔.

that the coils in the back plane appear in the gaps between those in front. By this means a smooth luminous area nearly 12 mm. square is obtained. Lamps of the foregoing types, when focused (by means of a large condenser) on to a piece of finely ground glass, provide an even and brilliant source of light, adjustable in dimensions, which is extensively used for low- and medium-power photo-micrography (Shillaber, 1944).

A lamp which has obtained considerable popularity as a high-power source for microscopical work is the low-voltage ribbon-filament pattern. This is made in two ratings, a 6 V. 9 amp. and a 6 V. 18 amp., the filament being available mounted, either horizontally or vertically, in a cylindrical bulb 32 mm. in diameter. The 9 amp. filament is about 1 mm. wide and 14 mm. long, and is mounted in a straight length between the supports (Pl. 2, fig. 2). The 18 amp. rating is 2 mm. wide and is mounted with the centre portion bent forward in front of the supports. It is thus nominally 10 mm. behind the front glass and 22 mm. from the back.

The robust nature of such filaments (especially the larger) permits their operation at the very highest temperatures, approaching 3000° K., thus rendering them particularly suitable for use with blue filters in high-power observational work, or for direct projection on to medium-size screens. As a dark-ground illuminant, particularly with wide aperture lenses and oil-immersion paraboloids, this lamp is probably the most efficient available to the amateur worker.

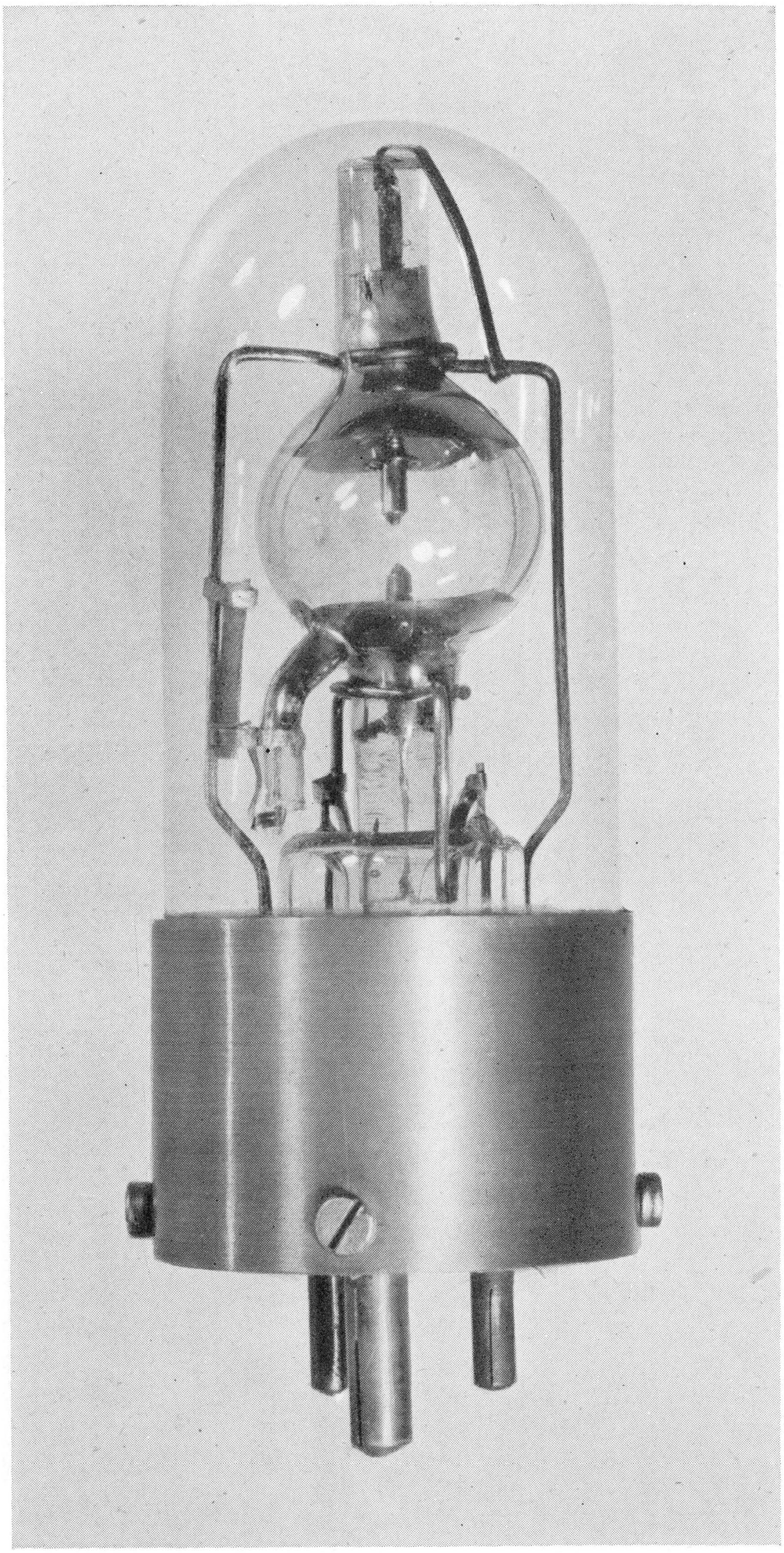
Arc lamps. These also are of several types, the carbon arc, the enclosed tungsten arc, and the various gas discharge lamps, all of which strictly speaking come in the 'arc' category.

It is not proposed to deal here with the carbon arc in detail, since its use by the amateur is comparatively rare and innumerable treatises on the subject have been written (Cricks, 1933; Hardy & Perrin, 1932; Shillaber, 1944) since Sir Humphry Davy demonstrated the first electric arc in 1800. It is sufficient to say that in the larger sizes no other artificial light source can compare with it for brilliancy, spectral range, or efficiency, and it is still the standard illuminant for all large projector systems and for purposes where its high radiation in the violet and ultra-violet can be employed to advantage. Such limitations as it has are due to the mechanical necessity of having the negative carbon mounted in front of, and hence partially obscuring, the positive crater (from which the light is derived) and the vapour and intense heat which is generated whilst the arc is in operation. All these features tend to preclude its use with condensing or projector systems of high aperture and correspondingly short working distance. The arc, in fact, is nothing like as efficient when employed as an illuminant on the microscopical bench with its small but highly corrected lens systems as it is when used, for example, for a searchlight, where the dimensions of the optical system are large and the working distance of little importance.

A form of enclosed arc which has much to recommend it as a high-power light source is the tungsten bead arc known as the Pointolite. The arrangement of this lamp can be seen in Pl. 2, fig. 4. The arc is formed between a thin tube of refractory material, seen on the right, which becomes conducting when heated, and a tungsten ball which under these conditions becomes white hot and acts as the main source of light. When cold the ball is situated underneath, but out of contact with, a short spiral of tungsten wire which constitutes the starting filament and can be heated by closing an auxiliary circuit. The ionization resulting from the presence of this hot spiral enables the arc to strike between it and the tungsten bead. The latter is mounted on a strip of compound metal which bends to the right as it warms up, so transferring the arc from the starting filament to the refractory cylinder (which encircles the leading-in wire of the filament), where it is maintained so long as the lamp is in use. On switching off, the stem gradually returns the bead to its starting position under the spiral heater in readiness for the next switching operation. As with all arcs, its negative resistance characteristic requires a ballast resistance connected in series with it to maintain stability. The heating of the starting filament may be carried out either by means of a special resistance and switch provided with the apparatus or by direct connexion to a 2 V. accumulator.

The 100 c.p. lamp described has a nominal consumption of 150 W. of which about 60 W. are consumed in heating the tungsten bead, and is intended for direct current operation. The a.c. pattern involves the provision of two beads and is not usually regarded as satisfactory for microscopical use, since only one of the two can be effectively used in the visual field. The relatively large bulb in which the arc is enclosed, whether a.c. or d.c., makes the use of high-aperture condenser systems difficult, and the spherical form of the luminous source renders useless the apparent doubling of its area by the superimposition of the reflected image from a mirror. Despite these disadvantages, however, the large dimensions of the source (a sphere nearly 3 mm. in diameter), together with the very high working temperature which the massiveness of the tungsten bead permits, makes this an extremely useful lamp for many purposes.

Dealing now with gas discharge tubes, the only ones which are of interest to the microscopist are those employing mercury vapour, the so-called 'mercury arcs', a form of lamp of special value to the research worker because of the intensity and variety of the spectral lines available. It consists of a sealed transparent tube, of hard glass for ordinary purposes, and of quartz when use is to be made of the ultra-violet radiation, so constructed that a pool of mercury is formed at each end when the tube is in its normal working position, approximately horizontal in most cases. Electrodes, sealed into each end of the lamp so as to be in contact with the pools of mercury, are connected, through a suitable series resistance, to the supply terminals. The lamp mounting is so arranged that the tube can be slightly tilted, thus causing a stream of mercury to traverse from one pool to the other. On restoring the tube to normal the stream is ruptured and an arc is formed which elongates until its poles reach the electrodes at each end. Owing to the low boiling-point of mercury and the high conductivity of the vapour, quite a small voltage suffices to maintain the arc indefinitely, the vapour being continuously condensed at the cool ends of the tube, so returning to the poles to be again vaporized by the heat of the arc. Alternating current lamps may be con-



250 W. compact-source, high-intensity, mercury-vapour lamp.
Approx. $\times 1\frac{1}{4}$.

structed with either a single tube, or two tubes connected in V form; only the former is suitable for optical work, and most high-pressure mercury arcs are now made in this way whether for a.c. or d.c. operation. A typical example is the M.E. 250 W. high-intensity lamp (Bourne, 1945) shown in Pl. 3. Designed for operation on a 240 V. supply, it has a vertical arc of 3·75 mm. length and 1·5 mm. width, the brightness at the centre being 180 candles/sq.mm. The mode of operation differs from that of low-pressure arcs in that the mercury contained in the bulb is completely volatized at the working temperature, the pressure inside the bulb then being approximately 20 atm. When the lamp is first switched on, the discharge strikes between two starting spirals of activated tungsten wire mounted on the shank of the main electrodes. After the lamp has warmed up the arc transfers to the shorter path between two tungsten blocks. Since the efficiency of this type of lamp depends on the temperature of the coolest part of the bulb, special care is taken to avoid cold spots where the mercury would condense. Some 10 min. is required after switching on before the light output builds up to its maximum. Arc stability on a.c. is ensured by the use of a series-connected choking coil. The radiation from a low-pressure lamp follows the general distribution of the mercury-arc spectrum, so that a large proportion is confined to the green and yellow regions with smaller amounts in the blue, violet and ultra-violet. A short list of the principal wave-lengths with the percentage of the total visible light appearing in each is given in Table 1, which refers to an open arc. The effect of enclosing the discharge inside the transparent envelope of the lamp is to inhibit to some degree the free characteristic radiations of the individual atoms, with the result that a faint continuous spectrum appears in the background. The intensity of this spectrum increases as the vapour pressure increases, until in the high-intensity lamp described the conditions inside the tube approximate to those of an incandescent solid body and the spectrum becomes continuous. The lines normal to the mercury are, however, strongly emphasized, so maintaining the yellow-green tint usual with all mercury discharge tubes.

Table 1. *Percentage of visible light in the prominent lines of the mercury-arc spectrum*

Wave-length (μ)	Colour	% light
0·4058	Deep violet	0·05
0·4358	Blue violet	0·48
0·5461	Green	45·4
0·5780	Yellow	46·3
0·6300, 0·6700	Red	0·5

A form of illuminant incorporating the features of both the tungsten and the mercury arcs has been devised in which the bulb containing the tungsten bead is filled with mercury vapour derived from a globule of mercury contained in the bulb. The addition of the mercury-vapour emission to the tungsten radiation raises the colour temperature to some 4000° K.

The illuminating system. Given a light source suitable for the work contemplated, it becomes of interest to consider how the microscope substage and its ancilliary apparatus must be arranged if maximum advantage is to be taken of the illumination available. To be efficient such apparatus must provide facilities for producing a critical image of the illuminant (source image) in the plane of the object and at the requisite N.A., this image being at the same time large enough to illuminate as much of the object as is to be observed, photographed, or projected at one setting. For the two latter purposes, moreover, both the brightness and the uniformity of the illuminated field also become points of major importance.

In considering the many arrangements possible for the substage apparatus and their suitability for various purposes, it will be necessary to refer to the appropriate optical diagrams, and to study some simple mathematical relationships concerning them. To unify, and thus render more easily comprehensible, the various factors involved, a short list defining the symbols used throughout the discussion is given in Table 2.

Table 2. *Symbols employed in the text and diagrams*

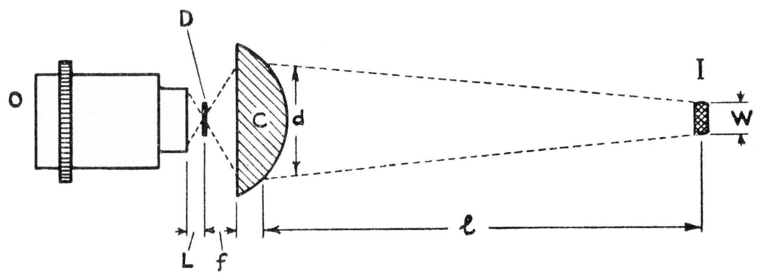
(All distances in mm.)

O	*Objective.*	*LC*	*Lamp condenser.*
F	Focus.	*Z*	Working focus.
A	Angular aperture.	*T*	Diameter of front lens, or diaphragm.
L	Working distance from object.	α	Angular aperture.
D	Diameter of objective field.		
P	Diameter of visual or projected field.	*R*	Reflector (radius of curvature).
		I	Light source.
C	*Condenser* (Substage).	*W*	Width of light source.
f	Focus	*s*	Area of light source.
a	Angular aperture.	*B*	Brightness of light source.
l	Working distance from lamp, or lamp condenser.		
d	Diameter of back lens.		
M	Magnification.		
S	Area of projected field.		
r	Diameter of Ramsden circle.		
t	Optical tube length.		

Low-power illumination. To many the satisfactory illumination of low-power transparent objects presents considerable difficulty. Part of this is due to a belief, not justified by any theoretical considerations, that the use of a ground-glass screen or bulb as a means of smoothing and spreading the light derived from an ordinary electric lamp is liable to spoil the performance of the objective in use.

That this does, to some extent, occur in practice is due to the fact that, when a frosted glass is employed, the effective light source, although of high intensity only in the centre, is spread over a far larger field than the objective can utilize. The resulting surplus of light causes stray reflexions to appear on the sides of the objective mount and the microscope tube. It is thus desirable that a diaphragm be mounted in front of the lamp limiting the field to exactly that covered by the objective. The diaphragm may take the form of a series of thin metal plates each pierced with a hole of appropriate size, or an iris capable of being opened out to a diameter of some 40 mm.

It can be shown (Walsh, 1926) that when using a diffusing screen with a diaphragm mounted reasonably close to its surface,* the opening may be treated as a luminous source, and thus the conditions as regards critical illumination are complied with if the edges of the diaphragm are in focus in the visual field simultaneously with the object. Taking a 50 mm. objective as an example, the field *D* covered when using a medium-power eyepiece is about 6 mm., so that the focus (f) of a substage condenser which will just cause this to be filled using a light source 40 mm. in diameter at a distance of 200 mm. (8 in.) is given by $f = \frac{6 \times 200}{40} = 30$ mm. This is much greater than the focus of the average condenser, whether with or without the top lens. It is thus apparent that, where low-power work is of special interest, a condenser having a focus of between 25 and 50 mm. is extremely valuable. To make it suitable for objectives of from 25 mm. upwards it should have an N.A. of about 0·2, which implies a back diameter, in the case of a lens of 30 mm. focus discussed above, of 12 mm. A $\times$ 8 aplanatic or 'platyscopic' magnifier complies



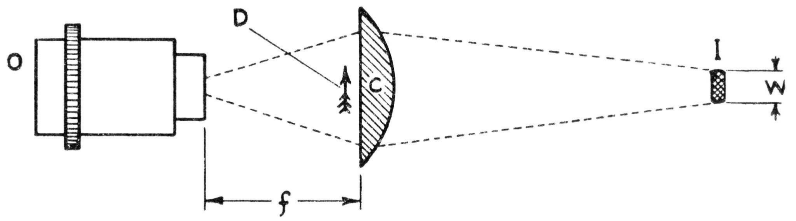
Text-fig. 5. Arrangement of substage condenser and illuminant for general purposes.

very closely with this specification and, suitably mounted, forms an extremely useful substage accessory. The foregoing assumes that the condenser can be used in the ordinary way (Text-fig. 5), that is, mounted sufficiently far below the stage to permit the lamp diaphragm to be focused on the slide.

An alternative method of using such a condenser, and one which is preferred by many workers, is to mount the lens practically flush with the stage so that the image of the light source is focused on the front lens of the objective. Although by this method no difficulty whatever is experienced in obtaining a large well-lit field, the character of the image so obtained often leaves much to be desired and, on removing the eyepiece and inspecting the back of the objective, it will usually be found that a comparatively small image of the light source appears in the centre of the lens, the rest being as inoperative as if it were masked by a small-aperture diaphragm. The condition is shown in Text-fig. 6, from which it is evident that the boundary of the relatively small source image is acting as the diaphragm in question, and that full use of the objective can only be made if the image of the source, when thrown on to the front lens, is large enough to cover it completely.

* The ground glass should be mounted just sufficiently far behind the diaphragm to put the frosting out of focus when the edge of the latter is sharp in the field.

In the case of the 50 mm. objective discussed previously, the working distance is about 30 mm., and the diameter of the front lens 8 mm. The difficulty in filling a front of this size with a condenser of 30 mm. focus is obviously even greater than in filling a field of only 6 mm., when the condenser is used in the normal way, so that, unless facilities exist for fitting condenser lenses of exceptionally long focus (Nelson, 1913), and so capable of producing source images of large dimensions, this method is to be deprecated as unlikely to enable an average objective to perform to the best advantage. The use of a lamp condenser in combination with the substage illuminator is, for a similar reason, prone to cause the same defect. This will be dealt with under the general discussion on such condensers.



Text-fig. 6. Substage condenser arranged to give large illuminated field.

Medium- and high-power illumination. The illumination of objects to be examined under medium- and even under high-power objectives, is probably the easiest problem presented to the microscopist once the use and limitations of the substage condenser are fully understood (Beck, 1938). The focal length of a well-corrected condenser can be deduced from a knowledge of the aperture and the diameter of the back lens. The latter is usually decided by the type of mounting employed, either the objective fitting, when the maximum possible diameter is 15 mm., or the Abbe fitting, when the diameter may be as much as 25 mm. Assuming in each case an N.A. of 1·3, the foci are ($f=d/2a$) 5·77 and 9·6 mm. respectively. The advantage of the larger fitting in deciding the maximum slip thickness through which the condenser will work is at once obvious.

Taking as an example the illumination of an object under a 4 mm. objective the field of view of which is 0·45 mm., the diameter of the lamp diaphragm required to produce a disk of this size with a lamp distance of 200 mm. is in the case of the large fitting 0·9 cm., and in that of the small one 1·5 cm. ($T=D\times 200/f$). These dimensions are well within the area of maximum brightness of a 60 W. frosted bulb lamp of the 'coiled coil' type; indeed, unless a green or other screen is interposed, the brilliance of the field may be too high for comfortable vision.

A 2 mm. objective, whilst requiring an illuminating disk of only half the preceding, will not show so brilliant a field, since the aperture of even the highest grade 2 mm. is rarely twice that of a good 4 mm., and, if the condenser employed is a dry one limiting the N.A. to less than 1·0, the reduction will be considerable, since the brightness is dependent directly on the ratio of effective aperture to magnification. For a given combination of these two factors, the only effect of the introduction of a lamp condenser is to increase the apparent size of the illuminant; it cannot increase, and will almost certainly decrease, the field brightness.

Contrast. A factor which is frequently of even more importance than the brilliance of the visual field against which a microscopic object is seen is the degree of contrast attained. Where the objective employed is optically defective the aberrations present will make some degree of loss of contrast inevitable, but, in any case, flooding of the optical system with light of a greater angle than it is capable of utilizing will result in reduction of contrast and hence loss of resolution for fine detail. As with the lower powers, no matter what type of illuminant is used, a 'lamp diaphragm' is essential as a means of reducing the source image to a circle approximating to the dimensions of the visual field. A practical difficulty which arises when this technique is put into operation is that resulting from the fact that a high-grade condenser will only give its best performance with a slip of given thickness, and thus only under this one condition is the back lens of a high-aperture objective exactly filled with light when the lamp diaphragm is set small enough to appear in the field as a sharply defined circle. For all other thicknesses (assuming that the slip and condenser top are in oil contact) the lamp distance will have to be modified, the lamp being set slightly nearer or farther from the normal position, the diaphragm being, at the same time, so adjusted that the back lens is completely illuminated without at the same time allowing any stray light to be 'spilt' into the microscope tube. The precise extent of this adjustment will depend on the performance of the condenser when used on slips thicker or thinner than those for which it is designed, and is very much facilitated by the use of objective mounts in which the brass rims behind each of the components are cut so away that light entering the lens at an angle slightly greater than the working angle is not reflected back into the field. No amount of 'dead black' is as efficient in this respect as the avoidance of any suspicion of a close-fitting 'tunnel' behind the lens, and some mounts leave a good deal to be desired in this matter.

The use of oil-immersion condensers would be greatly simplified, both in regard to focusing and the avoidance of the difficulties resulting from difference of slip thickness, if the condensers were constructed in two parts: a front lens designed to be carried flush with the stage, and oiled to the slide when so desired, and a back unit (comprising the remainder of the lenses) which should be carried in a focusing mount attached to the front fitting. A well-known dark-ground illuminator designed by Conrad Beck already incorporates this construction, which would, in the case of an oil-immersion condenser, not only eliminate the difficulty of maintaining oil contact under varying conditions of focus, but would minimize the first-order errors resulting from deviations in slip thickness from the calculated value.

Field brightness. In the foregoing discussion the use of various types of lamp has been considered. The apparent brightness of the visual field will depend, however, not only on that of the illuminant, but on the effective aperture of the optical system and the number of glass surfaces involved.

Dealing first only with the effect of aperture, the brightness of the field of any optical device will be the same as that of the illuminant, provided that the pupil opening of the eye is the 'aperture stop' of the system, or that the Ramsden circle at the eyepoint of the ocular is as large as, or larger than, the diameter of the pupil, at the same level of illumination. The necessary condition is nearly always fulfilled in the Galilean telescope (opera glass) and sometimes in the ordinary field telescope or prismatic binocular; it is but rarely true for the microscope.

For all cases where the above is not complied with, the brightness will be reduced by the square of the ratio between the Ramsden circle and pupil diameters. The former may vary from $\frac{1}{3}$ to 3 mm., and can usually be measured directly on a suitable scale, or can be calculated if the magnification and N.A. are known $\left(r=\frac{2\times A\times t}{M}\right)$. The average diameter of the pupil under conditions of fair illumination may be taken as about 3 mm., and the smallest practicable Ramsden circle as 0·3 mm. (1400 diam. at N.A. 1·4 with $t=160$ mm.), in which case the ratio of visual field to illuminant brightness is $(0{\cdot}3/3{\cdot}0)^2 = 1/100$th, i.e. 1%.

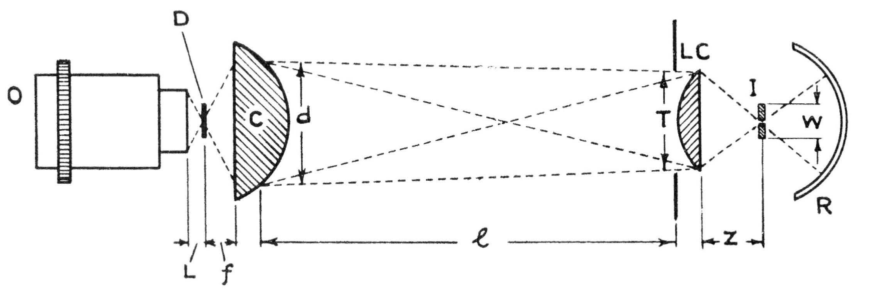
The maximum surface brightness of a frosted 60 W. 'coiled coil' lamp is about 0·1 candle/sq.mm., twice that of a piece of white paper viewed in direct sunlight; it is hence amply bright enough for use when the Ramsden circle is reasonably large, and in some cases a reducing filter, either neutral or coloured, may be essential, but when high magnifications involving small Ramsden circles are concerned the use of any but lightly coloured filters will tend to make the field brightness unduly low.

This condition is further accentuated by the losses resulting from the reflexion occurring at the various glass surfaces interposed between the eye and the illuminant. The reflexion factor for rays striking normally on to a glass surface is about 4% for every surface involved, and each glass unit, apart from oiled or cemented contacts, comprises two surfaces. The simplest low-power system will probably have two lenses in the eyepiece, objective, and condenser, a total of 12 surfaces. The total loss due to reflexion will then amount to $[1-0{\cdot}96^{12}]=38\%$, which is very appreciable. A high-power system may well contain as many as 20 surfaces, so the loss due to these will be $[1-0{\cdot}96^{20}]=56\%$ or more than half the light; this can be serious if the nature of the specimen, filter, etc., are such as of themselves to reduce the brightness of the field to an inconveniently low value.

High-intensity illumination. The Köhler system. It will be evident that the brightness needed for projection, in any form, is such that only the intrinsic brightness of the source itself (without the interposition of any diffusing screen) is great enough, and consideration of the factors controlling the production of a projected image of good intensity will also cover those involved in photography, or any problem where the greatest possible intensity of illumination is essential.

The widely held notion that a 'point source' of infinite intensity is the ideal for optical purposes is very far from being correct, indeed, the main objection to all the high-intensity sources available is that, with the exception of the carbon arc and the 'grid' pattern projection lamp, the dimensions of the light-emitting device are comparatively small.

In the 18 amp. ribbon-filament lamp, which may be taken as a typical example, the filament is only 2 mm. wide, so that the width of the source image in the field of an 'objective thread' condenser of 5·77 mm. focus, at a lamp distance of 200 mm., is 0·058 mm., about one-third the field diameter of an average 2 mm. objective. The use of the Abbe size fitting would increase this to 0·096 mm., and though this is still too small to provide even illumination over the whole of the field, the substantial improvement emphasizes the value of the larger condenser. Three methods of increasing the apparent size of the illuminating source are available, the simplest and most obvious being to reduce the distance (l) between the lamp and the substage. Difficulties arise, however, if this is made unduly small, since not only will the separation between condenser and slip become too great to ensure reliable oil contact, but the corrections of the condenser will be so disturbed as to make satisfactory adjustment impossible. A second method involves the use of a moderately powerful positive lens mounted close to the lamp filament and so acting as a simple magnifier. Since the effect of this lens is to reduce the divergency of the rays from the lamp, the setting of the condenser will be closer to the slip



Text-fig. 7. Köhler illumination with high-aperture lamp condenser and spherical reflector.

than usual, and difficulties due to slip thickness may arise; an appreciable amount of enlargement may, however, often be obtained in this way. The third method is by the use of a 'lamp condenser', with the light source and the back focal plane of the substage condenser at its conjugate foci. Arranged in this way, the latter 'sees' the lamp condenser as an evenly illuminated disk having the diameter of the condenser lens and the brightness of the illuminant (so-called Maxwellian view). The arrangement is shown in Text-fig. 7, where C is the back lens of the substage condenser having a diameter d, LC the lamp condenser of diameter T, and I the light source of width W. The distance l between C and LC is assumed to be 200 mm., and Z (that between LC and I) such as will cause a sharp image of I to be focused on C. (It is assumed here that the back lens of the condenser is also, sufficiently nearly, its back focal plane.) An image of the lamp condenser then appears as a brightly illuminated disk of diameter D, in the object plane between the objective and the substage condenser.

The scheme described is that known as Köhler illumination, and is the general arrangement aimed at whenever a lamp condenser is employed. On inspection of the diagram, however, it becomes apparent that certain conditions must be complied with if it is to be applied to a high-aperture optical system without loss of possible resolution. Of these the first and most important is that the diameter of the source image, when focused on the substage condenser, must be large enough to cover completely the working diameter of the back lens, usually the whole of it when a 1·3 N.A. objective is employed. If this condition is not fulfilled, a 'diaphragm' will be formed which will shut off the outer zones of the condenser (just as the outer zone of the objective is cut out in Text-fig. 6), and its effective aperture reduced accordingly. Similarly, if the image of the illuminant, as the result of chromatic errors, has a coloured fringe round the edge, this will be equivalent to surrounding the condenser with a coloured diaphragm, with unpredictable effects on the nature of the image appearing in the eyepiece field.

The magnification required of the lamp condenser to produce a source image of 15 mm. (in the case of the small, 'objective thread', condenser) from a filament 2 mm. wide is $7\frac{1}{2}$ diameters, which involves a lamp/lamp condenser distance (Z) of 26·7 mm. The diameter T of a lamp condenser large enough to fill a 2 mm. objective field of 0·2 mm. diameter under these conditions is given by

$$T=\frac{D\times 1}{f}=\frac{0{\cdot}2\times 200}{5{\cdot}77}=6{\cdot}92 \text{ mm.},$$

and the numerical aperture will therefore be

$$\frac{\frac{1}{2}T}{Z}=\frac{6{\cdot}92}{2\times 26{\cdot}7}=0{\cdot}13.$$

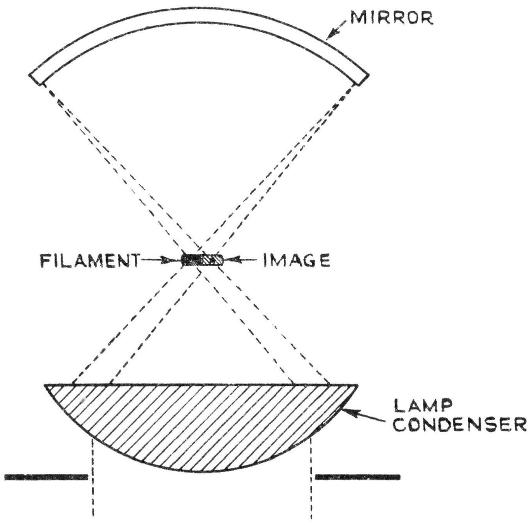
This value could also have been obtained more directly by applying the rule that, if the conditions regarding the Köhler illuminating system defined earlier are fully complied with, the product of lamp-condenser N.A. and illuminant diameter must equal the product of objective N.A. and field diameter

$$\alpha\times W=A\times D.$$

Thus, to utilize both the whole of the 0·2 mm. field and the 1·3 N.A. of a 2 mm. objective, using a high-intensity illuminant 2 mm. wide, we require an achromatic and aplanatic lamp condenser of 0·13 N.A., one, for example, having a clear diameter of 7 mm. and a focal length of 27 mm. with a working distance of some 20 mm. if it is to clear the surface of the average bulb in which the filament is mounted. The case of the 6 mm. objective of 0·95 N.A. and 0·73 mm. field can be shown similarly to require a lamp condenser of 0·35 N.A. and the same working distance.

Such performances are comparable with those of objective lenses of similar power and are altogether superior to anything obtainable with an ordinary 'bull's eye'. This explains the usual failure of attempts to use the latter when anything approaching critical illumination with oil-immersion or high-aperture lenses is required. Although suitable lamp condensers are in fact available, the problem is greatly simplified if the dimensions of the light source can be enlarged. A ready means of doubling the effective dimensions of many sources, and thus halving the N.A. called for, is to fit a spherical mirror behind the filament so that a real image of the remote side of the latter is focused immediately beside it and in the same plane.

The application of such a mirror is sketched in Text-fig. 8, where the filament is shown in the plane of, and slightly displaced from, the centre of curvature of the mirror, the displacement being one-half the filament width. A reflected image of the latter appears in the same plane and a similar distance to the right; thus image and filament exactly touch in the centre and the combination can be 'picked up' by the lamp condenser and focused on to the back of the substage; the effect is shown in Pl. 1, fig. 1. The main disadvantage of this device lies in the fact that the rays from the back of the filament, forming the reflected image, not only suffer some loss of intensity at the mirror, but traverse the lamp bulb three times; blackening of the latter therefore reduces their brightness to a much greater extent than is the case with the direct rays which only traverse the bulb once. For this reason, although in Text-fig. 7 the use of a spherical mirror is indicated, the calculations are based on the actual filament width only.



Text-fig. 8. Details of arrangement employing spherical mirror.

An outstanding advantage of the Köhler system lies in the fact that, whatever the shape or size of the illuminant, the visual field is always an evenly illuminated disk, the diameter of which can be controlled by the lamp-condenser diaphragm without in any way affecting the N.A. of the substage system, this being determined only by its own diaphragm. The arrangement is thus particularly suitable for projection and photomicrography where, as mentioned earlier, the levels of illumination required are much higher than those needed for direct observation. It also lends itself readily to the estimation of the total quantity of light available when using any given objective, even if the power considered is not such as would normally require the Köhler system as a means of obtaining satisfactory field illumination.

Referring again to Text-fig. 7, it will be evident that the amount of light contained within the cone focused on the object by C is exactly the same (neglecting losses by reflexion) as that collected by LC, and that this is determined by the brightness and useful area S of the illuminant and by the angular aperture of the lamp condenser. The former can be readily ascertained from published information giving the main characteristics of typical light sources (see, for example, Table 3), but in regard to the latter, reference to Text-fig. 1 will show that, for a flat diffuse radiating surface, the light reaching

Table 3. *Brightness of common light sources*

Source	Temp. °K.	Colour temp. °K.	Brightness per sq.mm. Lumens*	Brightness per sq.mm. Candles
Paraffin flame	1500	2050	0·04	0·013
Acetylene	1730	2360	0·3	0·11
Tungsten (Worthing & Forsythe, 1925)	2700	2770	16·6	4·98
Tungsten	2800	2878	23	6·94
,,	2900	2986	31·4	9·49
,,	3000	3094	41·7	12·57
,,	3100	3202	55	16·47
,,	3200	3311	70·3	21·1
,,	3300	3422	89·4	26·85
,,	3400	3533	112·7	33·7
,,	3500	3646	138	42·2
Mercury arc:				
Low pressure	—	—	0·072	0·023
Medium pressure	—	—	12·5	4·0
High pressure	—	—	500	180
Carbon arc:				
Ordinary	—	3700	470	150
High intensity	—	—	2800	900
White paper in diffuse daylight	—	—	0·001–0·01	0·0003–0·003
White paper in sunlight	—	—	0·01 –0·1	0·003 –0·05
60 W. frosted bulb	—	—	0·3	0·1

* Although, strictly speaking, 'lumens per sq.mm.' is only applicable to a perfectly diffusing body, the figures in this column give a useful idea of the luminous flux available in practice.

the outer zones of a condenser lens, one subtending, for instance, 30° either side of the normal to the lamp, tends to be less intense than that reaching the centre, and allowance must be made for this when estimating the total light collected by a lens of given aperture. Text-fig. 9 shows the relative amounts of light which can be collected by condensers with angular apertures up to 70°, the curve being calculated with reference to the light emitted on one side of the filament only.

An example will demonstrate the method of calculation and the use of the table and curve:

Objective. 50 mm. N.A. 0·15. Field diameter 7 mm. (using × 5 eyepiece).
Illuminant. 2 mm. circle in centre of tungsten strip run at 3300° K.

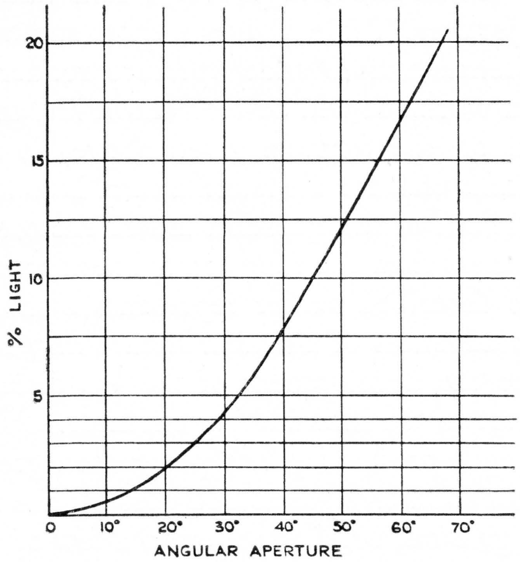
Numerical aperture α of lamp condenser $\dfrac{A \times D}{W} = \dfrac{0{\cdot}15 \times 7}{2} = 0{\cdot}53.$

Angular aperture of lamp condenser N.A. $0{\cdot}53 = 64°$.
Emission from tungsten at 3300° K. = 89·4 lumens per sq.mm. (Table 3).

Emission from 2 mm. circle $= \dfrac{89{\cdot}4 \times \pi \times 2^2}{4} = 280$ lumens.

Proportion collected by lens of 64° angle = 18% (curve, Text-fig. 9).
Total light in optical system = 18% of 280 = 51 lumens.

Of this about 40% must probably be considered as lost by reflexion from the various lens surfaces,* so that the amount available for illuminating the field would be 30 lumens.



% OF TOTAL RADIATION FROM FLAT DISC COLLECTED BY LENS OF GIVEN APERTURE.

Text-fig. 9.

The dimensions of the screen which could be illuminated by this light flux will depend on the brightness required; the lowest value which can be viewed in comfort is probably about 0·3 candle/sq.ft., which involves an illumination of approx. 1 lumen for each square foot of screen area, and on this basis 30 lumens would provide adequate brightness on a screen 6 ft. in diameter. If, on the

Table 4. *Data for objectives of high* N.A. *suitable for projection*

Focus (mm.)	N.A.	Air angle (degrees)	Field in mm.	Projection index	Magnification on 8 ft. screen (diam.)
50	0·17	19	7·0	1·42	340
25	0·3	35	3·0	0·81	800
16	0·45	54	2·15	0·94	1100
12	0·65	81	1·38	0·81	1750
6	0·95	144	0·73	0·49	3300
4	0·95	144	0·46	0·19	5200
2	1·37	—	0·21	0·085	11500

Columns 5 and 6 assume that the eyepiece and 'throw' are such as will cause the field diameter (col. 4) to fill the screen exactly.

other hand, the brightness were reduced to 0·1 candle (that of most epidiascopes) the disk diameter could be increased to 10 ft., but much would then depend on the transparency of the specimens it was proposed to show. Raising the temperature of the tungsten to 3500° K. would increase the available illumination by nearly 50%, but the life of the projector lamp would be seriously reduced, probably to some 10 hr., by this expedient.

* Cf. p. 20.

The ability of a microscope objective to perform well as a projector lens is limited by the fact that objectives of high N.A. and magnifying power have very small fields, and the usefulness of any given lens is proportional to the square of the product of N.A. and field $(A \times D)^2$. This value falls off rapidly for high-performance objectives. Table 4 gives a short summary* of the relevant data for a series of lenses whose wide aperture renders them particularly suitable for projection work. It will be seen, however, that though the 'projection index' (based on the formula given above) is reasonably high for powers up to the 12 mm., that for the 4 and 2 mm. is so low as to make large-scale projection almost out of the question unless enclosed illuminants of far higher intrinsic brightness than the tungsten filament are available. The high-pressure mercury arc described earlier represents a substantial step in this direction, and further advances of a similar nature may be looked forward to with confidence, since the development of the gas discharge tube is now a matter of major interest to the illuminating engineer.

The whole art of light production has progressed greatly during the last fifty years, and has now so many aspects and possibilities that it has only been practicable for me to give but brief attention to a few of them in this survey. A short list of references is, however, appended, and this will, I hope, be of assistance to those desiring to study the subject in greater detail.

In concluding, I would like to express my indebtedness to Dr J. W. T. Walsh, of the National Physical Laboratory, for his kindness in reading through the proofs, and my thanks to Messrs the British Thomson-Houston Co. for the loan of the lamps shown in Pl. 2, figs. 1 and 2, and to their research department for the photograph reproduced in Pl. 3; also to Messrs the Edison Swan Electric Co. for technical information concerning their Pointolite lamp.

* The N.A., etc., are those for the Holoscopic series by Messrs W. Watson and Sons, Ltd.

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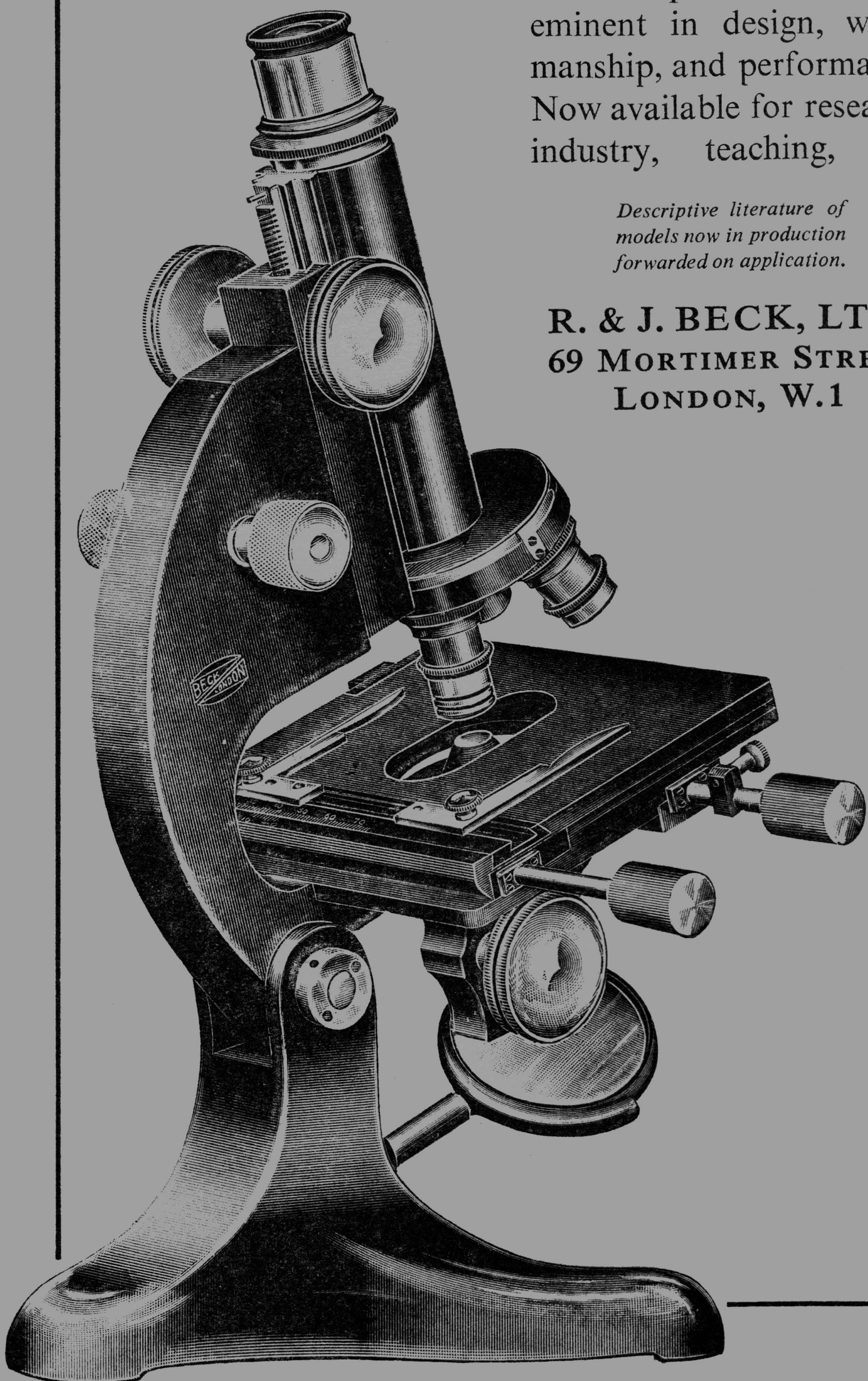

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