Concentrated-Arc Lamps

The concentrated-arc lamp [23] is a new type of radiation source developed by the Western Union Telegraph Company. In May 1943, when its development was still in the laboratory stage, Contract OEMsr–984 was negotiated with the Western Union Company for the further development and study of this type of lamp as an electrically modulated source of near infrared radiation for communication purposes, primarily in connection with Project Control NS–159.

During the contract period from May 1943 to August 1945 the basic theory of operation of the lamp was investigated, the design and methods of fabrication were improved, the number of useful sizes, types of construction, and operating circuits was increased, the desired radiation characteristics were enhanced, and the average operating life of the lamps was lengthened. Nearly 6,000 lamps of various types were supplied to the Armed Services and to other government agencies and contractors for wartime use. The principal application of the lamps by NDRC Section 16.4 was their use in the early models of an infrared voice and code communication system [24] (Navy type E) by Northwestern University Contract OEMsr–990. The active cooperation of those working under this contract in measuring the radiation characteristics and investigating the basic mode of operation of the lamps was of material assistance in motivating and accelerating the successful improvements in design and construction of the lamps under the Western Union contract. Concentrated-arc lamps were also used by the Army in a narrow-beam, battery-operated aural signal unit for code and voice communication; by the Navy in a hand-held equipment of medium beam width for voice communication between airplanes, or between airplanes and ground stations; by various Armed Service agencies and contractors in boresighting equipment; and by the Office of Strategic Services in equipment for projecting aerial photographs from the same angle at which the exposures were made.

The Western Union Telegraph Company has also developed manufacturing facilities for lamps of several standard types which are now commercially available.[25] These standard types are rated at 2, 10, 25, and 100 watts. Except where otherwise indicated, the material which follows refers exclusively to lamps of these standard types.

Lamp Design and Construction

The name of the concentrated-arc lamp is derived from the small cathode spot of high brilliance from which, in the standard types of this lamp, the major portion of the radiation is emitted. These lamps consist basically of two permanent electrodes sealed into a glass bulb filled with argon gas at a pressure of one atmosphere. The unique radiation characteristics are largely due to a specially prepared zirconium oxide cathode. The major portion of the emitted radiation is a continuum having a spectral distribution similar to that of a black body near 2800 K. Superimposed on the continuum are intense spectral lines which originate from a highly excited layer of zirconium vapor and argon gas very near the cathode surface. The arc current tends to return the zirconium ions to the cathode, thus renewing its surface and resulting in a lamp life which may exceed 1,000 hours when the lamp is not modulated. A much shorter life results when the lamp is operated at a high per cent current modulation. The anode is designed for efficient cooling in order to minimize the vaporization of material from it which might contaminate the cathode.

By proper cathode design the diameter of the radiation source may be made so small as to approximate a point source. The concentrated-arc lamps may possess modulation ratios (Section 1.1.4) and brightness values comparable with those of the carbon-arc lamp while having the added advantages of nonvaporizing electrodes and a fixed position for the cathode spot.

Figure 8 shows a variety of experimental designs which have been successfully constructed, including several lamps in sizes larger than standard. Certain characteristics of the four standard lamp types are summarized in Table 5. In the standard type, the 100-watt lamp is available only in a side projection model similar to item 7 of Figure 8. The other sizes are available either in a side-projection or an end-projection model. In all of the standard types the anode consists of a metal plate with a hole through which the radiation from the cathode emerges.

Table 5. Operating data on standard types of concentrated-arc lamps.

Nominal lamp rating (watts)	Volts	Amp	Light source diameter (mm)	Brightness candles/mm² max	Brightness candles/mm² avg	Candle-power	Candle-power per watt	Life in hours	Bulb type	Base type	Max temp (degrees F) bulb	Max temp (degrees F) base
2	37	0.055	0.085	96	56	0.32	0.155	175	T5	Min, 3 pin	140	100
10	21	0.5	0.4	55	22	2.7	0.26	900	T9	Small, 8 pin	225	130
25	20	1.25	0.73	40	21	8.5	0.35	...	T9	Small, 4 pin	355	145
100	15.4	6.25	1.58	52	39	77	0.80	700	ST19	Medium, 4 pin	470	160

Cathode Construction. The cathode consists of a tantalum tube packed with finely ground fused zirconium oxide and drawn to a cored wire of the desired size. A short length of this wire is mounted in the lamp so that one end, with its exposed oxide, is $\frac{1}{32}$ to $\frac{1}{4}$ inch from the anode. When the arc is

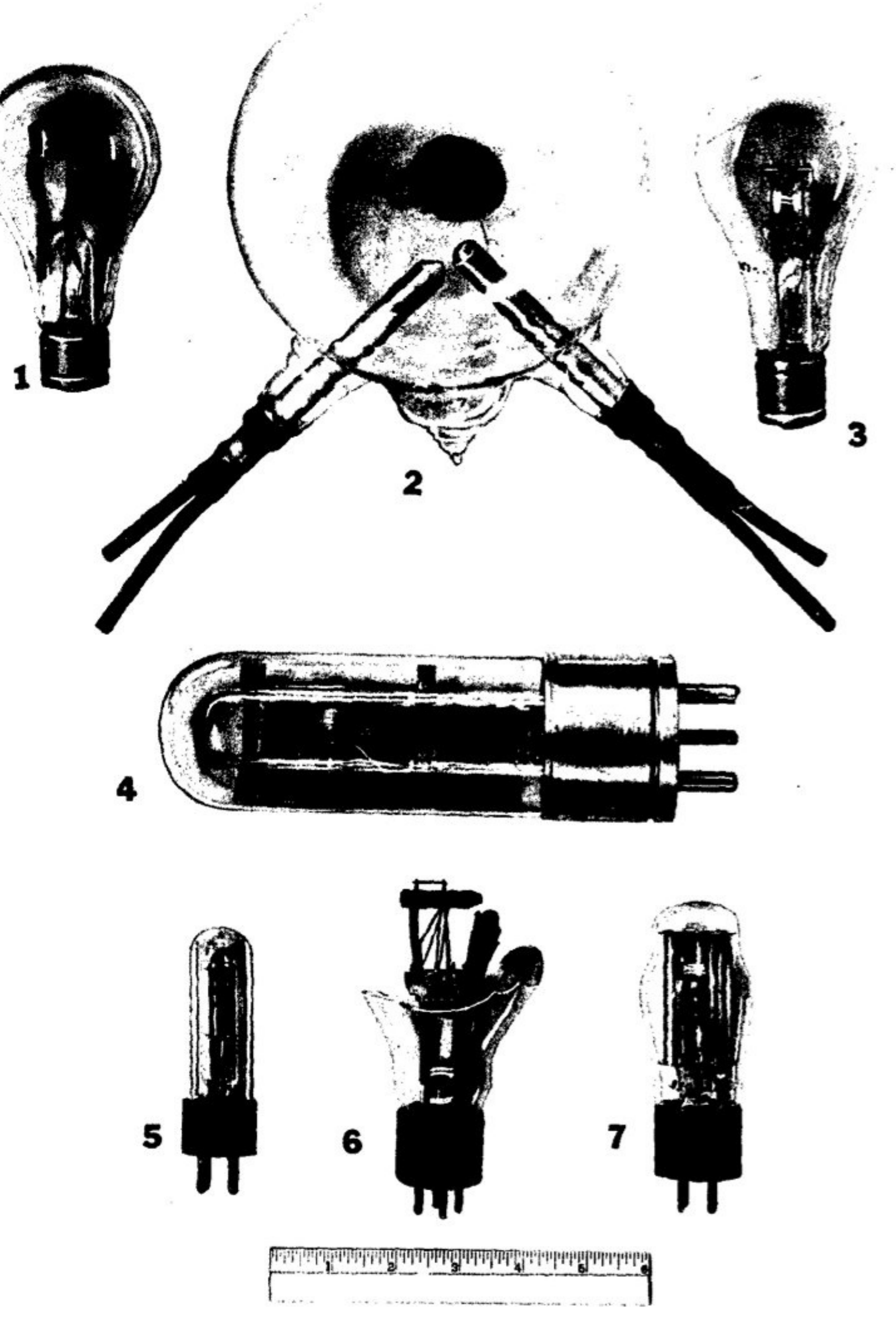

FIGURE 8. Experimental types of concentrated-arc lamps.

first struck, the oxide fuses to a hemispherical bead in the end of the wire. Tantalum is used as the sheath because of its high melting point and the ease with which it can be worked and drawn. For each lamp size this sleeve is proportioned to operate at a temperature no higher than 2000 K at the hottest point. A still higher operating temperature might result in improved efficiency for producing steady radiation but would probably be detrimental to the modulation characteristics of the lamp and to the stability of the cathode spot. The most stable and uniform operation is obtained when the cathode spot very nearly fills the activated zirconium oxide surface.

Anode Construction. The anode is made of molybdenum punched or cut from sheet stock and formed to the desired final shape in a small press. Except for the difficulty of shaping it, tungsten is an equally good anode material. The shape of the anode is not important; its dimensions are chosen only to provide adequate heat dissipation. The arc strikes to the edge of a hole, in the center of the anode, which also serves as a window for the cathode. It is found that experimental lamps rated at more than 300 watts have better characteristics if water-cooled anodes are provided.

Other Features of Construction. The radiation spectrum contains lines characteristic of the gas with which the lamp is filled. Argon and krypton are the most satisfactory gases, and the former is normally used.

The electrodes may be mounted in any position within the bulb so long as their relative orientation and spacing are properly preserved. The standard point cathode and perforated-plane anode structure lowers the breakdown potential required for starting the lamp and also results in lengthened lamp life, since the arc may operate from any point on the edge of the hole in the anode.

The surface of the glass bulb must be large enough to avoid overheating at any point and may be smaller for Pyrex or Nonex than for soft glass bulbs. Standard commercial tube- and lamp-type bulbs may be used for side-projection models, but special measures are ordinarily required to provide sufficiently good optical quality for the windows in end-projection types. The lamps may be mounted in various types of bases, the principal requirements being that they withstand the high voltages used in starting the lamps and that they be polarized. Molded Bakelite bases of the radio-tube type are preferred, such as those listed in Table 5. Prefocus bases can be provided if they are needed, for example, to preserve the alignment of an optical system when the lamp is exchanged or replaced.

STATIC ELECTRICAL CHARACTERISTICS AND OPERATING CIRCUITS

The volt-ampere characteristic curve for the concentrated-arc lamp has a negative slope, just as for other well-known arcs. However, if the arc current is increased beyond the point at which the cathode spot just fills the activated zirconium oxide surface, the slope of the volt-ampere curve tends to increase to zero and may even become positive. Once the arc is established, stable d-c operation requires only that sufficient positive ballast impedance be included in the circuit to neutralize any negative resistance exhibited by the lamp over the desired operating range of current.

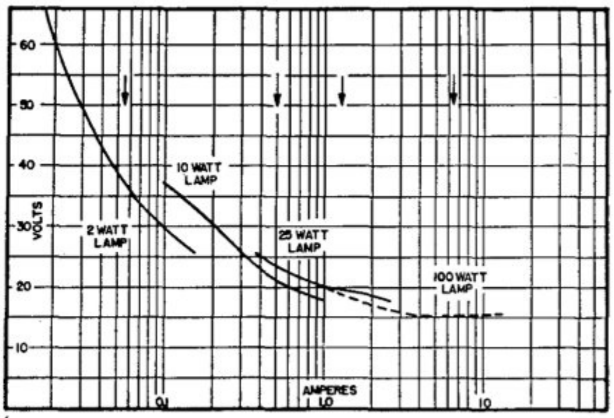

FIGURE 9. Average static volt-ampere characteristics of aged concentrated-arc lamps. Arrows indicate normal operating current.

Since the characteristics of a lamp change somewhat during its operating life, the data chosen for presentation below are average values for lamps aged sufficiently to have well-stabilized characteristics. The average static volt-ampere characteristics of the four standard lamp sizes are shown in Figure 9. Other average static characteristics for lamps of the 10-watt size, as an example, are shown in Figure 10.

The concentrated-arc lamps operate on relatively low-voltage direct current but require high-voltage starting circuits. By means of rectifier power supplies they can be started and run from an a-c source if desired. Such power units must include a high-voltage starting supply, a low-voltage operating supply, and adequate provisions for switching the lamp from one supply to the other at the proper time.

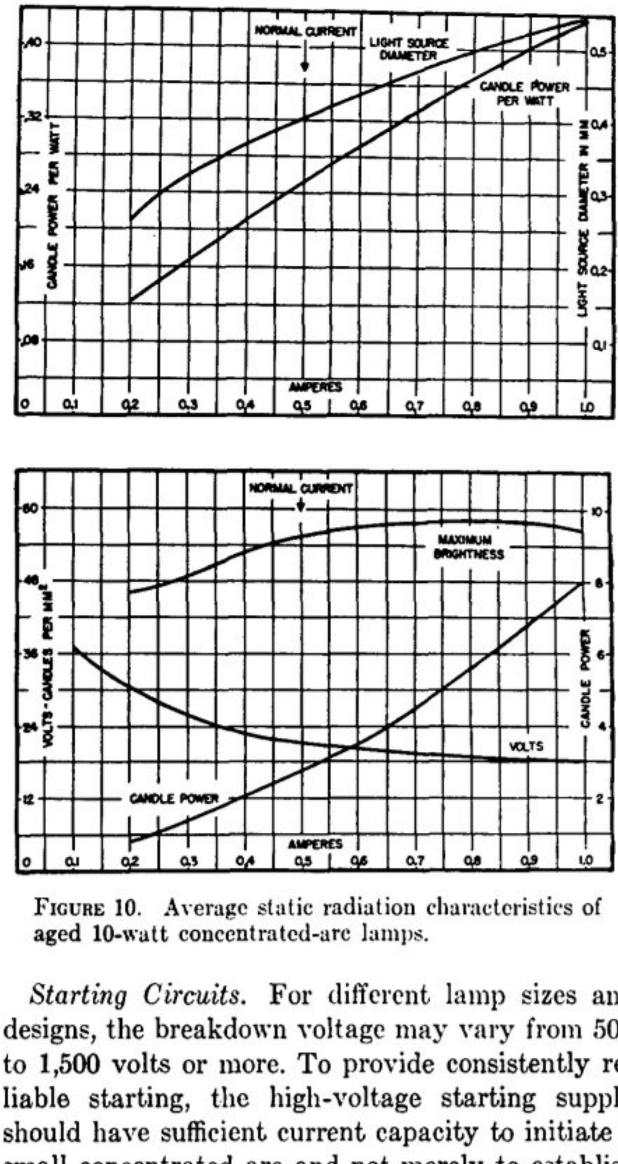

FIGURE 10. Average static radiation characteristics of aged 10-watt concentrated-arc lamps.

Starting Circuits. For different lamp sizes and designs, the breakdown voltage may vary from 500 to 1,500 volts or more. To provide consistently reliable starting, the high-voltage starting supply should have sufficient current capacity to initiate a small concentrated arc and not merely to establish a high-voltage spark discharge, since the starting current must cause the arc voltage to fall to a value equal to or less than the open-circuit voltage of the operating supply. Three methods which have been employed to start the arc are described in the following paragraphs.

In the first method, the lamp is connected to the d-c operating supply in series with the proper ballast resistance, and the output from a high-frequency spark coil is applied to the circuit. This method is often convenient in the laboratory, but is not considered satisfactory for general use, since the radio-frequency characteristics of the associated wiring may determine whether a given lamp will fire, and also the open-circuit voltage required for the d-c operating supply is likely to be higher than for other starting methods.

In the second method, the transient inductive voltage pulse obtained by interrupting the current through a choke in series with the lamp is used to break down the arc gap. The lamp then continues to operate from the same power source which energized the starting circuit. The principal advantage of this method lies in the fact that relays may be used to make the circuit automatically self-starting and to repeat the starting cycle automatically if the lamp is accidentally extinguished. However, this method is completely satisfactory only for the 2-watt lamp; for larger lamps the third method is more efficient and reliable.

The third method utilizes more expensive components and power requirements, but at the same time provides more positive and generally satisfactory starting. It consists essentially of a poorly regulated high-voltage rectifier having an open-circuit voltage of 1,000 to 2,500 volts.

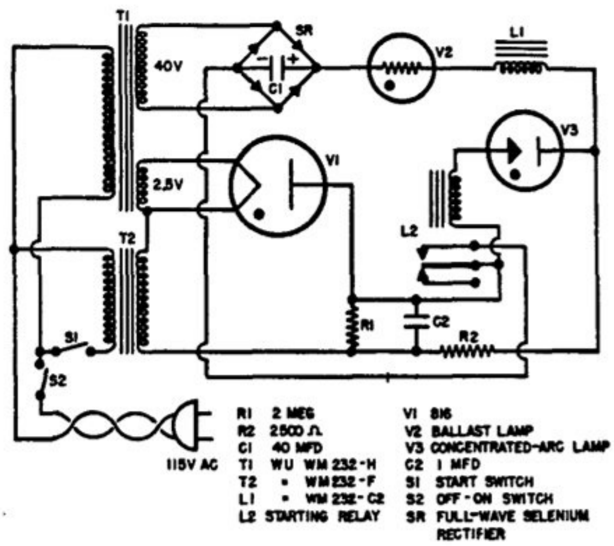

FIGURE 11. Power supply for 25-watt concentrated-arc lamp.

A representative power supply circuit for starting a 25-watt lamp and operating it from a selenium rectifier is shown in Figure 11. After the filament of the starting rectifier tube V1 has been heated by closing the main switch S2, the starting switch S1 is closed, applying plate voltage to the rectifier tube and rectified high voltage directly to the lamp terminals. The arc gap instantly breaks down, and a current of 100 to 200 milliamperes flows through the lamp and the coil of the starting relay L2. Operation of the relay connects the output of the selenium rectifier to the lamp in parallel with the high voltage supply and the lamp current rises to its normal value of 1.3 amperes. Since the selenium rectifier current also flows through the relay coil, the relay contact remains closed and the lamp continues to operate after the starting switch is opened.

Fully automatic methods for starting the lamp and for switching over to the operating circuit may be added when necessary. The added cost and complexity of this measure are frequently not justifiable if the lamp is to be used simply as a source of steady radiation, but may be essential if it is to be electrically modulated as the radiation source for a communication system.

Operating Circuits. The concentrated-arc lamps can be operated from any d-c source capable of delivering a sufficiently smooth current at the required voltage. Except for the 2-watt lamp, an operating potential difference of about 16 to 24 volts at the lamp terminals is ordinarily adequate (see Figure 9), to which must be added an allowance of about 50 per cent for the potential drop across the series ballast impedance. The required power may be obtained from storage batteries, a motor-generator set, or a-c power with an electron-tube or a selenium rectifier. The final choice of power supply in each case will, of course, depend on the requirements of the particular application and the available facilities. The selenium bridge-type rectifier is most commonly used in the power supply units constructed by the Western Union Telegraph Company. A typical circuit for such a unit is shown in Figure 11. For the 2-watt lamp, a special a-c operated power supply has been devised [23a] in which very satisfactory starting and operating are achieved with only one transformer and one rectifier tube. This circuit also provides fully automatic starting and switch-over to continuous operation.

Because the arc acts as a negative resistance it is essential for stable operation of the lamp that enough positive impedance be included in the operating circuit to neutralize this characteristic. In general, a ballast resistance is sufficient if the voltage drop across it is about one-half of that across the arc. A rheostat with provision for manual control may be satisfactory, or a constant-current ballast tube of the type frequently used in electronic circuits may be more convenient, for example, a tube such as those manufactured by the Amperite Company. With a ballast tube of this type it is best to keep other impedances in the circuit as low as possible in order to secure maximum effectiveness of current regulation. The degree of regulation required depends, of course, on the type of power supply used and the other conditions of each specific application.

By means of specially constructed experimental arc lamps it has been demonstrated that the radiation characteristics of the cathode spot in the d-c operated concentrated-arc lamp can be duplicated by raising the cathode to incandescence either by joule heating or by electron bombardment. Many lamps of the 10-watt and larger sizes can also be operated directly from a low-frequency a-c source, the lamps acting as self-rectifiers. Ballast impedance should also be included in the circuit for this type of operation.

Static Radiation Characteristics

As shown in Table 5, the maximum brightness of the cathode spot in the standard concentrated-arc lamps is from about 40 to 100 candles per square millimeter. These values are about one-half as great as for the crater of a small d-c operated plain carbon arc, and from three to ten times as great as for incandescent tungsten filaments near 3000 K. Up to the current value at which the cathode spot completely fills the zirconium oxide surface, the size of the spot rather than its brightness is principally affected by changes in the arc current. An increase in brightness will result from still higher current, but the life of the lamp will be shortened. At current values very much less than normal the spot becomes variable in size and position. The maximum brightness is always found near the center of the spot. The lamps are not sufficiently stable either in total intensity or brightness distribution over the cathode spot to constitute a satisfactory substitute for incandescent tungsten lamps as photometric standards.

Intensity measured as a function of angle from the normal to the cathode has the distribution expected for a plane disk which radiates in accordance with the cosine law.

During the first few hours of operation the maximum brilliance of the cathode spot increases to about 130 per cent of the initial value. Thereafter the brilliance, candlepower, and cathode spot diameter all show a gradual decrease throughout the remaining life of the lamp. The life is said to be terminated when the arc is no longer concentrated, that is, when the cathode spot is dull and extended rather than white and concentrated or when the lamp can no longer be started with the standard equipment ordinarily used for this purpose. These conditions are usually caused by shrinkage or loss through vaporization of the cathode filling material. The average life is 175 hours for 2-watt lamps and 900 hours for 10-watt lamps. Individual lamps in the 25-watt and 100-watt sizes have had lifetimes up to 5,000 hours when not modulated, but sufficient data are not available to indicate an average life for these sizes. The life of a lamp operated on direct current without modulation is apparently no different for intermittent start-stop operation than for continuous operation.

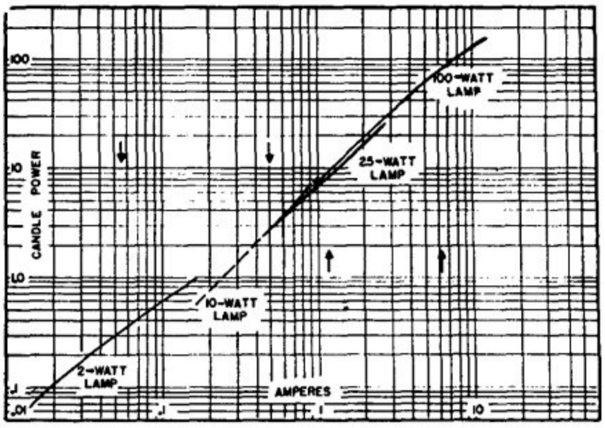

FIGURE 12. Average static candlepower characteristics of aged concentrated-arc lamps. Arrows indicate normal operating current.

Intensity versus Current and Power. As shown in Figure 12, the relationship between candlepower and current is almost linear over a very wide range of current for each lamp size. The major part of the candlepower change is due to an automatic change in the diameter of the cathode spot as the current is varied.

The efficiency of concentrated-arc lamps, measured in candlepower per watt input to the lamp (not including the power expended in the ballast impedance) as a function of current, is shown in Figure 13. The higher efficiency values for the lamps of larger size may be due to relatively lower heat losses from the activated radiating surface to the cathode supporting structures. The figures are, on the average, only about one-half as great as for incandescent tungsten lamps. Moreover, because of the spatial distribution characteristics of a disk-type radiator,

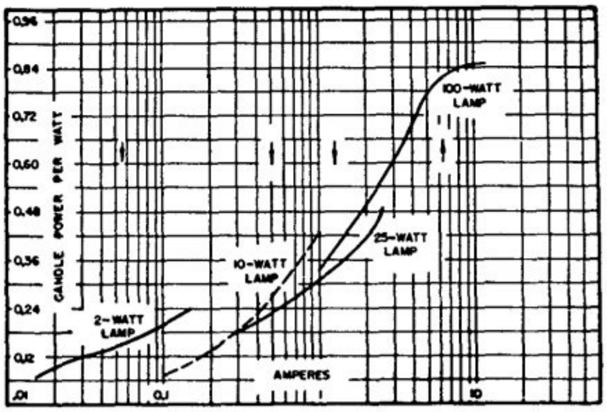

FIGURE 13. Average static luminous efficiency of aged concentrated-arc lamps. Arrows indicate normal operating current.

the total flux from a concentrated-arc lamp is only about one-third of that from a tungsten lamp of equal hololuminous intensity, or about one-sixth of that from a tungsten lamp operated at equal power.

Spectral Distribution. A typical spectral distribution curve for the wavelength region from 0.3 to 1.0 μ is shown in Figure 14. The spectrum consists

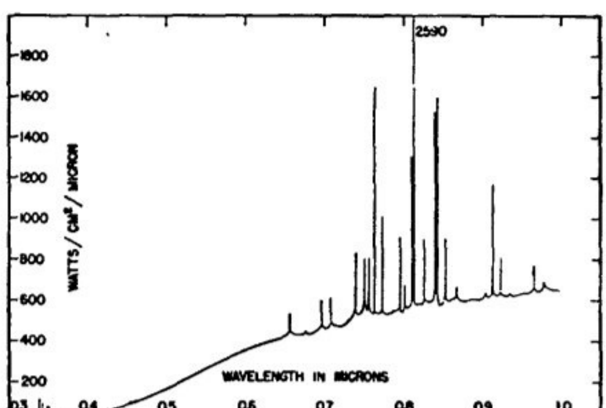

FIGURE 14. Static spectral distribution of radiation from concentrated-arc lamps.

essentially of a continuum upon which are superposed spectral lines of zirconium and of the filling gas. The peak of the radiation curve occurs near 1.0 μ and the curve resembles that of a black body near 2800 K, lying somewhat above the black body curve on both sides of the peak. The spectral distribution in the near infrared is thus quite similar to that for an incandescent tungsten lamp, and because of the large amount of radiation in the visible region a relatively dense filter is required to provide the security which is essential for applications in military signaling and communication systems. It has been estimated that more than 90 per cent of the total radiant energy originates from the incandescent cathode spot, in contrast to the relatively small amount which originates in the gaseous arc column.

Dynamic Electrical Characteristics

When an a-c voltage wave is impressed on the terminals of a concentrated-arc lamp through which direct current is flowing, the resulting a-c current wave lags behind the applied a-c potential wave by an angle whose magnitude depends on the impressed frequency. The modulated radiation wave in turn lags behind the current wave, but by an amount which is generally much smaller than the current voltage lag. Distortion of the radiation wave is not large for frequencies in the audio range, so that the quality of voice reception in systems using this source is determined principally by factors other than arc characteristics.

The dynamic electrical characteristics may be summarized as follows:

1. The equivalent internal impedance of the lamp is composed of a variable resistance and an inductive reactance.

2. The resistive component decreases with a decrease in the unmodulated direct-current operating value, becoming negative at low d-c values. The magnitude and sign of the resistive component also depend on the frequency of the modulating potential.

3. The inductive reactance component increases with a decrease in the direct-current operating value. The equivalent inductance is almost inversely proportional to modulation frequency, the inductive reactance being essentially independent of frequency.

4. The impedance is definitely nonlinear over the medium range of current modulation ordinarily employed.

5. The modulated radiation is almost directly proportional to the modulated current within the usual range of per cent current modulation, but lags behind it by a small phase angle which varies so slowly with frequency as to be of little importance in communication systems.

Typical curves showing the dependence of the electrical characteristics on frequency for lamps operated at rated d-c values and at 50 per cent current modulation are given in Figure 15, which refers specifically to the 10-watt lamp. The effective impedance of the lamps varies from a few hundred ohms in the 2-watt size to only a few ohms in the 100-watt and larger sizes. It is of interest to note that a minimum occurs in the curve of impedance versus frequency; the frequency at which it occurs becomes lower as the size of the lamp is increased. It is thought that the lamp may have negative resistance at some much higher frequency range also, since self-sustained radio-frequency oscillations have sometimes been found to exist in the lamp circuits.

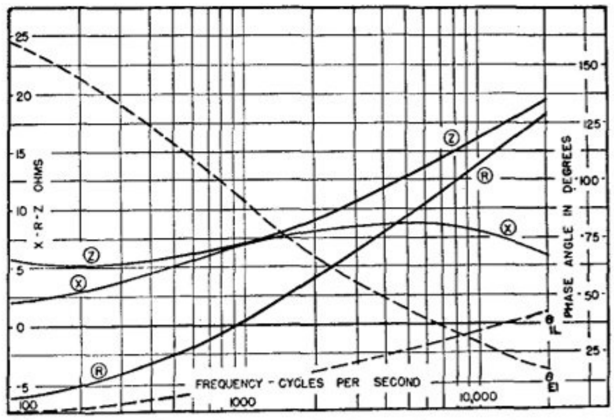

FIGURE 15. Impedance and phase characteristics of 10-watt concentrated-arc lamps.

Modulating Circuits. A sine-wave modulating current will produce essentially a sine wave of radiation from the concentrated-arc lamp, the only distortion being the relatively unimportant phase distortion. A sine wave of voltage will not produce this result, however, since the volt-ampere characteristic is nonlinear in both amplitude and phase. Moreover, the arc is limited in the amount of current it can pass because of the limitations of heat dissipation and current saturation. When overdriven it will to some extent rectify the applied signal, causing an additional d-c component to flow and diminishing slightly the d-c terminal voltage.

When stability of operation and low distortion are important, as for use in a communication system, the following general requirements should be observed in the operating and modulating circuits.

1. The effective impedance in series with the lamp, including the effect of other circuits in parallel with the lamp circuit, should always be greater than any instantaneous negative impedance presented by the lamp.

2. The best linearity between the electric input and the modulated radiant output is obtained when the lamp is modulated by a constant-current generator. Such a generator, having infinite internal impedance, also provides a maximum of stability.

3. The electric modulation source should be capable of supplying the peak instantaneous modulation power over the desired frequency band to a load having distinctly nonlinear characteristics and yet not be overloaded itself.

4. The possibility of extinguishing the arc by overmodulation can be minimized by removing the low frequencies for which the possible period of overmodulation is equal to or greater than the time in which the arc may be extinguished, or it can be completely eliminated by limiting the amplitude of the signal.

5. The d-c operating supply should be sufficiently smooth to prevent the introduction of undesired modulation components or frequencies.

The impedance of the 2-watt lamp is sufficiently high so that it can be successfully modulated in the plate circuit of a vacuum tube, the modulating voltage being applied to the grid. The larger lamps do not permit modulation by this method.

The most economical and generally satisfactory method of modulating the lamp is to apply the modulating current directly through the lamp and not through the ballast resistance and other circuit

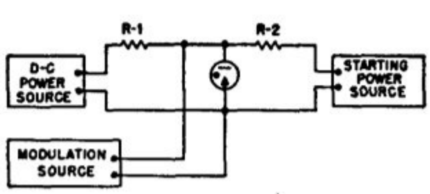

FIGURE 16. Schematic method of modulation.

components. This basic method is shown schematically in Figure 16; its successful application depends on keeping the shunt impedances of the starting and operating circuits high as compared with the impedance presented by the lamp. In practice it is necessary to modulate lamps larger than the 2-watt size through an impedance-matching power transformer and a series blocking condenser. The actual power required to modulate the lamp may vary from 50 to 100 per cent of its normal d-c power rating, depending on the size of the lamp and the operating conditions which it is desired to meet.

Characteristics as a Source of Modulated Radiation

Radiation from the concentrated-arc lamp appears to consist of the following three parts which are listed according to the total radiation emitted: continuous radiation from the incandescent cathode spot, line radiation from the excited gas and vapor, and some continuous radiation, at least in the shorter wavelength visible regions, originating in the excited gas and vapor. As would be expected on this basis it is found that the modulation characteristics of the emitted radiation depend upon its wavelength, upon the modulating frequency, and upon whether average characteristics of the entire radiation emitted by the lamp are investigated or only the characteristics of that portion of the radiation which originates in the arc stream or at a selected region of the cathode.

A rather detailed experimental investigation of the modulation characteristics has been made from which the following conclusions were drawn.[24a] A part of the radiation, most pronounced in the blue and ultraviolet regions of the spectrum, responds almost instantaneously to changes in the arc current. A considerably larger part, whose relative value also varies with wavelength, follows the arc current with a time lag of the order of 10^{-4} second. A third part, especially prominent in the infrared region and believed to arise primarily as thermal radiation from a sharply defined incandescent spot on the cathode surface having a relatively low true temperature of the order of 2000 K, is not subject to appreciable modulation over the useful range of audio frequencies. The relative amount of infrared radiation which cannot be modulated at useful frequencies is thought to depend critically on the thermal insulation of the material forming the thin, activated surface of the cathode, and on the composition and behavior of this material under bombardment by ions from the arc column. Presumably this radiation can be modulated only by changing the temperature of the cathode surface, the thermal inertia of which is too great to permit appreciable modulation within the audio-frequency range.

The spectral distribution of modulated radiation from the concentrated-arc lamp at a modulation frequency of 1,000 cycles per second is shown in Figure 17. The relative dependence of the modulated intensity upon wavelength is illustrated by comparing the curve of Figure 17 with the static spectral distribution curve of Figure 14. The data for Figure 17 were obtained by using an a-c amplifier

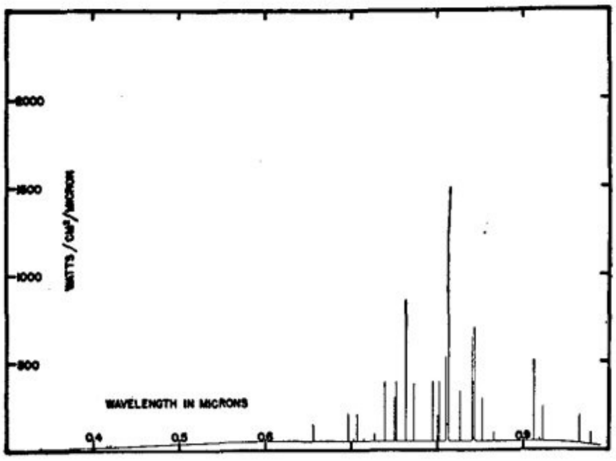

FIGURE 17. Spectral distribution of 1000-cycle modulated radiation from concentrated-arc lamps.

following the photoelectric radiation detector so that the unmodulated radiation at each wavelength was not measured. A series of similar curves obtained for other modulation frequencies show that as the modulation frequency is increased the amplitude of the continuum, which originates primarily from the cathode, decreases by a much larger factor than the amplitude of the spectral lines, which originate in the cathode glow region. A high modulation ratio for the spectral lines exists throughout the entire audio-frequency range, the upper frequency limit for successful modulation presumably being determined by the deionization time of the gas.

The dependence of the modulation ratio upon frequency and upon spectral region is shown for one lamp in Figure 18. The ultraviolet curve was obtained by using a combination filter (Corning 430 with Corning 584) which has a transmission peak at about 3600 Angstrom units, in conjunction with a photomultiplier tube (RCA type 931) having an ultraviolet-sensitive antimony cathode. The other curves represent the response of an infrared-sensitive cesium-cathode phototube to the modulated component of the radiation transmitted by the following filters: Corning 430 (blue), Corning 241 (red), and Polaroid XR7X (infrared).

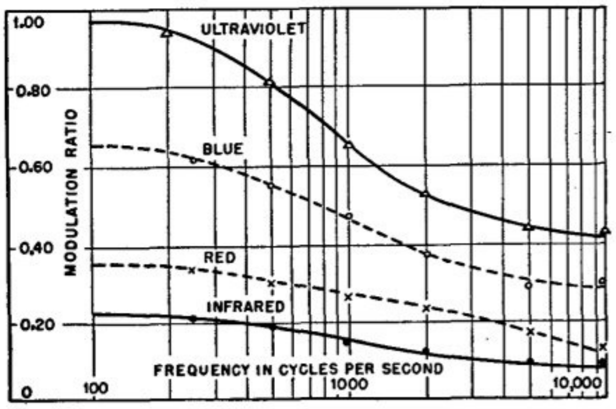

FIGURE 18. Modulation ratio *versus* frequency for different wavelength regions of concentrated-arc radiation.

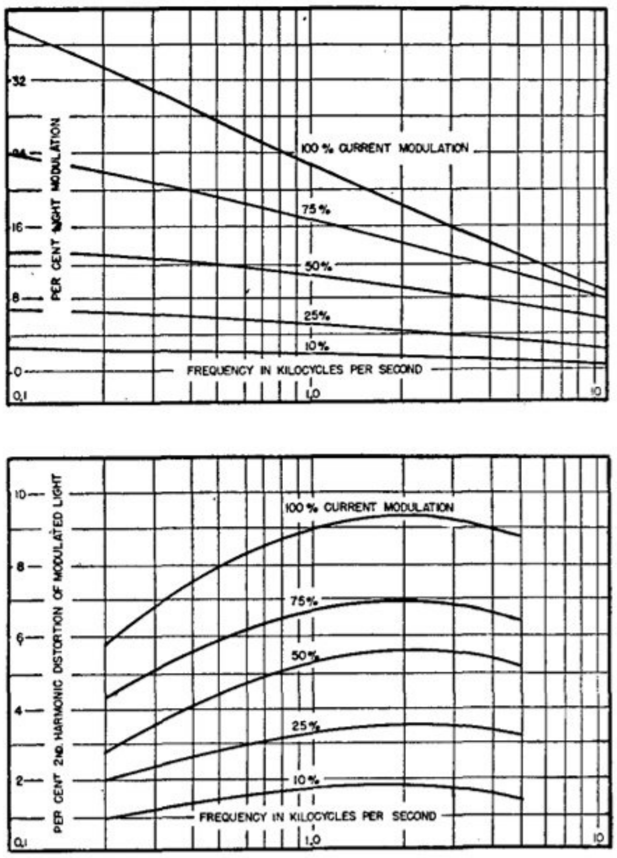

FIGURE 19. Modulation characteristics of 10-watt concentrated-arc lamps with reference to a cesium-surface detector.

The modulation characteristics of the 10-watt concentrated-arc lamp, as an example, are shown on a somewhat different basis in Figure 19. These curves were obtained by using the entire radiation from a lamp with no filter interposed and with an infrared-sensitized cesium-cathode phototube as the detector. The per cent modulation of the emitted radiation at 100 per cent current modulation is, by definition, the modulation ratio. The per cent modulation of the radiation shows a decrease as the lamp size is increased, but, because of the greater quantity of radiation emitted by the larger lamps, the total modulated radiant energy is considerably greater for the large than for the small lamps. The lower graph of Figure 19 shows the percentage of the modulated radiation having the second-harmonic frequency. The distortion of the modulated radiation which results from the lack of an accurately linear relationship between lamp current and emitted radiant energy has been found to consist largely of this component, and increases with an increase in modulating frequency, per cent current modulation, and lamp size. By limiting the current modulation, the distortion can ordinarily be limited to a range within the permissible limits for usual audio-frequency amplifier practice so that it does not perceptibly affect the overall fidelity of a communication system.

It is seen, therefore, that the per cent modulation of the emitted radiation may vary over a rather wide range, depending upon the exact conditions in which the lamp is used. For certain special applications in which only a small amount of radiant flux having the highest possible per cent modulation is desired, a lens and slit arrangement may be used to isolate that portion of the radiation which originates from the cathode glow or from the center of the cathode spot. The per cent modulation under some conditions may be 50 per cent greater for lamps filled with krypton than for lamps filled with argon. Very promising results have also been obtained in experimental lamps filled with gas at a pressure of 10 to 15 atmospheres instead of the usual one atmosphere and by the use of especially designed experimental cathodes which will not be described here. Experimental variations in anode construction have also been investigated. Although some of these measures result in lamps of increased brilliance and higher radiant efficiency or modulation efficiency, they have not yet been successfully developed to a point suitable for application in large-scale production.

Life of Lamps when Modulated. When the current through a lamp is modulated, the life of the lamp may be considerably reduced, probably due to the loss of zirconium vapor from the cathode glow region during the portion of the modulation cycle in which the cathode is least negative. The amount by which the lamp life is reduced apparently depends upon the average value of the direct current and upon the waveform, frequency, and amplitude of the modulating current, particularly if the polarity applied to the lamp is actually reversed during any portion of the modulation cycle. The exact nature of the dependence of lamp life upon these factors is not known, but under some conditions the life has apparently been reduced by as much as 90 per cent.

Applications in Wide-Beam Optical Systems

Because of its small diameter and high brilliance, the cathode of a concentrated-arc lamp constitutes an ideal source for projecting a narrow beam of radiation which can be electrically modulated for voice or code communication purposes. When the cathode is located at the focal point of the projection system, the angular spread of the beam is approximately equal to the angle subtended by the cathode spot at the vertex of the reflector or the optical center of the lens or equivalent lens system. Thus for a system having a focal length of 8 inches, the value of the cathode spot diameter shown in Table 5 for the 25-watt lamp corresponds to a computed angular beam spread of only about 0.2 degree.

Although the lamps have been used in narrow-angle projection systems by other agencies, their principal application within Section 16.4 occurred in the early stages of development of the type E infrared voice and code communication system,[24] for which a beamwidth variable between 15 and 40 degrees was originally requested (see Chapter 4). The problem of redistributing radiation from what is essentially a point source into a fairly uniform beam having a spread of this order of magnitude is rather specialized and has been treated in detail elsewhere.[26]

Some of the problems associated with the production of a wide-angle beam from a very small source are the following: (1) since the total flux available from the source is limited by its small size no matter how high its brilliance, and since for any given total flux available from the source the intensity available at a receiver will vary inversely as the solid angle into which it is spread, it is essential that the greatest possible fraction of the flux emitted by the source be collimated within the specified angular limits of the beam and that the source and its mountings obscure the smallest possible portion of the collimated beam; (2) aberrations in classical idealized optical systems utilizing, for example, surfaces of revolution having conic sections, give rise to nonuniformities of intensity across the beam; (3) the small size of the source demands extraordinarily high precision in the preparation of the reflecting or refracting surfaces since an irregularity in the beam pattern caused by an imperfection in the optical surface cannot be smoothed over by flux originating from an adjacent area of the source, as is the case with an extended source.

The possibilities of various types of optical systems have been investigated both theoretically and experimentally. With the 100-watt concentrated-arc lamp as the source it has been found possible to produce a rectangularly shaped beam having angular dimensions 18x8 degrees and with a sufficiently uniform intensity distribution to be satisfactory for communication and signaling systems. In the most compact and efficient system devised for this purpose (see Chapter 4) the source is mounted, facing in the direction of the emergent beam, at the focus of a spun Alzak parabolic reflector having a focal length of 0.6 inch, 6 inches in diameter and 7 inches deep. An $f/1.2$ plano-convex lens is used to collimate radiation that would otherwise pass uncollimated out the front opening of the reflector. Over the front of the reflector is placed an 18x8-degree spread lens of a type which is available, for example, from the Holophane Company, Newark, Ohio. The multiple-facet construction of the spread lens serves not only to give the desired divergence but also smooths out the irregularities which would otherwise exist due to the surface imperfections in commercially available optical elements. More complete details of this and related systems and a general discussion of source and transmitter optics and of other factors in relation to the performance characteristics of complete communication systems are given in Chapter 4 and elsewhere.[24b,27]

The beam candlepower of the 18x8-degree transmitter described above, using the 100-watt concentrated arc as the source, is approximately 5,000 equivalent holocandles with reference to a cesium-surface vacuum phototube.

Infrared Filters for Concentrated-Arc Lamps

Since the spectral energy distribution of radiation from concentrated-arc lamps consists principally of a continuum with a distribution similar to that for the radiation from incandescent tungsten lamps, the infrared filters required to give them sufficient visual security for military purposes are quite similar to those required for use with tungsten lamp sources. Basic problems and general considerations pertaining to infrared filters are outlined in Chapter 2, while those selected for use in specific near infrared systems are indicated in Chapters 4, 5, 6, and 7.

The ehT values of filters measured with reference to the modulated radiation from electrically modulated concentrated-arc lamps are considerably lower than the values for the same filters with reference to radiation from unmodulated or mechanically modulated tungsten lamps for two reasons. First, the near infrared component of concentrated-arc radiation is relatively smaller than for incandescent tungsten radiation, the arc radiation being richer in energy at visible wavelengths. Second, as shown by Figure 18, the modulation ratio at different wavelength bands decreases with increasing wavelength, so that an infrared filter apparently discriminates more strongly against the modulated infrared components than its spectral transmission curve, or experimental tests made with an unmodulated lamp, would indicate.

The ehT values of three representative infrared filters with reference to radiation from an arc fully modulated at 1,500 cycles per second, as measured by two different infrared detectors, are shown in Table 6. Also included for each of these filters is the calculated visual range of a transmitter having an intensity of about 5,000 holocandles in the absence of a filter, such as the one described in the preceding section. Corresponding ehT° values for the Polaroid XR3X41 filter, with reference to radiation from an incandescent tungsten source at a color temperature of 2848 K, are about 27 per cent for the cesium-cathode phototube and about 45 per cent for the thallous sulfide photoconductive cell (see Chapter 3).

Discussion

Concentrated-arc lamps in the four standard sizes which are now commercially available constitute an interesting and potentially valuable source of near ultraviolet, visible, and near infrared radiation. The lamps have been successfully used for a number of applications requiring a high-intensity, concentrated radiation source. The feasibility of constructing lamps up to 1,000-watt ratings using water-cooled electrodes has also been demonstrated, and experiments initiated before the conclusion of NDRC sponsorship indicated the possibility of further improvements in radiation efficiency and electrical modulation characteristics.

TABLE 6. Effective holotransmission of various filters and calculated visual range of a 5,000-holocandle transmitter using the concentrated-arc lamp.

Filter	ehT for modulated radiation component from arc fully modulated at 1,500 cycles: Gas-filled C_s phototube	Thallous sulfide cell	Calculated visual range (yards)
Wratten 87	0.35	0.55	8,000
Polaroid XR3X41	0.06	0.16	70
Polaroid XR7X25	0.03	0.14	35

A great many scientific questions regarding the operation of concentrated-arc lamps and the explanation of their characteristics remain unanswered and should be explored in greater detail. For example, estimates for the temperature of the cathode surface based on (1) the spectral distribution of the radiated energy, (2) Stefan's law and the total energy radiated, and (3) the electron emission needed to maintain the arc using the work function of metallic zirconium which might be produced by reduction of the oxide, differ by nearly 1000 K. Other questions immediately arise, such as whether the thin activated layer at the cathode spot is molten or solid during operation; the origin of the continuum, its spectral distribution, and its relationship to other continua; the possible relation between the semiconducting properties of the cathode surface and the time lag in the emitted radiation; and the frequently contradictory results of measurements made in different laboratories on lamp life, modulation ratio, spectral distribution of modulated and unmodulated radiation, etc.

Although the possibility of using concentrated-arc lamps in wide-angle modulated-beam communication systems was successfully demonstrated, a less concentrated type of source, such as the cesium-vapor lamp described in the following section, is generally to be preferred for this purpose.