The Cesium-Vapor Lamp

The cesium-vapor lamp was developed by the Lamp Development Laboratories of the Westinghouse Electric Corporation under Navy contract and was made available in 1944 for NDRC use as a source of near infrared radiation. Two different sizes of this lamp have been standardized in cooperation with Northwestern University under Contract OEMsr–990 for use as the source in infrared communication and signaling systems [24,28] developed by that contract (see Chapter 4). It is understood that the development of additional sizes of this lamp for other applications has been initiated.

The radiation emitted by this lamp originates in the column of a low-pressure arc discharge in cesium vapor. About 20 per cent of the input power is radiated in the two cesium resonance lines at wavelengths of approximately 0.85 and 0.89 μ. Since most of the radiation originates in the arc column, a much higher modulation ratio may be achieved than is possible for a concentrated-arc lamp. The visual security required for military applications may be achieved with a much less dense filter than is needed for sources which have a high-intensity continuous spectrum. The electrical characteristics and methods of operation are very similar to those described in Section 1.3.2 for concentrated-arc lamps and will be described largely by reference to that section.

Lamp Design and Construction

The details of construction of the 90-watt type CL–2 cesium-vapor lamp are shown in Figure 20. The same general type of construction is used in other sizes of this lamp, for example, the 50-watt lamp employed in the aircraft communication systems [28] described in Chapter 4. The inner bulb is made of heat-resistant glass (Corning No. 705) coated with a special alkali-resisting glaze to prevent corrosive attack by the cesium vapor. It contains a small amount of cesium metal and is filled with neon or other rare gas at a low pressure. The electrodes consist of coiled tungsten filaments, spaced about three inches apart, by means of which the lamp is preheated for 1 to 3 minutes and the cesium metal is vaporized. The cathode filament is coated with a barium-strontium oxide mixture to afford the copious emission of electrons needed to maintain the arc. The outer envelope is a T–16 bulb, evacuated to reduce heat losses and mounted in a standard 4-pin base.

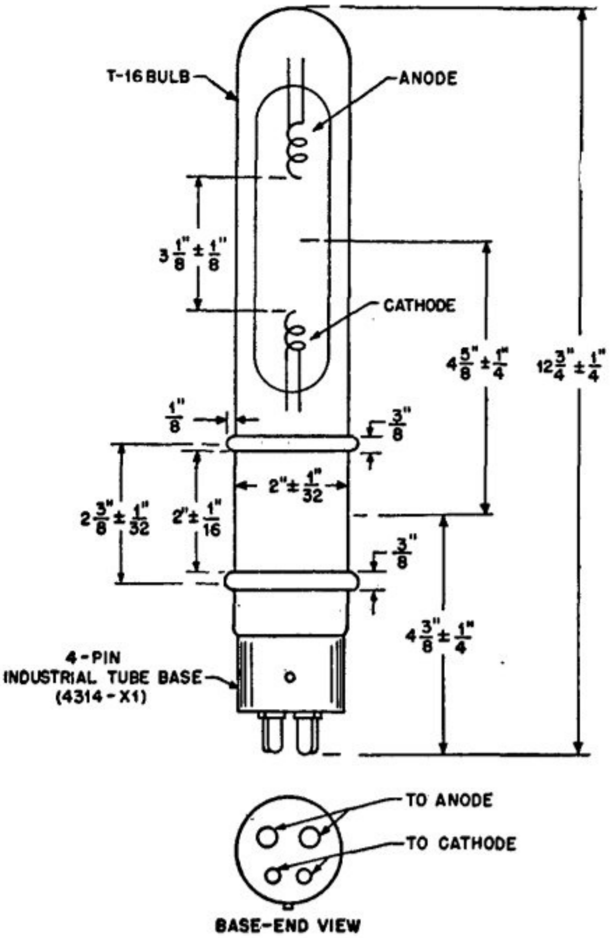

FIGURE 20. The Westinghouse type CL–2 cesium-vapor lamp.

ELECTRICAL CHARACTERISTICS AND OPERATING CIRCUITS

Since the arc is maintained in a metallic vapor, the electrical and radiative characteristics are both complicated by thermal time-lag effects in that the instantaneous characteristics are dependent on the immediately previous thermal history of the lamp. The 50-watt lamp, which has an electrode spacing of 1.5 to 2 inches, is normally operated at about 12 volts and 4 amperes direct current. The type CL–2 lamp consumes about 90 watts when operated at 5.5 amperes direct current. The static volt-ampere curve is essentially flat from 1 to 8 amperes. The average voltage at the lamp terminals over this range of current may vary between 11 and 25 volts, not only for different lamps but also for a given lamp over its lifetime. The circuit requirements for stable d-c operation are essentially the same as for concentrated-arc lamps. The static radiant intensity of the lamp is approximately proportional to the direct-current value when thermal equilibrium is attained. Presumably the operating temperature, electric power input, and radiant output might be increased by continuously heating the starting filaments. However, continuous operation of the filaments from the normal 2.5-volt a-c supply was found to introduce a 120-cycle ripple in the radiation output large enough to be objectionable in a communication system.

The dynamic internal impedance of the 90-watt lamp at 1,500 cycles per second is of the order of 1.6 ohms when the lamp is operated at 5.5 amperes direct current. It consists principally of a resistive component, plus an inductive reactance of the order of 0.4 ohm. The variations of impedance with frequency and with the magnitude of the direct current are identical in nature with those for concentrated-arc lamps, but, in many respects, the electrical behavior is considerably superior. The cesium lamp is much more stable and can be operated up to 100 per cent current modulation without danger of being extinguished. Moreover, the dynamic voltage-current relation is very nearly linear over a much larger current modulation amplitude than for concentrated-arc lamps, and the radiant energy emitted is essentially proportional to and in phase with the arc current over the entire audio-frequency communication band. A considerable improvement in the tone quality and intelligibility of voice communication therefore results from the use of this lamp.

Because of the long filament and lead structure of the lamp a considerable variation in its performance may result from different modes of connecting the modulating circuit to the electrodes. The most uniform performance from different lamps is obtained by connecting the modulating current to the center taps of the filament transformers. The principles of operation and the characteristic features of the modulating circuits required for optimum performance are identical with those already described for the concentrated-arc lamp.

Starting Circuits. The starting of the cesium-vapor lamp is affected by several factors. The cesium vapor condenses on the inside of the bulb when the lamp is inoperative so that, because of time-lag effects, its vapor pressure depends much more critically upon the recent thermal history of the lamp than upon the pressure of the inert filling gas. The condensed cesium may, under certain circumstances, partially or completely short-circuit the arc gap for starting purposes. Some of the cesium originally available is gradually lost by combination or absorption in the bulb, and the condition of the starting filaments with reference to electron emissive properties is also important.

It is therefore impossible to enumerate the optimum starting conditions for all circumstances. However, it is found that reliable starting is attained in most applications by preheating the filaments for one minute and then applying 400 volts alternating current or 500 volts direct current. The starting arc current should lie preferably between 0.5 and 1.0 ampere. The filament heating source is disconnected once the arc is established on the operating power supply. The switch-over requirements and the general types of circuits which can be used for starting and operating the lamps are quite similar to those already described for use with the concentrated-arc lamp.

Radiation Characteristics

Due to the low intensity of the spectral lines emitted in the visible region, the visual intensity of the bare 90-watt cesium lamp is only about 5 candles. With reference to a cesium-surface detector, however, the intensity is from about 90 to 150 equivalent holocandles for the 90-watt lamp, and about 70 holocandles for the 50-watt lamp. The visual output apparently varies at some power of the lamp current greater than unity, so that the luminous intensity of the lamp increases during modulation even though the average current remains constant. This visual effect is entirely eliminated if the lamp is viewed through a relatively light infrared filter such as Wratten 87. The spatial intensity distribution is essentially that to be expected from the sine distribution law for a linear source, and the total flux emitted is about three times as great as that from a plane disk source of equivalent intensity, such as a concentrated-arc lamp, for which the cosine intensity distribution law is followed.

Being concentrated principally in the two cesium resonance lines at an average wavelength of about 0.87 μ, the useful infrared radiation from the lamp is essentially monochromatic. The ehT values of filters for cesium lamp radiation are therefore very close to the spectral transmission values of the filters at this wavelength and are almost independent of whether a cesium-cathode phototube, a thallous sulfide photoconductive cell, or some other type of infrared photodetector is used.

The useful near infrared radiation originates exclusively in the arc column and has a very small time lag behind the modulating current. A high modulation ratio is therefore to be expected; its average value is found to be about 0.92 from 200 to 5,000 cycles per second, decreasing at higher frequencies to a value of about 0.70 at 10,000 cycles. Since the useful modulated infrared radiation is almost monochromatic, the modulation ratio is essentially independent of whether or not the source is covered with a filter.

After a few minutes of operation to permit stabilization, the arc becomes a fairly well-defined cylindrical column, about one-half inch in diameter, which may be somewhat bowed due to thermal convection currents. After a few hours of operation a brownish stain begins to appear on the inner bulb, probably due to a reaction of the cesium with the glass. This may eventually reduce the visual intensity of the arc by a factor of three or more without appreciably affecting the intensity of the near infrared radiation. The construction and operating characteristics of the lamp are similar to those of the familiar sodium-vapor lamp so widely used as an efficient, monochromatic source for visual illumination.

Spectral Energy Distribution. Since the lamp is normally operated with the power to the starting filaments cut off, a well-developed cesium line spectrum constitutes its principal radiation in the visible and near infrared regions. Additional energy is, of course, radiated in a thermal continuum having an energy distribution centered at much longer wavelengths, corresponding to the relatively low operating temperatures of the electrodes and the lamp envelope. The relative amount of energy radiated in various wavelength regions is shown in Table 7. Only two strong spectrum lines occur in the blue region, with the result that visual security is achieved with a filter of much lower opacity than would be required for a source of equivalent holocandlepower having a continuous spectrum. The second band listed includes the resonance lines, which contain most of the useful near infrared radiation. The experimental measurements were made with a vacuum thermocouple enclosed in a glass bulb, using a series of filters having different cutoff wavelengths. Although certain idealized assumptions were made in computing the values given in the table, the results are certainly correct as to order of magnitude.

TABLE 7. Distribution of energy radiated by the cesium arc.

Wavelength region (microns)	Per cent of total energy
0.3 – 0.78	3
0.78 – 0.9	22
0.9 – 1.4	5
1.4 – 3.5	11
Beyond 3.5	59 (remainder)

LIFE TEST RESULTS

Accelerated life test data were obtained at Northwestern University with the lamps operated on a continuous start-stop cycle in equipment especially constructed for this purpose. The sequence of operations during this test was as follows:

1. Preheat the filament for 5 minutes.
2. Start the lamp from a 480-volt, 0.5-ampere d-c starting circuit.
3. Operate 6 minutes at 5.3 amperes direct current.
4. Operate 49 minutes at 5.3 amperes direct current with 3.6 amperes (rms) modulating current at 1,500 cycles per second superposed, corresponding to 95 per cent current modulation.
5. Allow the lamp to cool for one hour before repeating the above cycle of operations.

In this test the frequency of starting the lamp is greater than would occur in usual field practice, and the per cent current modulation is higher than average speech modulation would require by a factor of two to four. In practical use the lamps are ordinarily operated at a stand-by current of one ampere instead of being allowed to cool completely before being restarted. The results of these tests should not be interpreted as applying directly to any other operating conditions, but they are indicative of the order of magnitude which can be expected for lamp life.

Thirty-eight type CL–2 90-watt lamps were tested in this manner, including one lamp which was initially faulty. The life was found to vary from 0 to 380 hours. The shortest life of a lamp successfully started on the cycle was 2 hours. One half of all the lamps tested were expended at or before 65 hours.

Lamps may fail in one of two ways. (1) A crack may develop in the inner bulb, usually near the anode, with the result that the arc can no longer be started at all, or the leakage of gas from the inner bulb will permit an arc to start between the leads in the outer bulb and melt them. (2) If no crack develops, the lamp is considered to have failed when all the cesium is used up. The anode then becomes brilliantly incandescent and produces a discolored bulge in the inner bulb. Although a lamp may remain operable with the residual gas for many hours after this occurs, its electrical and radiative characteristics are so altered that it is of little value.

APPLICATIONS IN OPTICAL SYSTEMS

The total flux emitted by a linear cesium lamp source is about three times that from a plane disk source (such as a concentrated-arc lamp) having equivalent hololuminous intensity in directions perpendicular to the line and plane, respectively. Nevertheless the linear extent of the arc is so great that it is difficult to collimate a high percentage of the emitted flux within a beam width approximating 20 degrees. Although a higher flux-gathering efficiency can generally be obtained with reflectors than with lenses, the efficient use of reflectors is rendered more difficult by the fact that the source is so large (2 to 3 inches long by ½ inch in diameter, and is, moreover, not transparent to its own radiation.

For the 90-watt lamp, the most economical, efficient, compact, and simple optical system is that adopted for the type E transmitter [24c] (see Chapter 4). The lamp is mounted axially in an Alzak-surface aluminum reflector 7 inches deep, approximately parabolic with an aperture of 14 inches and a focal length of 1.75 inches. The width of the resulting beam is somewhat smaller than was originally desired, being approximately 13 degrees between the points corresponding to one-half of the peak beam intensity; the peak hololuminous intensity of the transmitter measured at the center of the beam is 40 to 45 times that of a bare lamp, dropping to about ten times at 10 degrees from the axis of the beam. About 30 per cent of the emitted flux misses the reflector entirely while another 20 per cent is lost at the reflecting surface. The remaining 50 per cent of the total flux is projected within a cone of 60 degrees total angle. About 33 per cent of the total is projected within a 30-degree cone and about 22 per cent within a 20-degree cone. When the desired beam width is only about 20 degrees, a somewhat shorter arc would result in a higher optical efficiency value for this type of mounting.

In the communication systems for aircraft[28a] using the 50-watt lamp, a similar method of mounting was used in the plane-to-ground transmitter unit (see Chapter 4). In the interest of compactness a reflector 3 inches deep having a 7.25-inch diameter and ⅞-inch focal length was used. The width of the beam between the points of one-half of the peak beam intensity is 16 degrees and the peak holo-luminous intensity of the transmitter measured at the center of the beam is 18 times that of a bare lamp. The peak beam intensity with reference to a cesium-surface detector when no filter is interposed is about 1,400 equivalent holocandles. Other transmitter units in which a still wider beam was desired were constructed by using combinations of plane mirrors, with a corresponding reduction in the peak beam intensity. Details of these units may be found in the references given above.

Infrared Filters for the Cesium-Vapor Lamp

The general characteristics of infrared transmitting filters are treated more fully in Chapter 2, while the operating characteristics achieved in communication systems using certain specific filters with the cesium-vapor lamp are outlined in Chapter 4. The basic theoretical considerations from which the optimum transmission characteristics of a filter may be predicted in attempting to meet specifications on visual security and operating range for a particular transmitter and receiver combination are given in detail elsewhere.[24d,29]

Because the cesium-vapor lamp emits a line spectrum rather than a continuum, the numerical relation between its visual and holo intensity with reference to a near infrared radiation detector is quite different from that for an incandescent tungsten source or a concentrated-arc lamp. This difference is necessarily reflected in the choice of an optimum filter for the two types of source. Since most of the radiation that is useful for infrared communication systems is concentrated at 0.85 and 0.89 μ, it might appear that the ideal filter for the cesium lamp would transmit all of the radiation at these wavelengths and none at the shorter wavelengths which contribute little to the communication range but much to the visual effect. Even with this supposedly ideal filter, however, the 0.85-μ resonance line alone would make a sufficiently large contribution to the visual range so that the security requirements for communication systems (about 400 yards or less) would not be met by a transmitter of sufficiently high holo intensity to provide the desired communication range. Although the 0.89-μ resonance line makes, on an equal energy basis, an equal contribution to the range of a communication system, it makes a much smaller contribution to the visual range because of the rapid decrease in eye response between these wavelengths (see Chapter 2). A filter having an ideally sharp cutoff between the two resonance lines, so that no radiation from the 0.85-μ line and 100 per cent of the radiation from the 0.89-μ line would be transmitted, would have an ehT value of about 40 per cent with reference to a cesium-surface detector, while the visual range would be only about 10 per cent of the value which would exist if both resonance lines, but no radiation of shorter wavelength, were fully transmitted. Thus a sharp cutoff in the desired wavelength region can contribute materially to the performance of a system utilizing the cesium-vapor lamp.

The transmission curve of any actual filter rises gradually over a fairly wide wavelength band from zero to the maximum transmission value. It is possible to get a much steeper curve with organic dyes which may be incorporated in filters of the plastic resin type than with the pigments which can be incorporated in all-glass filters. Plastic filters developed by Polaroid Corporation under Contract OEMsr–1085 and Ohio State University under Contract OEMsr–987 (see Chapter 2) are found to have about equally favorable characteristics for use with the cesium-vapor lamp. It is important that the transmission cutoff lie between 0.81 μ, the upper wavelength limit for lines present in the cesium-lamp spectrum which contribute much more strongly to the visible range than to the operating range, and 0.85 μ, the wavelength of the shorter of the two resonance lines in which most of the energy useful for infrared communication purposes is transmitted.

It should also be recalled that, because of the essentially monochromatic quality of the near infrared radiation from the cesium lamp, the ehT value of a filter for this radiation is essentially the per cent transmission of the filter at a wavelength of approximately 0.87 μ and is therefore essentially independent of what near infrared detector is used. In Table 8 are shown the transmission values of certain filters for cesium lamp radiation, together with the visual range of a type E transmitter when covered with each of these filters. The last two types listed are recommended for securing optimum performance of a system utilizing the cesium lamp with the "non-ideal" filters which are actually available while maintaining the highest feasible degree of security for military operation. Details concerning the measurement of visual range may be obtained from the

TABLE 8. Transmission (ehT) of various filters for cesium-lamp radiation and visual range of the type E transmitter.

Filter	Transmission (ehT)	Visual range (yd)
Corning glass, 3.2 mm, 2566	0.31	500
OSU resin plastic, early sample	0.59	700
Polaroid sandwich, polyvinyl alcohol	0.80	700
OSU resin plastic, latest sample	0.80	700

references given above. Other considerations which must affect the choice of a filter for military equipment, such as mechanical strength, shock resistance, and weathering characteristics.