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TECHNICAL REPORT NO. 128

JUNE 17, 1949

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RESEARCH LABORATORY OF ELECTRONICS
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

The research reported in this document was made possible through support extended the Massachusetts Institute of Technology, Research Laboratory of Electronics, jointly by the Army Signal Corps, the Navy Department (Office of Naval Research) and the Air Force (Air Materiel Command), under Signal Corps Contract No. W36-039-sc-32037, Project No. 102B; Department of the Army Project No. 3-99-10-022.

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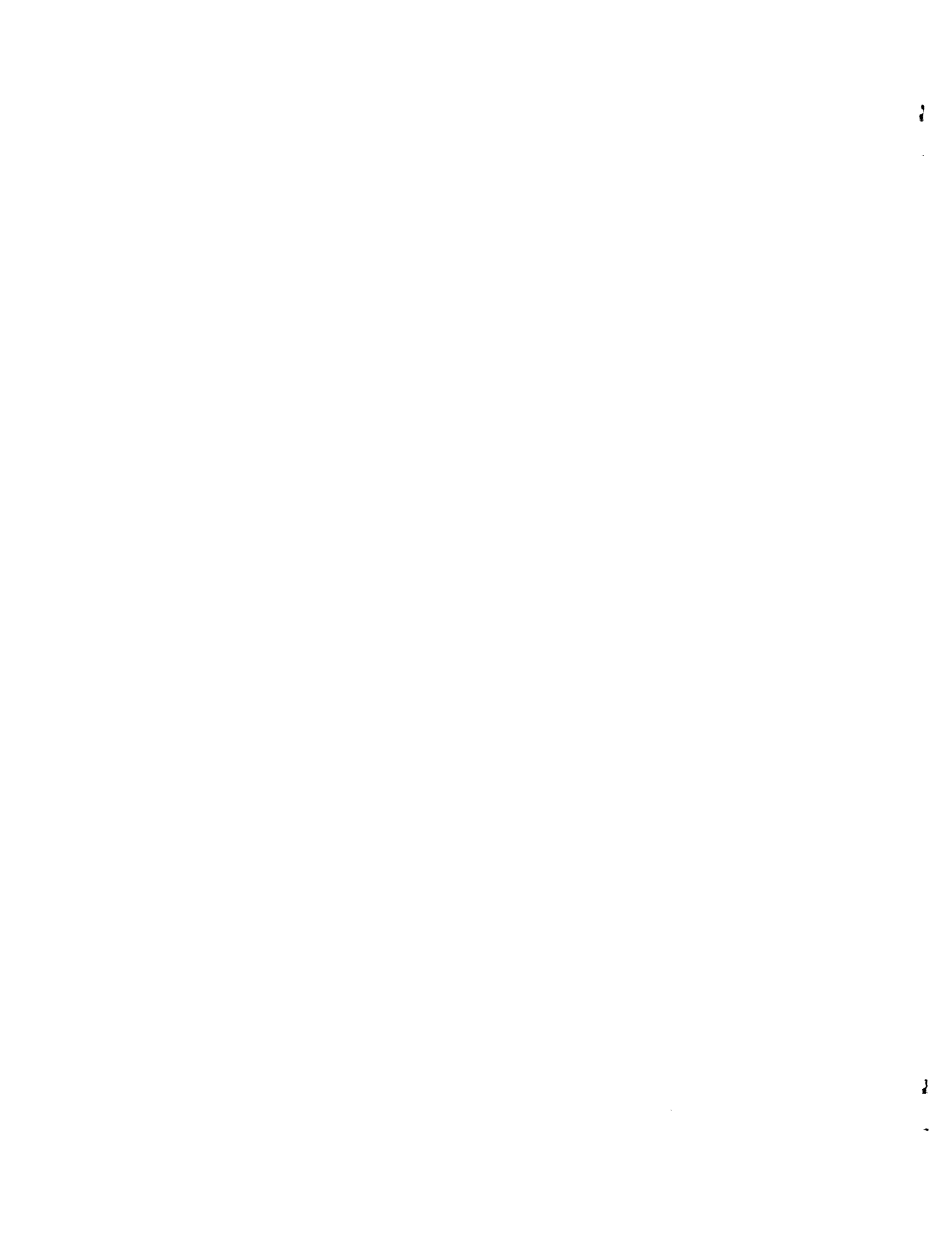
Richard K. Steinberg

Abstract

A hot-cathode arc in cesium vapor has been studied by the use of a plane Langmuir probe to investigate the potential distribution, electron temperature and electron density in the plasma. The range of arc currents and vapor pressures over which satisfactory probe measurements may be made are determined.

In some cases it was possible to maintain the discharge with a total arc drop of less than the ionization potential of cesium (3.87 volts). Potential "humps" along the arc are shown to be absent, and ionization by the high-energy electrons of a Maxwellian electron velocity distribution is found unsatisfactory as a possible mechanism for positive ion production in the arc. The mechanism of successive electron collisions can account for the observed ionization on the assumption that the effective lifetime in the excited state is increased by the process of the imprisonment of resonance radiation.

* This paper is an abridged version of a thesis submitted in June, 1949, at the Massachusetts Institute of Technology, in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Department of Physics.



HOT-CATHODE ARCS IN CESIUM VAPOR

I. Introduction

The principal purpose of this work was to obtain information which would lead to a better understanding of the mechanism by which positive ions are produced in an electric arc in cesium vapor, particularly when the total voltage across the arc is less than the ionization potential of cesium. Although various explanations for low-voltage arcs have been advanced, none of them seems to enjoy universal acceptance.

Of these explanations, at least four appear to be plausible. One is that the potential gradient is not uniform along the length of the arc, but instead, a potential "hump" may exist somewhere in the arc, and there may be two points or regions with a potential difference at least as great as the ionization potential. Another explanation involves the existence of oscillations in the arc. These oscillations may be of the relaxation type at frequencies of the order of kilocycles per second, or they may be, crudely speaking, bunches of electrons or positive ions vibrating in the electric fields produced by their own displacements from their equilibrium positions. The frequencies of the latter type of oscillations may be as high as thousands of megacycles per second. With oscillations in the arc, there is the possibility that potential differences greater than the ionization potential of the gas will be present even when the average total arc drop is much less. A third explanation is based on the fact that probe measurements on the plasma of an arc usually indicate that the velocity distribution of the electrons is reasonably close to Maxwellian, at least over the range of energies for which probe measurements can be made. Without attempting to give a detailed explanation of how the high electron energies are attained, this velocity distribution function is assumed to be obeyed for all energies. Then from the probability of ionization function of the gas under consideration, it is ascertained that the number of electrons with energies greater than the ionization potential is sufficient to create ions as fast as they diffuse from the plasma to the walls. The fourth explanation does not require that a single electron deliver the entire amount of energy necessary for ionization; rather, it suggests that it is possible for an electron to deliver only enough energy to excite an atom, with the remainder of the ionization energy coming from one or more successive collisions with other electrons. For reasons to be explained, this last mentioned mechanism is believed to be the one by which the cesium vapor arc is maintained.

Only a small amount of work on cesium vapor arcs has been reported. A series of papers by Mohler (1) is probably the most outstanding.

II. The Experimental Tubes

Two tubes were constructed. The first, which will be referred to as tube No. 1, contained a plane nickel cathode and a plane tantalum anode, both 2.5 cm in diameter, mounted in a glass tube with an inside diameter of 5.3 cm. The cathode and anode were mounted on a glass and quartz assembly which could be moved along the axis of the tube by tilting the tube and shaking it slightly. The cathode-to-anode separation was 12.7 cm. Both the anode and cathode were constructed with built-in tungsten heaters capable of raising their temperatures to at least 1000°C. Low-resistance, flexible, copper wire was used for making connections between the movable assembly and the lead-ins through the glass envelope. Actually, for most of the measurements, the cathode heater was turned off entirely because the arc itself caused sufficient heating to maintain the required thermionic emission.

A plane tantalum probe with a diameter of 0.25 cm was installed in tube No. 1 about 1 cm from the tube wall and with the plane of the probe parallel to the tube axis. The variation in position of the probe with respect to the arc was obtained by moving the cathode-anode assembly. A small glass tube was placed over the probe lead and the edge of the probe so that only the front surface of the probe "faced" the discharge. The same material was chosen for the anode and the probe to eliminate the uncertainty in the potential measurements which would otherwise arise from the contact difference of potential between different materials. In the case of cesium vapor, this difference would be particularly difficult to evaluate because cesium condenses on various surfaces to a thickness of the order of one atomic layer even when the temperature of the surface is hundreds of degrees centigrade higher than the temperature of the cesium supply. This layer of cesium lowers the work function of the surface by as much as 3 ev in some cases. The amount of lowering is strongly dependent on the fraction of a monatomic layer present and therefore dependent on the temperature.

Although annoying when making potential measurements, the cesium layer could be put to good use at the cathode. Thermionic currents of at least 2 amp/cm² were attainable at cathode temperatures lower than 800°C because of the lowering of the work function of the cathode surface by the cesium. A text by Reimann (2) includes a more extensive discussion of the phenomenon together with references to original literature.

The cesium supply was contained in an appendix to the tube which consisted of a glass tube about 6 in. long. The cesium temperature, and therefore the vapor pressure, was controlled by the temperature of an oven which enclosed the appendix. To prevent bulk condensation of the cesium

on the glass walls where it would cause low-resistance leakage paths between the various leads, a separate oven which could be maintained at a temperature higher than the temperature of the cesium was constructed for the main body of the tube. A glass window was installed in one side of the oven to provide a means for viewing the arc.

Tube No. 2 contained a series of probes in line as a means for measuring various plasma properties as functions of distance along the arc. In tube No. 2, the diameter of the front face of the cathode was 4.3 cm and the inside diameter of the glass tube was 4.6 cm. The anode was simply a disc 4.3 cm in diameter. The material for both the cathode and anode was tantalum. Four plane probes, each similar to the one used in tube No. 1, were mounted in a line along the length of the tube, and the distances from the center of the probes to the anode were 0.5, 2.5, 12.5 and 14.7 cm. The cathode-to-anode separation was 15.2 cm.

Both tubes were baked at 500°C for one hour, and the cathode and anode of each were heated to a bright red for several minutes either by means of their heaters or by radio frequency induction heating. The pressure at the time the tubes were sealed off the vacuum system, as indicated by an ionization gauge, was about $(3)10^{-6}$ mm Hg. This reading corresponds roughly to the vapor pressure of cesium at room temperature and is the highest vacuum that could be expected.

III. Cesium Vapor Pressure and Atom Density

The most recent and probably the most accurate vapor pressure data which were found were those of Taylor and Langmuir (3). They measured the vapor pressure up to a temperature of 73°C by utilizing a method which makes use of the fact that practically every cesium atom which strikes a hot tungsten surface leaves as a positive ion. From their data, they derived the following formula for the vapor pressure of cesium in equilibrium with the liquid state:

$$\log_{10} p = 11.0531 - 1.35 \log_{10} T - \frac{4041}{T} \quad (1)$$

where p is the pressure in millimeters of mercury, and T is the temperature of the cesium in °K. They claim an accuracy of 3 percent up to 327°C and 8 percent up to 727°C when extrapolating the curve beyond the range over which data were taken. Table I shows the cesium vapor pressure and atom density at various temperatures as determined from Eq. (1) and the equation of state.

Table I. Cesium Vapor Pressure and Atom Density

Temperature °C	Vapor Pressure mm Hg	Atom Density per cc
30	0.0000023	$(7.3)10^{10}$
100	0.00054	$(1.4)10^{13}$
150	0.0089	$(2.0)10^{14}$
200	0.079	$(1.6)10^{15}$
250	0.45	$(8.3)10^{15}$
300	1.9	$(3.2)10^{16}$

IV. Plasma Potential

The usual Langmuir technique was used for making measurements of the plasma potential. A text by Loeb (4) includes a discussion of the method and its limitations.

It was found that there was a rather limited range of arc currents over which reliable probe measurements could be made. Oscillations with frequencies in the range from 1000 to 10,000 cps would occur in the arc when the arc current was reduced below a certain critical minimum value. This minimum was a function of vapor pressure (cesium temperature) and was lower at the higher pressures, as shown in Fig. 1. The amplitude of these oscil-

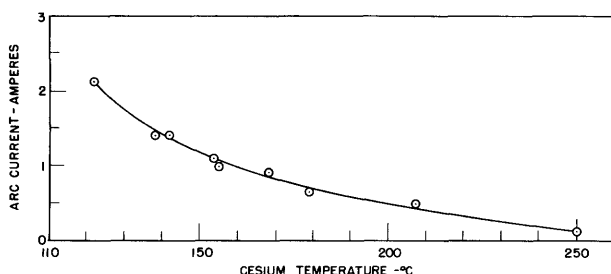


Fig. 1 Minimum arc current for non-oscillating condition as a function of cesium temperature (tube No. 1).

lations depended upon several parameters including vapor pressure, cathode temperature and arc current, but they usually had an amplitude of the order of 1 volt as indicated by an oscilloscope connected across the anode and cathode. Since the oscillations could not be eliminated by circuit modifications, the measurements reported below apply only to those values of arc current for which no oscillations existed.

The upper limit to the arc current at which reliable probe measurements could be made was set by the fact that at the higher arc currents the probe characteristic curve did not have a well defined bend in it, or it had no bend at all, at plasma potential. Instead, the probe current would continue to rise as the probe voltage was increased until the probe was drawing the entire arc current. Also, the probe currents obtained at the

higher arc currents were sufficient to cause probe heating, which, because of the cesium layer, changed the work function of the probe and introduced another source of error in the measurements. With tube No. 1, good probe characteristic curves were obtained with arc currents up to 3 amp, and up to 1.9 amp with tube No. 2. The limitations just described were such that no reliable probe measurements at all could be made at cesium temperatures below about 150°C. Measurements were not made at cesium temperatures higher than 250°C because of possible damage to the tubes by chemical attack by cesium.

Sample logarithmic plots of probe characteristic curves are shown in Fig. 2.

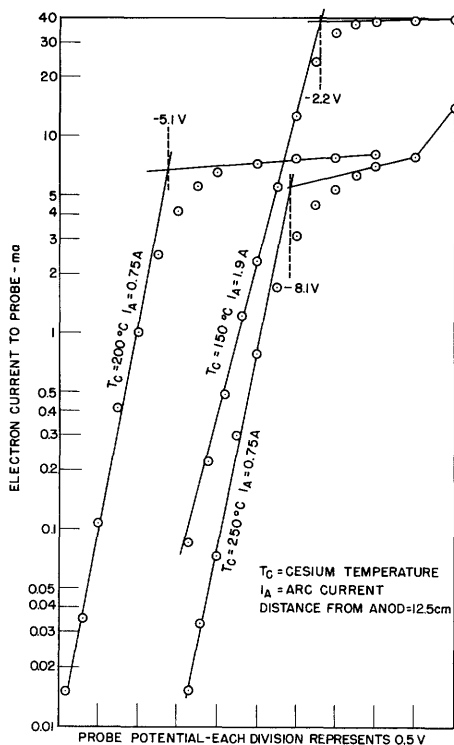


Fig. 2
Sample potential determinations
(tube No. 2).

Probe data taken at potential negative with respect to floating potential were found to be of little value. Figure 3 shows the negative portion of the probe characteristic curves taken with the plane probe in tube No. 1 when the cesium temperature and arc current were held constant at 175°C and 3 amp respectively, but when the main oven was at various temperatures from 223°C to 301°C. The lower oven temperatures appear to cause a much greater positive ion current to the probe. Similar sets of curves were obtained at cesium temperatures of 125°C and 250°C. It was discovered that even when the oven temperature was much higher than the cesium temperature, enough cesium would condense on the glass surfaces in the tube to cause leakage which, although small, was great enough to cause substantial errors in the measurement of positive ion currents. Thus, since the plane probe was doubtlessly in contact with its glass shield, the shield could have acted as a part of the probe, with the effect of increasing its area. The increase in leakage resistance with temperature would then account for the smaller probe currents found at the higher oven temperatures. The negative probe currents that were obtained at an oven temperature of 300°C were possibly a reasonably good measure of the positive ion current present, but, again due to the cesium layer on the surface, thermionic emission from the probe surface is of the same order of magnitude at this temperature.

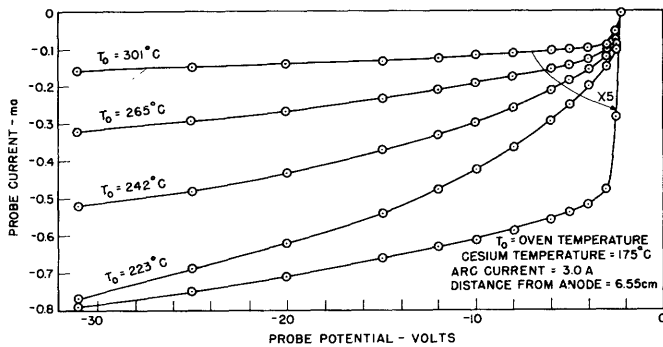


Fig. 3 Negative current portion of probe characteristic curves (tube No. 1).

From kinetic theory the relationship

$$I = n \left(\frac{kT}{2\pi M} \right)^{\frac{1}{2}} \quad (2)$$

may be obtained, where I is the random current of gas particles crossing unit area in unit time, n is the number of particles per unit volume, k is Boltzmann's constant, T is the absolute temperature and M is the mass of the particle. This equation indicates that if the electron and positive ion densities and temperatures were equal, the ratio of random electron current to random positive ion current would be equal to the square root of the ratio of the ion to electron masses. The square root of this ratio is approximately 500 in the case of cesium. In order to determine plasma potential more accurately, the positive ion current was assumed to be $1/500$ of the random electron current and this correction was applied to the measured values of probe current. The logarithmic plots so obtained (of which those in Fig. 2 are examples) were substantially linear in the region of rapidly varying electron current to the probe. The utilization of the data obtained at probe potentials more negative than floating potential was not attempted except to confirm, as near as could be ascertained, the fact that 500 was a reasonable value for the electron-ion current ratio.

Experimental work on mercury vapor by Robert Howe at the Massachusetts Institute of Technology, and by others, has indicated that the random electron-ion current ratio is actually less than the square root of the mass ratio in spite of the fact that the electron temperature is usually found to be quite high. In the plasma potential determination, a considerable variation in the ratio which is used causes only a small variation in the potential measurement.

For tube No. 1 the plasma potential, referred to the anode as a function of distance from the anode, is shown plotted in Fig. 4 for various cesium temperatures and arc currents. It was intended to take data with the probe at positions close to the cathode but the movable assembly became

damaged before this was accomplished. However it happened to be possible to take some data using the tantalum electrode as the cathode and the nickel electrode as the anode, with a cathode-to-anode separation of 8.5 cm and with the probe 0.9 cm from the cathode. The data so taken are represented by crosses and dotted lines in Fig. 4. The indication is that the plasma potential is at least a reasonably linear function of distance to within 0.9 cm from the cathode. Most of the data were taken with the cathode heater current turned off entirely and the arc itself was used as a source of cathode heating power. In order to obtain electrons for starting the arc it was necessary to use the cathode heater.

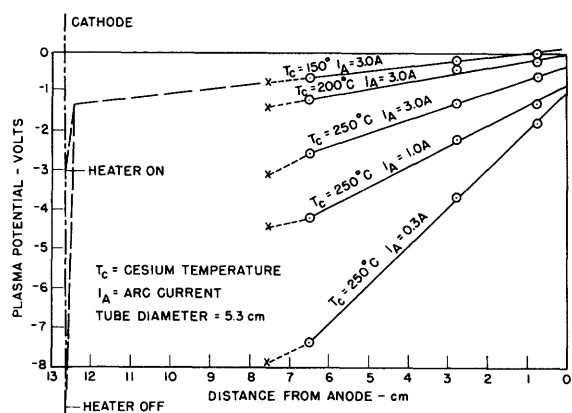


Fig. 4 Plasma potential (tube No. 1).

below the value obtained without the heater. Excessive heating caused the cesium layer to evaporate faster than it was deposited, so that in spite of the increased temperature, the resulting increase in work function of the cathode surface caused a reduction in the available thermionic emission and an increase in arc drop. At a cesium temperature of 150°C and an arc current of 3 amp, for example, the total arc drop was 9 volts with the heater off. By using the heater, the drop could be reduced to a value as low as 3 volts. This example is shown graphically in Figure 4.

The results, to be described later, obtained with tube No. 2 indicate that a linear extrapolation of the plasma potential to within 0.5 cm of the cathode is justified. Table II indicates the arc drops which were recorded at the times the probe data were taken.

Table II. Total Arc Drop (Tube No. 1)

Cesium Temperature °C	Arc Current Amp	Arc Drop Volts
150	3.0	3.0 - 9.0
200	3.0	6.6 - 7.8
200	1.0	6.0 - 10.4
250	3.0	5.5 - 10.7
250	1.0	8.2 - 13.5
250	0.3	21.5

With the tantalum cathode and nickel anode, the arc drop could be made as low as 2 volts. It was possible, though difficult, to reproduce these minimum values; the difficulty arose from the fact that it was necessary that a large portion of the cathode be at the optimum temperature for thermionic emission and that the cathode heating by the arc tended to make the temperature non-uniform. The important point here, however, is that the potential of any point in the plasma when referred to the anode was found to be independent of cathode temperature and total arc drop. Several readings of potential were made under different conditions of arc drop and in each instance, even though the arc drop varied as much as 6 volts (the largest variation recorded), the potential of the plasma with respect to the anode stayed the same within experimental error, which was estimated to be about 0.1 volt. If the 150°C-3 amp curve is considered again, it is seen that the negative anode fall is no greater than about 0.2 volt, and that with a total arc drop of only 3 volts there are no two points in the discharge with a potential difference as great as the ionization potential of cesium (3.87 volts).

The plasma potential measurements obtained from tube No. 2 are shown plotted in Fig. 5. It can be seen that they agree both qualitatively and quantitatively with those obtained from tube No. 1 if consideration is given to the fact that the cross-sectional area of tube No. 2 was only 0.75 times as great as that of No. 1.

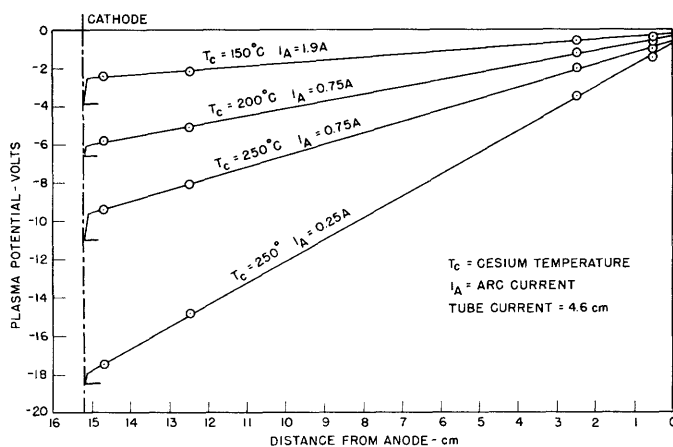


Fig. 5 Plasma potential (tube No. 2).

Most of the data taken with tube No. 2 were taken with the cathode heater turned on and adjusted to yield minimum obtainable total arc drop. The total arc drop is indicated for each curve at the left edge of Fig. 5. The curve corresponding to a cesium temperature of 150°C and an arc current of 1.9 amp shows no indication that there are two points in the tube with a potential difference greater than the ionization potential of cesium, a result similar to that obtained from tube No. 1. Cathode falls of from 0.8 to 1.5 volts were found.

The total arc drop as a function of arc current for tube No. 2 at the three vapor pressures studied is shown plotted in Fig. 6. For each curve the points represent the lowest drop which was attainable with the

particular cathode which happened to be in use. For the higher arc currents, i.e. above about 3 amp, the heating of the cathode by the arc itself was

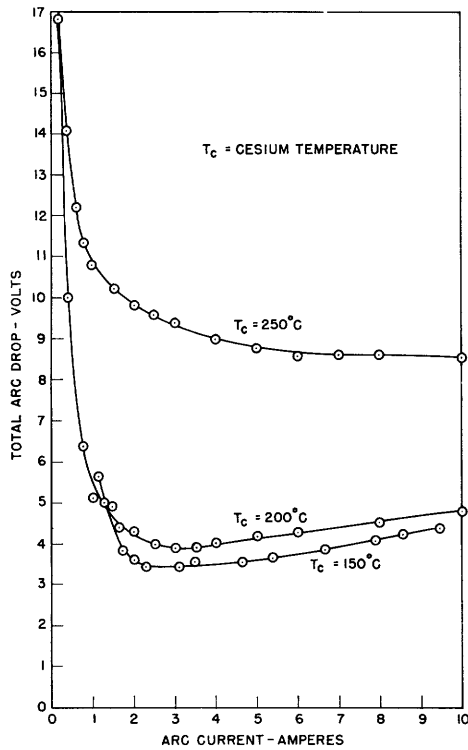


Fig. 6 Arc voltage vs. arc current (tube No. 2).

sufficient to cause the cathode temperature to rise above optimum value for thermionic emission. Therefore it was necessary, in obtaining these data, to measure the arc drop immediately after starting the arc. Within a few seconds the arc drop would rise by as much as a volt or more above its initial value. If the cathode had been capable of emitting even greater thermionic currents the total arc drop might have been less because there was no apparent lower limit to the cathode fall other than zero.

The random electron current as a function of distance along the arc for two typical cases is shown in Fig. 7. The random current near the cathode was high, as shown, when the cathode heater was used to enable the cathode to emit a copious supply of thermionic electrons. When the heater was turned off, making it necessary for the arc itself to heat the cathode through the high cathode fall thus created, the random electron current near the

cathode was as much as an order of magnitude less. This effect was in spite of the fact that no measurable difference in the space potential was noted.

An indication of the electron temperature may be obtained from the slope of the curve representing the logarithm of the electron current to the probe as a function of probe potential. Actually, the term "temperature"

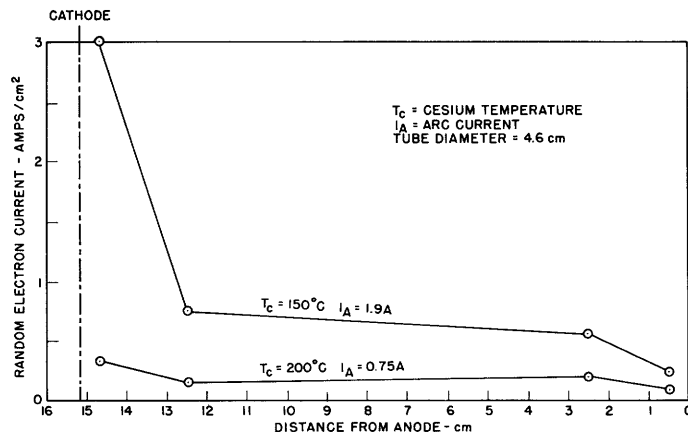


Fig. 7 Random electron current density (tube No. 2).

does not have a well-defined meaning when applied to the particles in the plasma of an arc; nevertheless, the temperature obtained in this manner is

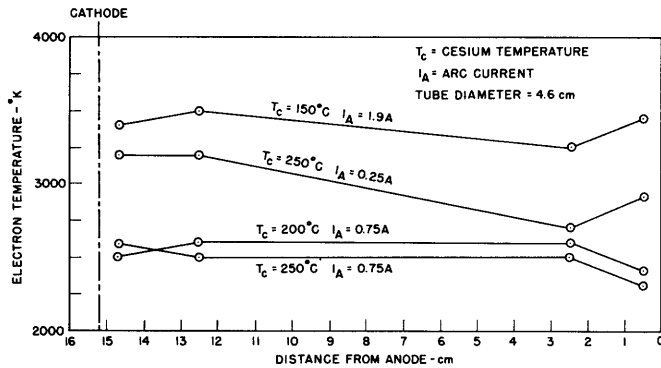


Fig. 8 Electron temperature (tube No. 2).

plotted as a function of distance along the arc in Fig. 8. Both of these sets of data were obtained with the four plane probes in tube No. 2. Similar results were obtained with tube No. 1.

V. Oscillations

Except for the low-frequency oscillations, previously mentioned, which occurred when the arc current was reduced below a certain critical value, no oscillations were found. During all of the runs an oscilloscope which was responsive to frequencies up to 2 Mc was connected across the anode and cathode of the tube to check for the existence of oscillations, and data were taken only when no oscillations were indicated.

A search was made under various conditions of arc current and vapor pressure for oscillations at frequencies higher than might have been indicated on the oscilloscope. To carry out the search, a radio communications receiver, a radar search receiver and a crystal detector were employed in conjunction with various tuned circuits and Lecher wires connected in the arc circuit. A failure to find oscillations, no matter how thorough the search, does not establish the fact that no oscillations were present; however it is believed to have been reasonably well established that no oscillations were present at frequencies below an upper limit of about 10,000 Mc/sec. According to a derivation given by Tonks and Langmuir (5), it is possible for electron oscillations in a plasma to occur at a frequency of $(8980)n^{1/2}$ where n is the number of electrons/cm³. The highest electron density found in the range of arc currents and vapor pressures over which data were taken was $(1.6)10^{12}$ electrons/cm³. This density was obtained near the cathode of tube No. 2 when the cesium temperature was 150°C and the arc current was 1.9 amp, and it would imply a frequency of 12,000 Mc which might have been higher than the crystal was capable of

detecting. However, 12,000 Mc is an upper limit to the possible frequency, and even under the same arc conditions the electron density near the anode was $(1.6)10^{11}$ electrons/cm³. This density would indicate a frequency of 3,600 Mc, which was known to be within the range over which the detecting instruments would function.

High-frequency oscillations have been reported occasionally in connection with tubes containing arcs, and certainly can be obtained with tubes of special design. The existence of the oscillations so found is usually not assured by the mere presence of the arc but is critically dependent on such factors as arc current and potentials of the various electrodes that may be present in the tube. The evidence is not strong that the oscillations that have been found were caused by electron resonances of the type described by Tonks and Langmuir. Some of the difficulties of the electron resonance theory are discussed by Neill (6) and by Armstrong (7).

It is believed that there is little evidence to support a theory of ionization based on oscillations, particularly since, even if their existence were established with certainty, it would yet remain to be shown that they had sufficient amplitude to produce ionization. On the other hand, the present failure to detect oscillations is an indication that the ionization could not have been dependent upon them.

VI. Ionization by Electrons with a Maxwellian Velocity Distribution

The number of ions lost to the walls per centimeter-length of tube may be obtained experimentally and is given by the expression $2\pi R i_+ / e$, where R is the radius of the tube in centimeters, i_+ is the positive ion current in amp/cm² as determined by probe measurement, and e is the electronic charge expressed in coulombs. For the range of atom density for which the discharge fills the whole tube, the number of ionizing collisions/electron/sec is then

$$\alpha = \frac{2\pi R i_+}{e \pi R^2 n} = \frac{2 i_+}{e R n} \quad (3)$$

where n is the number of electrons/cm³, and, for the examples to be considered, it will be assumed that n is not strongly dependent on distance from the axis of the arc. If their velocity distribution is Maxwellian, the number of electrons/cm³ with velocities between v and v + dv cm/sec is

$$nf(v)dv = 4\pi n \left(\frac{m}{2\pi kT} \right)^{3/2} v^2 e^{-\frac{mv^2}{2kT}} dv \quad (4)$$

where m is the mass of the electron in grams, k is Boltzmann's constant expressed in ergs per degree, and T_e is the electron temperature in °K. The number of ionizing collisions/sec that will be produced by an electron of velocity v is PvN/N_0 where N is the number of atoms/cm³ present, N_0 is equal to $(3.5)10^{16}$ and is the number of atoms/cm³ when the temperature and pressure are 0°C and 1 mm Hg respectively, and P is the probability of ionization per centimeter-length of path when N_0 atoms/cm³ are present. Note that P is the product of the atomic cross section for ionization and N_0 . The number of positive ions/cm³ produced per second by electrons with velocities between v and $v + dv$ is then

$$4\pi n \left(\frac{m}{2\pi k T_e} \right)^{3/2} P \frac{N}{N_0} v^3 e^{-\frac{mv^2}{2kT_e}} dv \quad (5)$$

If the substitution

$$v = \left(\frac{2Ve10^7}{m} \right)^{1/2} \quad (6)$$

where V is the electron energy expressed in electron volts, is made, expression (5) takes the form

$$(8)10^{14} \pi n \left(\frac{m}{2\pi k T_e} \right)^{3/2} \frac{e^2}{m^2} P \frac{N}{N_0} V e^{-\frac{eV}{kT_e} 10^7} dv \quad (7)$$

The probability of ionization for cesium is not known, but it will be assumed for the purpose of this calculation that it is zero for electron energies less than the ionization potential V_1 , and is constant with a value P_1 , at all energies above V_1 . After dividing by n , an integration of expression (7) from $V = V_1$ to $V = \infty$ yields the number of positive ions α' formed per second per electron. The result is

$$\alpha' = (2.0)10^{-7} \frac{P_1 N}{T_e^{3/2}} e^{-\frac{(1.16)10^4 V_1}{T_e}} \left(V_1 + \frac{T_e}{(1.16)10^4} \right) \quad (8)$$

where V_1 is in volts.

By using the data obtained from tube No. 2 when the cesium temperature was 150°C and the arc current was 1.9 amp, for example, it was found that α , as computed from Eq. (3), was approximately 16,700 ionizing collisions/electron/sec. Although i_+ and n vary along the length of the plasma, they

vary in approximately the same fashion so that α is reasonably constant. As described previously, i_+ was taken as 1/500 of the random electron current. Then, upon using 3.87 volts for V_1 and 3400°K for T_e , it was found by equating α to α' that P_1 must be at least 3000 ions/electron/cm of path. Data for the probability of collision taken by Brode (8) indicate that it is 650 collisions/cm at V_1 and drops off considerably at higher electron energies. Brode's probability of collision includes elastic and exciting collisions as well as ionizing collisions. From these results it is concluded that the number of electrons with sufficient energy for ionization which is made available from the Maxwellian distribution is not adequate to sustain the plasma. The results of additional examples are shown in Table III.

By working along similar lines Killian (9) concluded that, for mercury vapor, the ionization produced by this mechanism was sufficiently great in some cases to make up for the loss of ions caused by diffusion to the walls. However he obtained values for electron temperature up to 38,000°K, which is rather high and is an indication that his arc was possibly oscillating. Because of the exponential term, α' is a rapidly varying function of temperature, and if the true temperature were even slightly less the mechanism would have been found insufficient in all cases. It should be noted that oscillations do not necessarily afford an explanation for the presence of high-energy electrons or the existence of a high electron temperature, as is sometimes implied (9)(10). It is easy to see, though, why oscillations might cause probes to indicate, erroneously, high-energy electrons or high electron temperatures. The explanation lies in the fact that, over a portion of the oscillation cycle, the probe at any potential setting is more positive with respect to the plasma than it would be in the absence of oscillations, and an increased electron current to the probe is produced. Because of the exponential current-probe potential relationship, the decrease in electron current that occurs over the opposite portion of the cycle does not cancel the effect. Thus at all probe potentials negative with respect to the average plasma potential, the electron current to the probe could be misleadingly large in the presence of oscillations.

An additional difficulty with the theory which assumes a Maxwellian velocity distribution of electrons lies in the inability to explain how the supply of high-energy electrons is maintained in view of the fact that the number of high-energy electrons would be expected to be diminished because of the inelastic (exciting and ionizing) collisions which occur. It is somewhat surprising that probe measurements indicate conformance to a Maxwellian distribution over as wide a range as they do, but this conformance

is not a good reason to extrapolate the results beyond the range of the measurements which seldom extend to energies much higher than that corresponding to ionization potential. Further, measurements on the high energy electrons are subject to considerable error because of the uncertainties involved in extrapolating that portion of the probe characteristic curve which supposedly represents positive ion current.

VII. Ionization by Successive Collisions

The successive-collision hypothesis was suggested as far back as 1925 (11)(12)(13), but unless certain other phenomena are taken into consideration, which was not always done, ionization by successive collision appears unlikely. The reason is that the lifetime of an excited state is so short compared with the average time between collisions that there is only a small probability that an excited atom will still be excited by the time a second electron strikes it. If the case of an arc current of 1.9 amp and a cesium temperature of 150°C is taken as an example, and if Eq. (8), which assumes zero probability at energies below a certain critical value and a constant probability at higher energies, is employed, it is found that the number of excited atoms created per second per electron is $(8.1)10^3 P_e$. P_e is the probability of excitation, and the first critical potential of 1.48 volts was used. Now if $(4.8)10^{11}/\text{cm}^3$ is taken as the electron density and if the average lifetime of an excited state is 10^{-8} sec, it is found that the density of excited atoms is approximately $(3.9)10^7 P_e/\text{cm}^3$, which is about $(1.9)10^{-7} P_e$ times the density of unexcited atoms. Since an additional 2.39 ev are required to ionize an atom which has already been excited to the lowest excitation level, a second application of Eq. (8) indicates that the number of ions produced per second per electron is about $(1.1)10^{-4} P_e P_i^1$, where P_i^1 is the probability of ionizing an excited atom if all the atoms were excited. In correspondence with the units used above, the atomic cross section for ionization of an excited atom is equal to P_i^1/N_0 . When the result just obtained is compared with α , the necessary number of ions/sec/electron (16,700 for this example), it is seen that the product $P_e P_i^1$ must be at least $(1.6)10^8$ which is rather high. The assumption of a Maxwellian distribution of electron energies is possibly more justified in this case because the energies under consideration are not so great.

The phenomenon of imprisonment of resonance radiation is yet to be considered, and according to Holstein (14) the lifetime of an imprisoned light quanta in cesium vapor over a pressure range of 0.01-1 mm Hg is $(1.2)10^{-5} R^{1/2}$ sec, where R is the radius in centimeters of an infinitely long tube. Since it makes no difference which atom is excited, the passing of resonance radiation back and forth among the atoms has the effect of

increasing the lifetime of an excited state by over 10^3 in the present case.

Also, according to Klarfeld (13), the probability of ionization for excited atoms may be at least 10 times the probability for ionization from the ground state. The higher probability seems feasible when it is remembered that the wave function of an excited atom is much more spread-out than the wave function of an atom in the ground state. Thus when these two factors are considered it is found that P_e need not be greater than the square root of $(1.6)10^4$ or approximately 130/cm. This result causes ionization by successive collisions to appear more plausible. Additional examples are included in Table III.

Table III. Data Taken from Tube No. 2

Cesium Temperature, °C	150	200	250	250
Atom Density, per cc	$(2.0)10^{14}$	$(1.6)10^{15}$	$(8.3)10^{15}$	$(8.3)10^{15}$
Arc Current, amp	1.9	0.75	0.75	0.25
Electron Temperature, °K	3400	2600	2500	3000
Electron Density, per cc	$(4.8)10^{11}$	$(1.4)10^{11}$	$(9.5)10^{10}$	$(1.9)10^{10}$
Necessary P_1 , per cm (See Section VI)	3000	18,000	66,000	380
Necessary P_e , per cm (See Section VII)	130	410	290	72

VIII. Conclusion

Various properties of hot-cathode arcs in cesium vapor have been measured. In an effort to determine the mechanism by which the plasma of the arc is maintained it has been observed that no potential "humps" exist in the plasma, and, under certain conditions, no oscillations could be found. Sufficient ionization by the high-energy electrons of a Maxwellian distribution appears unlikely. If the phenomenon of imprisonment of resonance radiation is taken into consideration, it has been shown that ionization by successive collisions is a plausible mechanism for plasma maintenance in spite of the short lifetimes of the excited states.

Acknowledgment

I wish to thank Prof. W. B. Nottingham, under whose direction the work was carried out, for the many helpful suggestions received. I also wish to thank Dr. A. W. Hull of the General Electric Company Research Laboratory, Schenectady, New York, for suggesting the problem and for assistance received in the preparatory phase of the work.

References

1. F. L. Mohler, U.S. Bur. Stand. J. Res. 9, 25, 493 (1932); 10, 771 (1933); 16, 227 (1936); 17, 849 (1936); 21, 697 (1938). C. Boeckner, F. L. Mohler, U.S. Bur. Stand. J. Res. 10, 357 (1933).
2. A. L. Reimann, "Thermionic Emission," p. 135 ff., Wiley, N. Y. (1934).
3. J. B. Taylor, I. Langmuir, Phys. Rev. 51, 753 (1937).
4. L. B. Loeb, "Fundamental Processes of Electrical Discharge in Gases," pp. 232-257, Wiley, N. Y. (1939).
5. L. Tonks, I. Langmuir, Phys. Rev. 33, 195, 990 (1929).
6. T. R. Neill, Nature 163, 59 (1949).
7. E. B. Armstrong, Nature 160, 713 (1947).
8. R. B. Brode, Phys. Rev. 34, 673 (1929).
9. T. J. Killian, Phys. Rev. 35, 1238 (1930).
10. N. L. Oleson, C. G. Found, J. Appl. Phys. 20, 416 (1949).
11. K. T. Compton and C. Eckart, Phys. Rev. 25, 139 (1925).
12. W. Fabrikant, Techn. Phys. U.S.S.R. 5, 864 (1938).
13. B. Klarfeld, Techn. Phys. U.S.S.R. 5, 913 (1938); Comptes Rendus de l'Acad. des Sciences U.S.S.R. 24, 251 (1939).
14. D. Alpert, A. D. McCoubrey, T. Holstein, Phys. Rev. 76, 1257, 1259 (1949). (The information on cesium vapor was contained in a private communication from Holstein.)

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