POST-ARC CONDUCTIVITY AND METASTABLE STATES IN MERCURY

By M. L. Pool

Abstract

A mercury arc, excited between an anode and a Wehnelt cathode, was interrupted by a relay run by a rotating commutator. By means of a second relay run by the same commutator galvanometric current measurements could be made at any instant before or after the arc was interrupted.

Post-arc conductivity ascribed to residual positive ions and electrons.—Residual positive ions and electrons formed during the arc have been found to remain in measureable quantities under certain conditions for 1/10 sec. after the arc has been turned off. These ions and electrons cannot be rapidly removed from the arc space by the application of potentials to collecting electrodes because there are formed about the electrodes space charge sheaths which effectively restrict the potentials applied to a small region. The *thickness of these space charge sheaths* about both the anode and cathode gradually increase with time and finally fill the entire arc space, whereupon the post-arc current ceases. For ion concentrations from 10^{12} to about 10^7 the decay of the post-arc current is closely exponential for all voltages and for various forms of collecting electrodes. For concentrations below 10^7 the decay becomes much more rapid. *The critical restriking potential*, previously attributed to the existence of long-lived metastable atoms, is accounted for by the distorted electrical fields which are set up in the neighborhood of the filament as a result of electron diffusion from a region of high electron and positive ion concentration. The location of this region in the arc space is markedly dependent upon the filament temperature. The critical restriking potential is most sharply defined for low filament temperatures and for heavy arc currents. Cathode ray oscillograph curves show that impurities do not effect the critical potential.

Introduction

Attempts to measure the life of metastable atoms have been made by various investigators within the past five years. Among the apparently more direct methods of attack there are the post-arc absorption method and the post-arc conductivity method. The former was perfected by Dorgelo,[1] and his value for the longest life of a metastable mercury atom is 1/200 sec. The latter was devised by Kannenstine[2] in his work on metastable helium. Using his method on mercury Marshall[3] has reported the value 1/22 sec. If these values are true the life of a metastable mercury atom is of the order of a hundred thousand times that of an ordinary, excited mercury atom.

But Eckart[4] has pointed out that post-arc conductivity may equally well be accounted for on the hypothesis that 1/22 sec. measures the time that

[1] Dorgelo, Physica, 429 (1925).
[2] Kannenstine, Astrophys. Journal **55**, 343 (1922); **59**, 133 (1924).
[3] Marshall, Astrophys. Journal **60**, 244 (1924).
[4] Eckart, Phys. Rev. **26**, 454 (1925).

positive ions remain in the arc space after the arc has been turned off. Among the things to be desired from a positive ion hypothesis is an explanation as to how the critical restriking potential can be accounted for and an estimate of the time required to sweep the arc space free of the residual ions.

This paper is a report of a series of experiments which have been made in order to obtain more definite knowledge regarding the characteristics of low-voltage post-arc conditions, and in particular regarding the factors upon which the critical restriking potential depends.

Apparatus and Method

A drawing of the discharge tubes used is shown in Fig. 1. A typical electric circuit is shown in Fig. 2. R_1 and R_2 are two relays run by a commutator

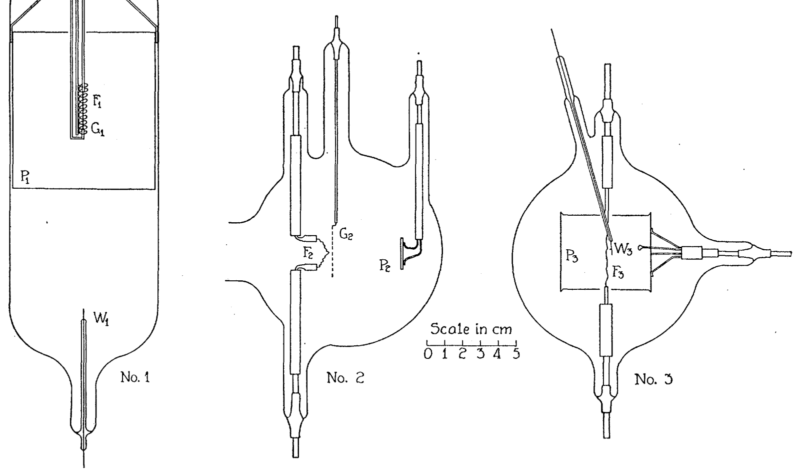

Fig. 1. Diagrams of the various tubes used. W_1 and W_3 are 4 mil tungsten wires, 1 cm long. G_1 is a nickel grid spiral supported on nickel leads. G_2 is a nickel grid 2.8×3.2 cm. P_1 is a nickel cylinder with open ends, area 214 cm^2. P_2 is a nickel plate, area 5.3 cm^2. P_3 is a nickel cylindrical can with closed ends, area 94 cm^2. F_1 is a tungsten filament, while F_2 and F_3 are oxide-coated platinum filaments.

of three segments. R_1 turns the arc on and off. By means of R_2 the galvanometer can be thrown into the circuit for any predetermined length of time (say 1/400 sec.) at any time before or after the stopping of the arc. By means of two movable sliding contacts this sampling of the current in the grid circuit at various instants could be done not only quite rapidly, but also without in any way affecting the rotation rate of the commutator. By merely a throw of a switch the galvanometer when either in the grid circuit or in the plate circuit could be replaced by a Western Electric cathode ray oscillograph. In some cases excitation of the mercury vapor was obtained by placing R_1 in the primary of an electrodeless discharge circuit.

Observations and Interpretation

A. *Post-arc currents and photoelectron emission.* Since there is ample evidence that two metastable states exist in the mercury atom and since the results of several experiments have been easily interpreted by supposing that an electron remains in either one of these states at least somewhat longer than in an ordinary excited state, one might well venture to say that in a mercury arc a large concentration of these longer lived excited atoms would be rapidly built up. If the arc is now stopped and if the electron in the metastable orbit eventually reverts to the normal level by the emission of radiation or if the metastable atom on collision with the electrode liberates electrons, one would expect it possible to detect electronic currents for an appreciable time after the stopping of the arc—especially so if the radiation is handed on from atom to atom until the energy finally escapes from the arc space.

Tube No. 1, Fig. 1, was therefore built for the purpose of measuring this anticipated current and of determining whether it were not possible to account for all post-arc conductivity by supposing that electrons are ejected from the electrodes.

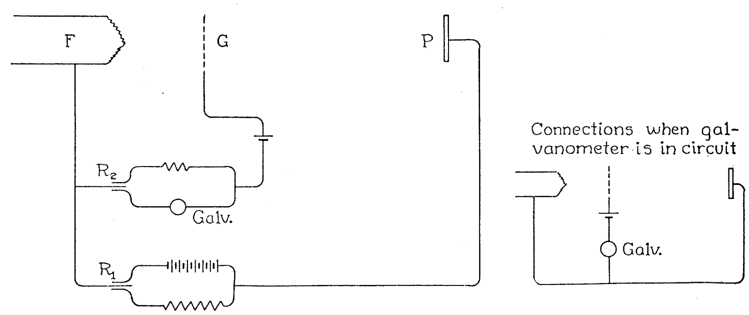

Fig. 2. Diagram of electrical circuits.

Thus in Fig. 3, the currents between the plates P_1 and filament F_1, 1/40 sec. after the arc has been turned off, are plotted as ordinates against the plate voltages as abscissas. The plate was maintained at any particular potential shown in Fig. 3 during the entire post-arc time, and 1/40 sec. after the arc had been stopped the galvanometer was put into the circuit for 1/150 sec. The potential drop across the filament was 5.6 volts and the plate voltage was measured from the positive side of the filament. It is seen that the plate current has its maximum negative value when the plate is -7.2 volts with respect to the center of the filament. As the plate voltage is made more negative the current markedly decreases and becomes virtually zero when the plate is -60 volts. If the post-arc plate current is due to photoelectron emission from the plate or to the Osterhuis effect, one would expect the current to reach a saturation value. However, if the current is due to the removing of residual ions and electrons, we can easily explain the curve observed by supposing that 60 volts applied to the plate for 1/40 sec. has practically swept the arc space free of these ions and electrons.

B. *Post-arc currents with various voltages on collecting electrode.* We shall now consider in detail the behavior of post-arc conductivity with various voltages applied to different collecting electrodes for the purpose of deciding whether or not that behavior is in accord with the assumption that only residual ions and electrons contribute to the post-arc currents observed.

Tube No. 2 as shown in Fig. 1 was used in obtaining the curves of Fig. 4. The currents between the grid G_2 and the filament F_2 are plotted against the time as measured from the instant at which the arc is stopped. The ordinates are in micro-amperes. The electrical circuit is shown diagrammatically and

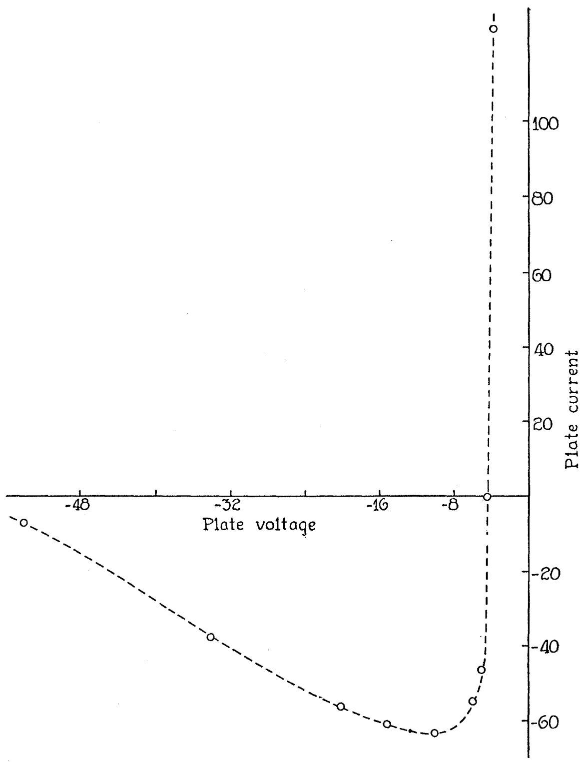

Fig. 3. Post-arc currents between P_1 and F_1 for various plate voltages 1/40 sec. after stopping the arc.

signifies that the arc was formed between the filament and the plate, and that during the time the arc was on, the grid G_2 was out of the circuit. The potential drop across the filament was 1.8 volts. When the potential applied to the plate is removed and the arc thus stopped, the grid is immediately made a few volts positive with respect to the filament; the current flowing between these two electrodes was measured by a sensitive galvanometer. The galvanometer, however, was not in the grid circuit during the entire post-arc time, as might be concluded from the abbreviated drawing. The details of the grid circuit are shown in Fig. 2. It is seen that the galvanometer can be thrown into the grid circuit (for 1/400 sec.) at various times after the arc had been stopped. The circles on the curves represent the instantaneous values of the current flowing in the grid circuit. Therefore, the smooth curve through these observed values shows how the current changes with time; the area under a curve is proportional to the quantity of electricity removed. The potential of the grid with respect to the filament is indicated at the left of each curve.

When the grid is made 3.0 volts positive with respect to the filament, it is seen from the curve +3.0 that at first the current is flowing in a direction opposite to that of the electrical field impressed. If $t=0$ designates the time when the arc is turned off, then at $t=0.005$ sec. the value of this negative

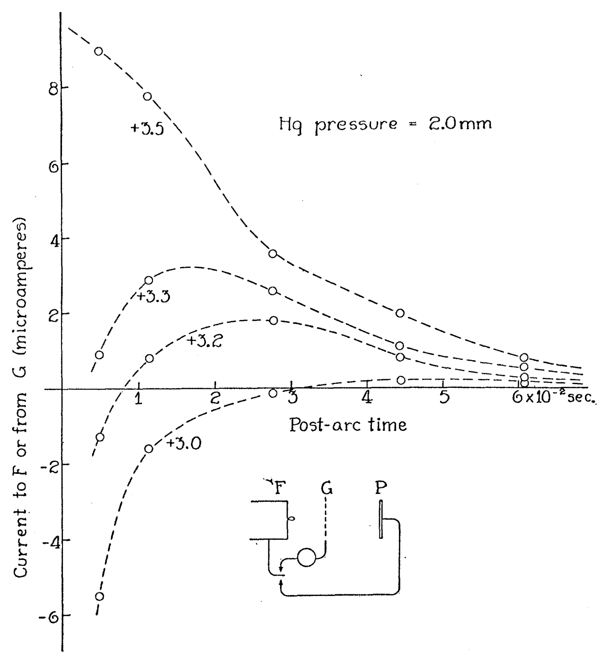

Fig. 4. Decay of post-arc currents between G_2 and F_2 when the grid potential is in the neighborhood of +3.2 volts.

current is 5.5 microamperes. This negative current persists until $t=0.03$ sec. Thereafter, a small positive current is detected which becomes virtually zero when $t=0.08$ sec.

Curve +3.3 shows that the current for all post-arc times is positive, but that the maximum current is reached only after 0.018 sec. after the arc had been turned off. Curve +3.5 shows that the current is a maximum at the beginning of the post-arc time and decreases rapidly at first and then more slowly later.

In order to interpret the above post-arc current curves it is undoubtedly necessary to bring into consideration the variation of the concentration of positive ions and electrons in different parts of the arc space. For an arc running under constant conditions concentration measurements have been made by several investigators using an exploring electrode according to the method of Langmuir.[5] The results obtained indicate that in the neighborhood of the filament there exists a region of negative space charge; between this negative space charge and the anode there is a region of high positive ion and electron concentration[6] (this region will be designated by $H\pm$); and in the neighborhood of the plate there is a region of low positive ion and electron concentration. At any instant in any small element of volume chosen outside the negative space charge about the filament, the concentrations of ions and electrons are nearly the same. In a low-voltage arc the ratio of the concentration of positive ions in the region $H\pm$ to the concentration near the anode is often as great as 100 to 1.

When the exciting potential applied to the anode is removed, it is to be expected that the ions and electrons in $H\pm$ rapidly decrease in number by recombining and by diffusing to regions of lower ion and electron concentration. It would also be expected that during this period of readjustment the current flow between the filament and an electrode, maintained at a small difference of potential, may be largely dependent upon the size of $H\pm$ and its location with respect to the electrode, and in addition upon the size of the negative space charge about the filament.

In the light of the above concepts let us, as an example, consider curve +3.2, Fig. 4. For $t=0.005$ sec. the current is flowing in a direction opposite to that of the applied field; i.e., the electrons, instead of going into the grid, are first diffusing into the filament from the region of negative space charge immediately surrounding it. The value of this electron diffusion current at this particular instant is 1.3 microamperes. At $t=0.01$ sec. the current is in the direction of the applied field and is 0.5 microamperes. This means that the electrons are diffusing about as rapidly into the filament as into the grid. At $t=0.03$ sec. the current is 1.8 microamperes. This means that the distorted fields existing immediately after the stopping of the arc have now nearly disappeared, and that the positive ions together with remaining electrons are moving under the influence of the applied potential.

C. *Influence of filament temperature on post-arc currents.* In Fig. 5 the post-arc currents in microamperes between the filament and plate of tube No. 2 are plotted as ordinates against the post-arc time as abscissas for the case in which the temperature of the filament is quite low. The arc was formed between the filament and the grid. If the filament is made very hot, the curves of Fig. 5 change over to those of Fig. 6. In Fig. 5 curve +3.3 (plate 3.3 volts positive with respect to the filament) begins with a positive value and decreases to zero for $t=0.021$ sec., has a maximum negative value for $t=0.035$ sec. and then approaches zero with increase in post-arc time. But in Fig. 6 curve +3.3 begins with a negative value, has a maximum

[5] Langmuir, Gen. Elec. Rev. **26,** 731 (1923).

[6] McCurdy, Phil. Mag. **48,** 898 (1924). Compton, Turner, McCurdy, Phys. Rev. **24,** 597 (1924). Compton and Eckart, Phys. Rev. **25,** 139 (1925). McCurdy and Dalton, Phys. Rev. **27,** 163 (1926).

positive value for $t=0.045$ sec., and then approaches zero with increase in post-arc time. The zero was the galvanometric deflection taken 1/4 sec. after the arc had stopped. The deflection then observed, due to thermionic emission from the filament, was, however, very small, especially when the plate was less than 3.5 volts with respect to the filament.

Since the curves of Figs. 5 and 6 are distinctly different in type and since they were obtained under identical conditions—barring the temperature change of the filament—we shall attempt to account for them by bringing into consideration the thickness of the electron space charge about heated filaments. If a hot filament emitting electrons is placed in a vacuum, there exists, as is well known, a negative space charge extending from the filament to the plate. If gas is admitted into the vacuum so that an arc may be formed this negative space charge existing throughout the tube contracts

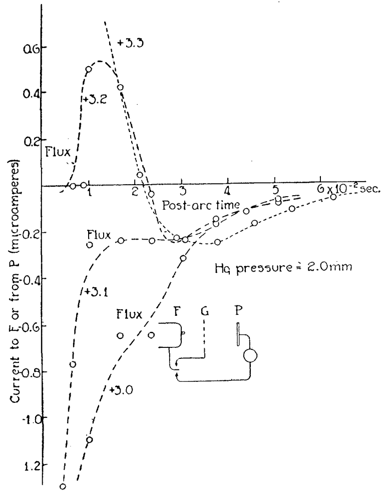

Fig. 5.

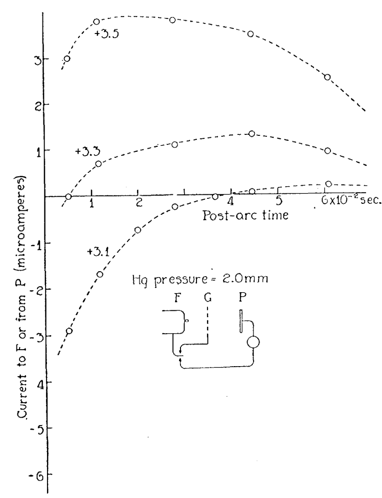

Fig. 6.

Fig. 5. Post-arc currents between G_2 and F_2 for low filament temperature, showing critical potential at $+3.2$ volts.

Fig. 6. Post-arc currents between P_2 and F_2 for high filament temperature.

inward toward the filament. If the filament is quite hot, the thickness of the negative or electron space charge, even for heavy arc currents, may be several millimeters. However, if the temperature of the filament is decreased, the thickness of the space charge decreases also. If the temperature is sufficiently decreased so that every electron emitted by the filament is immediately removed, the electron space charge becomes virtually zero.[7] Under these conditions where ionization is present there exists a thin positive ion space charge closely surrounding the filament. Surrounding this positive space charge is the region $H\pm$.

The curves in Figs. 5 and 6 may be interpreted then in the following way: For example, in curve $+3.3$, Fig. 5, when $t=0.01$ sec. we see that positive

[7] Compton, Turner and McCurdy, Phys. Rev. **24**, 597 (1924).

ions are moving into the filament and continue to do so until $t=0.03$ sec. In curve $+3.3$ of Fig. 6 the electron diffusion into the filament from the negative space charge about the filament reduces the positive current to a low value. This electron diffusion current in curve $+3.1$ predominates until $t=0.04$ sec. In curve $+3.1$ of Fig. 5 the diffusion of electrons from $H\pm$ through the positive ion space charge about the filament is so great that the observed current is negative during the entire post-arc time.

The points of significance brought out in the above three sets of curves are that the post-arc currents vary with time in a rather complicated manner, that there exists a critical potential about which the current curves change very rapidly in form, and that the behavior of these currents with respect to change in filament temperature and for various voltages upon collecting electrodes can be accounted for by residual ions and electrons.

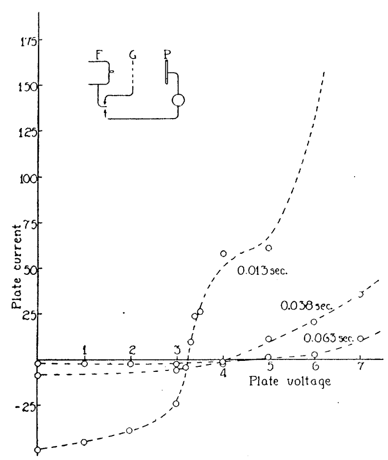

Fig. 7.

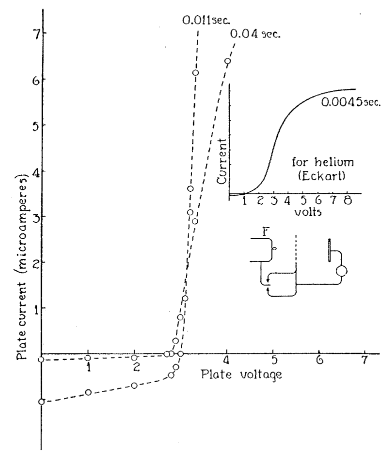

Fig. 8.

Fig. 7. Post-arc currents between P_2 and F_2 for constant time-waits after stopping the arc, low filament temperature.

Fig. 8. Post-arc currents between P_2 and F_2 for constant time-waits, medium filament temperature. Insert is Eckart's curve for helium where the time-wait was 0.0045 sec.

The curves to be considered immediately following verify and bring out under different conditions the phenomena already considered and indicate that the critical restriking potential observed in low-voltage arcs does not necessitate the existence of long-lived metastable atoms, but that the critical potential may be due to the peculiar potential gradients existing in the arc space.

D. *Post-arc currents for constant time-waits.* Experiments were made with tube No. 2 in which the post-arc current in the plate circuit was measured as a function of the plate voltage for constant time-waits after the stopping of the arc. In Fig. 7 the current in the plate circuit at $t=0.013$ sec. is negative until the plate is raised to $+3.2$ volts with respect to the filament; thereafter, the current is positive for greater plate voltage. If, however, $t = 0.038$ sec., the plate current is negative until the plate is raised to $+4.2$ volts. These curves were obtained when the filament temperature was quite low and are in good agreement, as may be seen, with the curves in Fig. 5.

With an increase in filament temperature the curves of Fig. 8 were obtained. As before the plate current at a given time-wait is plotted against the plate voltage. It is seen that these curves are in accord with those of Fig. 6.

Eckart has made similar measurements in helium. He found that the currents increased rather slowly with increase in plate voltage and concluded that the post-arc conductivity was due not to the ionization of metastable atoms, but to residual positive ions remaining in the arc space. However,

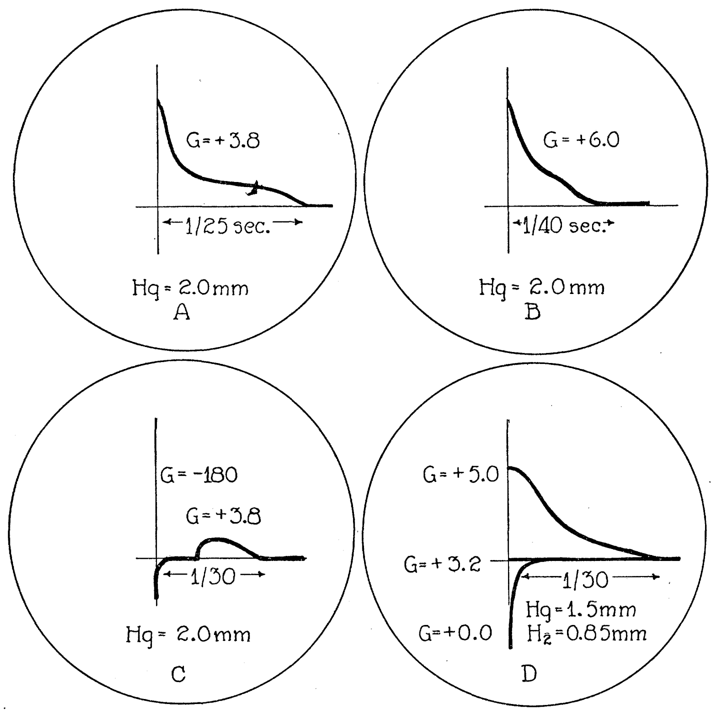

Fig. 9. Cathode ray oscillograph curves showing post-arc current decay between grid and filament as a function of grid voltage.

it is possible, as is seen in Fig. 8, to obtain curves that rise very rapidly when the plate is made about $+3$ volts with respect to the filament. One might naturally then conclude that this sudden increase in post-arc current is best explained as due to the ionizing of long-lived metastable atoms. But it will be noticed that the points at which the curves of Figs. 7 and 8 cross the axis are dependent upon the time-waits. This phenomena would be hard to account for solely by metastable atoms, but is obviously in agreement with the concept of changing potential gradients in the post-arc space due to diffusion and recombination of residual positive ions and electrons.

E. *Cathode ray oscillograph curves.* Fig. 9 shows some post-arc current curves obtained by placing a Western Electric cathode ray oscillograph between the grid and filament. The arc was formed between the filament and plate. The large circle represents the size of the screen; it is evident that detailed examination of these curves was possible. For curve A the grid was $+3.8$ volts with respect to the filament; whereas for curve B the grid was $+6.0$ volts. In the former the conductivity persisted for about 1/25 sec., in the latter the persistence was about 1/40 sec. The difference in the two curves may be accounted for by saying that in curve A the positive ions in the neighborhood of the filament move into the filament quite slowly and consequently liberate electrons from the filament for a longer time than do the more rapidly moving positive ions in curve B.

Curve D shows the type of conductivity obtained in mercury at 1.5 mm pressure when the grid is 0, $+3.2$, and $+5$ volts with respect to the filament and when hydrogen was admitted to a pressure of 0.85 mm. The introduction of air, nitrogen, carbon dioxide, helium, and argon has little or no effect upon the curves obtained. For pressures less than 0.5 mm a shorter persistence is noticed which might be expected when molecular diffusion begins to be effective. For example, if the pressure of Hg is 0.002 mm and that of H_2 is 0.01 mm, the current persists only 1/400 sec. Curves obtained with extremely pure mercury[8] were very much the same as those obtained with impure mercury.

F. *Experiments with electrodeless discharge.* In some of the experiments the mercury vapor was excited by an electrodeless discharge. While the discharge was on, the filament was hot but was disconnected from both the grid and plate. When the discharge was stopped, the grid was immediately made a few volts positive with respect to the filament. Observations made by means of the cathode ray oscillograph showed no post-arc currents at all, nor any indications of restriking until the grid was made about $+4.6$ volts. It is believed that these observations are additional evidence to support the concept of rapidly diffusing electrons with energies corresponding to the lowest radiating potential. Of course in an electrodeless discharge there does not exist any region $H\pm$, because throughout the discharge the distribution of ions and electrons is about the same. Consequently, when the discharge is stopped, approximately as many electrons would tend to diffuse in one direction as in another, and therefore large electron emission from the filament is not possible until it is made sufficiently negative to repel these diffusing electrons.

G. *Critical restriking potentials.* The experiments described above suggest that post-age conductivity is due (1) to the diffusion of positive ions and electrons from regions of high electron and positive ion concentrations to regions of lower electron and positive ion concentrations and (2) to the motion of these electrons and ions under the influence of the distorted fields existing when the arc is interrupted. Upon removing the exciting potential

[8] This mercury was upon two occasions kindly furnished by Professor W. D. Harkins; it had been distilled a great many times in his experiments on isotopes.

on the anode, the filament receives a shower of rapidly diffusing electrons; in order to repel them the filament must be made about five volts negative with respect to the region from which they come. If the filament is made still more negative, electrons in the neighborhood of the filament are driven to the plate and the arc current appears to persist for a few hundredths of a second. If the filament is able to emit electrons copiously the arc may restrike through the ionization of excited atoms that might be present in the arc space.

The question now arises whether or not there is any fresh ionization produced by the voltages applied in the curves of Figs. 4, 5, 6, 7, 8, 9; i.e., whether there is any restriking of the arc at all with the small applied potentials, or whether the currents observed are entirely due to the ions and electrons present in the arc space when the arc is interrupted.

The total quantity of electricity carried to the electrodes in curve A, Fig. 9, is approximately 10^{-4} coulombs which would require an average concentration over 500 cc. of at least 13×10^{11} ions per cc at the instant the arc was interrupted. From 0.01 to 0.04 sec. after the stopping of the arc the quantity of electricity removed by the electrodes was 5.5×10^{-5} coulombs which requires an average concentration of 6.9×10^{11} ions per cc at the beginning of the interval. The arc during this experiment was quite intense and the arc current was 0.3 amperes.

By means of a Langmuir exploring electrode (to be considered in detail later) the concentrations of ions and electrons about midway between the cathode and anode at various times after a 0.04 ampere arc was interrupted have been calculated; the results are given in Table I. If the concentration

TABLE I

Concentration of ions and electrons midway between cathode and anode at various times after the interruption of a 0.04 ampere arc.

Post-arc time	Current	No. of ions per cc.
0.0055 sec.	280×10^{-6} amps.	3.34 $\times10^{11}$
.0074 "	176 "	1.67 "
.0092 "	108 "	.78 "
.0112 "	66 "	.28 "
.0152 "	33 "	.12 "
.019 "	20 "	.051 "
.029 "	5 "	.0052 "
.040 "	1 "	.00033 "

after 0.01 sec. obtained from Table I is multiplied by 0.3/0.04, the ratio of the arc currents, we have a concentration of 4.4×10^{11}. This value is in fair agreement with 6.9×10^{11} mentioned above. Working with steady uninterrupted arcs Compton and Eckart[6] have measured concentrations near the cathode as high as 48×10^{11}.

Consequently, we may say that the post-arc currents observed in the above experiments are due probably entirely to residual ions and electrons and that metastable or excited atoms undoubtedly play only a minor role in the post-arc phenomena here considered. However, Dorgelo[1] has shown by absorption methods that metastable atoms actually do exist in the arc space 1/200 sec. after the arc had been turned off. These apparent long-lived atoms (1/200 or 1/22 sec.) can be accounted for by metastable atoms of short life (say 10^{-6} sec.) which are continuously being formed by the comparatively slow process of recombination of positive ions and electrons. Dorgelo has also observed that impurities markedly decrease the "life" of the metastable atom. As may be expected impurities, although having little or no effect on the rate of recombination of ions and electrons, would however decrease the concentration of metastable atoms by increasing their rate of disappearance after they have been formed.

H. *Time required to remove ions and electrons from arc space.* If large quantities of ions and electrons really exist in the arc space for 1/50 to 1/10 sec. after the arc has been turned off, one would expect it to be possible to rapidly sweep them from the arc space by the application of a high negative potential to the plate. However, Eckart observed that no effect on the post-arc current was noticed even when a negative voltage of -135 was applied and remarked that the result was somewhat disconcerting. A similar and

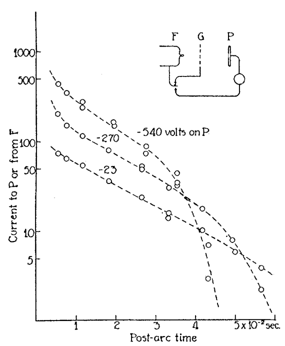

Fig. 10.

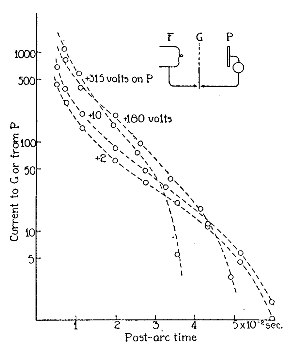

Fig 11.

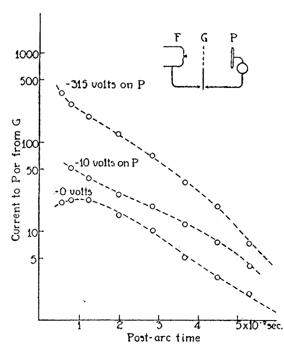

Fig. 12.

Fig. 10. Log plot of post-arc currents between P_2 and G_2 of tube No. 2 when P is highly negative.

Fig. 11. Log plot of post-arc currents between P_2 and G_2 when P_2 is highly positive.

Fig. 12. Log plot of post-arc currents between P_2 and G_2 when P_2 is highly negative.

related phenomena has been observed by Langmuir with regard to currents collected by negative electrodes placed in an arc running under constant conditions.[9] But before attempting to account for the slowness with which the ions are actually removed, we shall first consider a few experiments which were made with various high potentials on different collecting electrodes in order to observe the factors governing the removal of ions and electrons from the arc space after the arc has been interrupted.

Fig. 10 shows how the logarithm of the post-arc currents decreases with time when the plate is placed 540, 270, and 23 volts negative with respect to the filament. These potentials were upon the plate during the entire post-arc time. The arc was formed between the filament and grid. If curve -540 is compared with curve -23, it is seen that the rate of decay is approximately the same up to $t=0.03$ sec. Then for curve -540 the rate

[9] Langmuir, Science **58**, 290 (1923).

rapidly increases and when $t=0.045$ sec. the post-arc current has ceased. Curves in Fig. 11 show how the post-arc current decreases when the plate is made positive with respect to the grid; the filament is not in the post-arc circuit. Curves in Fig. 12 show the rate of decrease when the plate is made negative with respect to the grid; again the filament is not in the post-arc circuit.

Since the current curves in Fig. 10 are exponential for the greater portion of the post-arc time, we may write $i=i_0e^{-Kt}$ where K is 54.5, 55, and 70 respectively for curves -23, -270, and -540. Similar curves were obtained over an appreciable range in mercury vapor pressure; the value of K for different pressures is given in Table II. The increase in K for vapor pressures

TABLE II

Values of K for different pressures of mercury vapor.

Pressure	Temp.	K for plate -4.5 volts	K for plate -180 volts
.08 mm	78°C	180	285
.37	105	68	69
1.25	130	49	54
5.2	162	53	53
18.3	200	55	58

less than 0.5 mm is accounted for, as before, by molecular diffusion. The constancy of K for higher vapor pressures may well be expected in view of Eq. (2), below, since the mean free path L in the equation is raised to the 1/5 power. Eckart has reported that "some hasty experiments using mercury instead of helium showed that all phenomena were essentially the same and yielded values for b [$b=1/K$] of 0.01 to 0.02 sec."

Fig. 9*C* shows the type of post-arc currents between the grid and filament as observed by the cathode ray oscillograph when the grid for 1/60 sec. is made 180 volts negative with respect to the filament; thereafter the grid is put at 3.8 volts. The latter portion of the curve is very much like the curve in Fig. 9A, where the grid at all times is +3.8 volts with respect to the filament. According to these observations the persistence of post-arc currents is not in any marked way dependent upon the potentials applied to the collecting electrodes.

I. *Experiments with anode completely enclosing cathode.* In order to test the dependence of the persistence of post-arc currents upon the size of collecting electrodes tube No. 3[10] was used. Here the anode was a cylinder 5 cm in diameter with closed ends. The filament leads passed through small holes in the center of the end plates. The arc was formed between the filament F_3 and the cylindrical anode P_3.

In Fig. 13 the ordinates represent the logarithm of the currents between the anode P_3 and a 4 mil wire 1 cm long placed near the filament (see Fig. 1). Post-arc measurements were made with the filament completely out of the circuit. Since Figs. 13 and 10 are plotted on the same scale, it is easily

[10] Tube No. 3 was made and used by Dr. F. M. Kannenstine in some of his work on metastable helium.

noticed how much more rapid is the rate of decay of the post-arc current in the former than in the latter. For tube No. 3 the post-arc current ceases after 0.018 sec. when -93 volts is put on the plate; for tube No. 2 the current persists for 0.045 sec. even when -270 volts is applied. Curve 0 in Fig. 13 shows how the current flows between the wire and plate when no voltage is applied.

Related observations are plotted in Fig. 14. Here the currents between P_3 and the wire W_3 at a definite time after the stopping of the arc are plotted as ordinates against the potential of the wire as abscissas. The voltages are applied to the wire for 0.0125 sec., then the galvanometer is put into the

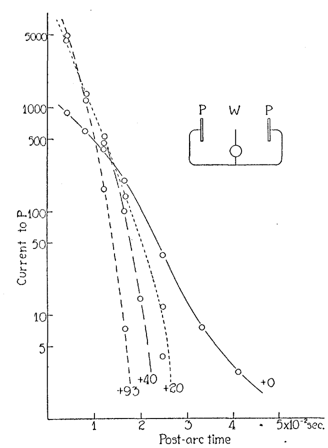

Fig. 13

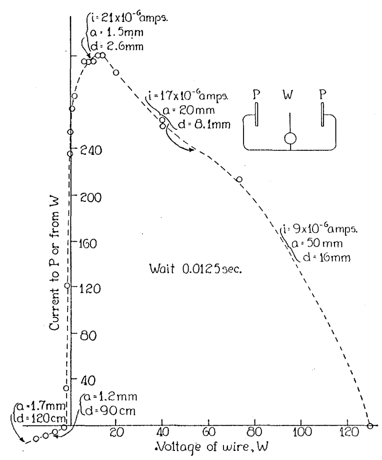

Fig. 14.

Fig. 13. Log plot of post-arc currents between P_3 and W_3 for tube No. 3 when W_3 is positive.
Fig. 14. Post-arc currents between P_3 and W_5 0.0125 sec. after stopping the arc as a function of the potential difference.

circuit for 1/400 sec. It is seen that the post-arc current has decreased to zero in less than 0.0125 sec. when 130 volts is applied and that the curve is quite unsymmetrical about the axes. Zero current is also obtained when the wire is put 1.7 volts negative with respect to the plate.

J. *Space charge sheaths about collecting electrodes.* The behavior of the post-arc currents shown in Figs. 10 to 14 may be accounted for by bringing into consideration the concept of space charge sheaths. Langmuir[11] has shown that for low gas pressures (say 0.002 mm) the current carried by ions between any pair of electrodes cannot exceed a definite value; this value depends on the form of the electrodes, on the potential difference between them, and on the charge and mass of the ions, but not in any way upon the concentration of ions.

McCurdy[12] has derived an equation which gives at high gas pressures (say 2 mm) the limiting currents that may be obtained between coaxial

[11] Langmuir and Mott-Smith, Gen. Elec. Rev. **27**, 449, 538, 616, 762, 810 (1924).
[12] McCurdy, Phys. Rev. **27**, 157 (1926).

cylindrical electrodes. McCurdy's equation when evaluated for electrons in mercury vapor is:

$$i=1.74\times 10^{-6}\frac{L^{1/2}V_0^{3/2}}{(aB)^{3/2}} \tag{1}$$

For positive ions in mercury vapor the numerical coefficient is 1.94×10^{-8}. L is the mean free path of the mercury atoms, V_0 is the potential of the collecting electrode with respect to the outer electrode, a is the radius of the outer electrode, and B is a function of the ratio of the two radii.

In the experiments here described the ions and electrons were in many cases drawn to plane electrodes; the corresponding current limiting equation may be obtained as follows: Poisson's space charge equation for plane electrodes is $d^2V/dx^2=4\pi\rho=4\pi i/u$, where u is the velocity of advance of an ion.
But

$$u=3Eel/4mv_t$$

where v_t is the random velocity of agitation.
Since

$$\tfrac{1}{2}mv_t^2=V_te=\tfrac{1}{2}eEL(M/1.134m)^{1/2}$$

$$\frac{d^2V}{dx^2}=\frac{16}{3}\pi i\left(\frac{m}{Eel}\right)^{1/2}\left(\frac{M}{1.134m}\right)^{1/4}$$

Putting $dV/dx=E$ and integrating, we have

$$E^{3/2}=8\pi i\left(\frac{m}{el}\right)^{1/2}\left(\frac{M}{1.134m}\right)^{1/4}(x-d)$$

$E=0$ when $x=d$, where d is the distance to the plane electrode which is the source of ions or electrons. Integrating again and solving foı d,

$$d=\left[\frac{(2.27)^{1/2}}{16\pi^2}\,\frac{e}{m}\left(\frac{5}{3}\right)^3\frac{1}{M^{1/2}}\,\frac{V_0^3L}{i^2}\right]^{1/5}$$

Evaluating for mercury, the thickness of the positive sheath is given by

$$d=4.5\times 10^{-4}(V_0^3A^2L/i^2)^{1/5} \tag{2}$$

For the negative sheath the numerical coefficient is 1.74×10^{-3}. In addition to the symbols used before, A is the area of the electrode.

Eqs. (1) and (2) have been applied to the observations made with tubes Nos. 2 and No. 3. In Table III there is given a set of data and calculations for curves +93, and +20 of Fig. 13. In this table t is the time after the arc had been stopped, d is the thickness of the positive space charge upon the cylindrical plate P, a is the radius of the negative space charge aıound the wire W, n is the number of ions per cc, i is the current in amperes.

Calculations for the curve marked +20 in Fig. 3 show that the thickness of the positive space charge sheath on the cylindrical electrode P is 1.5 mm at time $t=0.0045$ sec. The radius of the negative space charge sheath about the wire W is 0.77 mm and the number of electrons and ions per cc is 2.2×10^9. For $t=0.025$ sec. the thickness of the positive sheath is 19 mm, the radius of the negative sheath is 17 mm and the number of ions and electrons per cc is 1.6×10^5. It is admitted that in the determination of the radius of space charge sheaths and of the number of ions per cc there is a large error present even when the arc is working under steady conditions. In this set of experiments an attempt has been made to determine the size of these sheaths

TABLE III

Applications of Eqs. (1) and (2) to the observations.

t	i	d	a	n
		For curve +93, Fig. 13		
0.0045 sec.	316×10^{-6} amp.	3.2 mm	1.3 mm	1.3×10^9
.0085	77	5.6	4.1	1.0×10^8
.0125	12.5	12.0	7.2	1.0×10^7
.0170	0.4	41.0	12.0	1.9×10^6
		For curve +20, Fig. 13		
0.0045 sec.	300×10^{-6} amp.	1.5 mm	0.8 mm	2.2×10^9
.0085	106	2.3	1.1	5.2×10^8
.0125	35	3.5	1.9	10.0×10^7
.0170	10	8.8	6.8	2.9×10^6
.0250	0.5	19.0	17.0	1.6×10^5

at various instants during the changing conditions that exist immediately after the stopping of the arc. Consequently, no estimate is made as to the accuracy of the results. However, it will be recalled that the radius of the cylindrical electrode P is 25 mm and that the radius of the sheath about the wire W for $t=0.025$ sec. is 17 mm. This value is not unreasonable because for $t=0.028$ sec. no current was obtained—an indication that all ions and electrons have been removed, or what is equivalent, that the sheaths have swept throughout the arc space and may be considered as ceasing to exist.

When the post-arc potentials on P and W are reversed, very much smaller currents are obtained. Calculations give unreasonably large values for the thickness of the negative space charge sheath upon P, even when $t=0.005$ sec. The interpretation is that the large surface of P makes the removal of the electrons quite rapid, and before any galvanometric measurements can be made a large percent of these electrons have been removed. Thus for $t=0.005$ sec. there exists no negative space charge on P; throughout the arc space there is, however, a predominance of positive ions and consequently there exists everywhere a positive ion space charge.

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