THE ELECTRODELESS DISCHARGE IN MERCURY VAPOR

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Abstract

A method is described for studying the characteristics of the components of the electrodeless discharge in mercury vapor. A Hartley oscillator is used to excite the discharge, oscillating currents up to 45 amps. being obtained at frequencies from 5×10^6 to 12×10^6 oscillations per second. Shield experiments have been performed which clearly show the distinction between the dull glow discharge which is considered electric in its origin and the bright glow discharge which is shown to be electromagnetic in its origin; the dependence of the bright glow on the dull glow or on the effect of some ionizing agent is proved. The variation of the current necessary to start the discharge with the pressure of the mercury vapor has been investigated fully over the pressure range 0.002 to 0.2 mm of mercury. Curves are drawn and analyzed in terms of J. J. Thomson's electromagnetic theory of the discharge and Brasefield's electric theory. It is shown that neither theory is sufficient to explain the experimental facts; the predictions seem to hold for the bright glow with fair agreement but fail markedly with the dull glow.

Introduction

Two opposing theories have been advanced in recent years to explain the nature of the "electrodeless" discharge which occurs under proper excitation in a gas or vapor at low pressure. The usual arrangement is to insert the bulb containing the gas in a coil in which high frequency currents are flowing.

J. J. Thomson[1] has contended that the discharge is due to the alternating e.m.f. induced around the inside periphery of the discharge tube by the varying magnetic field of the coil. Townsend and Donaldson[2] however have strongly supported the view that the discharge is caused by the "electric forces"[3] between the ends of the coil. This second view is also held by those who have worked with external electrodes, for example Brasefield.[4]

In an attempt to reconcile the two explanations MacKinnon[5] constructed an exciting circuit which could be energized by either damped or undamped oscillations, for the reason that Thomson had used only damped oscillations while Townsend and Donaldson had used only undamped oscillations. From his experiments, MacKinnon concluded that the discharge was of "electromagnetic" origin when excited by the damped oscillations of Thomson and

[1] J. J. Thomson, Phil. Mag. **32**, 321, 450 (1891); **44**, 293 (1897); **4**, 1128 (1927).

[2] Townsend and Donaldson, Phil. Mag. **5**, 178 (1928).

[3] The term "electric forces" is used here to represent those forces due to the fact that two parts of the coil are at different potentials. For such a force the usual term "electrostatic" is here obviously a misnomer.

[4] Brasefield, Phys. Rev. **35**, 1073 (1930); **37**, 82 (1931).

[5] K. A. MacKinnon, Phil. Mag. **8**, 605 (1929).

"electric" when excited by the undamped oscillations of Townsend and Donaldson. With large currents in the undamped oscillator coil he was able to obtain a very bright glow, not reported by Townsend and Donaldson, which he thought was related to the "ring" discharge of Thomson. This led him to believe that the electromagnetic type of discharge occurred with the damped oscillations because the instantaneous coil currents were very large, and that the undamped oscillations would also cause the characteristic "ring" discharge of the damped case if the gas used had a sufficiently low ionizing potential. The results of the present work support MacKinnon's view in many details.

An ordinary Hartley circuit was used as a generator of the high frequency oscillations employed in the experiments to be described. The resistance of the circuit was kept low by the use of copper tubing for leads and inductance coils while the ratio of capacity to inductance was high; the result was the generation of large currents in the oscillator coil which also acted as the exciting coil for the discharge; thus currents of 45 amps. at frequencies from 5×10^6 to 12×10^6 cycles per second were easily obtained. These currents were measured by a Weston thermo-ammeter placed directly in the circuit between coil and condenser or by a current transformer and thermo-ammeter as described by Campbell and Dye.[6] All frequencies were measured by a General Radio precision wave-meter.

Over the whole pressure range studied (0.002 to 0.2 mm of mercury) the authors have observed both types of discharge described by MacKinnon; over parts of the range, however, special precautions were necessary to separate them. Mercury vapor was used in the bulb throughout the investigation except where indicated otherwise. The general procedure was as follows: The pressure in the bulb was held constant and the coil current gradually increased; at a critical value of the current a bluish white "dull glow" appeared inside the tube. When the current was increased to a second critical value, the discharge suddenly changed into an intense "bright glow"; at the same time, a large amount of power was drawn from the oscillator. At certain pressures this "bright glow" assumed the form of a ring around the inside periphery of the tube, in appearance very similar to the familiar "ring" discharge.

When no discharge was excited on inserting the tube in the coil, no change occurred in the oscillating circuit. When the dull glow was excited, no change occurred in the circuit nor was the discharge tube heated appreciably. But when the bright glow was strongly excited, the oscillating current decreased greatly, the plate current increased, the frequency remained the same and the bulb was heated appreciably.

Effect of a Shield

The "dull glow" has been excited readily either inside or outside the coil; in fact at certain pressures, it has appeared whenever the bulb was brought anywhere near the oscillator. This action in itself indicates the "electric"

[6] Campbell and Dye, Proc. Roy. Soc. **A90,** 621 (1914).

nature of this type of discharge. To investigate the case further a metallic shield was made by pasting narrow strips of tin-foil parallel to each other on a piece of paper and then connecting them together at one end by a transverse strip of foil. The paper was then rolled into a hollow cylinder with the axis parallel to the strips and the ends open. When this cylinder surrounded the bulb it caused very little electromagnetic loss due to eddy currents but served as an excellent shield against "electric forces." When the pressure and coil current were suitable for the excitation of the "dull glow," the presence of the shield always caused the glow to disappear whether the discharge tube was in the coil or outside. The glow never reappeared as long as the shield remained interposed between the tube and the coil, no matter how great the coil current was made (in our case up to 45 amps.).

If the "bright glow" had been existed strongly in the tube and the shield was inserted, the glow was apparently unaffected. If the bright glow was stopped however by a reduction of the current, it could not be made to reappear so long as the shield was in place even though the current reached the maximum of 45 amps. These experiments were repeated with a second cylindrical shield with closed ends; the results were the same.

When damped oscillations of approximately the same frequency as the undamped oscillations were used for excitation, the dull glow could be obtained only outside the coil; the shield affected it in exactly the same manner as before. The bright "ring" discharge which appeared inside the coil behaved toward the shield identically as did the bright glow of the undamped case.

When the conditions were right for maintaining the bright glow without a shield, it could be started and maintained inside the shield by exposing the tube momentarily to x-rays, or with a quartz discharge tube, to the radiation from a mercury arc in quartz. If a small ball of mercury was in the tube, the bright glow could be started similarly by simply twirling the tube and thus generating a faint glow of triboluminescence around the ball of mercury.

All of the above shield experiments have been repeated for air and carbon monoxide with similar results.

Variation of Starting Current with Pressure

The variation of the current necessary for starting the discharge in mercury vapor with changing pressure was very difficult to observe precisely. The external condition of the tube, slight impurities in the vapor and small amounts of liquid mercury all affected the starting current and the results at first were so erratic that it seemed as though no generalization could be made. Determination of the pressure was difficult as the measurement of the temperature of a furnace in which the bulb and coil were placed was not satisfactory because of the sudden rapid increase in temperature in the closed space when the oscillating current was turned on. A thermometer placed anywhere in the field of the coil proved unreliable.

Reproducible results were finally obtained with the following apparatus and procedure. The discharge tube is shown in Fig. 1; the bulb *a* was placed within the oscillator coil and both were enclosed in a transite box and heated by a blast of hot air; this furnace could be adjusted to any desired temperature from 120°C to about 200°C and maintained constant within a few degrees. The well *b* was outside of the furnace in a constant temperature bath which could be varied from 0°C to 100°C; it contained liquid mercury. Thus the pressure of the mercury vapor in the bulb was determined by the temperature of the mercury in the well, as read on a thermometer placed in tube *c*. The pressure corresponding to a given temperature was taken from a curve plotted from the data given by Kaye and Laby.

At the start of a run, the furnace was first raised to a temperature of say 180°C and kept there for about half an hour with the bulb and coil in place and the mercury well at a low temperature; this action insured that all the liquid mercury was evaporated from the bulb itself. The temperature of the well was then raised by adjustment of the constant temperature bath to the

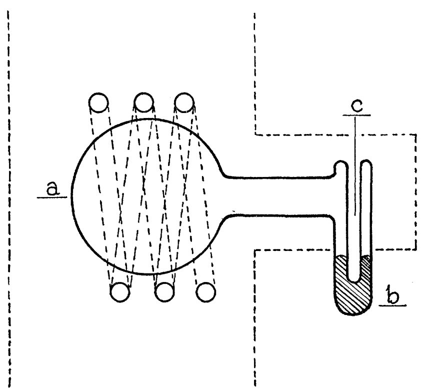

Fig. 1. The experimental bulb made of Pyrex. The broken lines show the position of the transite walls of the furnace.

value corresponding to the pressure at which the run was to be made. After a wait of about fifteen minutes at this temperature, readings of the starting current were taken at one-minute intervals. When these showed no consistent change, the average of six or more consecutive readings was taken as the starting current.

Table I shows a typical set of readings for starting currents; I_1 is the starting current for the dull glow and I_2 that for the bright glow. The values of I_2 are more consistent than those of I_1; this was generally the case.

TABLE I. *Currents necessary to start the electrodeless discharge.*

Frequency $= 7.2 \times 10^6$ cycles per second. Temperature of furnace $= 184$°C. Temperature of the mercury well $= 75.5$°C. Pressure of mercury vapor in discharge tube $= 0.066$ mm of mercury.

	1	2	3	4	5	6	Average
I_1 amps (dull glow)	5.00	4.80	4.85	5.00	4.90	4.95	4.91
I_2 amps (bright glow)	6.60	6.65	6.65	6.65	6.65	6.65	6.65

Figure 2 gives the curves illustrating the variation of starting current with pressure at a frequency of 7.2×10^6 cycles per second. Curve *bcdfh* is for the bright glow and curve *acefg* for the dull glow; all pairs of curves taken were very similar to these in shape. The minima at *b* and *e* occurred at the same pressures for the different curves and at about the same currents but the rest of the curve was often shifted along the current axis. Within the pressure range from *c* to *f* of Fig. 2 the starting currents of the two discharges followed each other as described above. To the left of *c* and to the right of *f*, the bright discharge appeared at points on the curve *ac* and *fg*; the dull glow did not precede the bright glow in these regions. When the power supplied to the oscillator was decreased however the bright glow was made to disappear but the dull glow remained. When the power was again increased, the dull glow

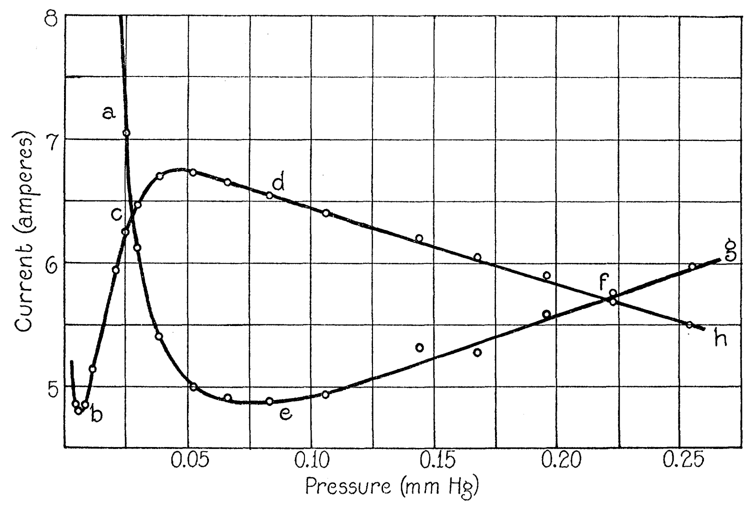

Fig. 2. Typical curves showing the variation of starting current with pressure in mercury vapor. Curve *bcdfh* is for the "bright glow" and curve *acefg* is for the "dull glow"; the former appears again as D_1 in Figs. 3 and 3a and the latter as D_1' in Fig. 3.

still being on, the bright glow reappeared at a considerably lower current than at first, corresponding to some point in the region *bc* or *fh*. Since our experiments with the shield have shown that the bright glow does not appear at any pressure unless preceded by the dull glow or by some external source of ionization, we have taken *bcdfh* as the true starting current curve for the bright glow, and *acefg* for the dull glow. Both types of discharge exist therefore over the whole range of pressures and may be started or stopped at will.

The minimum at *b* of the bright glow appears again in the curves D_1 of Figs. 3 and 3a; the last curve shows particularly how definite the minimum is.

Discussion of Results

Figs. 3 and 3a give the results of one set of experiments; many others were obtained like them. The full line curves *A*, *B*, *C* and *D* show the variation of starting current with pressure for the bright glow while the dotted curves

A', B', C' and D' are for the dull glow. Curves A_1, A_2 and A_3 were all taken at a frequency of 11×10^6 cycles per second; the oscillator coil had an induc-

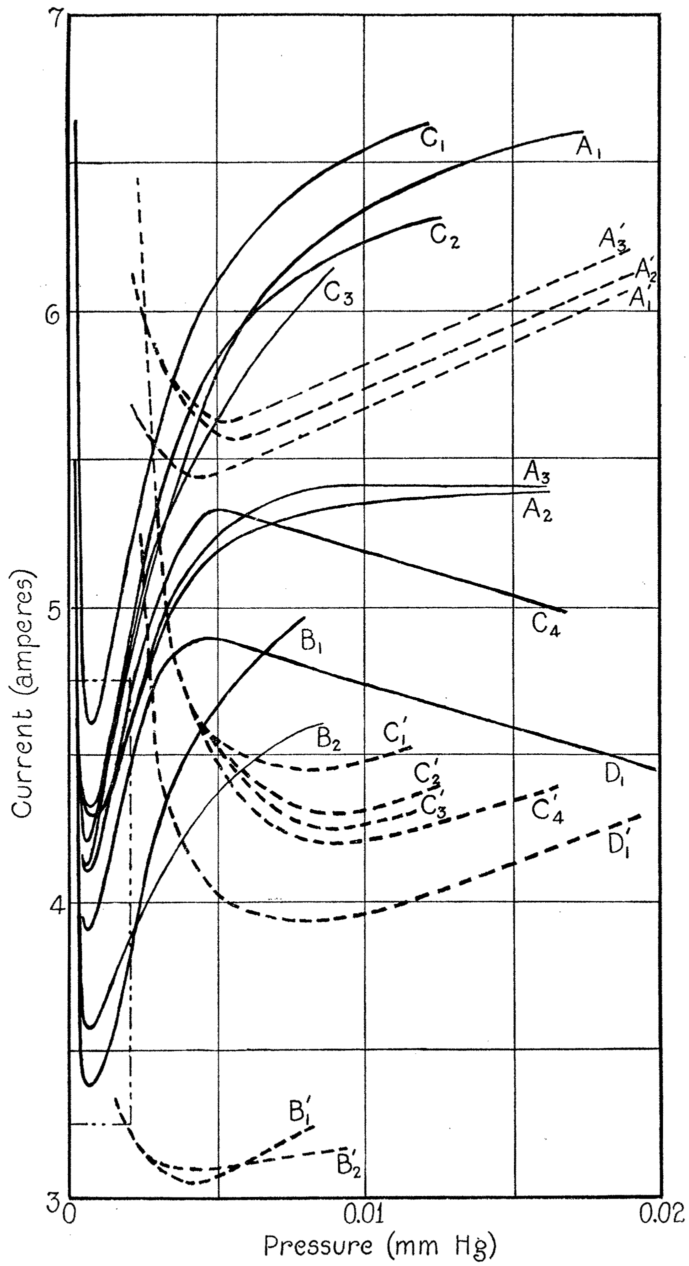

Fig. 3. A collection of curves illustrating the effect of changes in inductance and frequency of the oscillating circuit on the minimum starting current; the full lines are for the "bright glow" and the broken lines for the "dull glow"; the curves similarly labelled, e.g., A and A' were taken simultaneously. The region to the left enclosed by the chain lines is enlarged in Fig. 3a.

tance of 6.84×10^{-7} henries. Curve A_1 was taken on June 11 after the tube had been operated for a considerable period previously at a frequency of a 7.2×10^{6} cycles per second. The minimum at 0.0028 mm of mercury is very definite but is the only case in which such a low pressure minimum has been observed; the minimum at 0.0070 mm has therefore been chosen as the proper minimum for comparison with the other curves; no explanation can be offered at this time for the appearance of the two minima. Curves A_2 and A_3

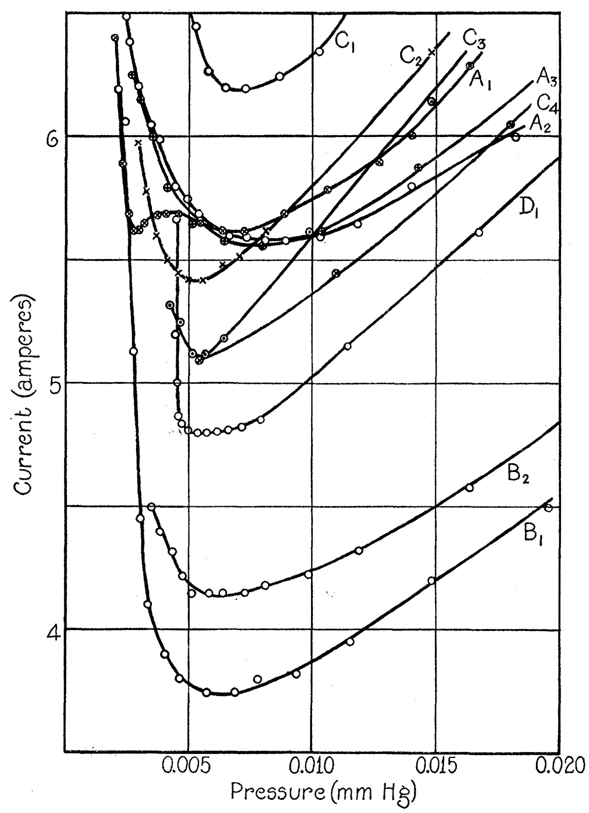

Fig. 3a. An enlarged view of the minima of the "bright glow" curves to show how sharply the minimum currents are defined.

were obtained on June 12. Figure 3a shows that their minima fall at a pressure of 0.0085 mm.[7]

Curves B_1 and B_2 were obtained on June 13; the frequency was kept at 11.0×10^{6} cycles per second as for the curves A but the inductance was increased to 10.4×10^{-7} henries. The minima for B_1 and B_2 are seen to fall at

[7] A comparison of curve A_1 with A_2 and A_3 shows that the first curve taken at a given frequency after the discharge tube has been run at a lower frequency results in a displacement of the minimum to a lower pressure than occurs with succeeding curves taken under otherwise identical operating conditions. The coil currents at the minima for A_2 and A_3 are less than for A_1; this whole behavior is typical.

a lower pressure than with the curves A, the value being 0.0065 mm. The "electromagnetic" theory of Thomson and the "electric" theory of Brasefield (for external electrodes) demand that the ratio of the frequency to the pressure at which the minimum occurs should be a constant; here, however, a shift takes place in the pressure at which the minimum occurs without a change of frequency but with a change of inductance. The values of the coil current at the minima are considerably lower with the curves B than with the curves A; this may be accounted for in terms of the change in inductance from 6.84×10^{-7} henries in the latter case to 10.4×10^{-7} henries in the former; the coils were of two and three turns, respectively. The magnetic field at the minimum should be

$$H_0 = \frac{2}{a}\left(\frac{2V}{e/m}\right)^{1/2}$$

according to Thomson, where V is the effective ionization potential for the gas and a the radius of the bulb; thus the starting current at the minimum should depend only on the gas, the bulb and the coil. The approximate value of the field inside of a solenoid is $H = 2\pi ni\ (\cos\theta_1 - \cos\theta_2)$ (see Starling 5th Edition p. 229); the coil current at the minimum should thus have been 16.8 amps. for curves A and 10. 4 amps. for curves B, on the assumption further that the ionizing potential is 10.4 volts. If the effective ionizing potential is taken as 5.5 volts, these values become 12.2 amps. and 7.6 amps., respectively. Actually the currents were about 5.5 amps. for curves A and about 4.0 amps. for curves B.

The electric field at the minimum should be

$$E_0 = \pi f\left(\frac{2V}{e/m}\right)^{1/2}$$

according to Brasefield.[4] The shield experiments have given evidence of only diametral electrical fields; the recent experiments of Knipp[8] seem to confirm this observation. If this is the case

$$E_0 = \frac{\pi f L}{2Nr} I_0$$

where f is the frequency of the oscillation, L is the inductance of the coil, r is its radius and N the number of turns; I_0 is the peak value of the minimum starting current; this approximation for E_0 is based on the assumption of a linear drop in potential around the coil; a sine distribution leads to results of the same order. In effective amps. the above result becomes

$$I = \frac{2Nr}{1.414L}\left(\frac{2V}{e/m}\right)^{1/2}.$$

The coil current at the minimum should thus have been 2.24 amps. for curves

[8] Bulletin of the American Physical Society Vol. 6, number 1, p. 22, abstract 35, February 10, 1931.

A and 1.99 amps. for curves B, on the assumption that the ionizing potential is 10.4 volts. If the effective ionizing potential is 5.5 volts, these values become 1.63 amps. and 1.45 amps., respectively. The currents were actually about 5.5 amps. for curves A and 4.0 for curves B.

The observed values of the currents are of the same order of magnitude as the calculated values on either theory although the electromagnetic theory values are about twice as large as those observed and the electric theory values are between one fourth and one third as great, when the effective ionizing potential is taken as 5.5 volts. The electromagnetic theory predicts a change in the minimum current from curves B to curves A, the calculated ratio being 0.62. The electric theory predicts for diametral fields a shift corresponding to the ratio 0.89. The ratio of currents actually observed is 0.71.

Curves C_1, C_2, C_3 and C_4 were run in that order on June 14. Curve C_1 shows a minimum at a pressure of 0.0075 mm of mercury while the minima for the other three curves fall at a pressure of 0.0055 mm. The inductance was the same as for curves B, 10.4×10^{-7} henries, but the frequency had been lowered from 11.0×10^6 cycles per second to 7.2×10^6 cycles per second.[9] The ratio of the frequency to the pressure at the minimum for curve A_2 or A_3 and curve C_2, C_3 or C_4 is a constant within the limit of experimental error as predicted by both theories:

$$\frac{11.0 \times 10^6}{0.0085} = 1295 \times 10^6; \quad \frac{7.2 \times 10^6}{0.0055} = 1310 \times 10^6.$$

The ratio of inductance to capacity in curves A and C was constant. For curve B_1 or B_2 and curve C_2, C_3 or C_4 the ratios of frequency to pressure at the minimum are obviously not the same; the change in frequency resulted from a change in capacity in the circuit, the inductance remaining the same. Both theories predict that the coil currents at the minima for curves B and curves C should be equal as they are shown to be independent of the frequency. While successive values for curves B are increasing and those for curves C are decreasing, the values for the lower frequency are definitely higher than for the higher frequency.

Curve D was taken in an early set of experiments on May 22 and is included to show how well the results agree even after a lapse of time. The minimum falls at the same pressure as for C_2, C_3 and C_4; the coil current is lower than for the C curves but is above that for either B_1 or B_2.

The "electromagnetic" theory predicts that the minimum for curves A and B should occur at a pressure of 0.0035 mm for a frequency of 7.2×10^6 cycles per second and at 0.0054 mm for a frequency of 11.0×10^6 cycles per second, the ionizing potential being taken as 10.4 volts. We have found, however, that the dull glow or its equivalent must always be present before the

[9] Here again on running the tube after a change in frequency of the oscillator, the minimum for the first test is displaced with respect to the minima obtained in succeeding tests under otherwise identical operating conditions. In this case however the first minimum is at a higher pressure than the following, corresponding to a change from one frequency to a lower value.

bright glow comes on; we have considered therefore, that the effective ionizing potential is 5.5 volts. The calculated values of the pressure at the minima then become 0.0048 mm for 7.2×10^6 cycles per second and 0.0075 mm for 11.0×10^6 cycles per second; the observed values were 0.0055 mm for curves C at 7.2×10^6 cycles per second, 0.0085 mm for curves A at 11.0×10^6 cycles per second and 0.0065 mm for curves B at the same frequency; the agreement is fair.

The electric theory predicts that the minimum should fall at 0.0031 mm for 7.2×10^6 cycles per second and at 0.0046 mm for 11.0×10^6 cycles per second; the effective ionizing potential of 5.5 volts has been used to calculate these results. The agreement here is much less satisfactory than in the electromagnetic case. Throughout the calculations for the values of the pressures at the minima the mean free path of an electron in mercury vapor at 1 mm of Hg pressure and 25°C has been taken as 0.0149 cm as given by Compton and Langmuir.[10]

The diametral fields set up by the currents in the coil were sufficient to produce ionization but not at the pressures corresponding to the minimum of the bright glow; the mean free path of an electron in mercury vapor is not great enough to permit an electron to acquire sufficient velocity to cause ionization.

One other point in connection with the bright glow curves should be mentioned. Indications are that the furnace temperature, and therefore the bulb and vapor temperature, affects the position of the maximum in the region above 0.05 mm. For temperatures below 170°C, the maxima occur as with curve C_4; for temperatures around 185°C, the curves flatten out as in A_2 and A_3 and for still higher temperatures the curves continue to rise. Further work is in progress in an attempt to determine the relation between the shape of the curve and the furnace temperature.

The curves A_1', A_2' and A_3' were taken simultaneously with the A_1, A_2 and A_3 curves and represent the variation of starting current with pressure for the dull glow corresponding to curves A_1, A_2 and A_3 for the bright glow; the B' and C' curves have a similar interpretation. Curves A_2' and A_3' are entirely above A_2 and A_3; this is a significant fact because an observer could readily have failed to detect the existence of two types of discharge under these conditions. The procedure described above for separating the two components of the discharge was particularly important here; at some value for the current the two discharges appeared simultaneously corresponding to a point on one of the A' curves; the current was reduced until the bright glow disappeared, leaving the dull glow; the current was again increased and the bright glow reappeared at a point on the A curve. A change of inductance from 10.4×10^{-7} henries to 6.84×10^{-7} henries was made in passing from the B' to the A' curves but the frequency was kept at 11.0×10^6 cycles per second. The shift of the curves along the current axis is about twice as great for the dull glow curves as for the bright glow; the change of inductance should have

[10] Compton and Langmuir, Rev. of Mod. Phys. **2**, 208 (1930).

affected them alike. As pointed out above for the bright glow curves the observed ratio of the minimum currents was 0.71 and the computed was 0.89 on the basis of diametral fields; according to the theory the same calculation should hold for the dull glow but the observed ratio is only 0.39. If axial fields are assumed, the computed value for the ratio is 0.99; in either case the observed values for the dull glow fail to fit the theory and the discrepancy is much greater than for the bright glow.

Curves C' were obtained with the same inductance as for curves B' namely 10.4×10^{-7} henries but the frequency was reduced to 7.2×10^{6} cycles per second. On the basis of the electric theory there should have been no change in the values of the minimum currents in passing from B' to C' but actually there were very large changes. Again the shift along the pressure axis is in the wrong direction for the minimum should occur at a lower pressure as the frequency is lowered. Furthermore the currents observed at these minima were not sufficient to set up diametral fields powerful enough to cause ionization; the electrons could not possibly acquire sufficient velocity in the distance equal to the mean free path of an electron in mercury vapor at these pressures. This would seem to indicate that the process is one of multiple collisions.[11]

Curve D' is included to show that even the dull glow curves may be reproduced after a lapse of time although it was much more difficult in general to repeat the dull glow curves than the bright glow curves.

The authors wish to thank Mr. John Mills and Bell Telephone Laboratories for the use of power tubes used in this investigation. They desire, too, to extend their grateful appreciation of the help rendered by Dr. Ann Hepburn in the experimental work.

[11] This is the region of pressures, too, in which the bright glow curves show their change of shape with furnace temperature; it may be possible to explain the change in shape in terms of a variation of the terminal velocity of an electron moving through mercury vapor with the temperature of the vapor, the pressure being fixed by the temperature of the liquid mercury present.