The Field Emission Initiated Vacuum Arc. I. Experiments on Arc Initiation*

W. P. DYKE, J. K. TROLAN, E. E. MARTIN, AND J. P. BARBOUR
Physics Department, Linfield College, McMinnville, Oregon
(Received March 30, 1953)

It is known that electrical breakdown between metal electrodes can be initiated by field emission. The present work concerns a further study of that initiation process under conditions of excellent vacuum and a clean cathode surface.

As the field current density from the single crystal tungsten emitter is continuously increased, the normal emission is terminated by an explosive vacuum arc. Since this breakdown occurs in less than a microsecond, the experimental observations were obtained by use of pulse electronic techniques. The magnitude of the electric field, current density, and work function at the cathode were simultaneously determined prior to breakdown. From this investigation it has been established that:

(1) the vacuum arc was initiated at a critical value of the field current density of the order of 10^8 amperes/cm^2;

(2) breakdown was predictable and not random; in fact easily recognizable conditions preceding arc formation have been established; at current densities just below the critical value, an electron emission process was observed, which apparently involved both high electric fields and high temperatures;

(3) arc formation did not require cathode bombardment by material from the anode or from residual gases;

(4) breakdown was independent of the applied microsecond voltage in the range $5<V<60$ kv, provided the critical current density was not exceeded;

(5) the current during arc exceeded the initiating field current by a factor of at least 100.

INTRODUCTION

HIGH field current densities are known to initiate electrical breakdown between metal electrodes in vacuum[1] but the mechanisms involved in the initiation of that breakdown have not been well understood. The present work concerns a further study of the problem and is one of a series of investigations concerned with phenomena accompanying field emission of electrons at very large current densities.

Field emission was recognized as an initiating factor for the breakdown of static potentials of the order of 10 kv between metal electrodes in vacuum in earlier experiments.[2–4] When the static potential was increased to the order of 100 kv, electrical breakdown was increasingly dependent on total voltage[4] in contrast with its dependence on electric field at lower voltages. In other experiments,[1,5,6] when high voltages were applied for short time intervals, breakdown was dependent on the electric field at the cathode. In some experiments, breakdown was thought to be initiated by various mechanisms involving anode material;[3,4,7,8] however, more recently, positive ion emission coefficients have been found insufficient[9] for a proposed particle interchange mechanism.[4] Adsorbed gas on the cathode surface[5] and residual gas in the experimental tube[3] have been considered in other proposed explanations for breakdown. Few of those earlier experiments were favored by the high vacuum and clean surfaces available through recently developed techniques.[10,11] Electrical breakdown generally was observed at calculated values of the electric field about an order of magnitude less than that required theoretically[12] for appreciable field emission. It was supposed in most cases that the electric field was intensified in the vicinity of surface irregularities[13] which could not be resolved by optical microscopy. Arcing at electrical contacts on closure in air was recently recognized as being initiated by field emission at voltages less than 100 volts.[14,15]

Neither electrical breakdown nor appreciable field emission was observed for values of the electric field less than those for which field emission is predicted theoretically when very high vacuum and smooth, clean electrode surfaces were obtained. Under such conditions and with static potentials less than 20 kv, the field current density from a tungsten single crystal followed the value predicted by the wave mechanical field emission theory[12] up to a current density of the order of 10^6 amperes/cm^2.[1,16] At larger direct current densities, electrical breakdown was observed.[1] Under similar experimental conditions when microsecond potentials up to 30 kv were used, the field current density in-

* Most of the support for this work was extended by the U. S. Office of Naval Research; in part it was supported by the U. S. Air Force through the Microwave Laboratory of the University of California.

[1] W. P. Dyke and J. K. Trolan, Phys. Rev. **89**, 799 (1953).
[2] A. J. Ahearn, Phys. Rev. **50**, 238 (1936).
[3] W. H. Bennett, Phys. Rev. **39**, 182 (1932); **40**, 416 (1932).
[4] J. G. Trump and R. J. Van de Graaff, J. Appl. Phys. **18**, 327 (1947).
[5] W. Kilpatrick, Report of University of California Radiation Laboratory (unpublished).
[6] D. H. Goodman and D. H. Sloan, Phys. Rev. **82**, 575 (1951).
[7] W. H. Bennett, Phys. Rev. **45**, 891 (1934).
[8] Lawrence Cranberg, J. Appl. Phys. **23**, 518 (1952).
[9] Webster, Van de Graaff, and Trump, J. Appl. **23**, 264 (1952).
[10] R. T. Bayard and D. Alpert, Rev. Sci. Instr. **21**, 6, 571 (1950).
[11] W. B. Nottingham, Abstracts of Field Emission Seminar, Linfield College, 1952 (unpublished).
[12] A. Sommerfeld and H. Bethe, *Handbuch der Physik* (J. Springer, Berlin, 1933), Vol. 24, No. 2, p. 441.
[13] W. Schottky, Z. Physik **14**, 80 (1923).
[14] L. H. Germer, J. Appl. Phys. **22**, 955 (1951); **22**, 1133 (1951).
[15] L. H. Germer and J. L. Smith, J. Appl. Phys. **23**, 553 (1952).
[16] R. H. Haefer, Z. Physik **116**, 604 (1940).

creased with applied potential in the manner predicted by the theory (when space charge effects were recognized) up to a critical current density $\bar{J}_x$ in the range $10^7 < \bar{J}_x < 10^8$ amperes/cm^2.[1] Upon a further increase in current density, the normal field emission was terminated by a low-impedance vacuum arc which altered the emitter geometry. Evidence indicated that the vacuum arc was caused by thermal effects when the emitter was heated by a current density-dependent process, the resistive mechanism being one possibility.[2,17]

It was recognized that resistive heating would provide an upper limit for the current densities emitted stably and it was desirable to show whether or not the densities obtained in reference 1 corresponded to that limit. Calculations are presented in Part II of the present work for the temperature rise expected in a typical field emitter due to the resistive process when the simultaneous dissipation of heat by conduction is considered.

In Part I are presented several experiments concerning arc initiation under conditions of excellent vacuum and a clean tungsten cathode surface. The evidence[1] indicated that electrical breakdown under such conditions was not dependent on bombardment of the cathode by positive ions; however that evidence was largely indirect and by no means complete. The contribution of such cathode bombardment was evaluated by more direct methods in the present work in order to (1) determine whether or not yet larger current densities desired for several experiments were physically attainable, and (2) better identify the mechanisms fundamental to arc initiation. Bombardment of the cathode was minimized when the production of ions was limited by use of very high vacuum and clean electrode surfaces. Bombardment of the cathode by chemically active ions, if appreciable, was recognized[18] from its effect on the emission pattern from the clean tungsten emitter, which pattern was viewed in a modified Mueller projection tube.[19] In one experiment, bombardment of the cathode by ions formed at the anode was precluded by use of a voltage pulse whose time duration was short compared with the ion transit times.

In a second experiment, the arc formation was observed with various voltages up to 60 kv of microsecond duration to determine whether or not (1) large field current densities were emitted stably at high voltages, and (2) breakdown depended on total voltage in the manner reported by Trump and Van de Graaff[4] under other experimental conditions. No such effect was observed when voltages were applied for short time intervals by Kilpatrick,[5] Sloan and Goodman,[6] and by Dyke and Trolan;[1] however the voltages used in reference 1 were low, i.e., $5 < V < 32$ kv.

A third experiment is described in which the normal field current prior to arc was compared by direct measurement with the current during arc. The magnitude of the latter was previously inferred[1] from the voltage wave shape through circuit analysis.

Anomalies in the pre-arc performance of the field emitter were observed which showed that electrical breakdown is predictable and not random under the present experimental conditions.

EXPERIMENTAL METHODS

Field emission is known to initiate the electrical breakdown whose study is the subject of the present work. It therefore appeared logical that the mechanisms involved in the initiation of that breakdown could best be identified by an experimental method which permitted a simultaneous determination of the values of the variables fundamental to field emission, i.e., current density J, electric field F, and work function ϕ. These variables are related in the theoretical expression:[12]

$$J = 1.55\times 10^{-6}(F^2/\phi)\exp[-6.85\times 10^7\phi^{\frac{3}{2}}f(y)/F], \quad (1)$$

where J is in amperes/cm^2, F is in volts/cm, and ϕ is in electron volts.

In many of the earlier experiments, unresolved surface geometry of the emitter precluded accurate calculation of both F and J. When field currents were identified, use was made of the empirical relationship[20] between current I and voltage V:

$$I = C\exp(-B/V), \quad (2)$$

which is an adequate procedure provided that C and B are constants as supposed by the authors of Eq. (2), who noted the rigorous experimental conditions required for that purpose (very high vacuum and clean surfaces). Under experimental conditions which are less favorable but more frequently reported in earlier work, significant time-dependent changes in both C and B are expected in view of the recent field emission literature. These result from changes in ϕ due to surface contamination[11,16,18,19] and from changes in F due both to the growth of crystallites of impurities on the emitting surface[16] and to the surface migration of the emitter material.[21] A plausible combination of these effects results in a change in J in excess of a factor of 10^4 at constant voltage. Use of Eq. (1) when experimental conditions are such that C and B are not constant could result in failure (1) to identify field currents as such, and (2) to identify the mechanism by which field emission initiates electrical breakdown.

The transition between the normal field emission and the vacuum arc was studied previously[1] with improved field emission techniques[22] through which the values of electric field and current density were known accurately prior to breakdown. Those techniques were again used

[17] E. W. Mueller, Z. Physik **106**, 132 (1937).
[18] J. A. Becker, Bell System Tech. J. **30**, 907 (1951).
[19] E. W. Mueller, Z. Physik **106**, 541 (1937).
[20] R. A. Millikan and C. C. Lauritsen, Proc. Nat. Acad. Sci. U. S. **14**, 1 (1928).
[21] E. W. Mueller, Z. Physik **126**, 642 (1949).
[22] Dyke, Trolan, Dolan, and Barnes, J. Appl. Phys. **24**, 570 (1953).

in the present paper and in addition the values of the work function of the emitting surface were known from previously published data for clean tungsten,[23] when the cleanliness of the present emitting surfaces was determined by analysis of the electron emission pattern obtained in a Mueller projection tube.

Since the vacuum arc is initiated in less than a microsecond,[1] it was necessary to record the present data during individual time intervals of that order. Voltage was applied as a pulse of microsecond duration; voltage and current were recorded as oscillographs by previously published methods[1] and data were taken on an individual pulse basis. From measurements of the oscillographs, the current-voltage relationship was determined. A photograph of the electron emission pattern was taken during each microsecond current pulse.

The present experiments were conducted in the modified Mueller projection tube, shown in Fig. 1. Electrons diverged from the field cathode C and impinged on the anode, a phosphor screen P, where the enlarged electron emission pattern was viewed. The screen, a thin layer of willemite (1 mg/cm^2) was deposited on the inner surface of one hemisphere of the Pyrex envelope by the lacquer flow method. In order to provide a low-impedance anode which would conduct arc currents of the order of 100 amperes without significant anode potential drop, a thin layer of aluminum (1500A), connected electrically to the anode inseal A, was evaporated onto the inner surface of the phosphor and on the remaining inner surfaces of the Pyrex flask. The aluminum film was transparent to primary field electrons with energies used herein;[24] it was relatively opaque to lower-energy secondary electrons, to light, and to negative ions, thus limiting emission pattern aberrations due to those causes. Since the aluminum film shielded the cathode from stray fields due to charges which accumulate on insulating surfaces, it was possible to calculate the cathode electric field accurately from the measured potential and emitter geometry by previously described techniques.[22]

By use of the experimental tube in Fig. 1, it was possible to observe a series of electron emission patterns which were exposed during individual microsecond intervals at successively increased values of the applied potential during the transition from the normal field emission to the vacuum arc. From the emission patterns it was possible to detect surface contaminants, crystallite growth, and surface migration or other geometric change at the cathode. It was also possible to monitor residual pressure of chemically active gases and to detect gap traversal by anode ions.

Pressures of chemically active gases of the order of 10^{-12} mm of Hg which were used in most of the present work were obtained by methods discussed in references 1 and 11.

[23] M. H. Nichols, Phys. Rev. **57**, 297 (1940).
[24] D. W. Epstein and L. Pensak, RCA Rev. **7**, 5 (1946).

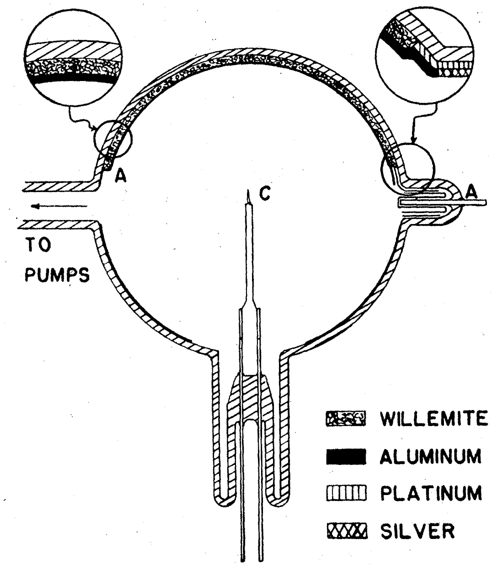


FIG. 1. Experimental field emission tube. (C), field cathode; (A), aluminum-backed-willemite anode.

Two changes in the voltage pulser of reference 1 are noted. In the present work, $\frac{1}{2}$-microsecond pulses were obtained from an artificial line, while shorter pulses were obtained from a 70-ohm coaxial cable. For high-voltage microsecond operation, a 100-kv, 100-ampere pulse transformer, supplied by the University of California Radiation Laboratory, was used.

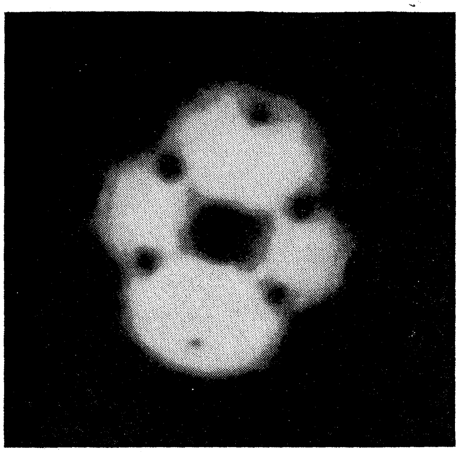
RESULTS AND CONCLUSIONS

1. Coincident Anomalies in the Current Pulse and Emission Pattern Which Mark the Onset of Breakdown

The experimental data from emitter 0–38 were recorded as shown in Fig. 2. Each emission pattern photograph and the oscillographs of the current and voltage waves with which it was coincident were obtained during a single-microsecond interval of operation. From those and other similar data from the same emitter, the current-voltage relationship for its combined direct current and pulsed operation was plotted in Fig. 3. In that figure, the several experimental points which are lettered correspond to the data with the same letters in Fig. 2. These data are typical of that from each of fifteen emitters which were tested.

The present study of electrical breakdown will consider the data at the large current extremity of the graph in Fig. 3; however, a brief parenthetical comment on the rest of the data in that figure may be instructive. The graph departs from linearity at C, such departure being similar to that observed for other emitters.[1] The departure was assumed to be an effect of space charge on the cold cathode emission. Figure 13 of reference 1 described the probable effect of the space charge upon the surface distribution of the field current density. That result is qualitatively confirmed by a comparison of the emission patterns in Figs. 2(C) and 2(D). The former was taken at the largest current for which space charge was negligible; the latter corresponds to a marked space-charge influence. As may be seen from the corresponding emission pattern, Fig. 2(D), space charge resulted in a relatively uniform current density (except in the high work function (110) crystal directions) over an increased emitting area including most of the emitter hemisphere. The correlation between current density, crystallographic direction and emitting areas on the surface of such hemispherical single crystal tungsten field emitters is described elsewhere.[17,25] A more quantitative analysis of the effects of space charge on field emission will be submitted for publication at a later date.

Marked changes in the normal performance of the field emitter were observed just prior to electrical breakdown. Anomalies appeared both in the current wave shape and in the emission pattern during a 30 percent increase in current density to the critical value $\bar{J}_x$ at which arc resulted. However, if arc was avoided by keeping the current density below $\bar{J}_x$, those pre-arc anomalies, and the entire performance of the emitter at all lower current densities were reproducible and reversible.



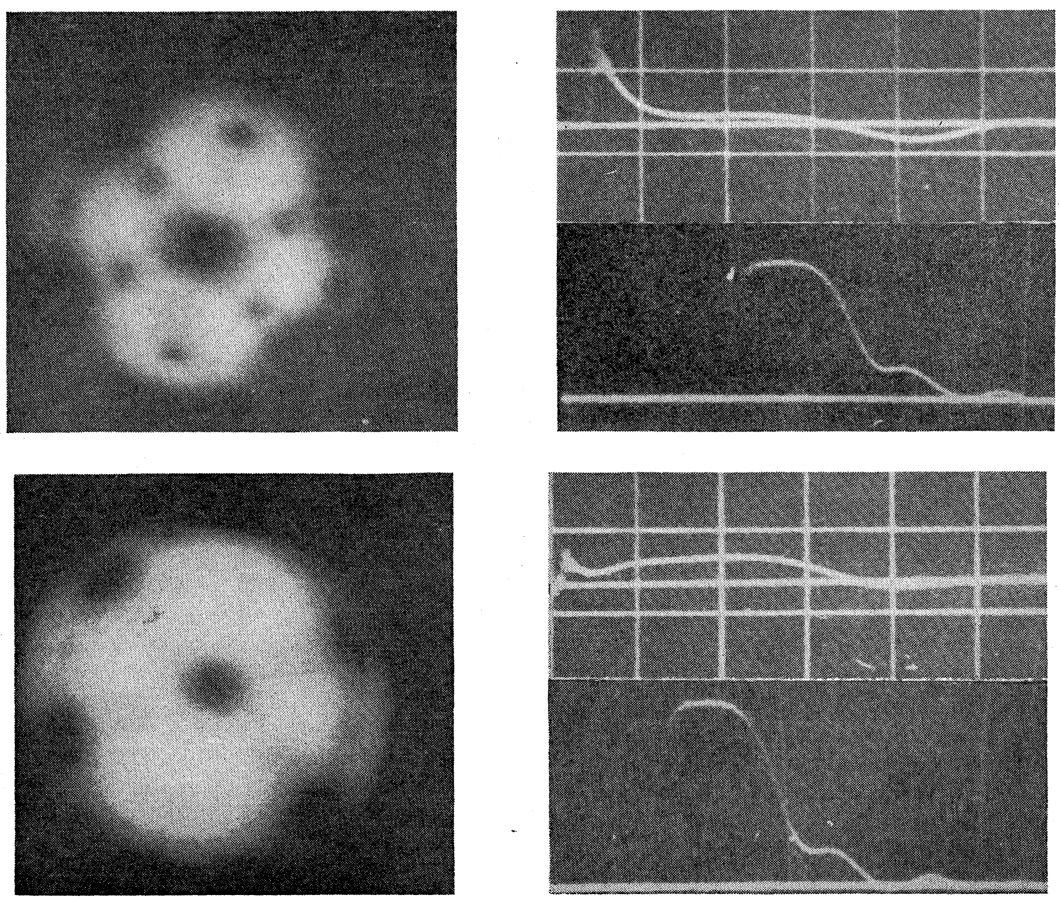


Fig. 2. Typical experimental data as recorded for emitter 0–38 including emission pattern photographs (left) and corresponding current and voltage oscillographs (right) at various current and voltage levels. Data are lettered corresponding to points with the same letter on the graph of Fig. 3. Direct current operation at (B), pulsed operation at (C), (D), (E), and (F). Peculiarities at the leading and trailing edges of the current pulse were due to circuitry, not field emission.

[25] I. N. Stranski and R. Suhrmann, Ann. Physik 1, 153 (1947).

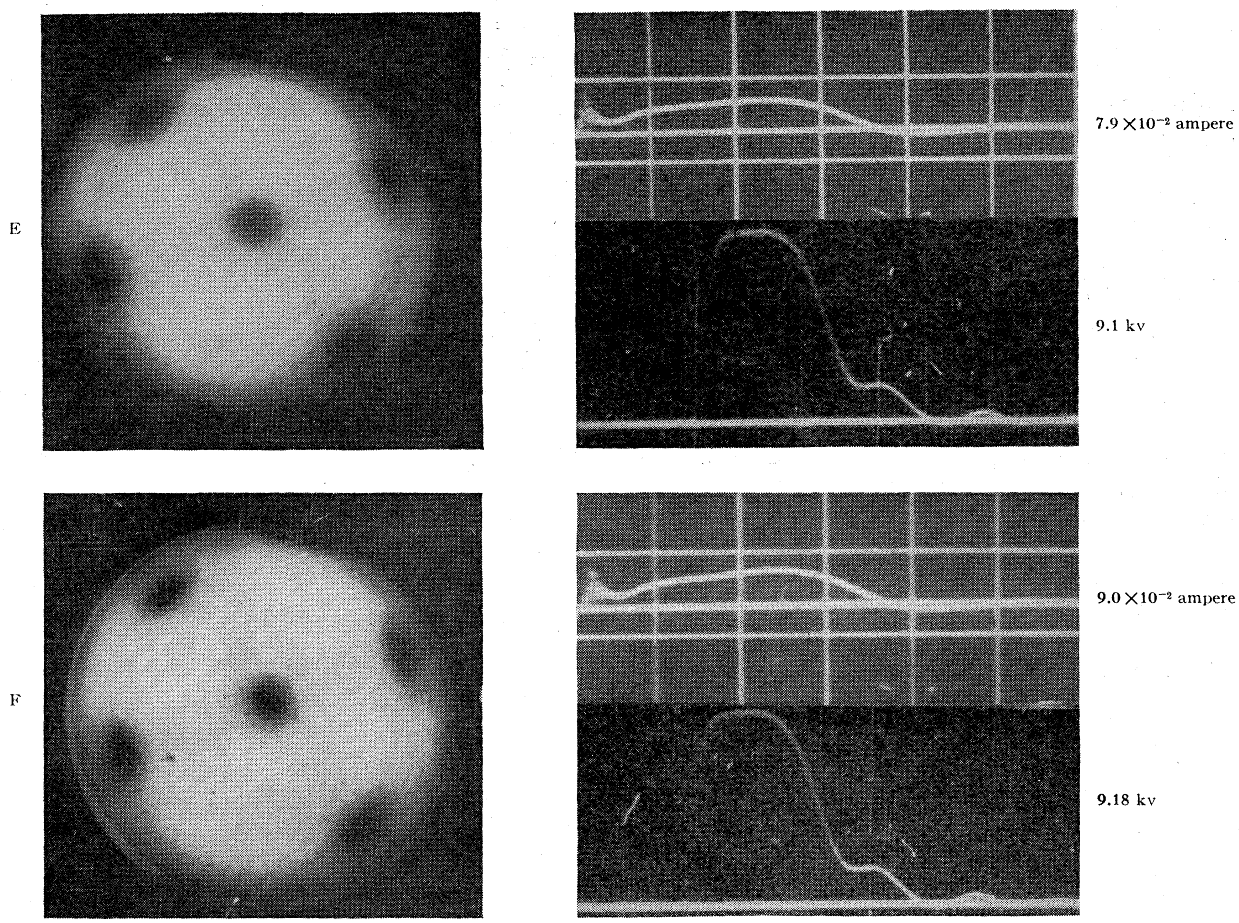


FIG. 2.—*Continued.*

One of the pre-arc anomalies in emitter performance was an increase in current with time while voltage was held constant [Fig. 2(F)]. That anomaly, previously[1] called "tilted current pulse" and abbreviated as "tilt" hereafter, was not characteristic of the cold cathode field emitter. The normal field current was constant when voltage was constant as was expected from Eq. (1). Such a normal current pulse is shown in Fig. 2(D), which was typical of that obtained from lower currents.

With the tilt there appeared simultaneously an anomaly in the emission pattern, a "ring" of electron emission concentric with and external to the normal pattern [Fig. 2(F)]. Evidently the ring was not due to electron emission under the influence of electric field alone, since the increase in ring intensity during the series of patterns 2(D) through 2(F) was considerably greater than that expected from Eq. (1) for the 3 percent increase in applied potential during the series. The expected change in current density was a factor of 1.6, while the observed change in intensity in the ring was in excess of an order of magnitude, based on an estimate aided by a densitometric analysis of the photographic negatives of the emission patterns.[26]

[26] Dyke, Trolan, Dolan, and Grundhauser (to be published).

Electrical breakdown in the form of an explosive vacuum arc occurred when the applied potential was increased 1 percent to 2 percent above the value for which ring and tilt were observed for each of four emitters which were so tested. Ring and tilt were thus identified with the onset of electrical breakdown. An important observation is that electrical breakdown was predictable and not random as often supposed.

Since electrical breakdown was predictable, it was avoided to prevent the usual emitter damage which accompanies breakdown [Figs. 5(C) and 7], in order to obtain the electron micrographs of emitter 0–38 shown in Figs. 4(A) and 4(B). From those micrographs the emitter geometry was determined as an aid to the calculation of both electric field and current density.[22] The emitter was stable during ring and tilt, as judged from the reproducibility of its performance (including ring and tilt) as shown in Figs. 2 and 3.

Ring and tilt were observed at a critical value of the current density in the range for which electrical breakdown was observed for other emitters.[1] The critical density $\bar{J}_x = 6\times10^7$ amperes/cm^2 for the present emitter was calculated from Eq. (7) of reference 1. $\bar{J}_x$ was approximately the average current density through the emitter cross section XX in Fig. 4(D), that profile of the emitter being an enlargement of Fig. 4(B). Further support is thus added to the previous observation[1] that electrical breakdown is initiated by a current density dependent mechanism under the present experimental conditions.

It will be shown in Part II of this paper that emitter temperature approaching the melting point of tungsten is expected from the resistive generation of heat during the emission of current densities approximately equal to the observed values of $\bar{J}_x$. It is presently supposed that the ring and tilt, and the electrical breakdown which they precede, were initiated by thermal effects accompanying that temperature increase. It follows from the resistive mechanism that the emitter temperature increases with time during microsecond intervals of operation and from the theory of Guth and Mullin[27] that such a temperature increase would cause a corresponding increase of current density with time. This effect is presumed to account for the tilted current pulse. Since the ring and tilt occur simultaneously, and since neither can be accounted for by cold cathode field emission alone, as noted above, it is probable that both effects are due to electron emission at high field and high temperature.

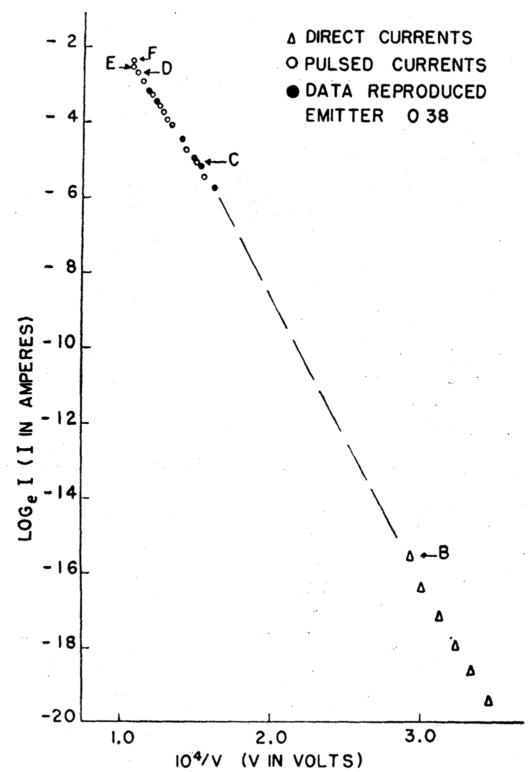


FIG. 3. Current-voltage relationship for combined direct current and pulsed operation of emitter 0–38. Data at (B), (C), (D), (E), and (F), correspond to the data at the same letters in Fig. 2. Space-charge effects were observed at currents above (C); anomalies in the normal emission preceding electrical breakdown were observed from (D) to (F).

[27] E. Guth and C. J. Mullin, Phys. Rev. 61, 339 (1942).

Available evidence indicates that the temperature required for ring and tilt was near the melting point of tungsten. Evaporated emitter material appeared to be the source of the positive ions which are required to neutralize space charge during the large increase in current accompanying the transition from field emission to vacuum arc.[1] Temperatures in excess of the melting point are required for the observed deformation of the cathode during arc [Figs. 5(C) and 7]. Furthermore, the increase in ring intensity during the series of Figs. 2(D) through 2(F) was considerably greater than the current density increase predicted theoretically[27] for temperatures less than 2000°K to which the theory is limited. When the emitter was heated to 2100°K from

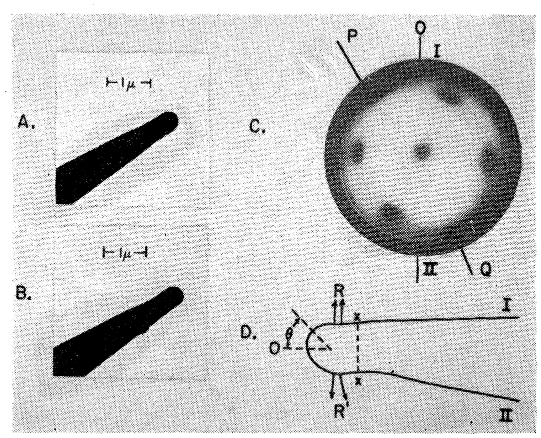


FIG. 4. (A) and (B), electron micrographs of two profiles of emitter 0–38 at 90° with respect to each other; (C), an emission pattern photograph from emitter 0–38 identical with Fig. 2(F). (D), an enlargement of (B), shows ring emitting area RR', minimum emitter cross section XX where current density was maximum; sides I and II correspond to those sides of the pattern at (C). θ, the polar angle for the approximate hemispherical emitter tip was measured relative to the apex.

an external heat source (its support filament) the emitter was stable during the emission of microsecond current densities less than $\bar{J}_x/3$ and no evidence of ring and tilt was then observed. Presumably temperatures greater than 2100°K are required for those effects.

It is important to note that the resistive generation of heat, together with the predicted[27] increase of current density with temperature, combine in a regenerative process yielding further increases in both current density and temperature. If, as supposed, the resistive mechanism produces an increase in temperature to a value near the melting point of tungsten, further increases in temperature by the regenerative process would lead to emitter instability, particularly in view of the large electrical force on the emitter tip. The tilt is regarded as evidence of that regenerative process. Emitter instability accompanied electrical breakdown [Fig. 5(C)].

The area from which the ring emission originated was located in the approximate region RR' [Fig. 4(D)]. That profile of the emitter is an enlargement of Fig. 4(B). Observed crystallographic detail in the ring at P and Q, Fig. 4(C), corresponds to (110) crystal faces[17,23,25] found at $\theta=\pi/2$ [Fig. 4(D)]; however the extent of the region RR' along the emitter shank is uncertain. It was not possible to use measurements of the dimension of the emission pattern ring to determine the area RR' since the magnification in the θ direction in that part of the emission pattern was quite small due to the large radii of curvature at the corresponding surfaces. This difficulty precluded calculation of the magnitude of the current density from the area RR' in the present experiment.

The electric field was calculated by the methods of reference 22 for surfaces where space-charge effects were negligible. By this method the field at R, Fig. 4(C), was 5.7×10^7 v/cm and that at R' was 6.3×10^7 v/cm when the applied potential was 9.2 kv, the value for which ring and tilt were observed. With the same potential, the electric field at the emitter apex was 7.4×10^7 v/cm. The latter field was calculated from Eq. (1) and the observed value of the current density since space charge near the apex precluded use of the methods in reference 22. Apparently the difference in fields between R and R' accounts for the observed difference in ring intensity in the emission pattern, Fig. 4(C), at the corresponding points I and II whose work functions are similar.

It may be concluded from this section that electrical breakdown was predictable under the experimental conditions used in this work. Easily recognizable conditions (i.e., ring and tilt) which precede arc formation have been established and these appear to be due to electron emission from the cathode in the presence of high electric field and high temperature.

Electrical breakdown occurred at a critical current density $\bar{J}_x$ of the order of 10^8 amperes/cm² for the microsecond field emission from clean tungsten in high vacuum. Breakdown apparently resulted from thermal effects when the emitter was resistively heated.

2. Arc Formation Without Cathode Bombardment from Ions Formed at the Anode

The electrical breakdown described in the previous section was apparently initiated by thermal effects when the emitter was resistively heated. The contribution of other heat sources appeared negligible. One such source, the bombardment of the cathode by positive ions, was intentionally minimized. High vacuum and, in some cases,[1] well-outgassed electrodes of high melting point were used to minimize the production of positive ions by field electrons. Direct evidence was obtained from the field emission patterns (Fig. 2) that bombardment by chemically active ions (and residual gas) was negligible prior to breakdown. Other evidence indicating that ion bombardment was negligible is seen from the observed dependence of the breakdown on current density. Breakdown due to ion bombardment might more logically be expected to depend on total voltage,[4] but this was not observed under the present conditions.

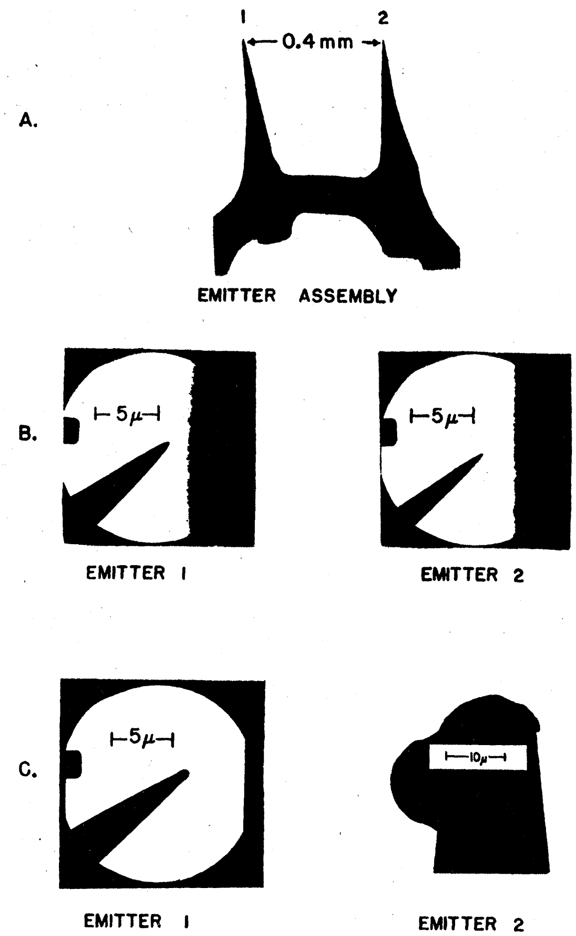


FIG. 5. (A), optical micrograph of twin emitter assembly showing emitter No. 1 and emitter No. 2 as marked. (B) electron micrographs before use. (C) electron micrographs after use.

Although the evidence against the initiation of the present breakdown by positive ion bombardment of the cathode was considerable, it was nevertheless largely indirect. It was recognized that bombardment of the cathode by chemically inactive ions might not be recognized through their effects, if any, on the emission pattern. That method would be particularly ineffective for detecting ion bombardment along the emitter shank for reasons which precluded an accurate evaluation of the current density in those areas in the preceding section of this paper. Furthermore, the useful features of the emission pattern were destroyed during the vacuum arc [see Fig. 6(D)] and any contribution of ion bombardment of the cathode at that time must be judged by other means. Experiments described in this and in the following sections of the present paper were performed to better evaluate such heating mechanisms prior to and during the breakdown process.

Experiments are described in this section in which vacuum arcs were observed when gap traversal by ions or clusters formed at the anode was precluded by use of a voltage pulse whose time duration was short compared with the gap transit times of the material in question. A suitable combination[28,29] was a $\frac{1}{2}$-micro-

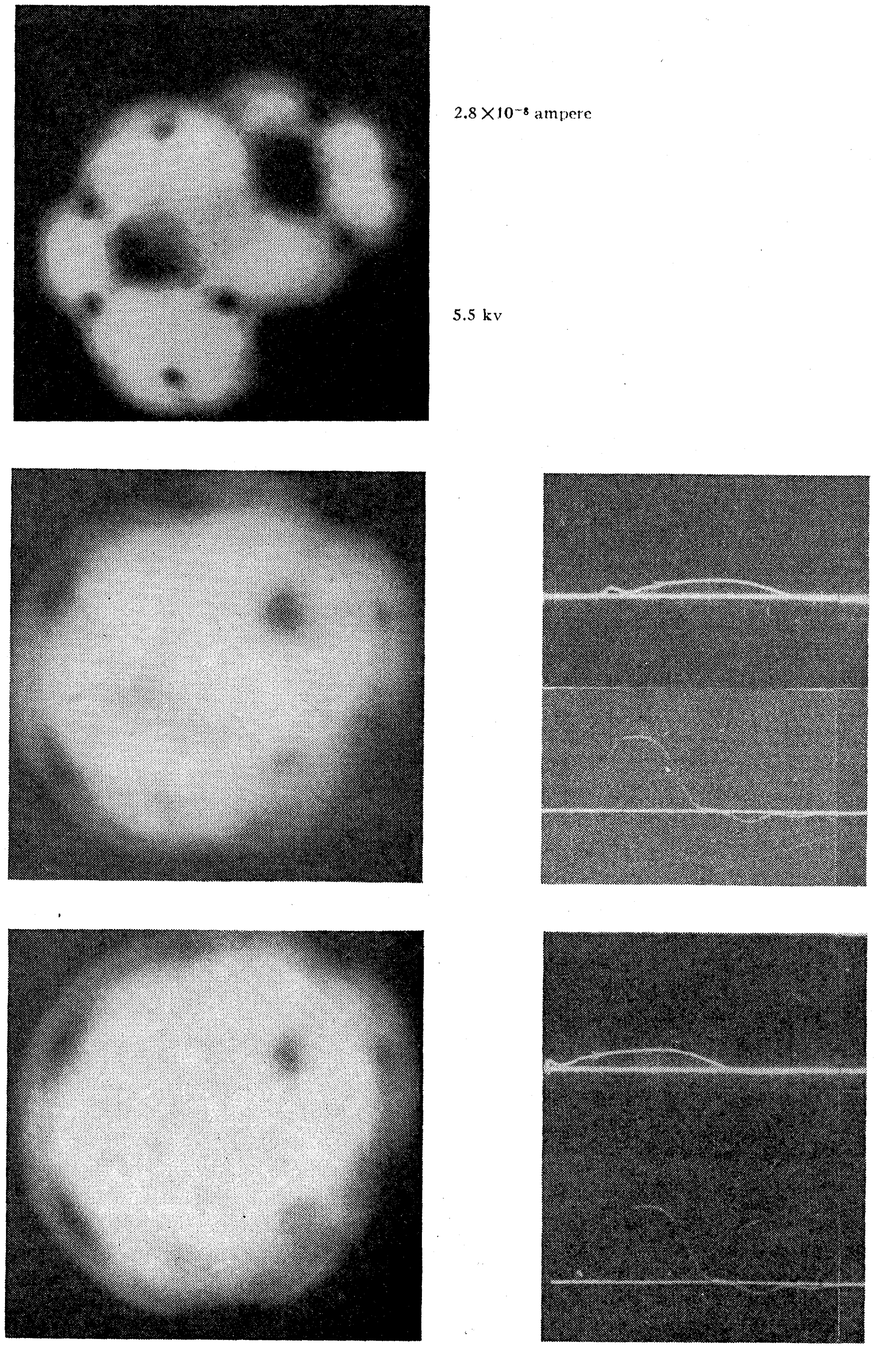


FIG. 6. Experimental data as recorded during the operation of the twin cathode shown in Fig. 5. (A) the combined emission pattern of both cathodes during direct current operation. (B) the combined pattern with current and voltage oscillographs during pulsed operation with space charge but without pre-arc anomalies. (C) ring observed concentric with emission pattern from cathode No. 2; total current trace from both cathodes "tilted." (D) photographs obtained during vacuum arc. (E) the emission pattern from the surviving cathode (No. 1) during direct current operation after the arc of cathode No. 2.

[28] K. R. Spangenberg, *Vacuum Tubes* (McGraw-Hill Book Company, Inc., New York, 1948).
[29] George Barnes (to be published).

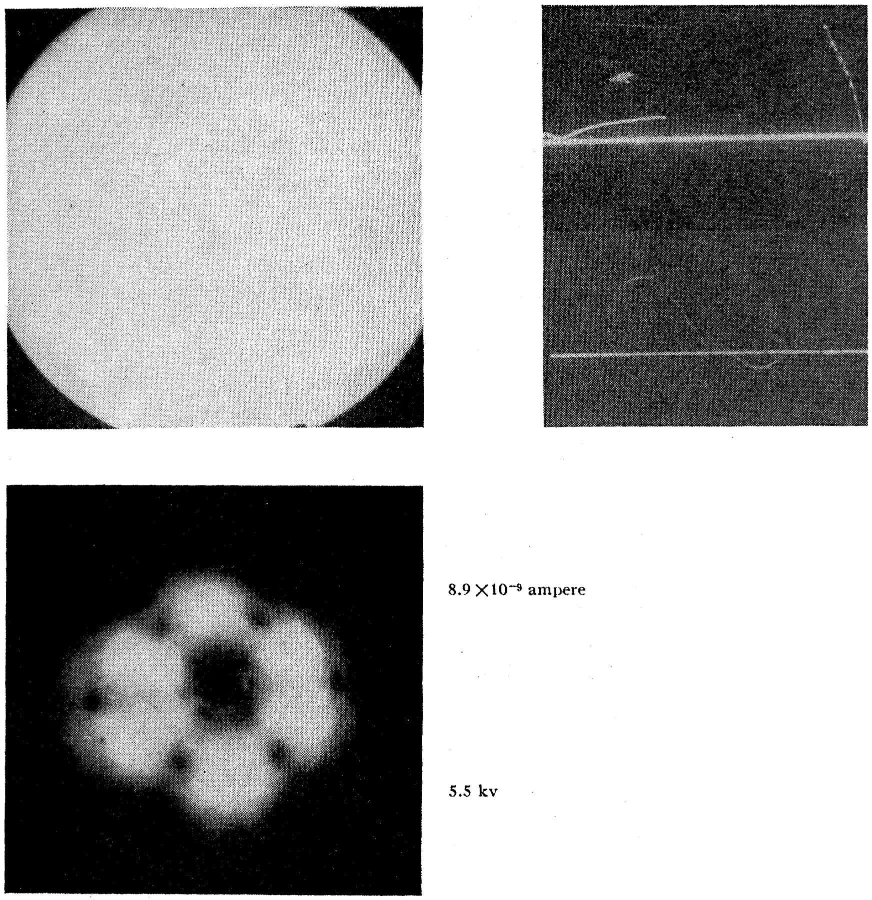


FIG. 6.—*Continued.*

second voltage pulse and 8.5-cm electrode spacing (Fig. 1) with voltages below 10 kv. Such an arrangement excluded gap transit during the pulse time by ions which were expected from sources such as aluminum from the anode or oxygen or nitrogen adsorbed thereon.

Thus operated, ring, tilt, and the electrical breakdown of emitter X-62 resulted at $\bar{J}_x = 4\times10^7$ amperes/cm², the corresponding values of current I and voltage V being $I=0.07$ ampere, $V=8.8$ kv. The value of $\bar{J}_x$ for this emitter was judged from its electrical behavior using Eq. (1) and the methods of reference 1. By this method, $\bar{J}_x$ was known within a factor of 3 and it is noteworthy that this value was in the range for which breakdown was observed for other emitters.[1]

The data from other emitters were similar when a pulse length of 5×10^{-8} second was used, and that period was considerably shorter than gap transit time of the ions and clusters noted above.

It is concluded that ring, tilt, and arc formation do not require the bombardment of the cathode by ions or clusters from the anode material or from its adsorbed gases under the present experimental conditions.

3. Arc Formation With Microsecond Potentials of Large Magnitude

Effects due to bombardment of the cathode by positive ions would be expected to increase with the applied potential because of increased ion energies. Although that mechanism was judged negligible in the experiments just described, it was postulated to account for the "voltage effect" observed by Trump and Van de Graaff[4] at higher voltages and under experimental conditions different from those used herein. More recently, however, positive ion emission coefficients have been found insufficient[9] for the proposed particle exchange mechanism.[4]

It was therefore desirable to observe arc formation with the present techniques and at higher voltages than those used previously.[1] For voltages in the range 50 to 100 kv an emitter of tip radius of the order of 10^{-4} cm was required. Quite by chance such an emitter, X-62-*A*, was formed in the experimental tube from emitter X-62 when the tip of the latter was increased in radius to 1.3×10^{-4} cm during the vacuum arc described in the preceding experiment.

It was thus possible to measure $\bar{J}_x$ at widely different voltages, i.e., 8.8 kv and 60.1 kv, other experimental conditions being identical. At the higher voltage, the critical current density $\bar{J}_x$ was identified by the ring and tilt, avoiding an arc in order to obtain electron micrographs of the emitter. The resulting value of $\bar{J}_x$ was known, within 20 percent, and it is significant that its magnitude, $\bar{J}_x = 2.5\times 10^7$ amperes/cm^2, was in close agreement with that which initiated the low-voltage arc in the same tube, i.e., $\bar{J}_x = 4\times 10^7$ amperes/cm^2. Both values are in the range found for other emitters.

The experimental results were similar when microsecond potentials up to 50 kv were applied to several field emitters in the point-to-plane type tubes of reference 1, the electrode spacing being 0.2 cm to 1.0 cm in various cases.

Cathode bombardment was not excluded by reason of ion transit time at the higher voltages described in this section. However, the breakdown did not appear to be initiated by that process. Arc initiation evidently depended on current density; no voltage effect was observed for the electrical breakdown of microsecond potential under the present experimental conditions, the total voltage range being $5 < V < 60$ kv when previous data[1] were included. It appears that the initiation of breakdown was again due to thermal effects accompanying resistive heating.

It should be noted that the present data from each emitter were obtained from a total of about two hundred individual microsecond current pulses. It is not known whether or not other processes would initiate breakdown if the cathode were repeatedly pulsed for long periods of time at the present voltage levels.

The importance of clean surfaces and high vacuum should be emphasized. Under less favorable conditions, breakdown was not predictable and occurred generally at lower levels of operation.

4. On the Bombardment of the Cathode by Ions During an Arc

Bombardment of the cathode by ions formed at the anode or in the residual gas was judged negligible during an arc or during its initiation based on evidence presented in the foregoing sections. Part of that evidence was indirect. The field emission pattern from clean tungsten is not sensitive to the small amounts of helium which are known to diffuse into evacuated Pyrex envelopes from the atmosphere.[30] Ion bombardment of a cathode during its arc could not be detected from its field emission pattern since the useful features of the pattern were then destroyed [see Fig. 6(D) for example]. Evidence on the magnitude of the bombardment of the cathode by ions formed from inert gas prior to arc or from any source during arc is provided in the following experiment.

[30] Saul Dushman, *Scientific Foundation of Vacuum Technique* (John Wiley and Sons, Inc., New York, 1949), p. 531.

Use of a field cathode to monitor the effects of ions during an arc at another cathode appeared feasible. A spacing between cathodes which was small [Fig. 5(A)], compared to their spacing from a common anode (Fig. 1) provided similar probabilities for the bombardment of each cathode by ions from the anode. With an anode to cathode spacing of 4 cm and a microsecond applied potential of 17 kv, gap traversal by ions was possible during the pulse time. The cathodes had nearly identical geometries [Fig. 5(B)] and hence nearly equal values of electric field and current density for a common value of the applied potential. This arrangement was chosen for reasons which follow.

If a vacuum arc was initiated by a current density dependent mechanism, as supposed, breakdown should occur first at that cathode with the greatest current density. If the arc involved primarily cathode phenomena, it was recognized that an arc at one cathode might not cause an arc at the other. In this event examination of the emission pattern of the surviving cathode would yield direct evidence concerning the magnitude of cathode bombardment by chemically active ions from the anode or the residual gas during arc at the other cathode. On the other hand, if an arc at one cathode initiated an arc at the other at a lower current density than that for which arc was expected at the latter cathode, then ion bombardment would be suspected.

Two needle-shaped tungsten field emitters on a common support filament [Fig. 5(A)] were fabricated by previously described techniques.[22] The two emitters had nearly identical cone angles after their simultaneous electrolytic etch in normal NaOH [Fig. 5(B)]. When the emitters were simultaneously heated in the experimental tube during the outgassing procedure both emitter tips were shaped into approximate hemispheres of nearly equal radii by the surface migration of tungsten-on-tungsten.[21] Electron micrographs of each emitter were obtained after the experiment [Fig. 5(C)]. That shown for emitter No. 1 was also approximately the geometry of emitter No. 2 before its arc, as will be argued in the following.

When operated in a Mueller projection tube (Fig. 1), emitter No. 2 supplied two-thirds of the total field current. The ratio of currents from the two cathodes was determined by a densitometric analysis of the photograph of their combined emission pattern prior to arc [Fig. 6(C)]. The result was consistent with the current ratio found from a comparison of the total current from both cathodes prior to arc [Fig. 6(A)] with the current from the single surviving cathode No. 1 after arc [Fig. 6(E)], the comparison being made at a common value of the applied potential.

The performance of the twin cathode during the transition from field emission [Figs. 6(A) to 6(C)], to the vacuum arc [Fig. 6(D)] is significant. Figure 6(A) taken at a small continuous current level shows the overlapping emission patterns from the two emitters. Oscillographs of the combined current from both emitters and of their common applied microsecond potential during operation at a relatively high field current density are shown in Fig. 6(B) [space-charge effects are comparable to those shown in Fig. 2(C)]. In Fig. 6(C), ring and tilt are apparent; however, the ring is concentric with the pattern from emitter No. 2. No ring appears concentric with the pattern from emitter No. 1. This observation is consistent with the supposition that ring and tilt are initiated at a critical current density, since the current density from cathode No. 2 was larger than that from cathode No. 1 by a factor of two, as noted above. Ring and tilt and the entire pre-arc performance of the twin emitter were reversible and reproducible as was the case for emitter 0–38 described earlier. No contamination of either cathode was observed prior to arc.

During arc initiation, Fig. 6(D), the current and voltage wave shapes were similar to those described in more detail in reference 1. Arc was initiated (at cathode No. 2 only) after the total field current from both cathodes had reached approximately the peak value expected during the microsecond interval [compare with 6(C)]. Arc was initiated abruptly, the current increasing during arc by a factor of approximately 100 judged from the corresponding decrease in voltage and the known pulser impedance. No emission pattern detail was observed during arc [Fig. 6(D)].

The emission pattern immediately following arc, Fig. 6(E), shows only emission from cathode No. 1. No emission was then obtained from cathode No. 2 whose geometry was altered by arc as shown in Fig. 5(C). It is significant that emitter No. 1 did not arc or suffer detectable geometric change during the electrical breakdown of its companion, although the electric fields at the two cathodes differed by only a few percent and their current densities differed by only a factor of two prior to arc. During later tests, cathode No. 1 exhibited ring and tilt at a current just twice that which it sustained without damage during the arc at its neighbor. In that case, ring and tilt were observed at a critical current density $\bar{J}_x=5\times 10^7$ amperes/cm^2 in the range reported for other emitters. (For other data on this emitter 2X4, see Table I, Part II of this paper.) This result provides direct evidence that the energy added to cathode No. 1 by positive ion bombardment during the arc at cathode No. 2 was not large compared with that supplied to cathode No. 1 by the resistive mechanism.

Further evidence supporting this conclusion is seen from the negligible contamination exhibited by cathode No. 1 as the result of the arc at its neighbor. The emission pattern, Fig. 6(E) taken immediately after that arc, and without any further treatment such as heating to remove contaminants, indicates only the most minute contamination on the (110) crystal face

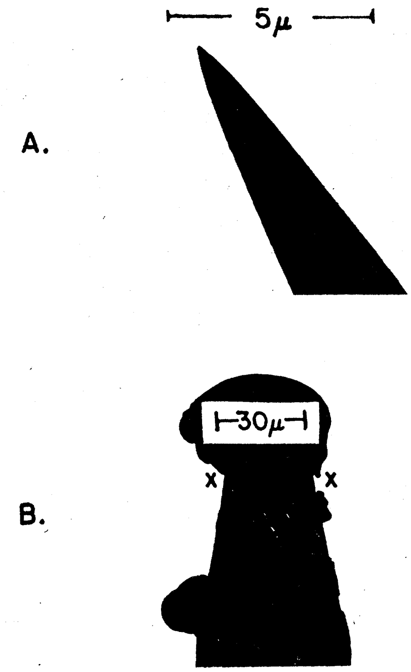


FIG. 7. Electron micrographs of emitter 0–61 before use (A) and after vacuum arc (B).

(central nonemitting area). That contaminant was probably tungsten[21] evaporated from the tip of emitter No. 2 during its arc (evaporated emitter material was postulated in reference 1 as a source of positive ions required to neutralize space charge during the large current increase accompanying the arc).

This experiment provides direct evidence that electrical breakdown involved primarily cathode phenomena under the present experimental conditions. Breakdown was dependent on current density but apparently independent of the effects of positive ions from anode or residual gas sources. Breakdown again occurred at a critical current density for which appreciable resistive heating was predicted.

5. Direct Measurement of the Current During Vacuum Arc

The current during a vacuum arc was previously[1] judged by indirect evidence to be of the order of 100 amperes under present experimental conditions. The arc current was measured directly in the present work.

Use was made of the ring and tilt to identify the largest stable microsecond pre-arc field current $I_x=0.1$ ampere for emitter 0–61. Arc was thus avoided during that initial measurement permitting the later decrease in sensitivity of the current measuring circuit[1] required for an accurate measurement of the total current I_a during arc. For the same emitter $I_a=46$ amperes. The low-impedance feature of the present vacuum arc is noteworthy.

The arc current of 46 amperes corresponds to a current density of 8.7×10^6 amperes/cm^2 at the cross section XX of the emitter profile in Fig. 7(B). That current density is about equal to the value required to raise the tip of the emitter 7(B) to its melting point in one microsecond in view of the calculations presented in Part II of this paper. The heat of fusion is small, and no large amount of material was vaporized during arc judged from the electron micrographs of Fig. 7. The evidence indicates that the resistive mechanism was adequate to account for the heat required by the observed emitter deformation during arc. Apparently energy was not supplied by other mechanisms at a rate large compared with that of the resistive mechanism.

PHYSICAL REVIEW VOLUME 91, NUMBER 5 SEPTEMBER 1, 1953

The Field Emission Initiated Vacuum Arc. II. The Resistively Heated Emitter*

W. W. DOLAN, W. P. DYKE, AND J. K. TROLAN
Physics Department, Linfield College, McMinnville, Oregon
(Received March 30, 1953)

Electrical breakdown between clean metal electrodes in high vacuum was observed when the field current density at the single crystal tungsten cathode exceeded a critical value of the order of 10^8 amperes/cm^2. At current densities just below the critical value, an electron emission process was observed which apparently involved both high temperature and high electric field. Calculations are presented for the emitter temperature increase due to the resistive mechanism for both the steady state and the transient solution. Emitter geometries used for the calculations approximated those obtained from electron micrographs of several emitters. The calculations show that the resistive heating was sufficient to melt the emitter at the critical current density, assuming the accepted value of the physical constants for the polycrystalline metal.

IN Part I of this paper evidence has been presented showing that the interruption of the microsecond field emission from the tungsten emitter by the occurrence of a vacuum arc is dependent principally upon current density J under conditions of clean emitter surfaces and excellent vacuum. It also has been pointed out that the experimentally observed values of the critical current density $\bar{J}_x$ for arc initiation lie in the range $10^7<\bar{J}_x<10^8$ amperes/cm^2 for microsecond operation, with the suggestion that heating of the emitter by a current density dependent mechanism may be the initiating factor of the breakdown. The purpose of this part of the paper is to present an analysis of the heat flow problem when an emitter of idealized geometry approximating those used in actual operation is heated resistively. The current density dependent mechanism proposed by Nottingham[1] is briefly considered. A comparison will be made between values of the current density for which an arbitrary large temperature increase is predicted by resistive heating and experimental values of $\bar{J}_x$.

A mathematical analysis of the resistive generation of heat and its simultaneous dissipation by conduction, using physical constants for the polycrystalline metal, was made possible when electron micrographs had revealed the geometry of the emitter,[2] whose shape in the present experiments was a cone whose half-angle was in the range 2.75° to 15.5°, with a hemispherical tip of radius between 1.5×10^{-5} and 1.5×10^{-4} cm. Although this geometry does not lend itself directly to any simple coordinate system, it may be closely approximated by a portion of a cone bounded by concentric spherical surfaces, orthogonal to the cone, for which ordinary spherical coordinates are suitable. Figure 1 shows a comparison between the idealized geometry and that of several typical emitters. The point $u=m$ is chosen to correspond to the position of maximum current density, which may be expected at the "neck" of constricted emitters [see Sec. XX of Fig. 4(D), Part I], or in the case of emitters without constriction, at a distance from the vertex of the emitter about equal to the radius of its hemispherical tip.

The flow lines for both electric current and heat are assumed to follow the radial coordinate curves of the system. Heat radiation is supposed negligible. Consideration of the resistive generation of heat, together with the usual laws of heat conduction, leads to the differential equation

$$u^4\partial^2T/\partial u^2+2u^3\partial T/\partial u-\alpha^2u^4\partial T/\partial t=b. \qquad (1)$$

Here u is the distance in cm from the vertex of the cone, T is temperature in degrees centigrade, t is time in seconds; $\alpha^2=c\delta/\kappa$, where c is specific heat, δ is density, and κ is thermal conductivity; b is defined by

* Support for this work was extended by the U. S. Air Force through the Microwave Laboratory of the University of California, and by the U. S. Office of Naval Research.
[1] W. B. Nottingham, Phys. Rev. 59, 906 (1941).
[2] Dyke, Trolan, Dolan, and Barnes, J. Appl. Phys. 24, 570 (1953).

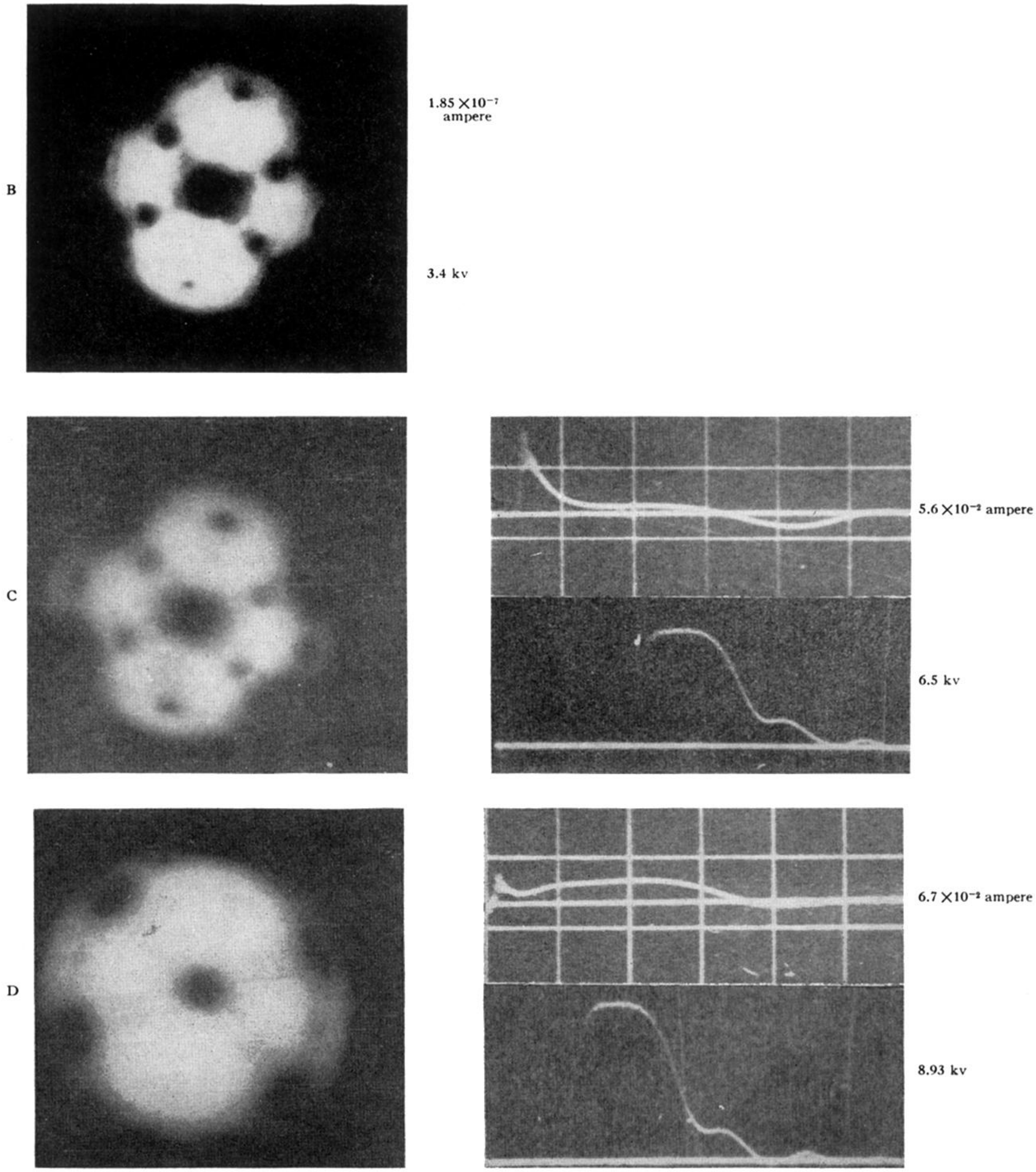
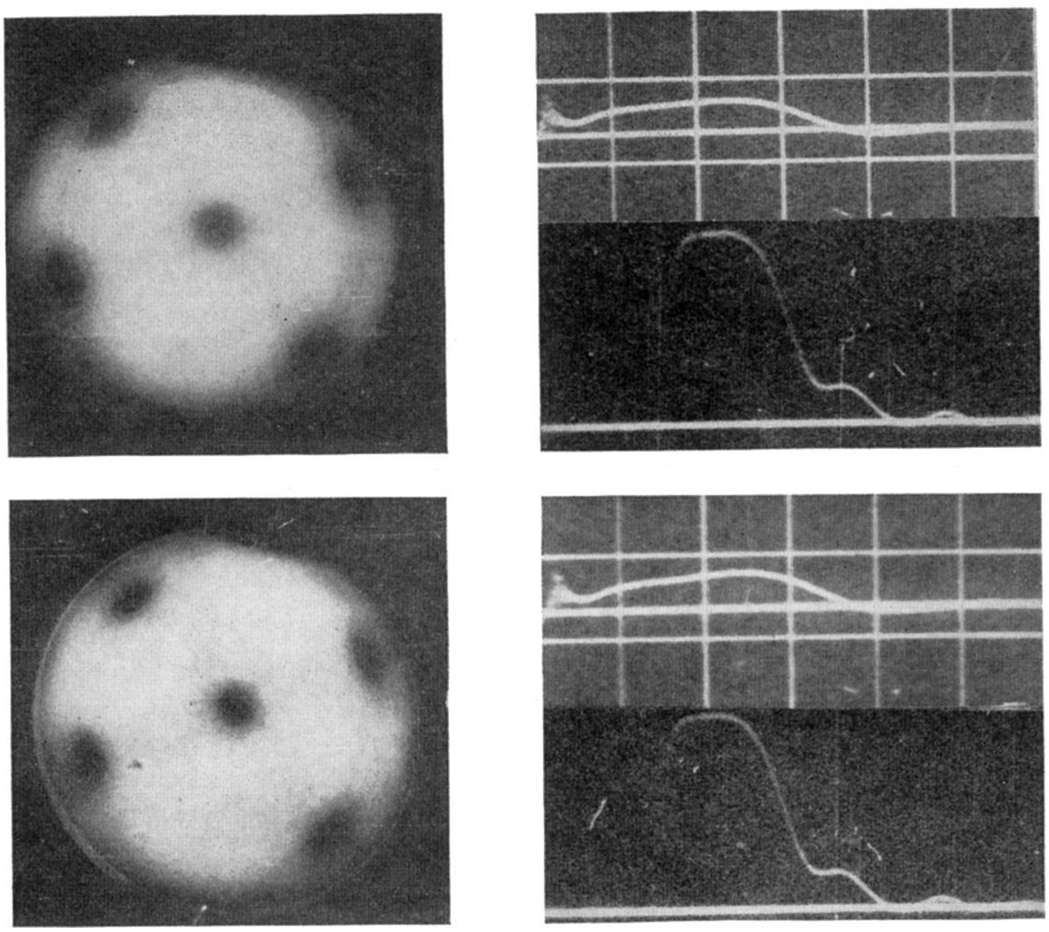


Fig. 2. Typical experimental data as recorded for emitter 0–38 including emission pattern photographs (left) and corresponding current and voltage oscillographs (right) at various current and voltage levels. Data are lettered corresponding to points with the same letter on the graph of Fig. 3. Direct current operation at (B), pulsed operation at (C), (D), (E), and (F). Peculiarities at the leading and trailing edges of the current pulse were due to circuitry, not field emission.

E

F



7.9×10^{-2} ampere

9.1 kv

9.0×10^{-2} ampere

9.18 kv

FIG. 2.—*Continued.*

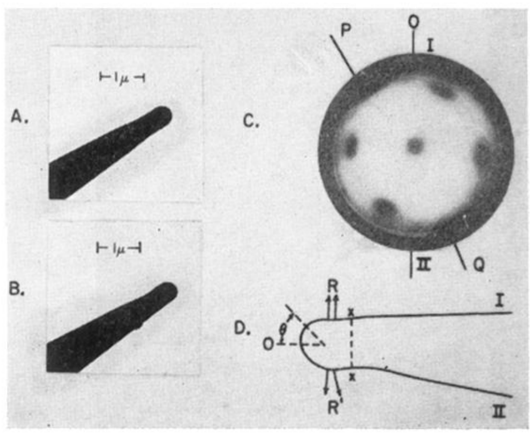


Fig. 4. (A) and (B), electron micrographs of two profiles of emitter 0–38 at 90° with respect to each other; (C), an emission pattern photograph from emitter 0–38 identical with Fig. 2(F). (D), an enlargement of (B), shows ring emitting area RR', minimum emitter cross section XX where current density was maximum; sides I and II correspond to those sides of the pattern at (C). θ, the polar angle for the approximate hemispherical emitter tip was measured relative to the apex.

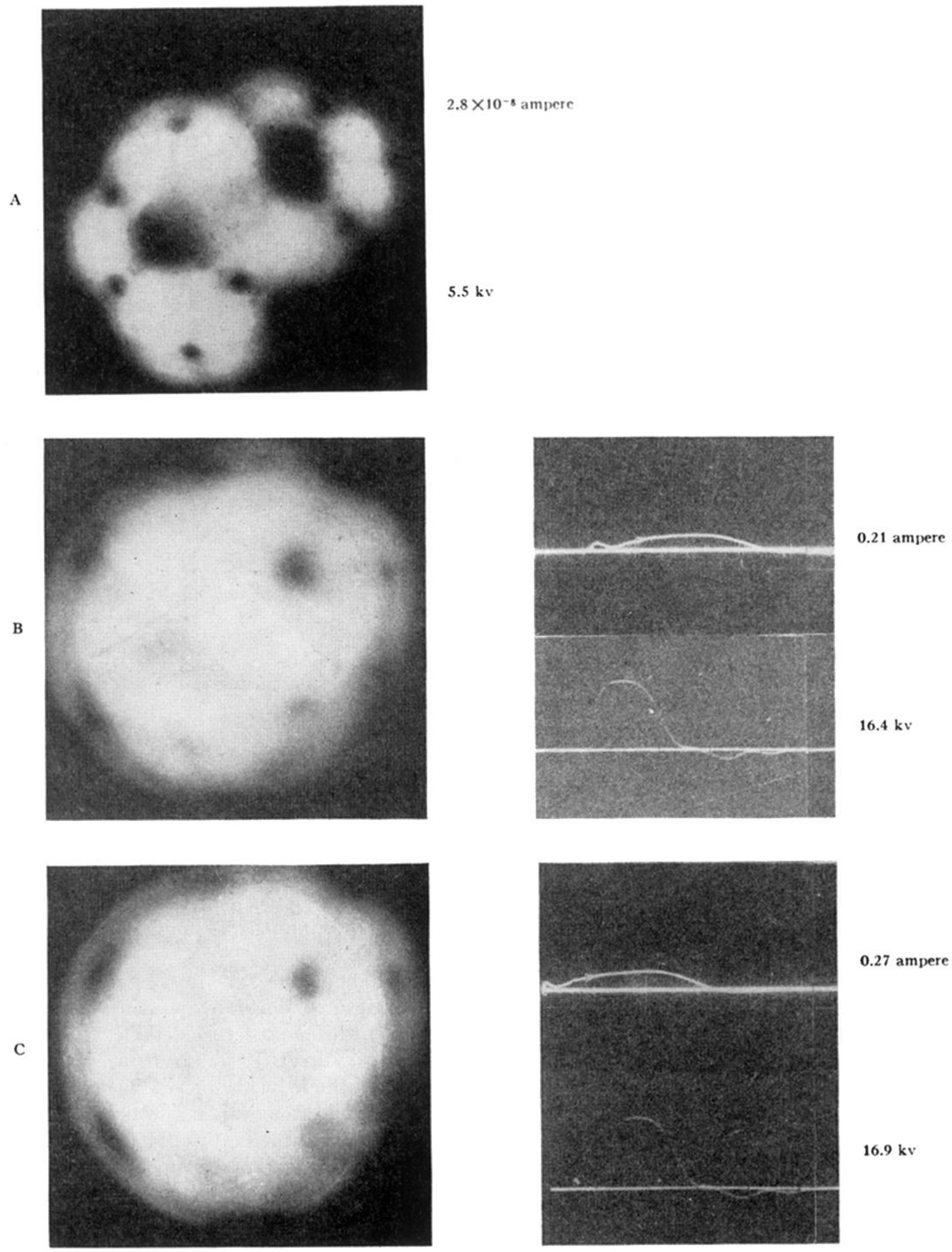


FIG. 6. Experimental data as recorded during the operation of the twin cathode shown in Fig. 5. (A) the combined emission pattern of both cathodes during direct current operation. (B) the combined pattern with current and voltage oscillographs during pulsed operation with space charge but without pre-arc anomalies. (C) ring observed concentric with emission pattern from cathode No. 2; total current trace from both cathodes "tilted." (D) photographs obtained during vacuum arc. (E) the emission pattern from the surviving cathode (No. 1) during direct current operation after the arc of cathode No. 2.

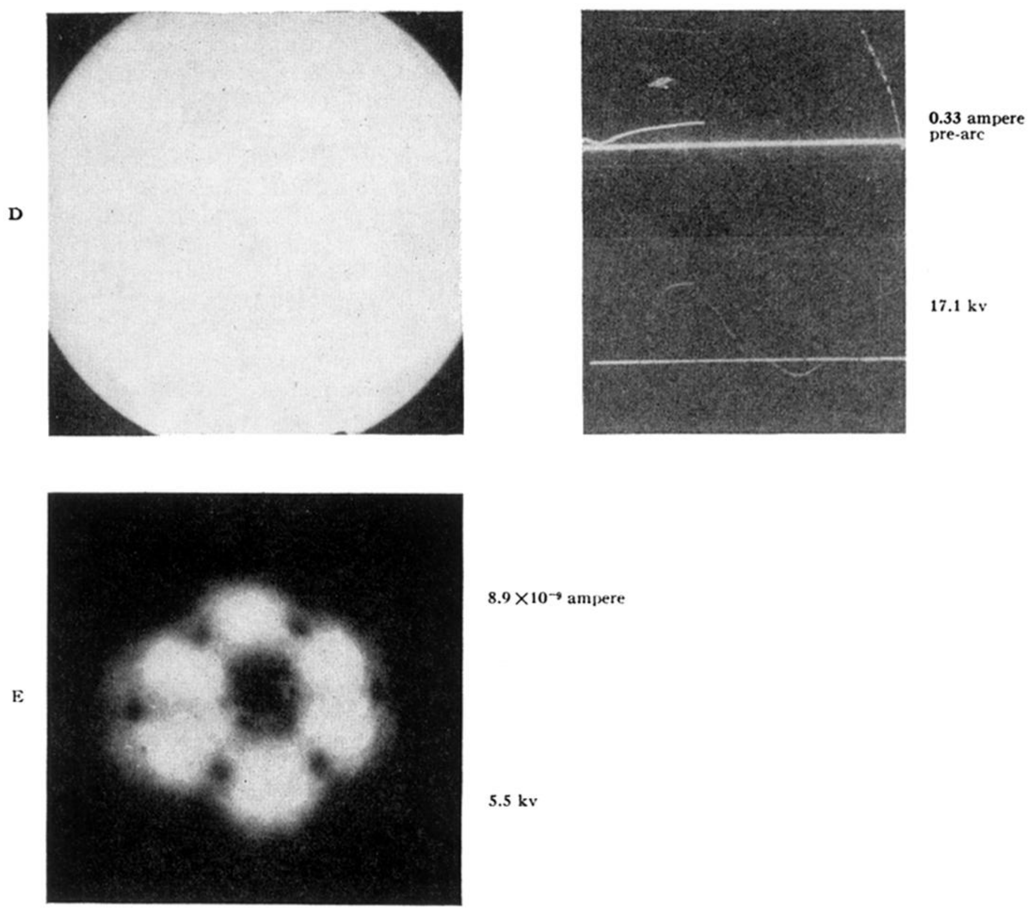


FIG. 6.—*Continued.*