

# Arcing of Electrical Contacts in Telephone Switching Systems

## Part IV — Mechanism of the Initiation of the Short Arc

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*A mechanism is presented for the initiation of the short arc. Breakdown in short gaps, occurring at measured fields of  $30 \times 10^6$  (+ 0 per cent, - 15 per cent) volts/cm for clean palladium and  $28 \times 10^6$  (+ 0 per cent, - 15 per cent) volts/cm for clean gold, are generally preceded by field emission currents from the cathode sufficient to cause heating and evaporation of the anode. This is followed by ionization of the metal vapor, enhancement of the cathode emission, etc.*

(1) *It is shown that to evaporate the anode by electron bombardment one must satisfy the requirement  $jVa/k = (\Delta T)_b$ . By combining this requirement with the field emission equation one may calculate the relation between arc initiation voltage and contact separation from the physical properties of the contact metal. These calculations are in agreement with the measurements.*

(2) *A breakdown is obtained only when a minimum power  $IV = \pi ak(\Delta T)_b$  is dissipated at the anode by electron bombardment. Measurements with clean palladium contacts have given  $IV = 1$  watt in agreement with the above relation. This concept of minimum power for arc initiation should replace that of minimum current for arc initiation. It is possible at 100 volts to initiate a breakdown between palladium contacts at 0.01 ampere which is 100 times smaller than the minimum current required for maintaining the arc.*

(3) *A breakdown will lead to an established arc only if the circuit can furnish enough current to maintain the arc plasma by sufficient metal evaporation; otherwise, transient unstable breakdowns are obtained.*

(4) *Breakdown time lags have been observed. They correspond approximately to the heating time of the anode by electron bombardment until*

evaporation occurs. It was shown that this time lag is theoretically inversely proportional to the square of the over-voltage.

(5) By limiting the circuit currents, it was possible to exceed the usual arc initiation field without breakdown. For palladium the field could be increased to  $36 \times 10^6$  volts/cm when a metal bridge formed electrostatically across the gap. The significance of electrostatic bridging in enhancing breakdowns, particularly in the presence of emission currents and their heating effects, is discussed.

#### INTRODUCTION

It has been shown<sup>1</sup> that an arc may be initiated between contacts at close separations at voltages well below the spark breakdown potential of the surrounding atmosphere. These arcs were found<sup>2</sup> to be initiated at approximately a constant field of the order of millions of volts/cm. The magnitude of the field is dependent primarily on the contact surface conditions. Essentially the same results were obtained in vacuum at small separations.<sup>3</sup> In this paper, arc initiation measurements were extended to a lower range of separation between 200 and 2000Å for palladium and gold contacts in air. Approximately constant field lines were still obtained for arc initiation with fields as high as  $30 \times 10^6$  volts/cm. These are the highest observed fields for arc initiation. The corresponding emission currents are appreciable and are shown to be responsible for setting off the chain of events leading to establishment of the arc.

#### NOTATION

$a$	Effective radius of electron field emission beam from cathode from a point on cathode surface
$d$	Separation between the contacts
$j$	Electron current density
$k$	Thermal conductivity
$l$	Height of surface irregularity on cathode surface
$m$	Mass of metal atom
$r$	Radius of curvature of a point on the cathode surface
$s$	Electrostatic stress
$t$	Time
$u$	Dimensionless parameter in heat conduction equations $u = a/2(\alpha t)^{1/2}$
$f(y)$	Nordheim elliptic function
$z$	Distance from the surface of the anode in the metal
$F$	True field strength
$I$	Electron current

$I_i$	Minimum electron current to initiate a breakdown
$R$	Circuit resistance
$T$	Temperature
$T_b$	Boiling temperature
$T_o$	Ambient temperature
$\Delta T$	Temperature rise
$(\Delta T)_b$	Temperature rise to boiling
$(\Delta T)_c$	Critical temperature rise leading to a breakdown
$V$	Voltage
$V_{ai}$	Arc initiation voltage
$V_{eb}$	Electrostatic bridging voltage
$V_o$	Initial voltage
$V_c$	Voltage across the contact
$\alpha$	Thermal diffusivity
$\phi$	Work function
$\xi$	Field intensification
$\rho$	Electric resistivity

## LINE

Consider a pair of contacts at a certain fixed separation. The separation here is defined as the minimum distance one contact has to move before physical contact first takes place. Due to surface irregularities one must consider this contact separation to be between two points one on each contact. Fig. 1 (a) shows a point on the cathode with a radius of curvature  $r$  and another on the anode with a much larger radius of curvature. By applying a voltage across the contacts a field distribution is obtained on the cathode point, Fig. 1 (b). This distribution is primarily dependent on the geometry involved and, in general, the maximum field is obtained at the tip of the point. If the fields obtained are high enough, perceptible field emission currents will be obtained at the cathode surface. Due to the extreme sensitivity of field emission to relatively small changes in the field, the corresponding distribution of current density on the cathode point approaches a rectangular distribution, Fig. 1 (c). Electrons emitted from the cathode are accelerated by the field in the gap and will bombard an area on the anode causing local heating, Fig. 1 (d). The maximum temperature obtained is a function of the thermal conductivity of the anode material and the size and energy of the field emission electron beam. Should this maximum temperature reach the boiling temperature\* of the anode material, evaporation will

\* It will be shown that heating to the softening temperature of the metal may be sufficient. Intensification of the field is then produced by electrostatic pulling of the anode metal.

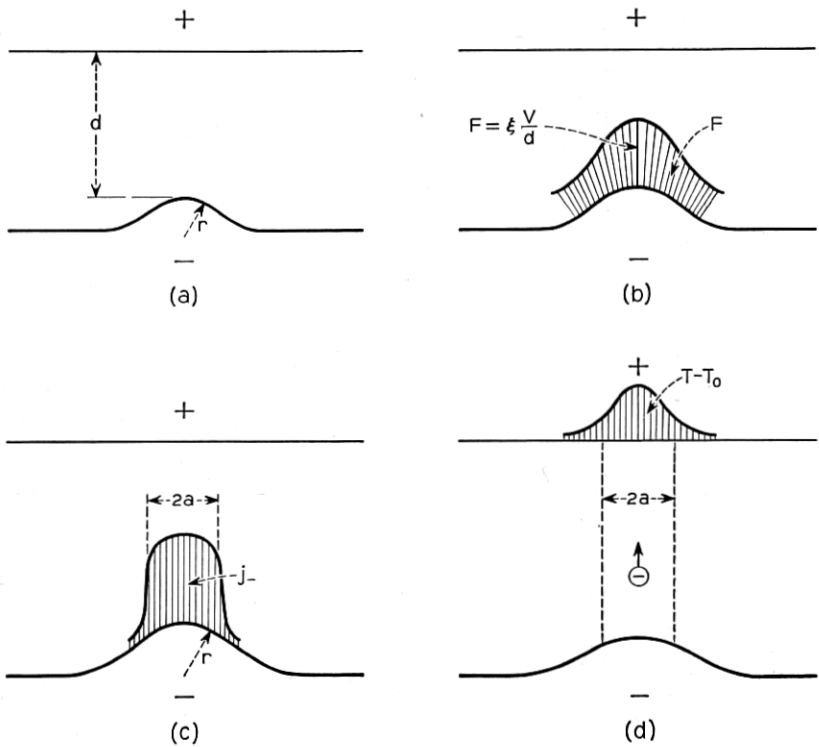


Fig. 1 — Schematic representations of contact geometry, electrostatic field, field emission current and anode heating by electron bombardment.

take place. This is the first step leading to the build-up of the arc plasma in the gap. If the potential drop is above the minimum ionization potential of the metal vapor, positive ions will be produced by electron-metal atom collision. The first ion front produced will travel towards the cathode with a cross-section greater than that of the initiating electron beam. This is due to the initial velocity of the metal atoms corresponding to the boiling temperature of the anode metal. The ion front streaming towards the cathode will increase the field at the cathode. This will multiply the original electron emission by both increasing the emission from areas already emitting and by introducing new emitting areas. This process will repeat and if the associated circuit conditions satisfy certain requirements the plasma is fully developed and the arc is established. Otherwise, a transient unstable breakdown takes place.



ARC INITIATION VOLTAGE VERSUS SEPARATION

In Reference 2 measurements of arc initiation voltage versus contact separation were given. It was concluded that breakdown fields of only a few million volts/cm were due to surface contamination. In the same reference it was indicated that when the contacts were cleaned by heavy arcing, fields as high as  $20 \times 10^6$  volts/cm failed to initiate the arc. With the range of contact separation then available it was not possible to further increase the field without obtaining spark breakdowns along longer paths. This result was obtained for the metals Ag, Ni, Pd, Pt and W.

To avoid the above difficulty a similar cantilever bar set-up was built with a contact separation resolution as low as  $200\text{\AA}$ . The accuracy of the separation setting is determined by the reproducibility of the zero point, i.e., the point at which physical contact first takes place. Best results were obtained by eliminating the use of direct current as a detector. Instead, the contacts were shunted by a pair of wires a few feet long which were directly connected to an oscilloscope through a high gain amplifier. The electromagnetic pickup of the wires is detected on the oscilloscope when the contacts are open and vanishes when the contacts are touching. When the contacts are clean it is possible to reproduce the same zero point to within less than half a division on the vernier of the micrometer. The accuracy of this setup was estimated at better than  $\pm 60\text{\AA}$ .

The contacts were cleaned by heavy arcing as described in Reference 2. The gap was set at a certain value and the voltage gradually increased. Breakdowns were detected on an oscilloscope. It was observed that in some cases rapid transient breakdowns might occur without being detected. These breakdowns were found to change the separation and the subsequent breakdown voltage obtained did not correspond to the original separation setting. This difficulty was overcome by using a different procedure demonstrated in Table I. In this case the desired separation

TABLE I — PROCEDURE FOR DETERMINING ARC INITIATION VOLTAGE AT A FIXED SEPARATION  
Separation  $d = 500\text{\AA}$

Voltage level approached . . . . .	110	120	135	150
Separation measured after reaching above voltage level $d$ in $100\text{\AA}$	5 5 5 5 5	5 5 5 5 5	12* 20* 5 5 5	
Arc initiation voltage . . .				150 140 140 130

\* Change in separation due to an undetected breakdown.

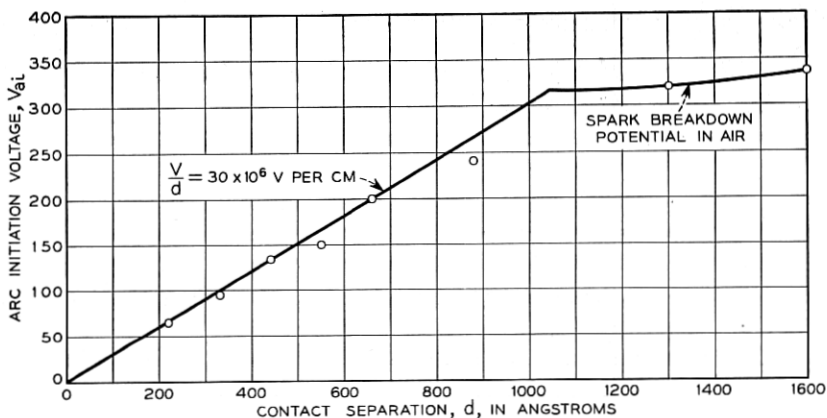


Fig. 2 — Arc initiation data for clean palladium contacts in air at low separations.

was  $500\text{Å}$ . The voltage was gradually increased to a specific voltage level of 110 volts. If reached without an observed breakdown the separation was remeasured. The table shows that after applying this voltage no change of separation occurred. This indicated that the arc initiation was above 110 volts. Repeating at 120 volts the results indicated that the arc initiation voltage still was not exceeded.

At 135 volts the first two measurements showed an increase in separation from an initial setting of  $500\text{Å}$  to  $1,200\text{Å}$  and  $2,000\text{Å}$ . The subsequent measurements gave no change. From this one concludes that the arc initiation voltage is in the neighborhood of 135 volts. Smaller voltage steps were then used. For illustration, the 150-volt level is shown where breakdowns were consistently obtained at or below 150 volts. By this process the boundaries of the arc initiation voltage are obtained and the average and spread are determined.

The results obtained for Pd contacts in air are shown in Fig. 2. For separations below  $1,000\text{Å}$  the arcs were initiated at a value of  $V/d$ , the apparent or gross field, of  $30 \times 10^6$  volts/cm. At higher separations breakdowns occurred along longer paths at the minimum sparking potential of air. Similar measurements were made for clean gold contacts. The value of  $V/d$  obtained was about  $28 \times 10^6$  volts/cm. These results are in accordance with the data of Reference 2 where it was shown that for all the metals tried the value of  $V/d$  at breakdown should be greater than  $20 \times 10^6$  volts/cm. These fields are appreciably higher than has been reported for these short gaps.\*

\* P. Kisliuk<sup>3</sup> has recently reported similar high fields in vacuum.

In an attempt to explore the subsequent process in the arc initiation mechanism, it was necessary to investigate the effects of the associated electrostatic stresses particularly at the high fields reported above.

#### ELECTROSTATIC PULLING OF METAL BRIDGES AT SMALL CONTACT SEPARATIONS

In this section an attempt is made to (1) establish that a breakdown cannot be produced without sufficient emission currents, and (2) determine the possible effects of the electrostatic stresses associated with the high fields leading to the breakdown.

For the measurements presented above, the circuits used were essentially low resistance circuits with little limitation on the currents they supplied. At the high fields obtained the field emission currents were appreciable. As will be shown later, these currents can cause heating of the anode or cathode leading to the subsequent steps of arc initiation. An experiment was then performed to investigate the effect on breakdown of limiting the circuit current by a high circuit resistance. A resistance of  $1.1 \times 10^7$  ohms was placed in the circuit. Emission of discharge currents during the application of voltage were observed by a microammeter in the contact circuit.

The same procedure used for the determination of the arc initiation voltage was applied. At a fixed separation a critical voltage was reached at which a rapid closure of the contact gap was observed. This voltage was found to be quite sensitive to the surface conditions of the contacts. Loose particles on the surface always produced closures at appreciably lower voltages.\* The results for carefully and frequently cleaned contacts were fairly consistent and reproducible. The results for Pd contacts are given in Fig. 3. For voltages below 300, emission currents were observed but were less than  $2 \times 10^{-8}$  ampere and the correction for the voltage drop across the circuit resistance was negligible. For larger separations higher fields could not be applied across the contact due to the establishment of glow discharge along a longer path. The voltage drop across the resistor was such that the voltage across the contacts was consistently maintained at about 320 volts.

The above data indicates that with the high resistance in the circuit the usual breakdown voltage, at a given separation, could be exceeded without breakdown up to a higher value at which sudden closure was obtained. This occurred at approximately a constant value of  $V/d$  of

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\* In extreme cases closures were observed at voltages below 10 volts for badly contaminated contact surfaces.

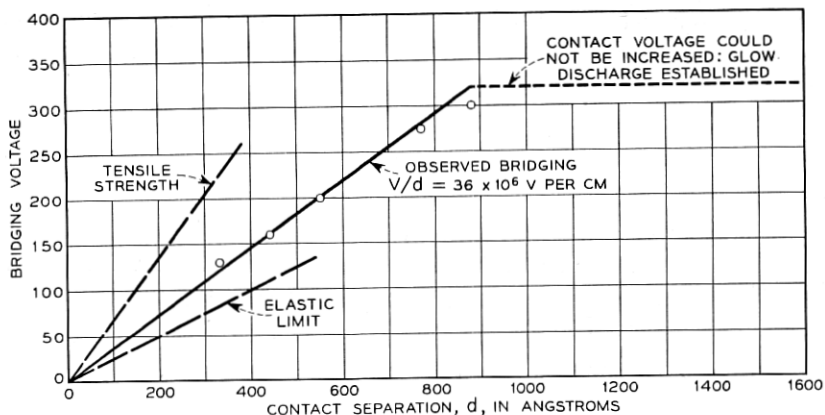


Fig. 3 — Electrostatic bridging of clean palladium contacts at small separations. Bridging voltages are corrected for potential drop across circuit resistor.

$36 \times 10^6$  volts/cm.\* This field could not have possibly been maintained at the contacts since the corresponding emission currents, calculated from equation (2), could not be furnished by the circuit due to the high resistance used. One, therefore, suspects that the local contact circuit, involving the contacts and a few millimeters of lead wire, were continuously discharging by field emission and recharging through the high circuit resistance as evidenced by fluctuations in the circuit current. By measurement, the current supplied by the circuit during this period was less than  $2 \times 10^{-8}$  ampere. The corresponding average power of these discharges was less than  $300 \times 2 \times 10^{-8} = 6 \times 10^{-6}$  watts since the voltages applied were below 300 volts. This power dissipation, as shown in a later section, is not sufficient to cause any significant change in the anode temperature that can account for the closures observed. This led to the following consideration of the effect of electrostatic pulling at the high fields reported.

The surface electrostatic stress due to a field  $V/d$  may be calculated from the following equation for parallel plates with a dielectric constant 1.0:

$$s = 4.42 \times 10^{-7}(V/d)^2 \quad (1)$$

where  $s$  is in dynes/cm<sup>2</sup> and  $V/d$  is in volts/cm. At the observed field  $V/d$  of  $36 \times 10^6$  volts/cm, the surface stress is  $5.7 \times 10^8$  dynes/cm<sup>2</sup>. Unfortunately, one cannot specify with certainty the yield strength of

\* Pearson<sup>4</sup> has previously obtained a constant field for gold contacts. In his work, however, the circuit currents were not limited and his measurements probably correspond to our data on arc initiation.

the metal that corresponds to these stressing conditions and dimensions. For *bulk* palladium<sup>5</sup> the elastic limit is about  $3.2 \times 10^8$  dynes/cm<sup>2</sup> and the tensile strength is about  $21 \times 10^8$  dynes/cm<sup>2</sup>. The corresponding fields, calculated from equation (1), are  $26 \times 10^6$  and  $69 \times 10^6$  volts per cm respectively, Fig. 3. This agreement would tend to substantiate the postulate that the observed closures were due to electrostatic pulling. This, however, is only true if the elastic and plastic behavior of the contact metal is similar to that of bulk metals. For these, the range of elastic strain is relatively small and this behavior is usually explained in terms of motions of imperfections, especially dislocations. On the other hand, for specimens that are small enough to be free of dislocations or have only a few, the elastic range may be much larger.<sup>6,7</sup>

The significance of electrostatic pulling in the initiation of the short arc may be summarized as follows. For the very soft or liquid metals, electrostatic pulling will precede the occurrence of high emission currents. This will cause an increase in the emission currents by intensifying the local fields. The arcing for these metals is essentially triggered by electrostatic pulling. For metals like palladium, on the other hand, field emission currents start the breakdown. In these cases, however, one should not preclude the significance of electrostatic pulling. It will be shown later, that due to the heating effects of the emission currents one may obtain at least partial bridging of the contact separation at lower fields than needed for the cold metal. This can cause an appreciable intensification of the local fields, the emission currents, etc. These effects are discussed in more detail in the following section.

#### DERIVATION OF RELATION BETWEEN ARC INITIATION VOLTAGE AND CONTACT SEPARATION

Consider the contact arrangement of Fig. 1 (d). When a potential  $V$  is suddenly applied, a field distribution on the cathode surface is obtained,  $F = \xi V/d$ , with a maximum value at the tip of the cathode point, where  $\xi$  is a field intensification factor which depends on the geometry and separation involved.

For illustration purposes only, Fig. 4 shows the calculated distribution of  $\xi$  over a two-dimensional surface. The corresponding distribution of current densities is also shown. This was obtained from the field emission equation:<sup>8</sup>

$$j_- = 1.54 \times 10^{-6} \frac{F^2}{\phi} \exp \left[ - 6.83 \times 10^7 \phi^{3/2} f(y)/F \right] \quad (2)$$

where  $f(y)$  is the Nordheim elliptic function<sup>9</sup> of the variable  $y = 3.79$

$\times 10^{-4} F^{1/2} / \varphi$ . A convenient tabulation of equation (2) is given in Reference 10. Due to the sensitivity of the emission to changes in the field, the current density distribution is generally much sharper than the field distribution. In the following analysis, the emission from the cathode point is approximated by a rectangular distribution over a 15-20 degrees circular area. The radius of this area is denoted by "a". For small separations, the electrostatic dispersion of the emitted electron beam may be neglected and an equal area of radius "a" at the anode is

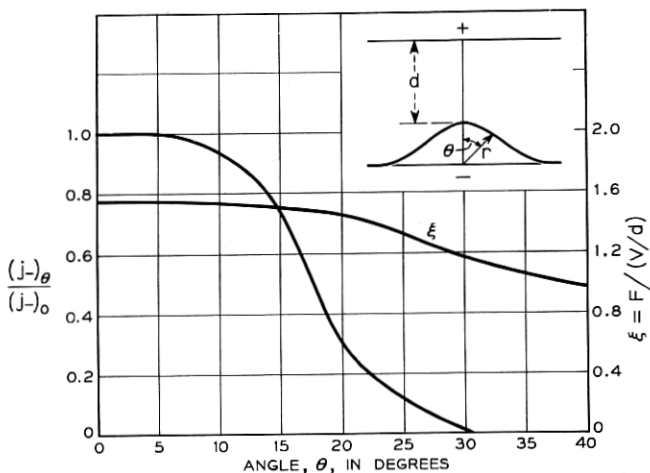


Fig. 4 — Illustration of field and current density distributions for a two-dimensional case:  $V/d = 30 \times 10^6$  volts/cm,  $\varphi = 4.0$  e.volts and  $d = r/2$ .

bombarded. A solution was worked out for the resulting temperature rise for points in the anode metal along the axis of the bombarded area:

$$\begin{aligned}
 (\Delta^T)_{z, t} = & \frac{j_- Va}{k} \left[ \frac{2}{a} \left( \frac{\alpha t}{\pi} \right)^{1/2} (e^{-(z^2/4\alpha t)} - e^{-(a^2+z^2/4\alpha t)}) \right. \\
 & \left. - \frac{z}{a} \operatorname{erfc} \frac{z}{(4\alpha t)^{1/2}} + \frac{1}{a} (a^2 + z^2)^{1/2} \operatorname{erfc} \left( \frac{a^2 + z^2}{4\alpha t} \right)^{1/2} \right] \quad (3)
 \end{aligned}$$

At the anode surface, the temperature rise at the center of the bombarded disc is

$$(\Delta^T)_{z=0} = \frac{j_- Va}{k} [(1 - e^{-u^2})/\pi^{1/2}u - \operatorname{erf}(u) + 1] \quad (3')$$

where  $u = a/(4\alpha t)^{1/2}$  and the asymptotic value is:

$$(\Delta^T)_{\max., z=0} = j_- Va/k \quad (3'')$$

Numerically, at  $j_- = 10^5$  amp/cm<sup>2</sup>,  $V = 100$  volts,  $a = 10^{-4}$  cm and  $k = 0.5$  watt/cm °C, the temperature rise is 2,000°C. Equation (3'') may be rewritten in terms of the field  $F = \xi V/d$ :

$$(\Delta^T)_{\max.} = (j_- F)(d/\xi)(a/k) \quad (4)$$

By combining this equation with the emission equation (2),  $j_-$  is eliminated and for any separation  $d$  and cathode work function  $\phi$  the temperature rise is calculated as a function of the applied field.

In studies of vacuum breakdowns initiated by field emission, it has been repeatedly observed that a sudden increase in emission is obtained by positive ion formation following an evaporation process.<sup>6, 11 to 15</sup> In studies with point cathode and large cathode-anode separations, evaporation has been attributed to the joule heating of the cathode. Also the rupturing of a point on the cathode due to joule heating and electrostatic pulling has been suggested. In these cases, one may assume that vaporization is generally due to a heated cathode rather than heating of the anode. The temperature rise of the latter is usually comparatively small due to the electrostatic dispersion of the electron beam.\* At small separations, however, where the dispersion of the electron beam is small, and for the same material for anode and cathode, the anode heating becomes more significant and the anode may evaporate before the cathode. This has been previously observed and reported. For instance,<sup>16</sup> using a rotating mirror camera studies of contacts separated at about a millimeter have rather consistently indicated *anode* evaporation to precede that of the cathode. It will be shown here, by a simple calculation that for small separations, one may generally assume the anode to evaporate before the cathode. For this we will consider an extreme case, where the contact geometry is so chosen that the temperature rise at the cathode is maximum and at the anode is minimum. The cathode emitting point is assumed to be a cylinder of radius  $a$  and height  $\ell$  with its base maintained at temperature  $T_0$ . The anode is assumed to be a semi-infinite body with a plane disc of the same radius  $a$  heated by electron bombardment. The temperature rise at the cathode due to joule heating is given by:

$$(\Delta^T)_- = I^2 \rho \ell^2 / 8.36 \pi^2 k a^4$$

The temperature rise at the anode is obtained from equation (3'')

$$(\Delta^T)_+ = IV / \pi a k$$

\* At longer gaps where high voltages are required for breakdown, it has been suggested<sup>17</sup> that the high energy electrons bombarding the anode may cause the emission of positive ions and photons which in turn will cause further emission from the cathode.

where  $I = j\pi a^2$ . The ratio of the two is given by:

$$(\Delta^T)_+ / (\Delta^T)_- = 26a(a/\ell)^2 V / I\rho$$

Numerically, for  $a = 10^{-4}$  cm,  $V = 100$  volts,  $I = 10^{-3}$  ampere and  $\rho = 10^{-5}$  ohm cm, the ratio of anode to cathode temperatures is  $2.6 \times 10^7 (a/\ell)^2$ . For the usual values of  $a/\ell$  commonly obtained on contact surfaces one concludes that the anode heating is more efficient and the anode is the source of vapor for the ion formation necessary for producing a breakdown.

If the mechanism of the breakdown simply involves cathode field emission followed by anode evaporation, one may substitute  $T_{\max.} = T_b$ , the boiling temperature of the anode, and calculate the relation between

TABLE II — ARC INITIATION FIELDS FOR  $d = 800\text{\AA}$ ,  $k = 0.7$  watt/cm. °C,  $a = 10^{-4} - 10^{-3}$  cm, and  $T_{\max} = 2,500^\circ\text{K}$  (boiling) and  $1,000^\circ\text{K}$  (softening).

	(1)	(2)	(3)	(4)	(5)
(1) $\phi$ e. volts	3.0	3.5	4.0	4.5	5.0
(2) $F$ calculated: $10^7 V/\text{cm}$ $T_{\max.} = 2500^\circ\text{K}$	24-21	30-26	36-32	43-38	50-45
(3) $F$ calculated: $10^7 V/\text{cm}$ $T_{\max} = 1000^\circ\text{K}$	22-19	27-23	33-29	39-35	45-41
(4) $F$ measured: $10^7 V/\text{cm}$		30 (Commercial Palladium)			

contact separation and arc initiation voltage. Table II, line 2, gives calculated values of the arc initiation field for:  $d/\xi = 800\text{\AA}$ ,\* a range of  $\phi = 3$  to 5 e.volts and  $a = 10^{-4}$  and  $10^{-3}$  cms.† In these calculations the effects of electrostatic pulling have not been considered. While the arc initiation field has been found to be below the field necessary for electrostatic pulling of the cold metal one should consider the effect of anode heating and the possible lowering of its tensile strength. For most metals the tensile strength decreases with temperature rise. For instance, for Pd<sup>5</sup> the tensile strength decreases by a factor of 10 when heated from normal temperature to about 1,100°C. Furthermore, most metals have a so-called "softening temperature" which is about  $\frac{1}{3}$  to  $\frac{1}{5}$  the melting temperature.<sup>19</sup> One may, therefore, expect that heating of the anode only to the softening temperature by electron bombardment should be

\* For the small separations used in this study,  $\xi$  is estimated at 1.0 to 1.1.

† These values of  $a$  correspond to the sizes of surface irregularities measured from cross-sectional photomicrographs of the contacts used in our experiment.



sufficient to pull a point electrostatically and increase the field by decreasing the separation  $d$ . This corresponds to an increase in the intensification factor  $\xi$  of the apparent field  $V/d$ . In Table II, line 3, calculations are given of the arc initiation field for  $T_{\max.} =$  softening temperature instead of the boiling temperature.

It is of interest to show from the above analysis, that the constant field criterion obtained experimentally for arc initiation is only approximately true and the field for arc initiation should decrease with increasing separation. Equation (4) shows that  $j_{-}F\alpha l/d$ . The emission equation (2) may be approximated by:  $j_{-}\alpha F^n$  where  $n$  is between 10 and 30 for  $\varphi = 3-5$  e.volts and for fields of the order of  $10^7$  volts/cm. By eliminating  $j_{-}$  one obtains  $F^{n+1}\alpha l/d$  and  $V_{a,i}\alpha(d)^{1-(1/n+1)}$  or  $V_{a,i}\alpha d^{0.9-0.97}$ .

#### LIMITING CONDITIONS FOR ARC INITIATION — CONCEPTS OF LIMITING POWER AND ARC INITIATION CURRENT

Replacing  $j_{-}$  in equation (3'') by the total current  $I = \pi a^2 j_{-}$  one obtains:

$$IV = \pi a k \Delta T \quad (5)$$

To produce a breakdown the temperature should rise to the boiling temperature of the metal with or without the effect of electrostatic pulling. Consider the circuit of Fig. 5 (a) consisting of an adjustable voltage source, a contact and a fixed resistance  $R$ . Let the applied voltage be  $V_o$  and the contact separation is gradually decreased. For each value of field there will be a field emission current  $I$  such that the voltage drop across the contact is given by  $V_c = V_o - IR$ . This relation is shown in Fig. 5 (b) as  $V_c$  versus  $I$ . For each contact separation there is an emission line as shown schematically in Fig. 5 (b). The point of intersection  $P$  of the circuit line and the emission line determines the only possible operating point. If the corresponding power  $IV$  is not sufficient to allow a temperature rise  $(\Delta T)_b$ , equation (5), no breakdown will occur. One can then decrease the contact separation further and the point  $P$  will slide along the circuit characteristic. The value of the power  $IV$  will increase to a maximum at  $V_c = V_o/2$ . This maximum power is  $V_o^2/4R$ . If this is still not sufficient to produce the temperature rise  $(\Delta T)_b$  no breakdown can occur and closure without breakdown is obtained. The condition for obtaining a breakdown is, therefore, given by:

$$V_o^2/R \geq 4\pi a k (\Delta T)_b \quad (6)$$

To verify this rather simple relation, the circuit in Fig. 5 (a) was used. The resistor  $R$  is a carbon resistor with the contact metal mounted directly at its end to reduce the effects of local capacities. For each value of  $R$  a limiting value of applied voltage  $V_o$  was observed below which contact closure occurred without breakdown. The results are plotted in Fig. 6 for Pd contacts. The results are fitted by the parabola

$$(V_o^2/R)_{\text{crit.}} = 4.2 \text{ watts}$$

Using  $(\Delta T)_b = 2,200^\circ\text{C}$ ,  $k = 0.7 \text{ watt/cm}^2\text{C}$ , one obtains the value of  $a$  from equation (5):  $a = 4.2/4\pi k(\Delta T)_b = 2.2 \times 10^{-4} \text{ cm}$  which is within the range of sizes of surface irregularities measured from cross-sectional photomicrographs of the contacts used. From this one concludes: *To initiate a breakdown there is a minimum circuit power  $V_o^2/R$  below which no breakdown will occur on closure. It is determined from the physical properties of the metal and the geometry of the contact surfaces.* The corresponding critical power at the contact  $(IV)_{\text{cont.}}$  is, as given by

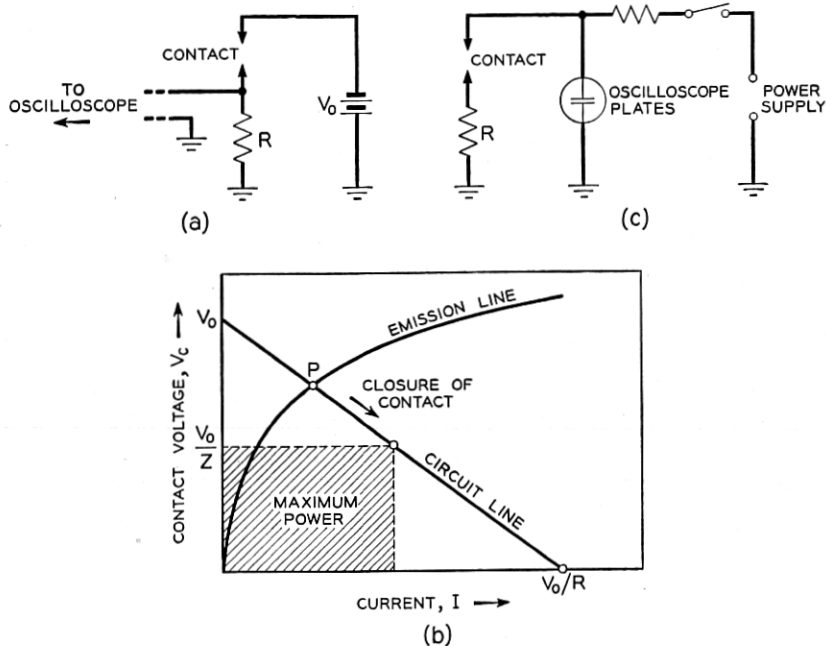


Fig. 5 — (a) Circuit for study of limiting conditions for initiation of a breakdown. (b) Circuit and field emission characteristics. (c) Circuit for observation of unstable breakdowns.

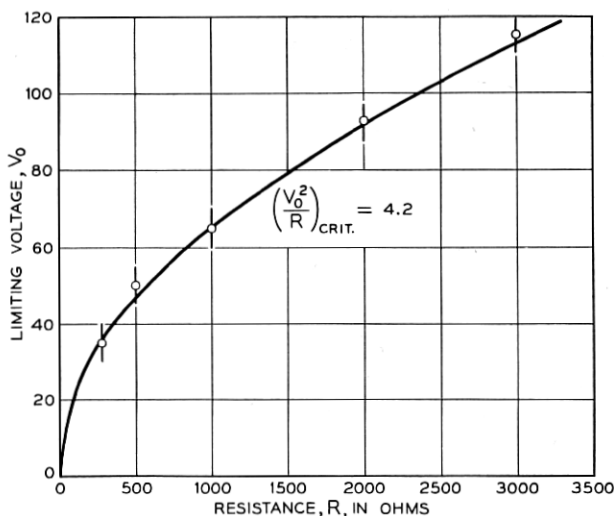


Fig. 6 — Limiting voltages for occurrence of breakdown as a function of circuit resistance for palladium contacts.

equation (5), equal to  $V_0^2/4R$  or  $\pi ak(\Delta T)_b$ . From this one obtains an expression for the breakdown initiation current:

$$(I)_i = \pi ak(\Delta T)_b/V \quad (7)$$

This current is a function of the physical properties of the contact metal, the surface geometry and is inversely proportional to the applied contact voltage. For the Pd contacts experimented with,  $(I)_i \cong 1/V$  and for  $V = 100$  volts  $(I)_i = 0.01$  amp. This is about two orders of magnitude below the minimum arcing current or arc termination current.<sup>2</sup> In other words, *the initiation of a breakdown will not necessarily lead to the establishment of an arc. The latter is only obtained if the circuit is capable of furnish-*

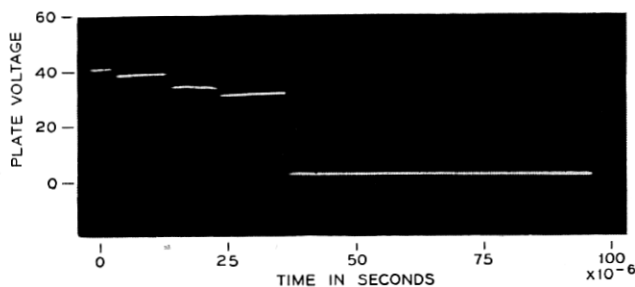


Fig. 7 — Typical transient on closure showing unstable breakdowns obtained with circuit in Fig. 6.  $V_0 = 40$  volts,  $R = 1000$  ohms and  $c = 5 \times 10^{-12}$  farad.

ing a current at least equal to the minimum arcing current. Otherwise, only transient and unstable breakdowns are obtained. These unstable breakdowns have been observed by using the circuit in Fig. 5 (c). The oscilloscope plates were used as the circuit capacitance and the resistance  $R$  was so chosen that the circuit could not furnish the minimum arcing current. By slowly closing the contacts transient breakdowns were observed and recorded. Fig. 7 is a typical recording of these breakdowns, followed by a closure.\*

#### TIME LAG IN ARC INITIATION

As discussed above, a breakdown only occurs when the anode temperature is raised by a certain amount  $(\Delta T)_c$ . The corresponding heating time is called the arc initiation time lag. In this section a relation is derived between time lag and overvoltage and actual observations of time lags are reported. Consider a pair of contacts with a separation  $d$  and a constant voltage pulse  $V$  is suddenly applied. The temperature rise is given by Equation (3') as a function of time. Let  $(V_{at})_\infty$  be the voltage which gives a temperature rise just equal to the critical value  $(\Delta T)_c$  at  $t = \infty$ . This is the minimum arc initiation voltage which corresponds to an infinite time lag and  $(\Delta T)_c = (j-F)_\infty da/\xi k$ . Now let a higher voltage  $V = AV_\infty$  be applied where  $A$  is slightly greater than 1. This will cause an increase of  $F_\infty$  to  $AF_\infty$  and of  $(j-F)_\infty$  to  $B(j-F)_\infty$  where  $B$  may be obtained from the emission equation (2). Substituting in equation (3'), the temperature rise due to the new voltage is obtained:

$$\Delta T = (\Delta T)_c B f(u)$$

where  $f(u)$  is the function of  $u$  given in equation (3'). The breakdown is obtained when  $(\Delta T) = (\Delta T)_c$  or  $f(u) = 1/B$ . Our interest is in values of  $B$  very close to 1.0 and  $u \ll 1.0$ . By expanding  $f(u)$  and neglecting higher orders of  $u$ :

$$1/B = 1 - u/(\pi)^{1/2}$$

and the time lag is given by:

$$(t)_{\text{lag}} = a^2/4\pi\alpha(1 - 1/B)^2 = a^2/4\pi\alpha(B - 1)^2 \quad (8)$$

for  $B - 1 \ll 1.0$ .

By definitions

$$B(jF) = (jF) + \frac{d(jF)}{dF} \Delta F \quad \text{or} \quad B - 1 = \frac{d(jF)}{dF} \frac{\Delta F}{jF}$$

By multiplying equation (2) by  $F$  and differentiating with respect to

\* Similar transients have been previously reported by Germer.<sup>18</sup>

$F$ , one obtains:

$$B - 1 = \frac{\Delta F}{F} [3 + 6.83 \times 10^7 \varphi^{3/2} f(y)/F]^*$$

Substituting in equation (8) the time lag is obtained as a function of the overvoltage  $\Delta V/V (= \Delta F/F)$ :

$$(\alpha t/a^2)_{\text{lag}} = \frac{1}{4\pi} \left( \frac{\Delta V}{V} \right)^{-2} \left( 3 + \frac{6.83 \times 10^7}{F} \varphi^{3/2} f(y) \right)^{-2} \quad (9)$$

i.e., the time lag is inversely proportional to the square of the overvoltage. Numerically for  $F = 3 \times 10^7$  volts/cm,  $\varphi = 4$  e.volts,  $a = 5 \times 10^{-7}$  cm and  $\alpha = 0.1$  cm<sup>2</sup>/sec:

$$(t)_{\text{lag}} = 0.65 \times 10^{-9} (\Delta V/V)^{-2} \text{ and for } \Delta V/V = 0.01, (t)_{\text{lag}} = 6.5 \times 10^{-6} \text{ sec.}$$

These time lags have been observed for palladium and gold contacts.† These were obtained by applying a constant voltage pulse, rise time less than  $10^{-7}$  second, across the contacts and recording the voltage at the contacts from a cathode ray oscilloscope. Fig. 8 shows a typical record showing a few voltage pulses applied in succession starting with the low voltage pulse. In this case the time lag was about  $15 \times 10^{-6}$  second. The time lags observed ranged between  $20 \times 10^{-6}$  second and less than  $10^{-7}$  with the majority in the lower end of this range. Similar time lags were also observed by recording the current flow through the contact gap. Fig. 9 is a typical recording of the field emission currents preceding arc initiation. The rise and drop at the left end of the trace are due to the charging and discharging of the oscilloscope circuit following the

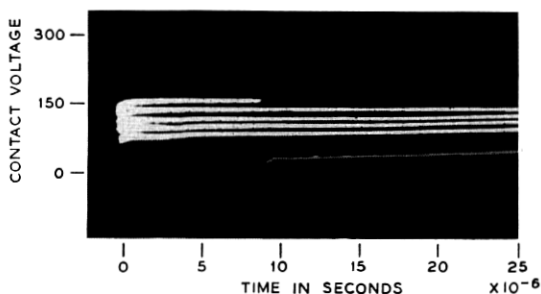


Fig. 8 — Typical recording of the time lag preceding the initiation of the short arc.

\* In differentiating, the Nordheim elliptic function  $f(y)$  was assumed constant.

† Due to the spread of our data on arc initiation voltage no attempt was made to correlate observed time lags with over-voltage to check Equation 9.

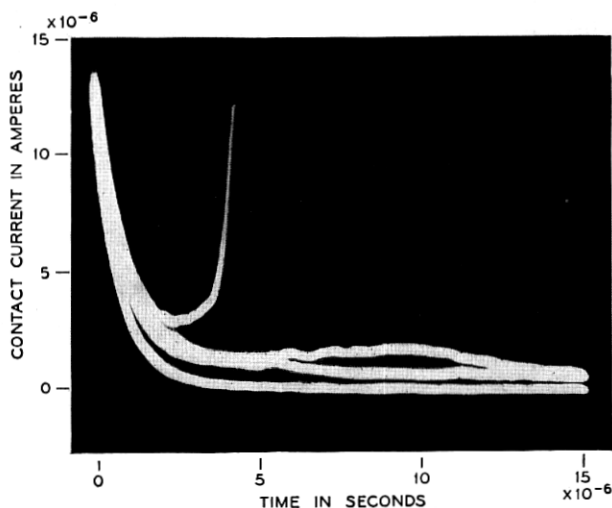


Fig. 9 — Field emission currents preceding arc initiation. Only the top line leads to an arc.

application of the pulse. The lower lines show field emission currents without arc initiation.\* The top line shows a transition into an arc.

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\* The decay of the emission currents at the end of the trace was due to the decay of the voltage pulse applied which was obtained from an R-C network with long time constant.