Arcing of Electrical Contacts in Telephone Switching Circuits

Part V — Mechanisms of the Short Arc and Erosion of Contacts

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This is a presentation of a study of the mechanisms of the short arc between closely spaced contacts and its erosion effects. The study is based on optical measurements of the erosion obtained on contacts after repeated arcing on closure or opening. Most experiments reported here are essentially of the probing type designed to test specific postulates and assumptions. For short arcs initiated at 250 volts, clean palladium, iron and nickel contacts have shown a reversal, with arc duration, in the direction of net transfer. Net anode losses were obtained with short duration arcs and net cathode losses with longer duration arcs. This reversal, however, did not occur with silver, gold or copper. For longer arcs initiated as air breakdowns from 500 volts, all the above metals indicated a net loss from the cathode. For arcs initiated at 250 volts between fully activated contacts, shallow cathode losses were generally observed with little or no buildups on the anode.

The first section of this paper is a summary of the experimental work done and the results obtained. In the second section, the data are analyzed and a tentative working model is proposed for the short arc and its erosion effects.

INTRODUCTION

The problem of contact erosion due to arcing has been the subject of a large number of investigations. The literature includes a considerable accumulation of data on the erosion characteristics of many contact materials. Due, however, to the vast variations in testing conditions adopted, there are considerable disagreements and discrepancies among results from different investigations. Inconsistencies even within one investigation are not uncommon.

In general, the erosion behavior of contacts depends, to varying degrees, on the following main parameters: the physical properties of the contact material, surface conditions, contact geometry and separation, arc duration, arc current and the surrounding atmosphere. In our study, most of these parameters were considered separately, whenever possible, with the primary objective of clarifying the mechanisms involved. Most experiments reported here are, in effect, of the probing type designed to test specific postulates and assumptions. The first section of this paper is a summary of the experimental work done and the results obtained. In the second section, the data are analyzed and a tentative working model is proposed for the short arc and its erosion effects. Because of the rather extreme complexity of the phenomena and the lack of basic data on the conduction properties of metal vapors, this model is at best a simplified one and is probably incomplete in some respects.

NOTATION

F	Field strength
I	Total current
M	Mass of an atom
N	Gas concentration
T	Temperature
T_0	Ambient temperature
T_b	Boiling temperature
ΔT_b	$T_b - T_0$
V	Voltage
V_i	Minimum ionization potential of a metal atom
V_c	Voltage drop in cathode fall
Q_i	Ionization cross-section
Q_e	Excitation cross-section
W	Atomic weight
a	Radius of arc spot
d	Contact separation
e	Electron charge
j	Total current density at cathode
j_-	Electron current density at cathode
j_+	Ion current density at cathode
k	Boltzmann's constant
p	Gas pressure
t	Time

v Arc voltage
z Distance from anode surface
θ Angular location of a point between contacts with respect to the center of the anode arc spot
λ Thermal conductivity

MEASUREMENTS

Contacts tested were made of crossed cylinders 0.050 or 0.125 cm diameter. Their surfaces were prepared by fine polishing followed by washing with alcohol and distilled water. They were mounted on a sound-head* and operated at 60 cycles/sec. Care was taken to avoid additional arcing by eliminating chatter of the contacts on closure. In the low-voltage experiments this was done satisfactorily by mechanical adjustment of the contact separation and by choosing a proper charging resistor to avoid excessive recharging during chatter opening. For the high-voltage experiments, however, it was necessary to adopt a mechanical switching scheme which prevents recharging until the contacts were fully open. The behavior of the contacts was regularly observed on an oscilloscope.

In most experiments, the circuit consisted of a coaxial cable with a characteristic impedance of 75 ohms and a period of 3.5×10^{-9} sec per foot. The cable was charged, during contact opening, to any desired voltage through a proper resistor. All lines were matched with a 75-ohm resistor at the contact end, thus allowing only one discharge per closure without spurious reflections. In all cases, therefore, constant arc current pulses were obtained. Their amplitudes were controlled by varying the charging voltage. Their periods were controlled by varying the cable length.† The use of this constant current pulse scheme makes the interpretation of the data far simpler and more direct. In each experiment, the contacts were subjected to 20,000 to one million operations, depending on the arc energy.

Since the main interest was in the contribution of each electrode to the maintenance of the arc, conventional weight measurements would have been of little significance. An optical measurement scheme was therefore adopted. It allowed a discrimination between losses and gains

* To avoid contact activation by organic vapors, the construction of these units was free of organic materials except for varnish insulation on the winding. From observations of the eroded surfaces and oscilloscope traces, as discussed in a following section on activated contacts, these contacts were free of activation.

† The velocity of closure of the contacts is estimated at about 5 cms/sec. During the longest duration arc. of 10^{-6} sec used in these experiments, the contact motion is only 500 A compared to an initial separation of about 25,000 A.

as indicated by craters and build-ups. It also permitted examination of the geometries involved. This was particularly important in cases where each electrode indicated both loss and gain and the detection of matched patterns for one pair of contacts was quite significant in determining the most probable directions of transfer. A microscope was used, with magnifications as high as 740, and a quantitative measure of metal loss was made. The losses measured were of the order of 10^{-7} cc and the accuracy is better than ± 50 per cent.

1. EXPERIMENTS WITH VARYING ARC DURATION ON CLOSURE

Test contacts were operated in laboratory atmosphere, using matched cables in lengths ranging between 5 feet and 260 feet. In all cases they were charged to a fixed voltage of 250 volts and allowed to discharge on closure. The arc durations for these cables varied between 17.5×10^{-9} and 910×10^{-9} sec. For control of the current, separately matched multiple cables were used in parallel. In most cases, at least three runs were made for each cable length. The volume of metal loss, appearing as a

TABLE I — EROSION OF PALLADIUM CONTACTS ON CLOSURE BY SHORT ARCS INITIATED AT 250 VOLTS, 3.2 AMPS

	Arc Duration 10^{-9} sec	No. of operations 10^3	Erosion: (loss, gain) 10^{-7} cc		Loss/total loss		Rate of loss 10^{-14} cc/erg	
			Anode	Cathode	Anode	Cathode	Anode	Cathode
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
(1)	17.5	540	0.72, n*	n, build-up†	1.0	0.0	1.7	
(2)	35	430	2.01, n	0.08, buildup	0.96	0.04	2.9	
(3)	52.5	320	1.9, n	n, buildup	1.0	0.0	2.5	
(4)	70	430	2.02, buildup	0.85, buildup	0.7	0.3	1.8	0.75
(5)	87.5	108	0.21, buildup	0.21, buildup	0.5	0.5	0.5	0.5
(6)	105	108	0.43, buildup	0.57, buildup	0.43	0.57	0.83	1.1
(7)	140	108	n, buildup	1.79, n	0.0	1.0		2.7
(8)	280	108	0.6, buildup	2.67, n	0.18	0.82	0.69	3.2
(9)	385	18	n, buildup	0.54, n	0.0	1.0		2.7
(10)	912	36	n, buildup	loss, n	0.0	1.0		not measured

* "n" denotes no loss or no gain or those that are too small to measure.

† Volume of buildups were not measured. In general, they match the geometry of a hole on the opposite electrode. This includes observations on lines 4 to 6 where each electrode showed both gain and loss.

TABLE II — EROSION OF PALLADIUM CONTACTS ON CLOSURE BY SHORT ARCS INITIATED AT 250 VOLTS, 1.6 AMPS

	Arc Duration 10^{-9} sec	No. of operations 10^3	Erosion: (loss, gain) 10^{-7} cc		Loss/total loss		Rate of loss 10^{-14} cc/erg	
			Anode	Cathode	Anode	Cathode	Anode	Cathode
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
(1)	35	650	1.8, *n**	*n*, buildup*	1.0	0.0	3.5	
(2)	105	108	0.97, *n*	*n*, buildup	1.0	0.0	3.8	
(3)	140	360	1.84, buildup	0.51, buildup	0.78	0.22	1.6	0.45
(4)	280	540	1.86, buildup	4.17, buildup	0.31	0.69	0.55	1.23
(5)	385	51	*n*, buildup	1.6, *n*	0.0	1.0		3.7

* See footnotes below Table I.

depression or crater on an electrode surface, was measured and the geometry sketched.

Tables I and II show the results obtained for palladium contacts with currents of 3.2 and 1.6 amperes. In both cases, a characteristic change in the direction of transfer is observed. In Table I, for instance, for arc durations 52.5×10^{-9} sec and less, lines 1 to 3, the losses were predominantly from the anode. The geometries observed generally consisted of a rather irregular yet definite buildup on the cathode and a corresponding hole on the anode. The geometrical resemblance between the anode hole and the cathode buildup was in many cases rather striking. This and the absence of buildups surrounding the cathode hole, strongly suggest that the arc was mainly maintained through vapor from the anode. This, however, does not necessarily exclude the possibility of some evaporation from the cathode. These arcs are called *anode arcs*. For arcs of longer duration, 70×10^{-9} to 105×10^{-9} sec in the case of Table I, lines 4 to 6, the observed erosion was distinctly different. It was characterized by the appearance of both a hole and a buildup on each electrode. The geometrical resemblance between a hole on one electrode and a buildup on the opposite electrode is a strong indication that both electrodes were contributing more or less equally to the maintenance of the arc. This stage of the arc is called the *mixed arc* stage. Further increase in the arc duration, above 140×10^{-9} sec in the case of Table I, lines 7 to 10, the erosion character changed once more. Holes were obtained on the cathodes and matching buildups on the anode. These arcs are called *cathode arcs*. They probably still involve some evaporation from the anode. Table II shows similar data for palladium contacts at 1.6 amp where a reversal in transfer is also indicated. Fig. 1 is a plot of columns

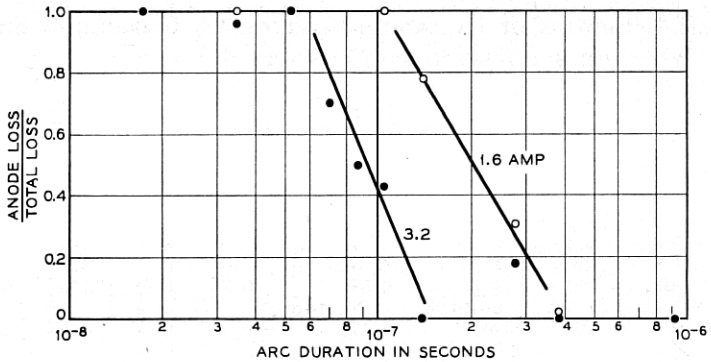

Fig. 1 — Reversal of transfer between Pd contacts on closure. Short arcs initiated at 250 volts.

5 and 6 from Tables I and II. It is shown that the reversal of transfer occurred later for the smaller current. It is believed, however, that due to the difficulty of premature closure, discussed below, not much emphasis should be given to the exact relative locations of the transition points for the different currents.

It should be pointed out that, while this observation of reversal in the arc transfer is unmistakable, its exact location is rather difficult to obtain with great consistency. This is because of the extreme proximity of the contacts when an arc strikes and the tendency of occurrence of premature closures. These are caused by the formation by the arc[1,2] of mounds which decrease the separation and the closure time. This difficulty was particularly noticeable with the longer cables. However, by proper adjustments such as the use of various retardation schemes for the moving contact, it was possible to satisfactorily decrease the frequency of premature closures. It is evident that the effect of premature closures is to allow only short duration arcs irrespective of the desired duration as set by the cable length. In extreme cases, where premature closures predominate, the phenomenon of reversal of transfer can be completely missed. The use of higher voltage presents additional means for decreasing the frequency of premature closures by initiating the arcs at wider separations. For experiments in air, however, one is limited by the minimum sparking potential of air.

Columns 7 and 8, Tables I and II, give the measured rate of metal loss from each electrode. This is defined as the volume of metal loss per unit arc energy. For instance at 3.2 amp, Table I, the rate of loss for

[1] L. H. Germer and F. E. Haworth, J. Appl. Phys., **20,** p. 1085, 1949.
[2] M. M. Atalla, B.S.T.J., **32,** p. 1503, 1953.

TABLE III — EROSION OF SILVER AND GOLD CONTACTS UNDER CONDITIONS BEYOND THE REVERSAL POINT OF PALLADIUM, INITIAL VOLTAGE 250

Current Amp	Arc Duration 10^{-9} sec	No. of operations 10^3	Erosion: (loss, gain) 10^{-7} cc		Loss/total loss		Rate of loss 10^{-14} cc/erg	
			Anode	Cathode	Anode	Cathode	Anode	Cathode
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Ag, 1.6	385	430	4.3, *n**	*n*, buildup*	1.0	0.0	1.15	
Ag, 3.2	385	270	5.8, *n*	*n*, buildup	1.0	0.0	1.25	
Ag, 6.4	140	79	3.5, *n*	*n*, buildup	1.0	0.0	3.5	
Au, 3.2	140	90	1.7, *n*	*n*, buildup	1.0	0.0	3.0	

* See footnotes below Table I.

both the anode and cathode arc stages is between 1.7×10^{-14} and 3.0×10^{-14} cc/erg. For the mixed arc stage, lines 4 to 6 of Table I and lines 3 and 4 of Table II, the rate of loss is consistently lower. This is an indication of considerable exchange of metal between the two electrodes during this arc stage.

The aforementioned erosion behavior of palladium, as characterized by the reversal of transfer with arc duration, was also obtained for iron and nickel contacts. These tests were performed at 250 volts and 3.2 amp for two cable lengths of 10 and 110 feet. For silver, gold and copper, on the other hand, no reversal in transfer was observed at 250 volts for various currents. Table III shows some quantitative data for silver and gold obtained under conditions which would normally cause cathode erosion for palladium contacts. As indicated, the losses for both silver and gold were from the anode. By raising the arc current to 6.4 amps, silver still failed to indicate a reversal. A tentative explanation of this behavior is proposed in a later section.

2. EXPERIMENTS WITH LONGER AIR BREAKDOWN ARCS ON CLOSURE

To study the effects on erosion character of a gas present between the contacts in the arc channel, the following experiment was performed. Instead of the 250 volts used in the aforementioned experiment, corresponding to a separation of about 25,000 Å, a voltage of 500 was used. Arcs obtained were therefore initiated as air breakdowns. The corresponding separation at which an arc is initiated in air is about 3×10^{-3} cm which is of the order of 60 mean free paths of an electron in atmospheric air. In these experiments this large separation eliminated the previous difficulty of premature closure. Table IV presents erosion data

TABLE IV — EROSION DATA FOR PALLADIUM CONTACTS ON CLOSURE BY ARCS INITIATED AT 500 VOLTS AS AIR BREAKDOWNS*

Current Amp	Arc Duration 10^{-9} sec (1)	No. of operations 10^3 (2)	Erosion: (loss, gain) 10^{-7} cc		Loss/total loss		Rate of loss 10^{-14} cc/erg	
			Anode (3)	Cathode (4)	Anode (5)	Cathode (6)	Anode (7)	Cathode (8)
3.2	35	184	*n*, buildup†	0.72, *n*†	0.0	1.0		2.5
3.2	280	36	*n*, buildup	1.85, *n*	0.0	1.0		4.0
3.2	385	18	*n*, buildup	1.2, *n*	0.0	1.0		3.8
6.4	17.5	216	*n*, buildup	0.55, *n*	0.0	1.0		1.6
6.4	35	108	*n*, buildup	0.82, *n*	0.0	1.0		2.4
6.4	70	54	*n*, buildup	1.6, *n*	0.0	1.0		4.7

* In the course of these experiments, some metal loss from the anode was occasionally observed. This was believed to be due to the statistical time lags of air breakdown which would cause a decrease in the contact separation at which the arc was initiated. By illuminating the contacts with ultraviolet this difficulty was eliminated.

† See footnotes below Table I.

for palladium contacts obtained at 3.2 and 6.4 amp. The direction of transfer was independent of arc duration and consistently from cathode to anode. Each anode generally showed a well defined buildup closely matching a hole on the cathode. In contrast to the buildups obtained with short arcs, which were usually irregular and sometimes had more than one peak, these were more regular and usually had a single peak. This difference may be attributed to differences between the initiation mechanisms of short arcs and air breakdowns. Short arcs are initiated by field emission and a sharp point on the cathode surface determines the location of the arc. This point does not necessarily correspond to the smallest separation and on successive closures the arc channel is more or less randomly located. For air breakdowns, on the other hand, surface irregularities are not as significant and the location of the breakdown channel is mainly at the cathode point nearest to the anode.

The rate of cathode erosion for palladium contacts by 500-volt air breakdowns, Table IV, Column 8, is between 1.6×10^{-14} and 4.7×10^{-14} cc/erg depending on current and arc duration.

For silver and gold contacts, the same erosion behavior was obtained. For the 500-volt air breakdowns, holes were obtained on the cathode and buildups on the anode. Table V shows typical data obtained from two test runs with silver and gold contacts. It is of interest to note that their rate of erosion is 4 to 5 times less than for palladium at similar conditions.

TABLE V — EROSION OF SILVER AND GOLD CONTACTS ON CLOSURE BY 500-VOLT AIR BREAKDOWNS

Current Amp	Arc Duration 10^{-9} sec	No. of Operations 10^3	Erosion: (loss, gain) 10^{-7} cc		Loss/total loss		Rate of loss 10^{-14} cc/erg	
			Anode	Cathode	Anode	Cathode	Anode	Cathode
Ag, 3.2	385	230	*n**, build-up*	3.4, *n*	0.0	1.0		0.85
Au, 3.2	140	90	*n*, buildup	0.64, *n*	0.0	1.0		1.1

* See footnote below Table I.

3. EXPERIMENTS WITH SHORT ARCS BETWEEN ACTIVATED CONTACTS ON CLOSURE

Contacts activated by organic vapors[3] have been shown to arc more readily than clean contacts. They are initiated at appreciably lower fields[4] and maintained at appreciably lower currents.[3] The following experiments were carried out to study the erosion behavior of activated contacts. For such contacts an arc is initiated at fields as low as 10^5 volts/cm. For an initial voltage of 250 this corresponds to a separation of 2.5×10^{-3} or about 50 mean free paths of an electron in atmospheric air. This indicates that activation experiments performed in atmospheric air at such a voltage would give erosion results that may be influenced by the presence of air in the arc channel as discussed in the previous section. This difficulty was eliminated by operating the contacts in a vacuum of 10 microns. Organic materials left in the construction of the sound head used for operating the contacts provided sufficient organic vapors for rapid activation of the contacts. The voltage transient across the contacts during closure was observed on an oscilloscope. At the beginning of the test, when the contacts were clean, a certain frequency of premature or early closures was observed. As the contacts became more active the frequency of premature closures decreased and finally disappeared. This was an indication that gradual activation initiated the arcs at progressively increasing separation. The period of activation was usually between 2 and 5 minutes, at 60 operations/sec, with the test continued for about one hour thereafter. Further evidence of contact activation was the formation of considerable quantities of black sooty deposits which were not metallic as indicated by fuming solubility tests.

[3] L. H. Germer, J. Appl. Phys., **22,** p. 955, 1951.
[4] M. M. Atalla, B.S.T.J., **32,** p. 1493, 1953.

Tests were performed on the more or less noble metals palladium, silver and gold and on the base metals copper, nickel, tungsten, iron and aluminum. Not only did the noble metals become active but also the base metals copper, nickel and tungsten. The sooty deposit which is typical for activated contacts was observed on all these metals. Contacts of iron and aluminum, however, failed to show any sign of activation even after as many as 6×10^5 operations.

The metals that were activated have shown one common erosion behavior. Metal loss was almost entirely from the cathode in the form of a shallow depression spread over a considerably larger area than obtained with clean metals. The anode showed little or no metallic deposits in contrast to the sizable buildups obtained with clean metals. For activated palladium the rate of erosion was measured at about 1.0×10^{-14} cc/erg which is about one-half to one-fourth the rate of erosion for clean palladium.

Additional experiments were performed on activated palladium and silver contacts in the presence of air at 50 volts. The degree of activation of the contacts was controlled by varying the concentration of d-limonene vapor in air. Only one result of these experiments is reported here concerning a characteristic difference between the erosion of activated palladium and silver contacts. Palladium contacts showed loss from the cathode even for concentrations of d-limonene vapor as low as 4 per cent of the saturation concentration. Silver, on the other hand, did not show erosion from the cathode until appreciably higher concentrations, 10 to 20 times that for palladium, were introduced.

4 EXPERIMENTS ON BREAK

The objects of these experiments was to compare the erosion of contacts by arcs obtained on opening with the erosion of similar arcs obtained on closure. This was done by allowing a cable to discharge from approximately the same voltage of 250 through two pairs of contacts, one during closure and the other during opening.* Palladium contacts were used with arc durations of 35×10^{-9} and 380×10^{-9} sec at 3.2 amp. The erosion behavior was almost identical for both pairs of contacts. For the short arc duration both contacts exhibited anode loss whereas for the long arc duration cathode loss occurred in both cases.

Measurements on Pd were also made with air breakdown arcs initiated during contact opening at 500 volts. Cathode loss, observed in similar

* The discharge on opening was obtained during the charging of the cable following first separation of the contacts. By adjusting the charging resistor it was possible to control the breakdown voltage.

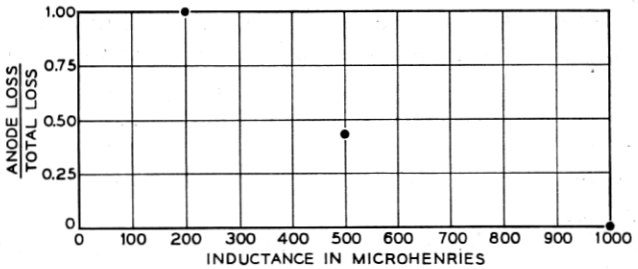

Fig. 2 — Erosion of Pd contacts on break of inductive circuit; I = 0.1 amp, V = 6 volts.

arcs on contact closure, was duplicated here. From these data one concludes that *there is no basic difference between the arcs and erosion effects occurring during the closure or opening of contacts, provided that the initiation conditions are the same.*

Another experiment was carried out on contact erosion due to arcing on break. While the results of this experiment did not yield additional basic information, beyond confirming the above findings, they are of some practical interest. A contact was made to open a 6-volt circuit containing a 60-ohm resistance and a variable inductance. Arcing on opening occurred in the form of a succession of short breakdowns whose duration varied with the circuit inductance. Three inductances, 200, 500, and 1000 microhenries, were tried with palladium contacts. The metal loss results are shown in Fig. 2. At 200 microhenries most of the arcing occurred at small contact separations thereby producing anode loss. At 500 microhenries, arcing was a mixture of short arc breakdowns and longer air breakdowns which caused loss from both electrodes. At 1,000 microhenries, arcing was predominantly due to air breakdowns at wider separations which gave loss mainly from the cathode. The results of this experiment should be useful in indicating the role of arcing in distorting results in low voltage experiments designed to study bridge transfer during contact opening.

In the following section an analysis of the data is presented, and a tentative mechanism of the short arc and contact erosion is proposed.

5. DISCUSSION — TENTATIVE MECHANISM OF THE SHORT ARC AND CONTACT EROSION

Germer and Smith[5] have attempted to record the voltage transient across a pair of contacts during the initiation of a short arc on a high

[5] L. H. Germer and J. L. Smith, J. Appl. Phys., **23**, p. 553, 1952.

speed oscilloscope. Their results have shown a rapid drop to the final arc voltage in a time less than the time resolution of the scope (about 2×10^{-9} sec). It was concluded that the arc initiation time was probably less than 10^{-9} sec. This indicates that in our experiments, all the discharges at small separations must have been maintained at the arc voltage for almost their entire duration, the shortest duration being 17.5×10^{-9} sec.

It has also been shown that short arcs in air[6] or in vacuum[7] are initiated by field emission electrons. Furthermore, from the size of arc pits obtained by Germer and Haworth, Kisliuk[8] has concluded that in the short arc, the electrons are emitted from the cathode primarily by field emission and the arc is maintained by ionization of the metal vapor from the electrodes by electron collision. For a metal with work function φ and minimum ionization potential V_i, the observed arc voltage usually exceeds the sum $V_i + \varphi$ by a volt or less. One may, therefore, postulate the existence of a cathode dark space, where electrons acquire enough energy to produce ionizing collisions, followed by an arc column where a plasma is maintained.

If V_c is the voltage drop through the cathode dark space, j_- the electron current density emitted from the cathode and j_+ the ion current density at the cathode edge of the plasma, the field strength F on an infinite plane cathode, is given by Mackeown's[9] equation:

$$F^2 = 7.57 \times 10^5 (V_c)^{1/2} j_- \left[\frac{j_+}{j_-} (1845W)^{1/2} - 1 \right] \qquad (1)$$

where W is the atomic weight of the ions, F is in volts per cm, V_c in volts and j_- is in amp/cm^2. For the short arc, where the separations are very small, the observed current densities indicate that the width of the arc is usually considerably larger than the contact separation or arc length. It is not too unreasonable, therefore, to neglect the edge effect and apply the above equation. Furthermore, this steady state equation should still be applicable to a changing arc, as will be shown to be the case for the short arc, provided that the changes occurring within an ion transit time are very small.

The cathode electron current density j_-, for an arc maintained by field emission, is further related to the field F at the cathode by the Fowler-

[6] M. M. Atalla, B.S.T.J., **34**, p. 203, 1955.
[7] W. S. Boyle, P. Kisliuk, and L. H. Germer, J. Appl. Phys., **26**, p. 571, 1955.
[8] P. Kisliuk, J. Appl. Phys., **25**, p. 897, 1954.
[9] S. S. Mackeown, Phys. Rev., **34**, p. 611, 1929.

TABLE VI — RELATION BETWEEN j_+ AND j_+/j_- AT AN INFINITE PLANE CATHODE; V_c = 10 VOLTS, W = 100 AND φ = 5, 4.5 AND 3 e. VOLTS.

j_+/j_-	0.05	0.1	0.2	0.4	0.6	1.0
$\varphi = 5$	10.5	8.40	7.07	6.04	5.53	5.00
j_+ $\varphi = 4.5$	6.93	5.64	4.85	4.15	3.77	3.45
10^6 amp/cm^2 $\varphi = 3$	1.43	1.22	1.04	0.905	0.844	0.780

Nordheim equation:[10]

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

where $f(y)$ is the Nordheim elliptic function[11] of the variable $y = 3.79 \times 10^{-4} F^{1/2}/\varphi$ and φ is the work function of the cathode metal.

Physically, (1) and (2) must be satisfied simultaneously at the cathode. By combining the two equations one may eliminate the field term F and obtain a unique relation between j_+ and j_+/j_- for a fixed value of φ.* Table VI presents calculations made at φ = 5, 4.5 and 3 e. volts. This is essentially the same procedure previously followed by Wasserab.[12] One observes from Table VI that for a wide range of j_+/j_- (at constant ϕ) the change in the ion current density is relatively small. For instance, a 2-fold decrease in j_+ corresponds to a 20-fold increase in j_+/j_-. *Short arcs, therefore, and more generally all field emission arcs, are maintained at approximately a constant ion current density at the cathode.* For most contact metals this density is of the order of 10^6 amp/cm^2.

It has been shown[6,7] that the short arc is initiated when the power density of the field emission electrons bombarding an anode spot becomes sufficiently high to cause anode evaporation. From this, one may con-

[10] A. Sommerfeld and H. Bethe, Handbuch der Physik (Verlag. Julius Springer, Berlin) **24,** p. 441, 1933.

[11] L. W. Nordheim, Proc. Roy. Soc., **A121,** p. 626, 1928.

* A third equation may be introduced relating j_+/j_- to the collision cross-sections and the gas density distribution in the gap. For the one-dimensional case, neglecting recombination, the equation is given by:

$$\frac{j_+}{j_-} = \frac{Q_i}{Q_i + Q_e} \left[1 - \exp\left(-(Q_i + Q_e) \int_0^d N \, dx\right)\right]$$

where Q_i and Q_e are the ionization and excitation cross-sections of the metal vapor. Due to lack of data on atomic cross-sections and the physical complexity of the pressure distribution between the contacts, no attempt has been made to calculate ionization rates in the gap. Instead, the analysis was carried out by leaving j_+/j_- as an adjustable variable.

[12] T. Wasserab, Z. Physik, **130,** p. 311, 1951.

clude that in its earliest stages, an established arc runs primarily in *anode* metal vapor. The evaporating spot on the anode is then minimum in size. For a constant current arc, which also operates at constant power, the corresponding rate of anode evaporation must, therefore, be a maximum since the maximum rate of heat conduction into the anode is proportional to the size of the anode spot, its boiling temperature and thermal conductivity. Fig. 3 is a diagrammatic representation of the conditions between a pair of contacts at an early stage of the arc. For radius a of the boiling anode spot, an approximately equal area on the cathode must constitute the electron emitting area, since the cathode field is maintained by the approaching positive ions which have been formed by electron collisions with the anode vapor. For a plane at a dis-

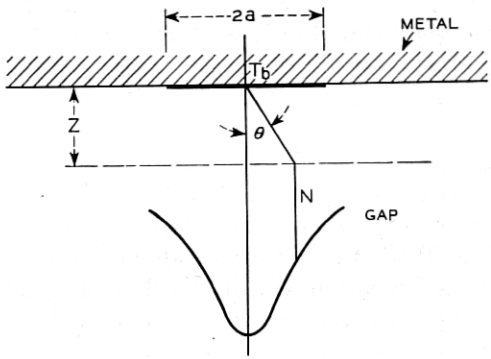

Fig. 3 — Vapor density distribution due to a small evaporating spot.

tance z from the anode, the density of vapor, originating at a small anode spot of radius a, is roughly inversely proportional to both z^2 and $(\cos\theta)^3$. From this, one should expect the electrons approaching the anode to have a strong tendency to scatter to the periphery. The resultant redistribution of the energy of the bombarding electrons over a larger area causes the boiling area to expand in size. On the average, therefore, the effective length of an electron path before reaching the anode will increase. The number of collisions, including ionizing collisions, will increase. Hence the ratio j_+/j_- increases with the size of the anode spot. This growth of the anode spot with time has been observed[13] by examination of the sizes of anode pits produced by single arcs of different durations.

According to Table VI, an increase in j_+/j_-, where both j_+ and j_- are measured at the cathode, corresponds to a proportionate decrease in

[13] W. S. Boyle and L. H. Germer, J. Appl. Phys., **26**, p. 571, 1955.

j_-, since the decrease in j_+ is relatively small. The rate of evaporation of the anode will decrease for three reasons: (1) the rate of energy dissipation by conduction increases with increase in anode spot size, (2) the electron current density is decreasing, and (3) the average energy of an electron reaching the anode is decreasing due to the increase in inelastic collisions. The cathode spot on the other hand, being approximately equal in size to the anode spot, is bombarded by ions of practically constant current density. Furthermore, each ion reaching the cathode will have the same high energy corresponding to the potential drop in the cathode fall. *All prevailing conditions, therefore, will tend to decrease the rate of energy dissipation at the anode while increasing it at the cathode. If the ion current becomes sufficiently high, cathode evaporation occurs.* This corresponds to a critical ratio j_+/j_- which is calculated in the following section.

For a plane cathode spot of radius a, the boiling temperature is reached at its center when

$$j_+(V_c + V_i - \varphi)a/\bar{\lambda}\Delta T_b = 1, \tag{3}$$

and evaporation takes place when it exceeds 1. The term in brackets is the energy of condensation of an ion on the cathode surface,[14] $\bar{\lambda}$ is an appropriate average thermal conductivity of the cathode metal for the temperature range between ambient and boiling, and ΔT_b is the temperature rise of the cathode to boiling. The total arc current I, in terms of j_+ and j_- at the cathode, is given by:

$$I = \pi a^2(j_+ + j_-) \tag{4}$$

Combining Equations (3) and (4) to eliminate a, the critical condition for maintenance of the cathode spot at boiling becomes:

$$j_+ \frac{(j_+)}{(j_-)} = \frac{\pi}{I} \frac{(\bar{\lambda} \cdot \Delta T_b)^2}{(V_c + V_i - \varphi)} \tag{5}$$

In a previous section it has been shown that a combination of the emission and space charge equations, (1) and (2), gives a relation of the form $j_+ = f(j_+/j_-, \varphi)$; See Table VI. This can be combined with (5) to eliminate j_+, thereby expressing j_+/j_- in terms of the cathode physical constants. *This is the critical ratio of j_+/j_- which must be exceeded to cause evaporation of the cathode spot.* Unfortunately, however, data on thermal conductivity above the melting point, are only available for the low melting point metals. For the majority of these, the change in the

[14] K. G. Compton, Phys. Rev., **37**, p. 1077, 1931.

thermal conductivity with temperature is rather small except at melting where a sudden substantial decrease in conductivity occurs. In Table VII values of λ_0, λ_b and λ_0/λ_b are given for various metals as obtained from the references indicated. For copper and silver, thermal conductivities were calculated from electric resistivity data using the Franz-Wiedemann[15] relation with the theoretical constant 2.45×10^{-8} (volt/°C)^2.

For metals whose thermal conductivities at high temperatures are not available, λ_b was taken as $0.5\lambda_0$ as suggested by the last column in Table VII. Table VIII is a summary of calculations of the critical ratio j_+/j_- for a number of metals. In these calculations, V_c was replaced by $V_i + \varphi$ and the term $V_c + V_i - \varphi$ in (5) by $2V_i$. The error involved is only a

TABLE VII — THERMAL CONDUCTIVITIES OF SOME METALS

Metal	λ_0[a]	λ_b	λ_b/λ_0
	watt/cm°C		
Cd	0.933	0.451[b]	0.45
Pb	0.352	0.209[b]	0.59
Sn	0.657	0.324[b]	0.49
Zn	1.13	0.602[b]	0.53
Al	2.03	0.84[b]	0.41
Ag	4.19	2.1[c]	0.50
Cu	3.88	1.9[c]	0.49

[a] Reference 16. [b] Reference 17. [c] Calculated from electric resistivity data for Ag (Reference 18) and Cu (Reference 19).

fraction of a volt[8] and, furthermore, one can carry out the calculations for metals for which the arc voltage is not certain. The thermal conductivity $\bar{\lambda}$ is taken as the arithmetic mean of λ_0 and λ_b.

Column 6 gives the minimum values of $j_+(j_+/j_-)$ which satisfy both the cathode emission and space charge equations, (1) and (2). This minimum value is a function of the work function and atomic weight of the cathode metal. Column 7 gives the values of $j_+(j_+/j_-)$ required for cathode evaporation as determined by the thermal conduction equation, (5). For a given current, these values are a function of the boiling temperature, the thermal conductivity and the minimum ionization potential of the metal. Column 8 gives values of j_+/j_- obtained from (1) and (2) at the given values of $j_+(j_+/j_-)$ of Column 7. These values of j_+/j_- must be exceeded in an arc discharge before cathode evaporation can occur.

[15] A. Sommerfeld and H. Bethe, Elektronentheorie der Metalle. Handbuch der Physik von Geiger und Scheel, Aufl. 24/2 (Berlin, Julius Springer, 1933).
[16] International Critical Tables.
[17] C. J. Smithells, Metals Reference Book, Interscience Publ. Inc., p. 576, 1949.
[18] Handbook of Metals.
[19] Handbook of Physics and Chemistry, p. 2247, 1953–1954.

TABLE VIII — CRITICAL RATIO j_+/j_- WHICH MUST BE EXCEEDED TO CAUSE CATHODE EVAPORATION. TOTAL CURRENT I = 1.0 AMP. TERM "INST" SIGNIFIES INSTANTANEOUS CATHODE EVAPORATION FROM BEGINNING OF ARC.

	Metal, ϕ[20] e. volts	ΔT_b °C	λ_b wat/cm °C	$\bar{\lambda}$ watt/ cm °C	$2V_i$ e. volts	$j_+(j_+/j_-)$ min. in arc. Eq. (1), (2) amp/cm²	$j_+(j_+/j_-)$ evap. Eq. (5) amp/cm²	(j_+/j_-) evap. Eq. (1), (2), (5)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
(1)	Pd, 4.8	2200	0.34	0.51	16.66	1.9×10^5	1.42×10^4	INST
(2)	Ni, 4.84	2900	0.29	0.435	15.27	3.6×10^5	2.13×10^4	INST
(3)	Fe, 4.36	3000	0.31	0.465	15.79	2.5×10^5	2.45×10^4	INST
(4)	Pt, 5.29	4300	0.35	0.525	17.92	1.6×10^5	4.97×10^4	INST
(5)	Ag, 4.3	1950	2.1	3.15	15.19	1.2×10^5	5.12×10^5	0.11
(6)	Au, 4.58	2600	1.5	2.25	18.45	9×10^4	3.15×10^5	0.072
(7)	Cu, 4.47	2300	1.9	2.85	15.45	2.5×10^5	5.62×10^5	0.065

It is evident that *for any metal if the entry in Column 7 is less than that in Column 6, some cathode evaporation will take place even during the earliest stages of the arc.* As shown in Column 8, this is the case for Pd, Ni, Fe and Pt. For Ag, Au and Cu, on the other hand, *the arc may be initiated as a true anode arc and only when relatively high ratios j_+/j_- are obtained in the discharge will evaporation from the cathode take place.* This ratio is highest for silver, 0.11, followed by gold, 0.072 and then copper, 0.065. Unfortunately, the present analysis cannot be carried further to determine whether such ionization rates can or cannot be obtained in a discharge, due to the lack of data on collision cross-sections for vapors of these metals. The analysis as such, however, establishes some basic differences among metals in their erosion behavior, by showing some to have stronger tendencies than others for cathode evaporation.* Our observations are in accordance with this conclusion where with Pd,† Fe and Ni it was possible to have enough cathode evaporation

[20] H. B. Michaelson, J. Appl. Phys., **21,** p. 456, 1950.

* It is of interest to point out that Froome[21] has observed similar differences for arcs at low gas pressures on Hg and Cu cathodes. For 10^{-7} sec. arcs on Hg, multiple non-stationary cathode spots were observed while with Cu the spots were not visible and often non-existent. From heat conduction calculations, similar to the above, Froome concluded that while Hg could be easily vaporized, Cu would not even be heated to red heat. For 30×10^{-6} sec arcs, however, cathode spots on Cu were observed.

† For Pd, the observed time for the reversal of the transfer is of the order of 10^{-7} sec, Fig. 1. This time is appreciable in terms of the electron and ion transit times and is attributed to thermal relaxation of the contact metal. It is of the same order as the observed time lags preceding the initiation of the short arc which were shown[6] to correspond to the heating time of the anode spot.

[21] K. D. Froome, Proc. Phys. Soc., (London) **60,** p. 431, 1948.

to exceed that of the anode while for Ag, Au and Cu this reversal was not obtained.*

When evaporation from a cathode spot occurs, it modifies the gas density distribution between the contacts by introducing a high density region near the cathode. This causes additional scattering of the emitted electrons which enhances the spread of the bombarded anode spot and decreases its rate of evaporation. It is, therefore, conceivable that a condition could be reached where the anode spot, radius a_+, becomes large enough compared to the cathode spot, radius a_-, that the rate of evaporation of the cathode exceeds that of the anode. The conditions under which this may occur will now be derived. The power dissipated at the cathode is $j_+(\pi a_-^2)(2V_i)$, and the power dissipated at the anode is $(j_+ + j_-)\pi a_-^2\varphi$, where both j_+ and j_- are measured at the cathode. The specified anode power is actually a lower limit since all the electrons are assumed to reach the anode with zero kinetic energy. This rate of evaporation is assumed to correspond to the difference between the power delivered by electrons or ions and the power dissipated by conduction through the corresponding electrode. The heat dissipated by metal melting is neglected.† For two hemispherical spots, one on each electrode, maintained at boiling temperature, the rate of cathode evaporation exceeds that of the anode if:

$$j_+\pi a_-^2(2V_i - \varphi) - 2\pi a_-\lambda\cdot\Delta T_b > (j_+ + j_-)\pi a_-^2\varphi - 2\pi a_+\lambda\cdot\Delta T_b \tag{6}$$

Combining with (4) and assuming that $j_-/j_+ \gg 1.0$, one gets

$$\frac{a_+}{a_-} > 1 + \frac{\varphi}{2\lambda\cdot\Delta T_b}\left[1 - \frac{j_+}{j_-}\left(\frac{2V_i}{\varphi} - 1\right)\right]\left[\frac{j_-}{j_+}\frac{Ij_+}{\pi}\right]^{1/2} \tag{7}$$

If ionization is due mainly to ionizing collisions between electrons and metal atoms, it can be shown that (for electron energies slightly above V_i), the maximum ion to electron ratio obtainable is $Q_i/(Q_i + Q_e)$, where Q_i and Q_e are the ionization and excitation cross-sections. No data is available to permit a calculation of this ratio for any of the metals in this investigation. For mercury, however, this ratio is about 1/7, for electrons at 0.2 volt above the minimum ionization potential of mercury.

* This statement is not meant to exclude the possibility of some cathode evaporation for these metals since our testing method is not capable of detecting cathode evaporation if it is much less than that of the anode.

† This is metal leaving the cathode surface. The error involved is discussed later.

This was obtained from ionization data[22] and excitation data.[23] A tentative calculation was, therefore, carried out for Pd at the two values of 0.1 and 0.2 for j_+/j_-. The corresponding values of j_+ are 7×10^6 and 6×10^6 amp/cm^2 respectively. At $j_+/j_- = 0.1$, the calculated ratio a_+/a_- is between 6 and 12, the lower value based on λ_0 and the higher value at λ_b. At $j_+/j_- = 0.2$, a_+/a_- is between 3.5 and 6.*

For metals such as Pd which exhibit a reversal to the cathode arc by showing cathode loss, one can make another estimate of the probable ratio j_+/j_- for such arcs from the measurement of the rate of erosion. If a_- is the radius of the cathode spot, the power used in evaporation is taken as the difference between the power dissipated at the cathode and the power dissipated by conduction to maintain the cathode spot at the boiling temperature. This neglects the energy carried away by molten metal which may escape the cathode spot and deposit elsewhere. Observations on single arc anode pits, however, have shown[1] that each pit was surrounded by a rim which contains most of the metal from the pit. For Pt the volume of this metal was less by a factor of three than the amount which can be melted by the arc energy. To correct for this melting effect in calculating the rate of metal evaporation, one must not assume that the melting energy of the displaced metal is lost since this metal still remains on a rather narrow rim surrounding the pit.† From the photograph in reference 1, it appears that the average width of the rim is 10 to 15 per cent, the diameter of the pit. The effect of displacing this molten metal, therefore, is a redistribution of the initial arc energy where 70 per cent of the energy is dissipated in the pit area and 30 per cent dissipated on a surrounding rim 10 to 15 per cent the diameter of the pit. For the degree of accuracy desired in our calculations, it appears justifiable to neglect this effect.

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[22] W. B. Nottingham, Phys. Rev., **55**, p. 203, 1939.

[23] H. Massey and E. Burhop, Electronic and Ionic Phenomena, p. 62. (Oxford, Clarendon Press, 1952).

* Single arc pit measurements were also made for Pd contacts at 3.2 amp arc of 0.39×10^{-6} sec duration initiated at 250 volts. The single anode pit observed had an average diameter of 16×10^{-4} cm corresponding to a current density of only 1.5×10^6 amp/cm^2. Comparing with Table VI, one finds that unless the cathode emitting spot is considerably smaller than the observed anode spot, this low density may be obtained only if high ratios of j_+/j_-, higher than 1.0, are attainable. This is unlikely for the low energy electrons in the short arc. Actually cathode observations, with 1,700 magnification, have shown a number of smaller individual pits, probably an indication of a non-stationary cathode spot in accordance with previous cathode observations,[24] of an average diameter of 2.4×10^{-4} cm. If only one of these pits carried the total current at any one time, the current density would be 70×10^6 amp/cm^2 corresponding to a j_+/j_- of about 0.1, Table VI. The measured ratio a_+/a_- is 6.7.

[24] J. D. Cobine, Gaseous Conduction, McGraw-Hill, 1941.

† It is evident that no correction is needed if the molten metal is not displaced.

No correction is needed for the heat of condensation of the metal deposited on the cathode spot in the form of neutral atoms, since these will be reflected, with or without loss of identity, from the cathode spot which is already at the boiling temperature.

The ratio of the evaporation power to the input power Iv is given by:

$$\frac{\text{Evaporation power}}{\text{Input power}} = \frac{1}{Iv}\left[j_+\pi a_-^2(2V_i) - 2\pi a_-\lambda\cdot\Delta T_b\right]$$

Eliminating a_-, through the introduction of the total current I, and setting $x = j_+/j_+ + j_-$, one gets:

$$\frac{\text{Evaporation power}}{\text{Input power}} = x\cdot\frac{2V_i}{v} - \frac{2\lambda\cdot\Delta T_b}{v}\left(\frac{\pi x}{Ij_+}\right)^{1/2} \tag{8}$$

For any value of j_+/j_-, or of x, j_+ is determined from Table VI for palladium and the power ratio in (8) may be obtained. From the physical properties of Pd* the volume evaporated per unit energy is about 1.8×10^{-12} cc/erg. If it is assumed that 50 per cent of the evaporated metal from the cathode is redeposited on the cathode, one can calculate the cathode loss per unit input energy from (8), for each value of j_+/j_-. Results of such calculations for Pd are given in Table IX. The erosion rate of the cathode of Pd contacts was measured at about 3.5×10^{-14} cc/erg, Tables I and II. These were obtained from measurements with arcs of durations sufficient to allow erosion reversal. During the first portion of each of these arcs, as much as 50 per cent of the total arc duration, metal was transferred from the anode to the cathode at an average rate of about 3×10^{-14} cc/erg. The rate of cathode loss† is probably as high as

$$(3.5 \times 10^{-14}) + (3 \times 10^{-14}) = 6.5 \times 10^{-14} \text{ cc/erg.}$$

From Table IX, one may therefore conclude that *for the latter stage or cathode stage of the short arc in Pd, an upper limit of 10 per cent of the total current is carried by positive ions.*

In the section on measurements, it was noted that for the longer arcs, initiated as air breakdowns, the erosion was consistently from the *cathode* for all the metals which were investigated. These experiments were performed in laboratory air at 500 volts and the corresponding contact separation was about 3×10^{-3} cm. At the high value of pd or Nd prevailing in the gap, the anode is, from the beginning, sufficiently

* Reference 17, p. 419.

† It is possible that this observed loss is not all due to surface evaporation but may be partly due to some metal leaving the surface in the molten stage. The calculated ratio j_+/j_- is only, therefore, an upper limit.

TABLE IX — RATIO OF EVAPORATION POWER TO INPUT POWER, AND RATE OF Pd METAL LOSS FOR A CATHODE ARC AT DIFFERENT VALUES OF j_+/j_-. CALCULATIONS ARE FOR $I = 1.0$ AMP. $\lambda = (\lambda_0 + \lambda_b)/2 = 0.51$ WATT/CM°C

j_+/j_-	0.04	0.06	0.08	0.10	0.20
$\frac{1}{x} = \frac{j_+ + j_-}{j_+}$	26	17.7	13.5	11	6
j_+ = amp/cm²	9.5×10^6	8.3×10^6	7.6×10^6	7×10^6	6×10^6
Evap. power / Input power	0.028	0.044	0.060	0.076	0.15
Cathode loss, rate, 10^{-14} cc/erg (based on 50 per cent of total evap. rate)	2.4	3.9	5.4	6.8	13

shielded while the cathode is being continuously bombarded over a relatively small area by high energy ions dropping through the cathode fall. If n_0 is a number of electrons leaving the cathode and Q is the total collision cross-section, then the number of electrons n_d reaching the anode without any collisions is given by:

$$n_d/n_0 = \exp(-NQ\,d) \tag{9}$$

At 10 volts, Q for both O_2 and N_2 is about 10^{-15} cm².[25] For atmospheric air at 300°K and $d = 3 \times 10^{-3}$ cm, (9) shows that practically no electron will reach the anode without an elastic or inelastic collision. Those having only elastic collisions will undergo little change in energy but will be scattered to an anode spot larger than the cathode emitting spot. If one assumes the inelastic collision cross-section to be 15–20 times less than the total collision cross-section, less than 1–3 per cent of the electrons will reach the anode with full energy. One concludes, therefore, that *for arcs initiated as gas breakdowns at small separations, erosion is generally confined to the cathode, provided that the product Nd is high enough to provide sufficient anode shielding.* These arcs initially run primarily in the gas between the contacts until cathode evaporation occurs when cathode vapor will contribute to the maintenance of the arc. The erosion data for palladium in air given in Table IV do substantiate this by showing an increase in the rate of cathode evaporation with increasing arc duration. At 3.2 amps, the rate of erosion increases from 2.5×10^{-14} cc/erg. for 35×10^{-9} sec arcs, to 4.0×10^{-14} cc/erg. for 280×10^{-9} sec. At 6.4 amp, it increases from 1.6×10^{-14} cc/erg. at 17.5×10^{-9} sec to 4.7×10^{-14} cc/erg. at 70×10^{-9} sec.

For *fully* activated contacts of Pd and Ag, erosion was also obtained

[25] R. B. Brode, Revs. Modern Phys., **5**, p. 257, 1933.

from the cathode. Since these experiments were performed at a vacuum of 10 microns, anode shielding must have been provided by means other than air between the contacts. Activated contacts are characterized by the sooty products deposited on the contact surfaces, the lower fields for arc initiation and the lower currents at which the arc can be maintained.[3,4] The activation deposits are organic and have poor conduction properties and probably low boiling temperatures. When the arc is initiated, the anode surface will present, at least temporarily, the physical properties of the deposit rather than those of the substrate. The anode arc stage, discussed above, will therefore be maintained in vapor from the anode deposit. Due to the low conductivity, boiling point and heat evaporation of the deposit, the evaporation rate and the rate of growth of the anode spot must be appreciably higher than for the clean metal.* Furthermore, according to (5), the cathode deposit will boil more readily and the transition to the cathode arc stage will occur sooner. *Shielding of the anode metal is provided, therefore, first by vapor from the anode deposit and then by vapor from the cathode deposit which may finally be mixed with cathode metal vapor.* Arc voltage transients across activated contacts, reported by Germer and Smith,[5] do substantiate this by showing a gradual transition, within one arc, from the higher arc voltage of the activating substance,[3] to the lower arc voltage of the contact metal. Finally, the lower cathode erosion rates observed for activated contacts are readily explainable as due to the arc energy expended in decomposing and evaporating the organic deposits.

* This is substantiated by the observation that arcs between active contacts can be maintained at much lower currents than for clean contacts. This indicates that at these lower currents, corresponding to lower dissipated power, enough vapor pressure was maintained between the contacts to provide the necessary ionization.