ACKNOWLEDGMENTS

The author is indebted to his colleagues at Telecommunications Research Establishment for much help and advice and particularly to W. D. Lawson who provided the single crystals and to W. H. Mitchell who built the micromanipulator. He is indebted to the Chief Scientist, Ministry of Supply, and to the Controller, H.M Stationery Office, for permission to publish this work

REFERENCES

BANBURY, P C, GEBBIE, H A, and HOGARTH, C A, 1951, *Semi-Conducting Materials*, ed H K Henisch (London Butterworths Scientific Publications) p 78

BARDEEN, J, and BRATTAIN, W H, 1948, *Phys Rev*, **74,** 230

GEBBIE, H A, BANBURY, P C, and HOGARTH, C A, 1950, *Proc Phys Soc* B, **63,** 371

GIBSON, A F, 1952, *Proc Phys Soc* B, **65,** 196.

HENISCH, H K, and GRANVILLE, J W, 1951, *Semi-Conducting Materials*, ed. H K Henisch (London Butterworths Scientific Publications) p 87

HOGARTH, C A, 1951, *Proc Phys Soc* B, **64,** 822

LAWSON, W D, 1951, *J Appl Phys*, **22,** 1444, 1952, *Ibid*, **23,** 495.

PUTLEY, E H, 1952, *Proc Phys Soc* B, **65,** 388.

Electrode Phenomena in Transient Arcs

BY J. M. SOMERVILLE,* W. R. BLEVIN AND N. H. FLETCHER

The New England University College, Armidale, N.S W, Australia

MS received 7th July 1952

ABSTRACT High current, short duration arcs between various metals in air have been studied by means of a Kerr Cell camera and by observation of the marks left on the electrodes. Growth of these marks with arc duration is discussed and shown to be due to heat conduction in the case of the anode marks and to motion of the emitting areas in the case of cathode marks Cathode spot temperatures are frequently too low for thermionic emission even on metals of high boiling point At very high rates of current rise both anode and cathode marks are multiple

§1. INTRODUCTION

When an arc strikes between two metallic electrodes, hot spots form on both anode and cathode within a very short time which is generally estimated to be of the order of 10^{-7} second or less. If the arc is prolonged the spots persist and most of the current is believed to pass through them. Cathode spots have been studied recently by Cobine and Gallagher (1948) and by Froome (1948, 1949, 1950) using techniques involving rapid motion of the spot across the cathode surface. The corresponding anode spots have received very little attention When the arc has ended, a visible mark is usually left on each electrode. To avoid confusion we will use the term 'electrode marks' to denote these and will reserve the term 'electrode spots' to denote the active areas of the electrodes at any instant during the life of the arc.

We have studied the electrode marks left by transient arcs with durations ranging from one microsecond to one millisecond, struck in air at atmospheric pressure, between solid metallic electrodes. There was no general movement of the arc across the electrode surface, the centre of the arc being apparently stationary. In our experiments, arcs were studied under conditions of constant

---

[*] Now temporarily at Department of Physics, University College of Swansea.

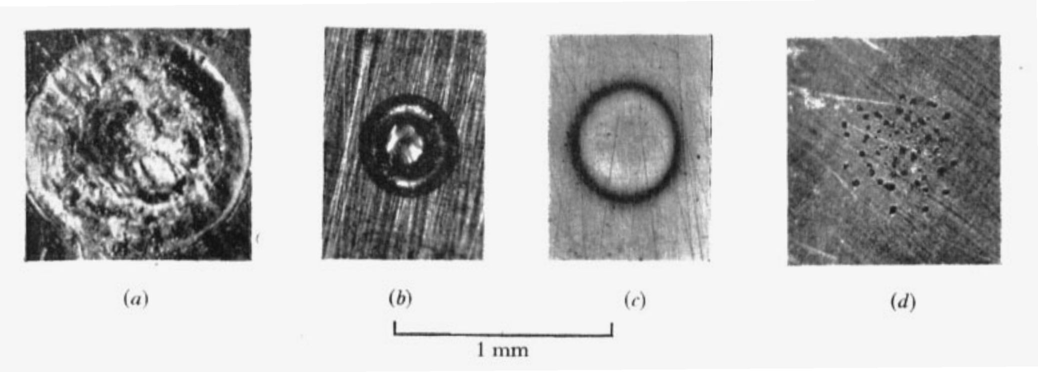

Fig. 1. Typical anode marks. (*a*) Tin anode, arc duration 1200 μsec, arc current 34 amp. (*b*) Aluminium, 200 μsec, 50 amp. (*c*) Copper, 200 μsec, 50 amp. (*d*) Tin, 1 μsec, 100 amp.

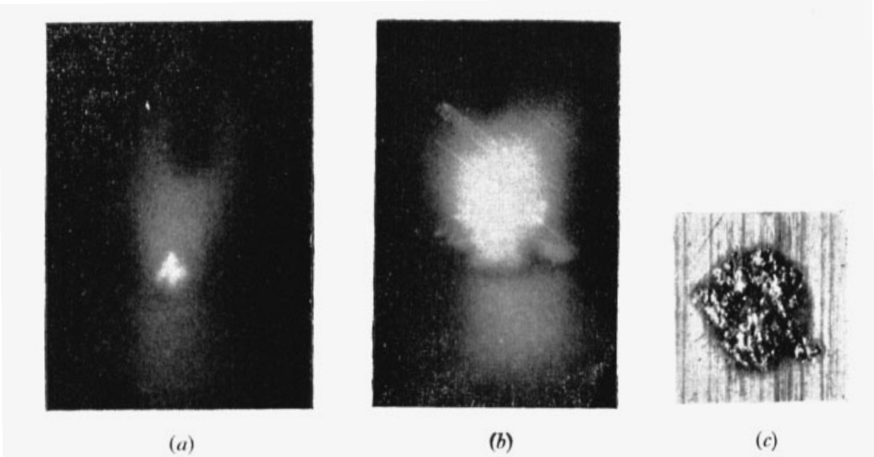

Fig. 3. Oblique photographs of the arc column and cathode spot for a 50 μsec 80 amp arc, (*a*) 6 μsec, (*b*) 40 μsec after initiation. Exposure 3 μsec. (*c*) Photomicrograph to the same scale of the cathode mark left by the arc in (*b*).

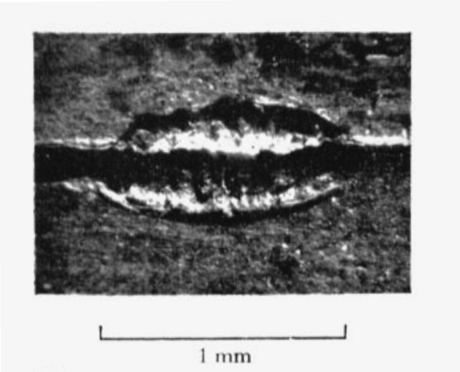

Fig. 2. Depth of melting of tin anode for a 200 μsec 50 amp arc.

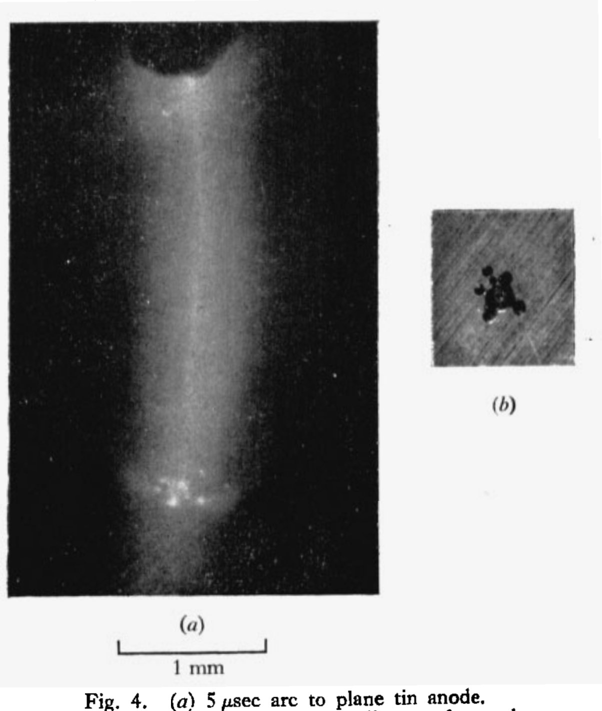

Fig. 4. (*a*) 5 μsec arc to plane tin anode. (*b*) Photomicrograph of corresponding anode mark.

current, each arc being formed by the discharge of an artificial line, so that the current rose rapidly to a value which it retained for the remainder of the time during which the line was discharging. By using different lines, arc durations of 1, 5, 20, 200 and 1 200 microseconds could be obtained with currents ranging up to 200 amperes. The arc was usually struck by moving the electrodes together until sparking occurred, the potential to which the line was charged varying from 1 000 to 5 000 v, depending on the current required. Observations of the marks left when the arc was struck by suddenly connecting the charged line to the electrodes at different electrode separations showed that, unless it was very small, the electrode separation had no great effect on the nature of the marks. Numerous metals were used as electrodes, special attention being given to tin which has, from our point of view, the advantages of a low melting point (232° c) and a relatively high boiling point (2 270° c). Examination, on a cathode-ray oscillograph, of the instantaneous potential across the gap showed it to be from 20 to 30 v, so that the discharge may be appropriately described as an arc.

We have examined microscopically the electrode marks left by these arcs. Such an examination is not an ideal means of obtaining information about the state of the electrode during the life of the arc because thermal processes such as melting and subsequent solidification take place after the arc itself has ceased, and one has the task of inferring an intermediate state from observation of the final marking. Nevertheless, we have found that something may be learned from this approach.

We have also used a Kerr Cell camera to obtain photographs of the arc at different times during its life. This camera was capable of taking three consecutive photographs with variable time intervals between the exposures. So that the three images would not be superposed, the light from the arc was split into three beams, each of which passed through a separate Kerr Cell shutter and formed a separate image on the film

§ 2. THE ANODE

Kerr Cell photographs taken of arcs between a fine wire cathode and the plane surface of a tin anode show a bright glow near the anode which defines the anode 'spot'. Such photographs, taken at various intervals after the initiation of the arc show that the diameter of the anode spot remains approximately constant as the arc grows older. In the case of an 80-amp arc, for example, this diameter is 0·03 cm, so that, assuming that all the current passes through the luminous spot, the average current density is of the order of 10^4 amp/cm^2. The area of the anode spot increases with the current.

Microscopic examination of marks left on the anode by arcs with a moderate rate of rise of current shows that a single circular region has been affected by the arc. For most metals this region appears to have been molten, but a few metals (e.g copper, tungsten) show only a discoloration of the surface. This latter group of metals also yields anode marks which show signs of melting if the surface is lightly oxidized or otherwise contaminated. Figure 1 (for all figures see Plate) shows a number of typical anode marks. For a given metal and arc duration, the mark area is approximately proportional to current.

For metals on which the anode marks have been molten, the melted area has a regular circular boundary and increases both with arc current and arc duration. Marks left on tin anodes by 80 amp 50μsec arcs have radii a little over twice those of the corresponding spots. It appears that the increase of the molten area with arc duration is due to melting around a central active spot. The depth to which melting occurs can be found by using as anode two pieces of tin tightly clamped together, the arc being struck where the two pieces join, welding them together at this point. On separation the depth to which melting has taken place can be clearly seen. (Figure 2 shows the melting down of the surface of contact of the two pieces of tin which have been subsequently broken apart.) For 50 amp 200μsec arcs the tin is melted to a depth of a little more than one-third of the radius of the anode mark. Depth of melting may also be studied by striking arcs on metal foil anodes of various thicknesses and observing the maximum foil thickness for which melting is apparent on the reverse side. Under these circumstances, where heat flow out of the back of the foil is largely prevented, the depth of melting is about twice as great as on a thick anode. Our observation of the appearance and behaviour of these anode marks is consistent with the belief that they are caused by the heating of the anode through electron bombardment which is concentrated over an area a few tenths of a millimetre in diameter.

On polished copper anodes, the anode mark is a discoloured area, probably consisting of oxides, which increases with arc duration. Kerr Cell photographs of the arc do not show a bright anode spot, but the appearance of the column near the anode suggests that the active area of the electrode does not vary much with time. The growth of the anode mark with time is probably due to oxidation around the active area.

The area and general appearance of the anode mark is independent of the material and shape of the cathode, and also of the inter-electrode distance, unless this is less than a few tenths of a millimetre. At these short distances the change in appearance is due to ejection of liquid metal from the molten area by the expanding air confined between the electrodes. If a 'Cellophane' screen is placed near the anode and a small hole is bored in it to allow the arc to strike, similar ejection of the anode metal occurs.

Anode marks left by arcs with a very high rate of current rise are usually multiple and are discussed later in this paper.

§ 3 THE CATHODE

Cathode marks are approximately the same size as anode marks and, like them, may or may not show signs of melting. In some other respects they differ from anode marks; their shape is usually less circular, their boundary more irregular, and their surface less smooth. Their appearance depends somewhat on the distance of the anode from the cathode, though the area is not altered significantly. In a previous publication two of us (Somerville and Blevin 1949) showed that the area of the cathode mark increased with arc duration and consequently that the apparent cathode current density, obtained by dividing the current by this area, decreased with time. We will now discuss whether this decrease is real or only apparent.

It is possible to advance several theories to account for the increase in the cathode mark area with arc duration. One which immediately suggests itself is that, when the mark has been molten, the increase in size may be due to progressive melting around a smaller active centre, as appears to be the case with anode marks. This explanation may be discarded because it is found that marks left on thin foil cathodes may have diameters ten or more times the thickness of the foil, without any sign of melting appearing on the reverse side. Clearly, if the large mark were due to melting from a small central spot, melting right through the foil would have taken place long before it had extended so far laterally. Moreover, the irregular appearance of many marks is inconsistent with melting from a centre.

It might also be thought that the increase in mark area on low melting point cathodes could be due to heat generated by dissipation of electrical energy in the resistance of the cathode material However, if the same current pulse is led into the cathode by actual contact with a very fine copper wire whose diameter is much less than that of the observed cathode mark, it is found that no mark is left on the cathode at all, showing that the Joule heat generated is much too small to cause any melting. Calculation supports this view

Clearly, in the case of the cathode materials with high melting points where no melting takes place, neither of these theories is applicable.

Holm (1946) has developed a theory which predicts an increase in the active spot area with time. He assumes the whole active area to be maintained at a temperature of 2000° c, and he calculates the area which the incoming energy, assumed delivered at a constant rate, is capable of keeping at that temperature. This area, which increases with time, he takes to be equal to the active spot area. We do not think that the whole area of the cathode mark attains a temperature as high as this at any one time during the first few hundred microseconds of life of the arc. Our reasons for this belief are as follows.

In the first place, melting is usually not apparent in cathode marks on clean metals with melting points above about 900° c. For example, the cathode marks of 50 amp 200 μsec arcs on tin, cadmium, lead, zinc, antimony and aluminium, whose melting points range from 232° c to 660° c, show definite but decreasing degrees of melting, while marks left by similar arcs on cathodes of silver, gold, copper, nickel, cobalt, platinum and tungsten, whose melting points range from 961° c to 3387° c, exhibit no melting at all, not even of a localized nature within the main mark area. The metals were found to be similarly grouped when marks left by 50 amp 20 μsec arcs were examined. When the surface is heavily oxidized or contaminated in other ways, melting may occur even on very high melting point metals such as tungsten.

Further information about the average cathode temperature at the centre of the mark may be obtained from a comparison of anode and cathode marks. It is found for tin that the depth of melting at the cathode, measured either by using foils or a split cathode, is about half the corresponding depth at the anode for a similar arc. Consequently one would expect that the average temperature at the cathode would be of the order of half that at the anode. As the anode temperature presumably cannot exceed the boiling point of tin, 2 270° c, the average cathode temperature would not be likely to exceed about 1 000° c. A comparison between cathode marks on tin and anode marks on cadmium is also instructive. These two metals have very similar thermal properties except for their boiling points, that of cadmium being 767° c (specific heats: 0·055, 0·054 cal g^{-1} (deg c)$^{-1}$, thermal conductivities: 0·22, 0·16 cal cm^{-1} sec^{-1} (deg c)$^{-1}$; latent heats of fusion: 14, 14·6 cal/g; melting points 321, 232° c for cadmium and tin respectively). Consequently heat flow and melting should proceed in a very similar manner in both. We find that tin cathode marks and cadmium anode marks have much the same diameter and the same depth of melting. This indicates that the average temperatures of the marks on each electrode were approximately equal, and therefore neither could have exceeded the boiling point of cadmium.

It is possible to go somewhat further and make an approximate calculation of the average surface temperature of the cathode at the centre of the mark, based on the observed depth of melting. Because this depth of melting is small compared with the spot diameter the problem approximates to that of linear heat flow into a semi-infinite metal solid whose infinite plane boundary is suddenly raised to, and maintained at, a temperature T_s greater than the melting point of the metal. If, as we shall see later, we are not justified in assuming the cathode mark area to be raised to a uniform temperature, then T_s represents an average surface temperature

Lightfoot (1930) has given an exact solution to this problem, taking into account the energy absorbed as latent heat. Suppose that a semi-infinite metal at temperature T_0 extends from the plane $x=0$ to infinity in the positive direction of x, and that at time $t=0$ the plane $x=0$ is raised to a temperature T_s and kept at that temperature. Then with some changes in notation and a little algebra we find, from Lightfoot, that the temperature at time t and distance x $(<2\mu(\kappa t)^{1/2})$ is given by

$$T = T_s - (T_s - T_0)\,\mathrm{erf}\,(x/2(\kappa t)^{1/2}) - (L\mu\sqrt{\pi}/s)\,\mathrm{erf}\,(x/2(\kappa t)^{1/2})\,(1-\mathrm{erf}\,\mu)\exp\mu^2 \qquad \ldots\ldots(1)$$

where L is the latent heat of fusion, s is the specific heat, and $\kappa = K/s\rho$ where K is the thermal conductivity and ρ the density of the metal. μ is a parameter. If ξ is the distance of the solid–liquid boundary from the plane $x=0$ at time t, then

$$\xi = 2\mu(\kappa t)^{1/2}. \qquad \ldots\ldots(2)$$

Suppose now that the temperature of the metal is raised to T_s, only for a time τ corresponding to an arc of that duration. At the end of the arc the melted boundary will have reached $x=2\mu(\kappa t)^{1/2}$ but, because of the heat stored in the melted region, melting will continue to a greater depth after the arc has ended. It is not difficult to show from (1) that, during the time τ the heat entering the metal per unit area is

$$2(Ks\rho\tau/\pi)^{1/2}\{T_s - T_0 + (L\mu\sqrt{\pi}/s)\,(1-\mathrm{erf}\,\mu)\exp\mu^2\}.$$

If *all* this heat went into melting the metal it would be melted to a depth d where

$$d = 2(\kappa\tau/\pi)^{1/2}\{T_s - T_0 + (L\mu\sqrt{\pi}/s)\,(1-\mathrm{erf}\,\mu)\exp\mu^2\}/(T_m - T_0 + L/s), \qquad \ldots\ldots(3)$$

T_m being the melting point of the metal.

In a semi-infinite metal all this heat will not be used in melting metal, but if instead of the semi-infinite metal we have a thin foil which just melts through to the other side, then, because heat flow out of the back of the foil is largely prevented, all the heat entering will be used in melting.

Considering d as the thickness of this foil, (3) gives an equation connecting T_s and μ. Another equation connecting these two quantities may be obtained from (1) by putting $T=T_m$, in which case from (2) $x/2(\kappa t)^{1/2}=\mu$ and (1) becomes

$$T_s - T_0 = (T_m - T_0)/(1-\mathrm{erf}\,\mu) + (L\mu\sqrt{\pi}/s)\exp\mu^2\,\mathrm{erf}\,\mu. \qquad \ldots\ldots(4)$$

Equations (3) and (4) can be solved simultaneously without great difficulty by computation or by graphical methods to give T_s and μ. The results of some such calculations, based on measured values of d obtained with tin foils, are given in the table. This shows that the temperature of the cathode surface near the centre of the mark, if constant, probably does not exceed 1 200° c. It will also be seen that the distance to which melting has reached by the end of the arc is approximately half the thickness d of the foil, so that the error in applying to a foil cathode the heat intake calculated for an infinitely thick cathode is probably not excessive.*

Tin Cathodes

τ (μsec)	d (cm)	μ	ξ (cm)	T_s (° c)
200	0.015	0.53	0.008	630
50	0.013	0.77	0.006	1160
20	0.008	0.73	0.0036	1090
5	0.0025	0.55	0.0013	670

We have just shown that if the temperature over the cathode mark is uniform, it is not likely to be high enough to give appreciable thermionic emission. It also seems unlikely that the current can be uniformly distributed over the whole area of the cathode mark because then the cathode current density of arcs lasting more than a few microseconds would be of the order of 10^4 to 10^5 amp/cm^2 which is much too low to give sufficient field emission (Mackeown 1929, Froome 1950, Wasserrab 1951). Our observations of the appearance of the cathode mark thus point to the conclusion that it must have had a fine structure during the life of the arc.

In order to determine whether this is so, photographs of the cathode region of the arc were taken with the Kerr Cell camera. Figure 3 shows two typical photographs of an arc struck in air between a thin copper wire anode and a plane tin cathode.† These photographs were taken obliquely, with the axis of the camera making an angle of about 20° with the plane of the cathode, and so the reflection of the arc column in the cathode can also be seen. Also included in the figure is a photomicrograph, to the same scale, of the cathode mark left by the arc in the second photograph. The growth of the luminous area with time is clearly shown, contrasting with the behaviour at the anode. In the second photograph several intense elements may be seen, apparently distributed round the periphery. These may well be emitting areas moving outward in a manner similar to those observed on liquid metallic surfaces by Froome (1949, 1950).‡ The peripheral appearance of the cathode mark in fig. 3 (*c*) rather supports the view that it was generated by several separate centres of activity moving radially outwards.

We have also struck arcs on the edge of thin foils held in a sandwich between two pieces of bakelite, with only the edge of the foil exposed This has the

---

* Our colleague Dr. R. C. T. Smith has obtained a more refined solution for the heat flow problem relating to arcs struck on thick electrodes Calculations based on preliminary experiments show that the mean temperature at the centre of the cathode spot can be well below the boiling point in this case also.

† In order to obtain greater clarity for reproduction, these are single photographs of two similar arcs They exhibit the same general characteristics as a sequence of photographs of a single arc.

‡ In a private communication some time ago Dr. Froome suggested to us that the increasing areas of our cathode marks with time might be explained in terms of the outward motion of line elements like those observed by him.

advantage of allowing all parts of the emitting area to be held in sharp focus at once, which cannot be done with oblique photographs of arcs on a plane cathode. Photographs of such arcs on the edge of thin foils show that there are many small discrete emitting areas distributed along the length of the foil.

§ 4 MULTIPLE ELECTRODE MARKS

When the rate of rise of the arc current is very high the anode mark is usually multiple and may consist of fifty or more small distinct marks distributed over an approximately circular area (fig. 1 (*d*)). These small marks tend to coincide with small surface irregularities, such as scratches, and their number and distance apart increases as the rate of rise of the current increases. Multiplicity occurs when this rate exceeds about 10^7 to 10^8 amp/sec, a value similar to that obtained by Froome (1949, 1950) as the condition for multiplicity of cathode spots on liquid mercury and sodium-potassium alloy surfaces. However, anode mark multiplicity does not appear to be directly associated with multiplicity of the cathode mark. For a 150 amp 1 μsec arc on plane tin electrodes, the anode mark is highly multiple and spread over a relatively large total area, the cathode mark single and of small area. The apparently single cathode mark probably has a fine structure during the life of the arc, but the following experiment shows that a correspondence between cathode and anode mark fine structure is unlikely.

A 150 amp 1 μsec arc was struck between two tin electrodes about 3 mm apart. Between these electrodes two 'Cellophane' sheets were placed, parallel to the plates and distant approximately 2 mm from them and from each other. In each sheet there was a small hole about 0·03 mm in diameter, the line joining the two holes being perpendicular to the plates. The arc passed through these two holes. (The current density in the holes had the very high value of 2×10^7 amp/cm^2.) Both marks were multiple, but it seems unlikely that any discrete channels linking the small anode marks to possible corresponding marks on the cathode could pass together through the two small holes in the 'Cellophane' and still retain their identity. Apparently anode mark multiplicity is associated with processes at or near the anode. In a further experiment a single 'Cellophane' sheet with a similar hole was placed between cathode any anode and its distance from the anode varied. As it approached within a few tenths of a millimetre of the anode the area over which the small anode marks were spread diminished, suggesting that multiplicity is not confined entirely to processes occurring at the actual anode surface. It should perhaps be added that we have checked that the small anode marks are not due to an oscillatory discharge of the small interelectrode capacity nor to any brush discharge taking place prior to the main discharge.

Figure 4 shows a photograph of a 50 amp 5 μsec arc of comparatively low multiplicity on a tin anode, the shutter being open for the whole duration of the arc. Note the correspondence in position of the anode spots in (*a*) and the marks in (*b*). There is also a characteristic single bright core at the centre of the column

Multiplicity of the cathode mark is not uncommon for arcs with a high rate of current rise. This is not unexpected in view of the general multiplicity of the cathode spot, and indeed absence of multiplicity is usually due only to melting together of the separate marks.

§ 5. THE INITIAL ELECTRODE TEMPERATURE

Arcs of various currents and durations have been struck on electrodes whose temperatures were held constant at points within the range −50° c to 220° c. The area of marks left on tin cathodes increased as the initial temperature was raised, the rate of increase becoming greater as the melting point (232° c) was approached. For example, a 50 amp 5 μsec arc struck on a tin cathode at 200° c leaves a mark about four times the area of that left on the same cathode at −50° c. Molten marks on oxidized copper cathodes showed a definite but much smaller increase through the same temperature range. Anode marks on these metals also increased with the temperature but to a much smaller degree.

§ 6 PRESSURE VARIATION

Arcs have been struck in air at pressures ranging from one atmosphere to 1 cm Hg. Marks on both electrodes were little different in appearance or area from those obtained at atmospheric pressure.

§ 7 CONCLUSION

Our experiments lead us to the following conclusions about high current, transient arcs in air.

(1) The active area at the anode does not increase with arc duration. Growth of the anode mark is due to heat conduction from this active centre.

(2) The cathode spot becomes multiple soon after the initiation of the arc, and the increase in mark area is due to an outward motion of these centres of emission. For arcs of duration less than a few hundred microseconds heat flow beyond the active area is not very important in mark formation.

(3) Even on some high boiling point metals, the temperature of the cathode spot does not exceed about 1200° c.

(4) Multiplicity at the anode occurs under similar conditions to those reported for cathode multiplicity , that is, when the rate of rise of current is very high It is possible to have multiplicity at one electrode only, and when it occurs on both there is no connecting fine structure in the arc column.

ACKNOWLEDGMENTS

We are greatly indebted to Dr R. C. T. Smith for many very helpful discussions about heat flow problems associated with this work. The project has been generously supported by the Commonwealth Electrical Research Board.

REFERENCES

Cobine, J D , and Gallagher, C J , 1948, *Phys Rev* , **74,** 1524

Froome, K D., 1948, *Proc Phys Soc* , **60,** 424, 1949, *Proc Phys Soc* B, **62,** 805, 1950, *Ibid* , **63,** 377

Holm, R , 1946, *Ark Mat Astr Fys* , **34B,** No 8

Lightfoot, N M H , 1930 *Proc Lond Math Soc* , Ser 2, **31,** 97

Mackeown, S S , 1929, *Phys Rev* , **34,** 611

Somerville, J M , and Blevin, W R , 1949, *Phys Rev* , **76,** 982

Wasserrab, T , 1951, *Z Phys* , **130,** 311