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Current Density of the Arc Cathode Spot*

J. D. COBINE AND C. J. GALLAGHER
Research Laboratory, General Electric Company, Schenectady, New York
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New measurements of the area of the arc cathode spot from measurements of width of tracks left on metals by a cathode spot moving in a magnetic field indicate that the current density is greater than values given by previous workers. At 2.6 amperes, we find the following values in air at atmospheric pressure: Cu 124,000 amp./cm^2, Al 29,500 amp./cm^2, W 74,000 amp./cm^2, Hg on Cu 20,700 amp./cm^2.

The Cu, Al, and W electrodes were first oxidized in a bunsen flame. For an arc burning in mercury vapor with a mercury cathode at a few microns pressure we find at 2.6 amperes a current density of 50,000 to 220,000 amperes per cm^2. Values at currents above 5 amperes could not be obtained because of the formation of multiple spots.

ESTIMATES of the cathode current density in the electric arc have varied widely, from a few hundred amperes per cm^2 to several thousand.[1] The chief source of uncertainty lies in determining the effective area of the current transmitting portion of the cathode, since in general the total current can be measured easily. It has been customary to assume that the small, highly luminous area on the cathode, the "cathode spot," corresponds closely to the current-carrying region, and efforts to measure the current-density have been limited to measurements of the size of the cathode spot. This same assumption will be made in this paper. The directly measured quantity is the diameter of the cathode spot, and from this we may infer the value of the current density.

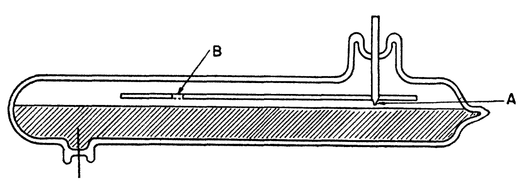

FIG. 1. Tube for mercury arc studies.

In our experiments the materials used as cathodes were mercury, copper, aluminum, tungsten, lead, brass, and mercury-copper amalgam. With the exception of the mercury, all the surfaces were lightly oxidized, and the arc was established in air at atmospheric pressure. With the mercury cathode, the arc burned in mercury vapor at low pressures of the order of 10–50 microns. It was found that the current which could be used was limited by the tendency of multiple spots to form at higher currents. The limiting current depended on the metal. For aluminum multiple spots formed at currents as low as 2 amperes, while for tungsten there was apparently but a single spot at currents up to at least 10 amperes. Other cathode materials appear to have limiting currents lying between these extremes.

The mercury cathode was studied in the tube shown in the diagram (Fig. 1). The arc was started by momentary contact between the tungsten point (A) and the mercury pool. An external magnetic field, perpendicular to the plane of the diagram, drives the spot to the opposite end of the tube. If the field is sufficiently strong (several hundred gauss) the spot travels in a straight line, with none of the wandering motion to the side which has limited the accuracy of observations by other experimenters. The vapor pressure is low enough that the spot moves in the retrograde direction[2] with the column trailing the spot. The spot is observed through the small hole (B) in the anode. If the level of the

* The material discussed here was presented in an invited paper at the New York meeting of the American Physical Society, January 1948.

[1] C. Granquist, Nova Acta Upsala **20**, 143 (1903); M. Reich, Physik. Zeits. **7**, 73 (1906); N. A. Allen, Proc. Phys. Soc. **33**, 62 (1921); A. Guntherschulze, Zeits. f. Physik **11**, 74 (1922); R. Seeliger and H. Schmick, Physik. Zeits. **28**, 605 (1927) and **31**, 691 (1930); W. G. F. Swann, J. Frank. Inst. **205**, 810 (1928); R. Tanberg and W. E. Berkey, Phys. Rev. **38**, 296 (1931); J. Slepian and E. J. Haverstick, Phys. Rev. **33**, 52 (1929); E. Nobel, Phys. Rev. **36**, 1636 (1930); L. Tonks, Physics **6**, 294 (1935); R. Holm, Arkiv. Mat. Astr. Fys. **34B**, No. 8 (1947); E. G. B. Stuckelberg, Helv. Phys. Acta. **1**, 75 (1928).

[2] N. Minorsky, J. de phys. et rad. **9**, 127 (1928).

mercury is properly adjusted, the slight random disturbances in the mercury surface will be sufficient to cause random make-and-break at the tungsten point. The average time between contacts can be adjusted by a slight tilt of the tube, so that as many as twenty new spots are formed per second.

The radiation from the spot is continuous and extends over the entire visible range. Thus, a red filter may be used to exclude most of the radiation from the mercury vapor. With a suitable microscope and filar eyepiece, the width of the trace can be measured after the observer has acquired some experience in accommodating to slight changes in position of successive traces. The moving spot may also be photographed through the microscope and the width of the resulting trace measured. Three such photographs are shown in Fig. 2, for mercury at 2.6, 5 and 10 amperes. The complicated structure of the 10-ampere trace makes it impossible to form any conclusion about the diameter of the spot. The average width of several traces at 2.6 amperes was 3.9×10^{-3} cm. For a circular spot this width would correspond to a current density of 220,000 amperes per cm^2. This value is higher than any of the values quoted in the literature by more than an order of magnitude.

The dimension of the spot along the direction of motion could be measured by means of a scanning technique. The principle is illustrated in Fig. 3. The image of the spot is focussed by means of a microscope objective onto the opaque screen. The screen has three fine slits of width considerably less than the diameter of the magnified spot. The opaque screen was a standard microscope slide coated with a thin layer of Aquadag. The slits were made by scratching the surface with a razor blade. Such slits can be made quite narrow with width of 0.005 cm easily reproducible. If the magnification of the lens is 6 or 7 diameters, the magnified spot is 10 or 15 times the slit width. The spacing between slits was large enough that the moving image had passed the first slit completely before the leading edge reached the next one.

The light passing through the slits strikes the cathode of a 931A photo-multiplier tube. The output if the multiplier is amplified in a wide-band amplifier and applied to the vertical plates

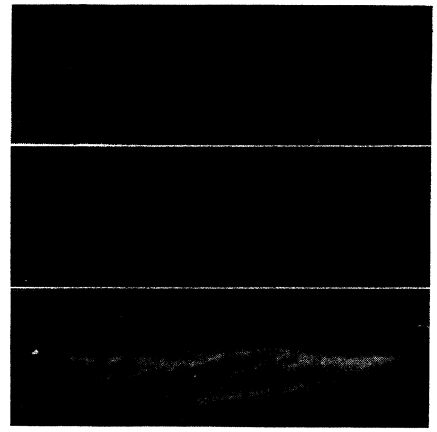

FIG. 2. Cathode tracks on mercury (direction of travel right to left).
(a) 2.6 amperes
(b) 5 amperes
(c) 10 amperes

of a Dumont 248 oscilloscope. The horizontal sweep is triggered by the signal, so that the pattern on the screen consists of three pulses. The leading edge of the first pulse is obscured by the triggering delay, but the next two pulses are the same in size and shape (Fig. 4).

From measurements of the width of the pulses and the distance between corresponding points, a value of the effective width of the spot may be deduced. As shown in the following analysis, the method is independent of the spot velocity, and depends only on the slit spacing, the lens magnification, and the geometry of the pattern on the oscilloscope screen. Let W = effective diameter of spot, MW = diameter of magnified image, d = distance between slits, L = distance on oscilloscope screen between corresponding points of pulses, S = effective width of pulse. Then, since the horizontal sweep is linear with time,

$$MW/S=d/L \quad \text{or} \quad W=Sd/ML.$$

All of the quantities on the right-hand side can be measured accurately. The limiting factor is S.

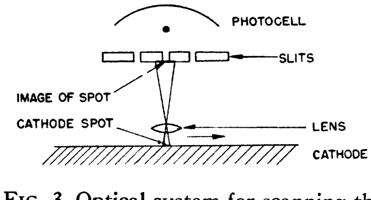

FIG. 3. Optical system for scanning the mercury cathode spot.

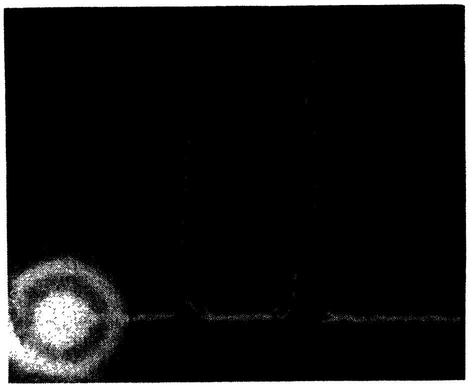

FIG. 4. Oscillograms of light distribution of cathode spots.

The width corresponding to any prescribed pulse height can be measured without difficulty, but it is uncertain which height should be chosen inasmuch as the sides of the pulse have a definite slope. The slope of the leading edge could be due to one or both of two possibilities:

1. The spot may not be uniform across its surface.
2. The gas very near the surface preceding the spot may give some contribution to the radiation.

In the latter case the intensity of the light must be far above that from the plasma in order to be seen by the photo-cell. The slope of the trailing edge of the pulse may indicate that there is a decay of activity in time after the "spot" has passed, or else there is a residual glow of high intensity in the gas. The total time for the spot to pass any point can be less than 5 microseconds. Since there appears to be no adequate way of determining how much of the radiating area is effective, it is probably best to take as an upper limit the width of the pulse across the base, corresponding to a minimum value of current density. The average diameter of the spot corresponding to the base of the pulse is 0.80×10^{-3} cm at 2.6 amperes, about twice the value obtained for the dimension perpendicular to the direction of travel. Thus, the current density would be lowered by a factor of 4, to about 50,000 amperes per cm^2, as a lower limit. The true current density is very probably greater than this figure.

It was not possible to apply the same techniques in observations of the cathode spot on solid metal cathodes. However, it was found that very interesting tracks could be obtained on metal cathodes which were traversed by a rapidly moving cathode spot. Such tracks could then be measured to give the extent of the active area at the cathode. Visible tracks could not be obtained on clean or highly polished metals, but only on electrodes having a definite layer of surface oxide. The arc was established in air at atmospheric pressure, and the spot was made to move rapidly

(a)

(b)

(c)

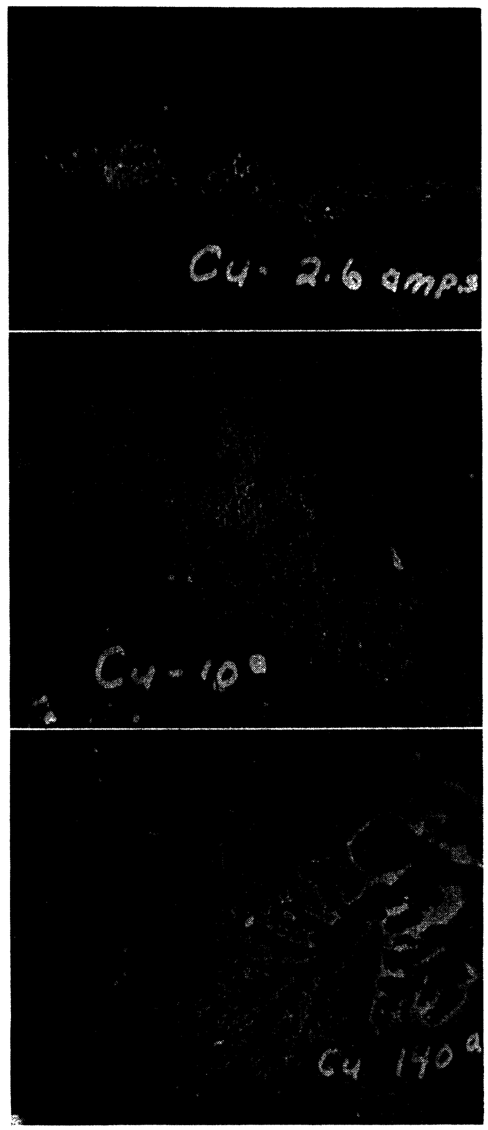

FIG. 5. Cathode tracks on copper (direction of travel right to left).

(a) 2.6 amperes
(b) 10 amperes
(c) 140 amperes

(5 to 10 meters/sec.) over the cathode by means of a magnetic field of about 2000 gauss. For these tracks the spot moved in the direction of the ponderomotive force.

Some examples of the tracks obtained are shown in Figs. 5–7. The effects of increasing the current are shown for copper, aluminum and tungsten. At low currents, single tracks are found; at higher currents multiple spots occur as in mercury. For oxidized aluminum, the tracks are very complex even at low currents, while for tungsten, there appears to be no branching for the currents observed although the track widens as the current increases.

(a)
(b)
(c)

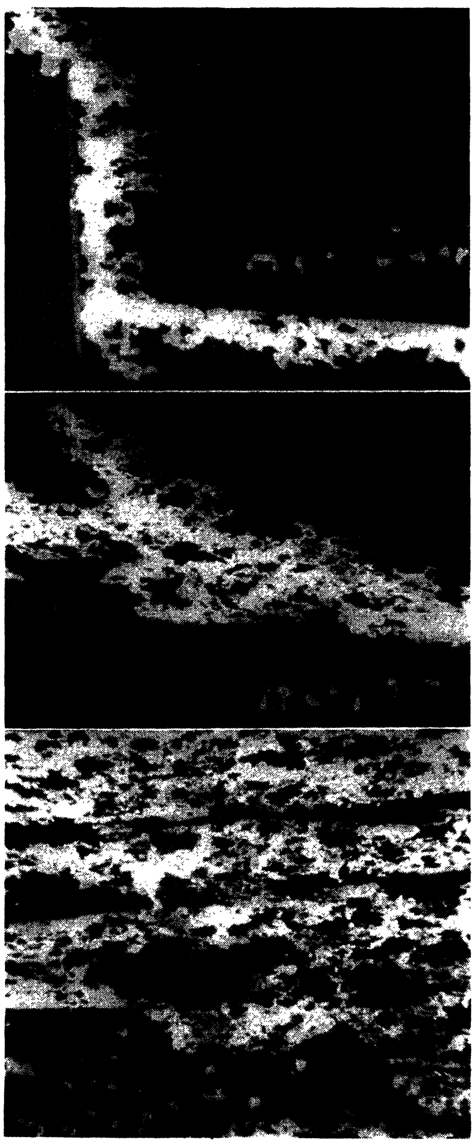

FIG. 6. Cathode tracks on aluminum (direction of travel right to left).

(a) 5 amperes
(b) 10 amperes
(c) 140 amperes

(a)
(b)

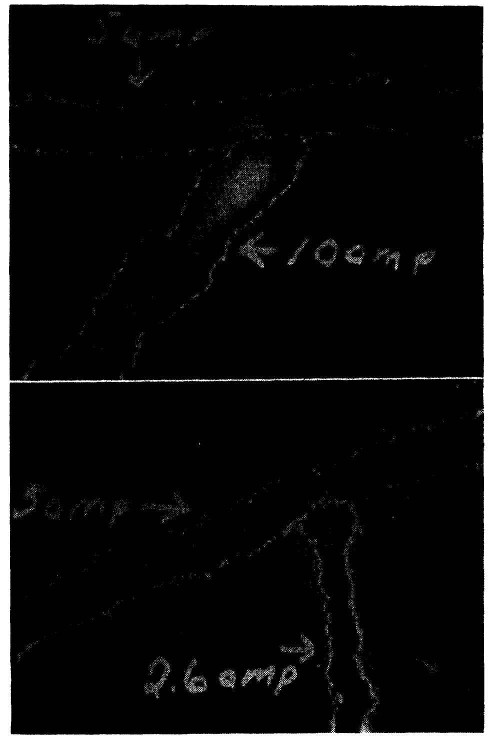

FIG. 7. Cathode tracks on tungsten.

(a) 2.6 and 5 amperes
(b) 5 and 10 amperes

It was found possible to get a non-branching track on aluminum by etching strongly in NaOH, rinsing in distilled water and alcohol, and drying. Occasionally, on all metals, short gaps were found in tracks. This does not necessarily mean an interrupting of current, since a new spot could be formed before the last one disappeared. The tracks on aluminum show some interesting features. The 5 ampere track shows that the "spot" is apparently reluctant to cross a scratch, either parallel to the direction of motion or perpendicular to it. The scratches were about 10 microns deep. The aluminum tracks appear to be much more complicated than for copper, with many of the branches apparently going in the reverse direction.

TABLE I.

Metal	Current-amp.	Width-cm	Current density amp. per cm^2
W	2.6	0.0067	74,000
	5.0	0.0083	92,000
	10.0	0.0164	47,000
Pb	5.0	0.0156	26,000
Al	2.6	0.0105	29,500
Cu	2.6	0.0054	120,000
Cu-Hg	2.6	0.0127	20,700
	5.0	0.0172	21,700
	10.0	0.0275	14,700

The widths of the various tracks which could be measured and the corresponding current densities, assuming circular geometry, are shown in Table I.

It is of interest to consider what a track consists of, since the very fact of its existence indicates a change in the nature of the surface over which the spot has raced. The appearance of the track suggests that the oxide at the spot is removed from the base metal, either by direct evaporation, or by chemical reduction on the surface followed by evaporation, so that the track is just the unoxidized base metal. Apparently some material is lost from the cathode, since it is possible to make accurate replicas of the tracks with Formvar films, which indicate that the penetration below the surface is of the order of 1 micron.

From the experiments described above we conclude that the current density in the arc cathode spot is of the order of 50,000 amp. per cm^2 for most cathode materials. It is now necessary to inquire whether such high values can be obtained by any of the mechanisms which have been previously proposed. There have been a number of mechanisms proposed to explain the current transport at the cathode for the so-called "cold-cathode" arc. The following four seem most worthy of serious consideration: 1. Thermionic emission of electrons.[3,4] 2. Field emission of electrons.[5,6] 3. Positive ion collection, with thermal ionization in the region near the cathode producing the ions.[7,8] 4. Electron emission through insulating particles on the surface resulting from positive ions on the insulator.[9]

The first of these, thermionic emission of electrons, appears adequate to explain the current transport with highly refractory cathodes, such as tungsten and carbon under conditions where they are incandescent, but has not seemed applicable to the lower boiling point metals, for which the possible thermionic emission at the probable maximum temperature would be far too small. The high current density values quoted in this paper make the thermionic theory even less plausible, unless one can assign to the emitting surface very low values of the work function. Although the work functions of the pure metals would be too high, the true work functions for the complex electrode surfaces used are not known so that this possibility is not definitely excluded. It is well known that the arc cathode spot cannot be readily established on a very clean metal surface, so that the possible lowering of the work function by surface impurities may be sufficient to establish the necessary thermionic emission. The best values of the

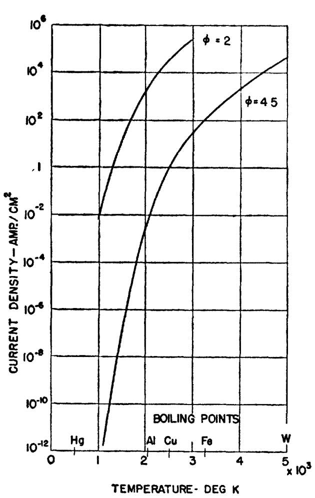

FIG. 8. Thermionic emission curves.

[3] J. J. Thomson, *Conduction of Electricity through Gases*, 3rd Edition (Cambridge Press, Cambridge, 1933), Vol. 2, pp. 596 ff.

[4] L. B. Loeb, *Fundamental Processes of Electrical Discharge in Gases* (John Wiley and Sons, Inc., New York, 1939), pp. 605 ff.

[5] I. Langmuir, Science **58**, 290 (1923); Gen. Elec. Rev. **26**, 731 (1923).

[6] S. S. Mackeown, Phys. Rev. **34**, 611 (1929).

[7] J. Slepian, Phys. Rev. **27**, 407 (1926).

[8] W. Weizel, R. Rompe, and M. Schön, Zeits. f. Physik **115**, 179 (1940).

[9] M. J. Druyvestyn, Nature **137**, 580 (1930).

photoelectric work function of the arious oxides are of the order of 4 volts or higher so that they would not be much better emitters than metals unless the boiling points were higher. The curves shown in Fig. 8 indicate what values of emission might be obtained from materials with work functions of 4.5 volts and 2 volts, respectively. The 4.5 volt curve, which may be taken as representative of most clean metals, shows that the possible current density is much too low even at the boiling point for metals such as Hg, Al, Cu, and Fe. The 2-volt curve would give considerably higher values of current density of the order of those obtained, but the presence of such low work function materials is improbable. Thus, it would appear that thermionic emission alone cannot explain the high current density, unless, as suggested by Thomson[3] and Loeb,[4] it is possible with such density of energy input to obtain local temperatures far above the boiling point.

The theory of field emission postulates that electrons are drawn out of the surface by the strong field set up at the cathode by the high density positive ion space charge outside the surface. The theory of field emission as given by Fowler and Nordheim,[10] indicates that barely measurable current density can be obtained at fields of the order of 10^5 volt/cm, but, as shown in Fig. 9, curves A, B, and C, the current densities we have measured would require fields of the order of 10^7-10^8 volt per cm for work functions as low as 2 volts. To explain these current densities on the field theory, one would have to assume for the work function the absurdity low value of 0.5 volt. Mackeown[6] developed a relation between the field at the cathode and the current density required to produce the field. The curves D and E of Fig. 9 were calculated from his relation, for two different ratios of positive-ion current to electron current. According to Mackeown's theory, fields of 10^7 volt/cm would require a minimum current density of more than 10^7 amp./cm², which is considerably higher than any measured values. Thus, for current densities such as we have measured, the field emission theory appears to be quite inadequate, even if the field be greater by a factor of ten as a result of surface irregularities.

[10] R. H. Fowler and T. Nordheim, Proc. Roy. Soc. **A118**, 229 (1928).

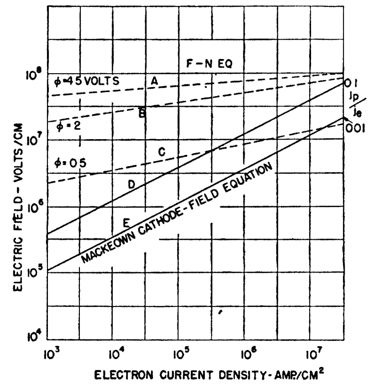

FIG. 9. Relations between cathode field and current density (electrical quantities in practical units).

- - - - - - Fowler-Nordheim equation

$j_e=6.2(10)^{-6}(E^2/\phi)\exp(-6.8(10)^7)\phi^{3/2}/E.$

———— Mackeown field equation

$E^2=7.57(10)^5V_c^{1/2}[j_p(1845W)^{1/2}-j_e].$

E = electrostatic field,
j_e = electron current density,
j_p = positive ion current density,
W = atomic weight.

A third theory originally advanced by Slepian[7] to apply to low current densities, and subsequently developed for higher current densities by Weizel, Rompe, and Schön,[8] attempts to show that electron emission is not necessary, but that the entire cathode current can be accounted for by positive ions generated in the gas adjacent to the surface by the various processes involved in thermal ionization. The latter authors carried through some calculations for a high pressure mercury arc in an attempt to show that the assumed mechanism would lead to correct values of voltage drop between the column and the cathode. The values calculated for the cathode drop were too high to agree with observed values, but current densities were also probably too low, by a factor of at least five. An increase in current density by this factor would lower the calculated cathode drop to some extent although not enough to give completely satisfactory agreement.

Druyvestyn[9] assumed that the "cold-cathode" spot depended on the presence of tiny insulating or semi-conducting particles, such as glass, or oxide layers Positive ions would build up these insulating particles to produce a high field, with electrons then emitted through the insulator. The theory does offer an explanation for the apparent necessity of the presence of oxides and also of the random motion of the spot, since the impurities could be removed by the ion bombardment and a new region would then be activated. It is not at all clear from Druyvestyn's picture that the observed high current densities can be accounted for, and leaves unexplained a number of the points as listed below.

None of these theories appears really adequate. They fail to explain the observed high current densities, and offer no clue as to the reason for several phenomena which must be intimately associated with the cathode mechanism. The following are several such phenomena which at present are left without explanation: 1. The high velocity stream of vapor (or particles) coming from the cathode.[11] 2. The continuous spectrum at the cathode spot.[12] 3. The retrograde motion of the spot in a low pressure arc on application of a magnetic field.[2,13,14] 4. The increase in stability at low currents when the spot is confined to a small area.[15] [illegible] The difficulty of establishing a spot on [illegible]n surface[16,**] and the random motion of [illegible]pot over the surface. 6. The failure of the merc[illegible] arc to re-ignite when interrupted for times as short as 10^{-9} second.[17]

Since none of these "classical" theories appears to give a complete picture of the cathode processes, it may well be that, as Loeb has suggested, a new approach is required, "to evolve a new physics of the microvolume with high rates of energy input."[18]

Note added in proof: Since this paper was submitted for publication Froome has reported even higher values of current density (10^6 amp/cm^2) for transient arcs of 1400 ampere peak current for copper, sodium, and mercury cathodes.[19]

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[11] R. Tanberg, Phys. Rev. **35**, 1080 (1930).
[12] J. Stark, Physik. Zeits. **51**, 750 (1904).
[13] C. G. Smith, Phys. Rev. **62**, 48 (1942); Bull. Am. Phys. Soc. **18**, 5 (1943).
[14] C. J. Gallagher and J. D. Cobine, Phys. Rev. **71**, 481 (1947).
[15] C. W. Lufcy and P. L. Copeland, J. App. Phys. **16**, 740 (1945).
[16] G. E. Doan and J. L. Myer, Phys. Rev. **40**, 36 (1932).
** We have observed that a "cold cathode" arc can be established on oxidized tungsten with the typical random motion of the spot, but that no spot can be formed on clean tungsten unless the temperature is high enough that thermionic electrons can be emitted.
[17] G. Mierdel, Zeits. f. tech. physik **17**, 452 (1936).
[18] See reference 4, p. 636.
[19] See K. D. Froome, Proc. Phys. Soc. **60**, 424 (1948).

(a)

(b)

(c)

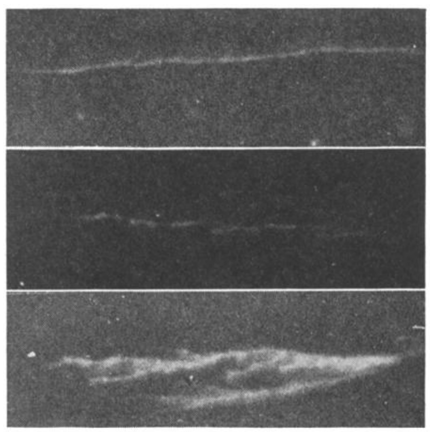


FIG. 2. Cathode tracks on mercury (direction of travel right to left).

(a) 2.6 amperes
(b) 5 amperes
(c) 10 amperes

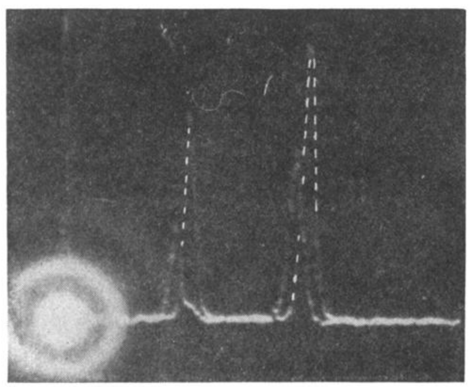


FIG. 4. Oscillograms of light distribution of cathode spots.

(a)
(b)
(c)

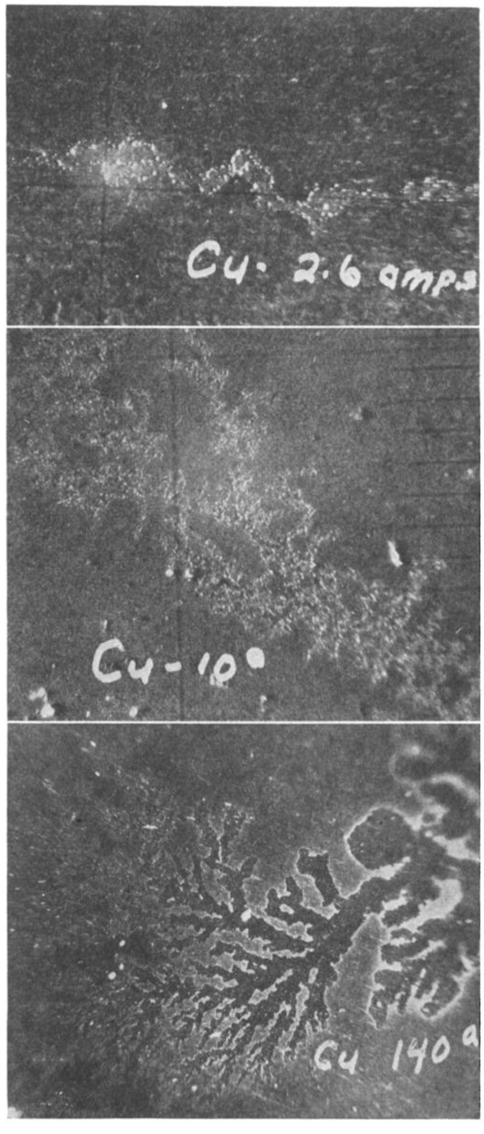


FIG. 5. Cathode tracks on copper (direction of travel right to left).

(a) 2.6 amperes
(b) **10** amperes
(c) **140** amperes

(a)

(b)

(c)

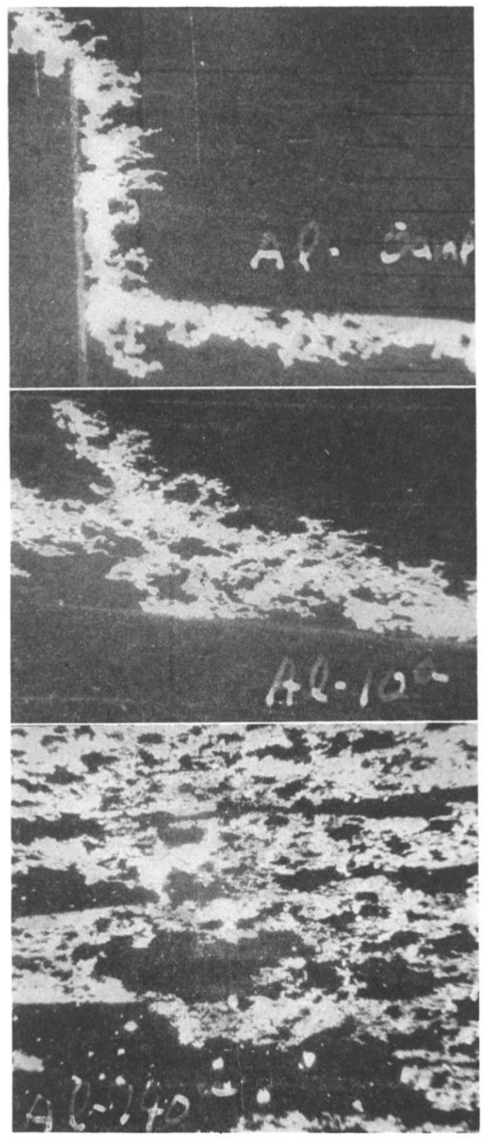
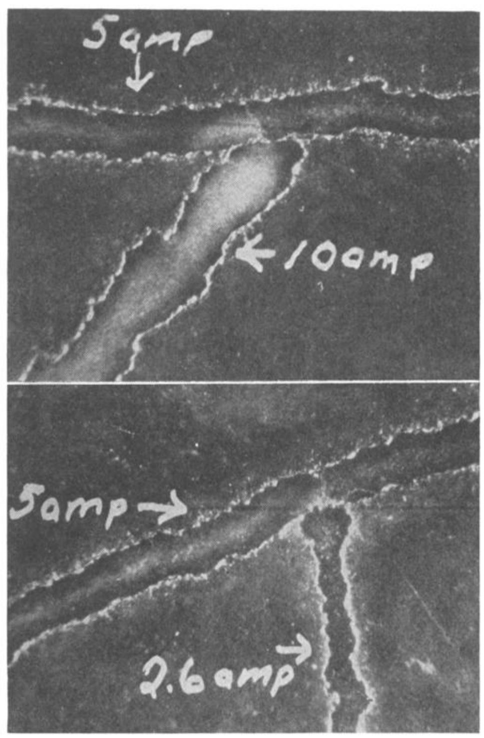


FIG. 6. Cathode tracks on aluminum (direction of travel right to left).

(a) 5 amperes
(b) 10 amperes
(c) 140 amperes



(a)

(b)

FIG. 7. Cathode tracks on tungsten.

(a) 2.6 and 5 amperes
(b) 5 and 10 amperes