Heat Dissipation at the Electrodes of a Short Electric Arc

By L. H. GERMER

Platinum contacts are brought together 60 times a second, discharging on each closure a condenser of 0.01 mf capacity charged to 40 volts. The heat flowing along each electrode is calculated from a temperature difference measured by thermocouples, and from this is determined the energy dissipated at each contact. If there is no arc on closure, the energy is the same on the two contacts, and is small. If there is an arc between the contacts before they touch, about 58 per cent of its energy is dissipated upon the anode and about 42 per cent upon the cathode. The distribution is the same in an arc between clean "inactive" electrodes and in the entirely different kind of arc occurring between carbonized "active" electrodes. This information may be significant in developing an understanding of closure arcs which are the sole cause of the erosion of electrical contacts on closure.

THIS paper is an account of direct calorimetric measurements of the energy dissipated at positive and negative electrodes when they are brought together to discharge a condenser. The experiments are called for by the fact that the erosion at the closure of electrical contacts is due to arcing,[1] and understanding how the energy of a closure arc is distributed between the electrodes is likely to help in developing a comprehensive theory of this arc which in turn may aid in the control of contact erosion.

The experimental method is an adaptation to the present problem of a procedure[2] used earlier in which crossed wires are separated and brought together 60 times per second by means of a magnetic loudspeaker unit, each closure discharging a condenser which is recharged after the wires have been separated. For the present experiments the two wires are made of platinum and are rather heavy, and the flow of heat in each of them is measured by a pair of thermocouples. There is a known length of wire between the two thermocouples of each pair which are connected in series to oppose each other, so that a galvanometer in either circuit will give a deflection proportional to the difference in temperature across the wire.[3] The flow of heat along each wire is calculated from this temperature difference and the thermal conductivity and dimensions of the wire. After making some corrections this gives the amount of energy dissipated upon the electrode at each discharge of the condenser.

The two platinum test wires have diameters of 0.0635 cm and each is about 2.2 cm long from its end to the point where it is clamped in a very

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[1] L. H. Germer, *Jl. App. Phys. 22*, 955 (1951).

[2] J. J. Lander and L. H. Germer, *Jl. App. Phys. 19*, 910 (1948), pp. 918–919.

[3] This is the experimental arrangement used by J. J. Lander in measuring heat flow in his determinations of Thomson coefficients. *Phys. Rev. 74*, 479 (1948), Fig. 3.

heavy copper block. The thermocouples are Chromel-Alumel wires of 0.012 cm diameter and one couple of each pair is welded to its platinum wire 2.0 cm from the point where the wire is clamped in its copper block; the other couple of the pair is electrically insulated by a glass coating and is buried in a deep hole in the block. The electrical contact is made between points of the platinum wires a little beyond the welded thermocouples, and opening and closing of the circuit is achieved by striking one of the platinum wires beyond the point of electrical contact with the insulated armature of a speaker unit vibrating at 60 cycles. Each heavy copper block with its platinum wire is mounted on a cantilever bar, the end of which can be moved by a screw to permit fine adjustment of the contacts. Adjustment can be made also by varying the voltage supplied to the speaker unit.

In order to minimize thermal disturbances this equipment is mounted on a heavy steel base, and the speaker unit, which dissipates about 0.01 watt during operation, is thermally insulated from the contacts by three concentric heavy aluminum covers each in very good thermal contact with the steel base. All of this equipment is covered by a silvered bell jar of 21 cm inside diameter. An aluminum covered Celotex housing surrounds the bell jar and the thermocouple galvanometer, except for a small glass window for reading the galvanometer. The galvanometer light is turned on for only about one second at the time of each reading. The experiments are made in a constant temperature room.

All of the significant tests consist in measurements of the heat flow along the platinum wires when they are brought together 60 times per second discharging at each closure a capacity of 10^{-8} f charged to a potential of 40 volts. At this potential an arc occurs between clean platinum electrodes if the circuit inductance is less than about 10^{-6} h, but there is no arc if the inductance is much higher than this.[1] If the electrodes are operated in the presence of any one of various organic vapors they become coated with carbonaceous material and arcing then occurs at every closure even when the inductance is quite high.[1] Measurements have been carried out under three different experimental conditions: (1) clean electrodes with a circuit inductance of 0.05×10^{-6} h and an *arc at every closure*, (2) clean electrodes with a circuit inductance of 10×10^{-6} h and *no arcing*, and (3) electrodes slightly carbonized by d-limonene vapor with a circuit inductance of 10×10^{-6} h and an *arc at every closure*. The condition of arcing on every closure, or of complete absence of all arcing, was readily determined for each experiment by continuous oscilloscopic observation.[4] The potential of 40 volts was chosen as the highest at which there is never a second arc (in the reverse

[4] See reference 1, Fig. 1.

direction) which would impossibly complicate interpretation of the data. Experiments under conditions 3 were carried out with the limonene vapor pressure maintained at about the lowest value at which activation can be produced (0.06 mm Hg in most experiments). At this low pressure activation does not develop until the electrodes have been operating for some time, but when it develops the open circuit potential after an arc is −5 volts which is also the value reached after arcing in the inactive condition. The observance of this open circuit voltage is proof that each arc is an arc in platinum vapor, and not carbon.

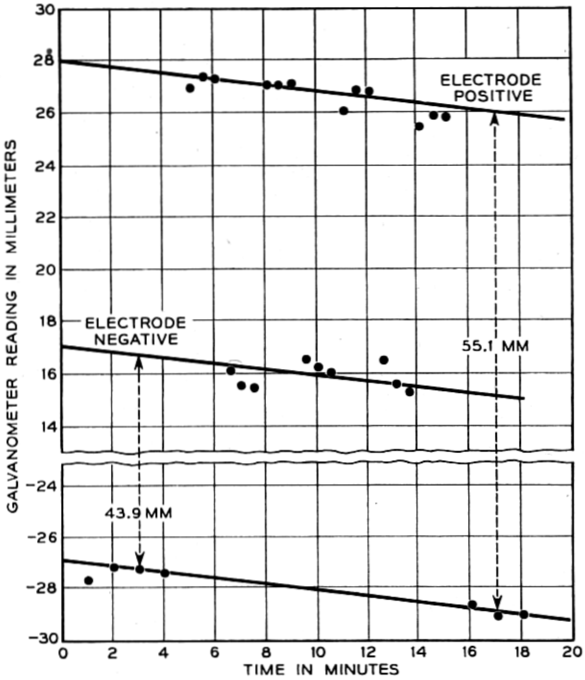

Fig. 1—Readings of the galvanometer in series with the thermocouples in the moving electrode, when the electrode was positive and when it was negative. Electrodes activated by vapor of *d*-limonene at a pressure of 0.06 mm Hg with 60 closures per second and an arc at every closure. Condenser of 0.01 mf charged to 40 volts, discharged on each closure through an inductance of $10 \times 10^{-6} h$. Galvanometer deflections in mm are transformed into ergs per closure by multiplying by 0.510. The experimental points obtained from this figure are marked by small arrows on Fig. 2.

An example of data taken upon active (carbonized) electrodes with a circuit inductance of 10×10^{-6} h (conditions 3), and an arc at every closure ending in an open circuit potential of −5 volts as verified by continuous observation of the oscilloscope recording the potential across the contacts, is given in Fig. 1. The ordinates are readings of the galvanometer when it was in series with the thermocouples in the moving contact. The circuit for charging the condenser to 40 volts prior to each closure was turned on at 4 minutes with the potential of the moving contact positive. The potential was reversed at intervals of $1\frac{1}{2}$ minutes and finally turned off at 15 minutes. The deflections of 43.9 and 55.1 mm occasioned by the energy dissipated at the contact by the discharge of the condenser respectively when the contact was negative and when it was positive are translated into temperature differences of $\Delta T = 0.1213$ and $\Delta T = 0.1523$°C by multiplying by $\alpha r \beta$ where $\alpha = 3.36 \times 10^{-9}$ amp/mm of the galvanometer deflection, $r = 33.7$ ohms circuit resistance, and $\beta = 2.44 \times 10^{4}$°C/volt thermocouple sensitivity. Neglecting for the moment small corrections due to radiation and convection losses, these temperature differences are converted into heat flow along the wire of 22.4 and 28.1 ergs per closure by multiplying them by the factor $B = 184.5$ obtained from the dimensions of the wire, the thermal conductivity of platinum $k = 0.699$ watt/cm°C, and the factor 60 representing the number of closures per second.

The heat flow in one of the wires differs from the heat dissipated by the arcs upon that wire because of radiation and convection losses, and because the higher temperature of the positive electrode results in some conduction of heat to the negative electrode at their point of contact. It has been found expedient first to obtain data which are intended to be free from the last of these three sources of error and then to correct for radiation and convection losses as obtained by calculation.

The energy in the electrode wires corresponding to the average excess temperature of the wires above their surroundings (0.07°C) represents the total energy of about 500 arcs. Thus the large scale temperature distribution in one wire is inappreciably changed during the time the wires are in contact after an arc, and the transfer of heat from one to the other can be corrected for by making measurements of ΔT across each wire for different fractions x of each cycle during which the wires are in contact and extrapolating the values so obtained to find ΔT_0 for zero time of contact. Data of this sort for experimental conditions listed as (1) above are plotted at the lower left side of Fig. 2, and for conditions (3) at the lower right side of the figure; the ΔT_0 values from these curves are written down on the first line of Table 1. On the upper half of the figure is plotted the total heat flowing along *both* wires as calculated by multiplying ΔT by the factor $B = 184.5$ (not correcting for radiation and convection losses).

All the solid circles on Fig. 2 (and Fig. 3 also) represent measurements upon the moving electrode, and the open circles measurements upon the stationary electrode. Differences between the solid circles and the open

TABLE I

HEAT DISSIPATION DATA

	Inactive Electrodes				Active Electrodes	
	(1) $L = 0.05 \times 10^{-6}h$ Arc at Every Closure		(2) $L = 10 \times 10^{-6}h$ No Arcing		(3) $L = 10 \times 10^{-6}h$ Arc at Every Closure	
	Anode	Cathode	Anode	Cathode	Anode	Cathode
1. ΔT_0 from Fig. 2	.1513°C	.1217°C	—	—	.1587°C	.1188°C
2. Correction to ΔT_0 from Fig. 3	+.0050	−.0050	—	—	+.0010	−.0010
3. ΔT_0 corrected for conduction at closure	.1563	.1167	.0445	.0453	.1597	.1178
4. Ergs/closure from ΔT_0	28.83	21.53	8.21	8.36	29.48	21.73
5. Radiation correction (ergs/closure)	0.12	0.09	0.03	0.03	0.12	0.09
6. Convection correction (ergs/closure)	1.63	1.23	0.32	0.33	1.71	1.19
7. Ergs/closure, final values	30.58	22.85	8.56	8.72	$w_+ = 31.31$	$w_- = 23.01$
8. Total ergs/closure		53.43		$w_0 = 17.28$		54.32

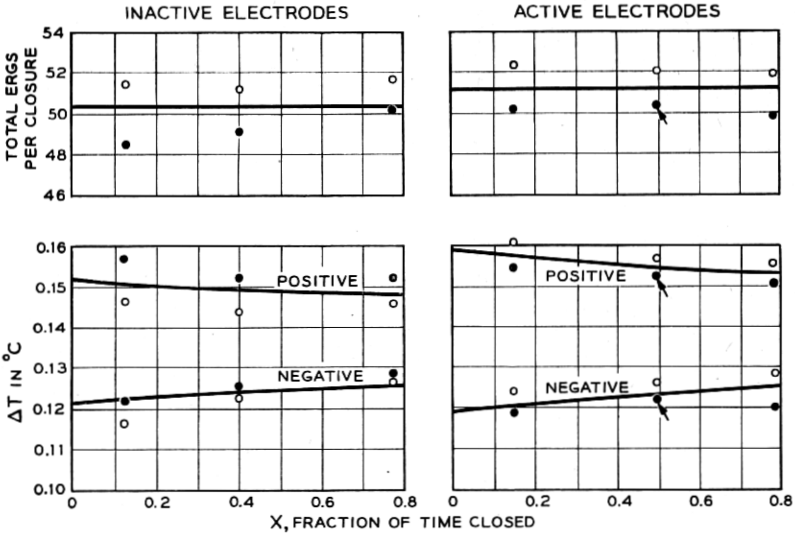

Fig. 2—Heat flow data at different values of x, the fraction of the time the electrodes are closed. Left hand curves, inactive electrodes, inductance $0.05 \times 10^{-6}h$, closing at 3.3 cm/sec. Right hand curves, active electrodes, inductance $10 \times 10^{-6}h$, closing at 2.5 cm/sec.

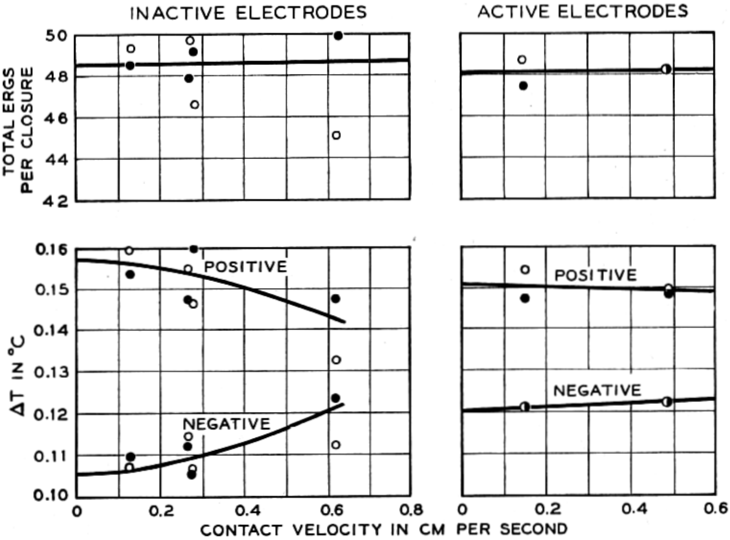

Fig. 3—Data for different velocities at closure, all for $x = 0.5$. Left hand curves, inactive electrodes, inductance $0.05 \times 10^{-6}h$. Right hand curves, active electrodes, inductance $10 \times 10^{-6}h$.

circles are to be attributed to differences between the electrodes, probably in the effective mean diameter. For observations in the active condition the solid circles of Fig. 2 are consistently higher than the open circles, but the opposite is true for measurements upon inactive surfaces. This reversal is not significant; it was brought about by an accident which necessitated rewelding the thermocouple to the moving electrode after the measurements upon the active surfaces had been completed and before the measurements upon the inactive surfaces. In earlier preliminary tests there was no difference of this sort; one must conclude that the welding operation altered the moving electrode. (In the case of the plots at the left of Fig. 3 below, some of the data were taken before the rewelding operation and some after.)

The continuous curves drawn on the lower half of Fig. 2 have the ordinates $W\epsilon_x/B$ for the positive electrode and $W(1 - \epsilon_x)/B$ for the negative, where W is the total energy per closure represented by the horizontal lines at the top of the figure and ϵ_x is the fraction of the energy flowing down the positive electrode. $(0.5 < \epsilon_x < 1)$. The energy lost by the positive to the negative electrode by conduction per closure is clearly $(\epsilon_0 - \epsilon_x)W$. The temperature difference between the wires near the point of contact is $(W/B)(2\epsilon_x - 1)$ and, from analogy with the electrical formula for the spreading resistance of a circular contact of diameter l, the heat flow from one electrode to the other per second is found by multiplying this temperature difference by lkx and the heat flow per closure by further dividing by 60. Equating the two expressions for heat flow one obtains $\epsilon_x = (60\,B\epsilon_0 + lkx)/(60\,B + 2lkx)$. The curves drawn on Fig. 2 have shapes determined by this expression with the two parameters ϵ_0 and l chosen to fit the experimental points. The resulting values of ϵ_0 and l are: $\epsilon_0 = 0.58$, $l = 11 \times 10^{-4}$ cm for the inactive electrodes and $\epsilon_0 = 0.57$, $l = 3.3 \times 10^{-4}$ cm for the active electrodes.

If the area of contact were truly circular and the contacting electrodes were crossed cylinders of perfect cross-section, these values of l would be simply related by elastic theory to the forces F holding the electrodes together when they are in contact. The formula[5] is $l = [6FD(1 - v^2)/E]^{\frac{1}{3}}$ where D is the diameter of the wires, E is Young's modulus for platinum and v is Poisson's ratio. If we take[6] $E = 13 \times 10^8$ gm/cm², the above values of l correspond respectively to forces of 5 and 0.1 grams weight. No significance can, of course, be attached to these values of force other than to observe that they are not wildly unreasonable.

The average lapse of time between the end of each arc and contact of

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[5] A. E. H. Love, "The Mathematical Theory of Elasticity," Cambridge, fourth edition, 1927, page 197, equation 56.

[6] R. Holm, "Electric Contacts," Hugo Gebers, Stockholm, 1946, p. 389.

the electrodes at or near the place where the arc occurred can be calculated from the velocity of the moving electrode at contact and the average separation of the electrodes when the arc took place. Measurements of this separation have been made earlier.[7] Rough calculation of the local temperatures of the electrodes near the point of contact, making use of this average elapsed time, have shown that when contact is made these local temperatures are still far above the mean temperatures at the ends of the wires (perhaps higher by 10°C). The local temperatures reach the mean temperatures in a time which is very short in comparison with 1/60 second, and thus the conduction of heat from the positive to the negative electrode due to this local high temperature is not corrected for by the extrapolations of the curves of Fig. 2. This correction can be made by obtaining ΔT measurements for different electrode velocities and extrapolating to zero velocity. Such data are plotted in Fig. 3. It is obvious that the curves of the lower half of this figure must become horizontal as they approach zero velocity, but no other theoretical deduction has been made regarding their shapes. The differences between the ΔT values at the velocities of the data of Fig. 2 and at zero velocity are the required corrections, and these are written down on line 2 of Table 1. The correction seems to be small (0.001°C), or perhaps zero, for the active electrodes (right-hand side of Fig. 3) but amounting to about ± 0.005°C for the inactive electrodes (left-hand side). That the former should be smaller than the latter is in line with our knowledge that an arc between electrodes which are approaching each other will occur when they are farther apart if the electrodes are active than if they are inactive.[7]

The values of ΔT_0 after applying the corrections of line 2 of Table I are written down on line 3. On line 3 are given also (columns 2) measured values of ΔT for inactive electrodes in a circuit containing an inductance of 10×10^{-6} h which completely prevented any arcing. On line 4 are values of the energy dissipated upon the electrodes per closure calculated from the ΔT_0 values of line 3. One must still consider corrections due to radiation and convection losses from the surfaces of the wires and radiation loss from the arc itself. These are taken up one at a time in the following paragraphs.

If the only correction were due to radiation from the surfaces of the warm wires, the heat put into the end of a wire per second w would be related to ΔT_0 by the equation

$$w = k\omega\Delta T_0/L + HA\Delta T_0/3, \tag{1}$$

where k is thermal conductivity, ω , L and A are respectively the cross-sectional area, length and surface area of the wire, and $H = 4T_0^3\sigma\epsilon$, the

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[7] L. H. Germer, *Jl. App. Phys.* September 1951, Table I, line 3. (in press)

"outer conduction."[8] For $T_0 = 300°K$ and the emissivity $\epsilon = 0.05$ at room temperature,[9] the second term of this expression reduced to ergs per closure has the values listed as "radiation correction" on line 5 of Table I; these corrections are negligible.

The convection loss from a horizontal cylinder of diameter D has been given[10] as $0.27A(\Delta T)^{5/4}/D^{1/4}$ in B.T.U. per hour with ΔT in °F, D in feet and A in square feet. For our system of units this becomes $4180A(\Delta T)^{5/4}/D^{1/4}$ ergs/sec. To make the differential equation for heat flow linear this can be written approximately $4180A(\Delta T_0/2)^{1/4}\Delta T/D^{1/4}$, and the heat put into the end of the wire per second taking account of convection loss would then be given by equation (1) with $H = 4180(\Delta T_0/2D)^{1/4}$. The second term of this expression reduced to ergs per closure has the values listed as "convection correction" on line 6 of the table.

That the heat lost from the arc itself is quite negligible is clear from estimates of the duration of the arc and of its superficial area. The arc time is $\pi(LC)^{1/2}$ which has the values 0.07 and 1.0×10^{-6} sec respectively for the inactive and for the active surfaces. The average area of the arc which is effective in radiating is probably a great deal less than the area of the pit formed on one of the electrodes $\pi d^2/4$. In some experiments it was found[11] that $d^3 = 3.8 \times 10^{-11}$ cm³/erg. If this estimate of pit diameter is right for the present tests, and we take the arc temperature to be the boiling point of platinum[12] 4803°C and the duration of the arc 1×10^{-6} sec, the radiation loss comes out to be 0.01 erg. This is a gross upper limit.

REDUCTION OF THE DATA

Not all of the energy in the charged condenser is dissipated in an arc on closure. *During* the arc some energy is dissipated by current flowing through circuit resistance, including spreading resistance in the electrodes at the site of the arc, and *after* the arc is over all of the remaining energy is so dissipated. We need to sort out the amounts of energy which are spent in these different ways in order to make a careful analysis of the data represented by the numbers on lines 7 and 8 of Table I.

The total energy is $e_0 = CV_0^2/2$ where $C = 10^{-8} f$ and $V_0 = 40$ volts in all of the experiments of this paper ($e_0 = 80$ ergs). The energy dissipated in an arc is $e_a = C(V_0 - V_1)v$, where $V_1 = -5$ volts is the potential across the

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[8] H. S. Carslaw and J. C. Jaeger, "Conduction of Heat on Solids," Oxford, 1948, equation (6), p 119.

[9] This low value seems to be well established. See the paper by A. G. Worthing in a book "Temperature," Reinhold Pub. Co., 1941, Fig. 7 on p. 1175.

[10] W. H. McAdams, "Heat Transmission," McGraw-Hill, 1942, equations (13a) and (19), pp. 240–241.

[11] L. H. Germer and F. E. Haworth, *Jl. App. Phys. 20*, 1085 (1949), Fig. 5 on page 1088.

[12] Reference 2, Table II on page 914.

open electrodes when the arc is over and $v = 15$ (for platinum)[13] is the arc voltage assumed to be strictly constant during the life of each arc which is very closely true. The energy left in the circuit after an arc is over is $CV_1^2/2$. The total energy dissipated in the circuit is $C[V_0^2/2 - (V_0 - V_1)v - V_1^2/2]$ during the arc, plus $CV_1^2/2$ afterwards. When closure occurs without an arc (conditions 2) the total initial energy $CV_0^2/2$ is dissipated in the circuit. Some of the circuit energy appears in the electrode wires and is measured, as shown by the numbers of lines 7 and 8 of columns 2. It can probably be safely assumed that the fraction of the circuit energy which appears in the electrode wires is the same whether or not there is an arc. With this assumption, and knowledge of V_1 and v, we can use the data of columns 2 and 3 to calculate two parameters, η, the fraction of the circuit energy which appears in the electrode wires, and θ, the fraction of the arc energy which is dissipated upon the positive electrode for the active condition. The data of columns 1 are not to be used with those of columns 2 and 3 because of a different electrical circuit and in consequence a different (and no doubt larger) value of η.

Quantities of interest are defined here:

total energy $e_0 = CV_o^2/2$
arc energy $e_a = C(V_0 - V_1)v$
energy which is measured | arc, $e_a + \eta(e_0 - e_a)$
(true value) | no arc, ηe_0
factor by which all energy measurements are in error (i.e., experimental error) ξ
fraction of arc energy at positive electrode θ
values obtained | arc, positive electrode, w_+
by measurement | arc, negative electrode, w_-
| no arc, total energy, w_0

From the way these definitions have been given it is clear that

$$\begin{aligned} w_0 &= \xi\eta e_0 \\ w_+ + w_- &= \xi[e_a + \eta(e_0 - e_a)] \\ w_+ &= \xi[e_a\theta + (e_0 - e_a)\eta/2] \end{aligned}$$

These equations yield

$$\begin{aligned} \xi &= [(w_+ + w_-)e_0 - (e_0 - e_a)w_0]/e_0e_a \\ \eta &= w_0e_a/[(w_+ + w_-)e_0 - (e_0 - e_a)w_0] \\ \theta &= [2w_+ - (e_0 - e_a)\xi\eta]/2\xi e_a. \end{aligned}$$

The known numerical values of C, V_0, V_1 and v give, in ergs, $e_0 = 80$, $e_a = 67.5$, circuit energy dissipated during an arc $= 11.25$, circuit energy dis-

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[13] Reference 1, Table II, page 957.

sipated after an arc = 1.25. We identify w_+ and w_- with the numbers so designated in Table I. When the value of w_0 is taken from the table we implicitly assume that the electrical spreading resistance at the contact is so much larger than the rest of the resistance of the electrode wires that substantially all of the heat w_0 is generated in the spreading resistance and not along the wires. With this assumption we obtain,

$$\xi = 0.765$$
$$\eta = 0.282$$
$$\theta = 0.580.$$

The final result of the experiment is represented by the number $\theta = .58$ which means that *a metal vapor arc between activated platinum electrodes dissipates 58 per cent of its energy upon the positive electrode and 42 per cent upon the negative electrode.* This result differs only slightly from $w_+/(w_+ + w_-) = 0.577$, the difference being the correction due to resistive heat developed equally in the two electrodes. For the inactive electrodes we obtain $w_+/(w_+ + w_-) = 0.572$ which is in close agreement, and it too must differ only slightly from the value which would be obtained if data were available for making the correction due to resistive heat.

RELIABILITY OF RESULTS

The fact that the experiments account for only $\eta = 0.765$ of the total energy need not be disturbing. It seems most likely that an inaccurate value for the thermal conductivity of the platinum wires and imperfect geometry of the wires account for this. The low resistance of the thermocouple circuits does not affect the indications of temperature difference which they give.

The large corrections of line 2 in columns 1 are highly uncertain as one sees readily by inspection of the corresponding curves of Fig. 3. If these corrections were taken to be zero one would obtain $\theta = 0.556$. It certainly seems unlikely that θ for inactive platinum electrodes can be less than this value.

INTERPRETATION

There are previous observations upon closure arcs between inactive electrodes which must be correlated with the results of these measurements There are no corresponding earlier data upon active electrodes.

A single closure arc between inactive platinum electrodes produces a pit on the positive electrode having a volume which is comparable with that to be expected if all of the energy of the arc is dissipated upon that electrode and is used there in melting and vaporizing metal with all of the molten metal blown out from the arc crater by the pressure of metal vapor.[14] The metal from the crater is deposited in a rim about it and upon the negative electrode. There is considerable roughening of the negative electrode but none of its metal has been found upon the anode. This roughening indicates, no doubt, that a small fraction of the energy is dissipated directly upon the cathode. Estimates of the amount of metal transferred from positive to negative, made after many thousands of closure arcs, have shown that about 1 per cent of the metal from an anode crater reaches the cathode. Microscopic examination of the surfaces after a single arc reveals that the transferred metal upon the cathode seems to be much greater in amount than the 1 per cent found after many arcs. There is thus a distinct disagreement between the results of transfer measurements after many arcs and what one sees upon the surface of the cathode after a single arc.

Measurements of the present paper could be accounted for by assuming that most of the energy of a closure arc is dissipated upon the anode in melting and boiling metal, and that the energy is then located in this displaced metal with 58 per cent of it finally freezing on the anode and 42 per cent on the cathode. This tentative conclusion agrees with microscopic observations upon the electrodes after a single closure arc but is in sharp disagreement with the results of measurements of transfer of metal resulting from many arcs.

At the time this paper is being written it is felt that more penetrating experiments are called for, and in particular transfer measurements upon both active and inactive surfaces under experimental conditions which are better controlled than any which have been made previously.

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[14] L. H. Germer and F. E. Haworth, *Phys. Rev. 73*, 1121 (1948) and Reference 11, Figs. 5 and 6.