Explosion of a Metal by an Electric Current

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The destruction of metal wire at currents of 5×10^5 5×10^6 amp/cm^2 was investigated. Two different types of processes were observed: rupture of the melted wire into macroscopic fragments by surface tension forces, and explosion of the melted wire caused by changes in its volume properties. The abrupt change in the electrical conductivity of melting tungsten, molybdenum, platinum, or nickel was measured. A previous conclusion, that the energy of the metal at which its electric conductivity vanishes depends on the current density, is confirmed.

THE physical mechanism by which metal wires explode when heated by electric current has not yet been clarified and even the external aspect of this phenomenon is differently presented by various investigators.*

We established a relationship between the explosion of the wire and the jump increase in its total electric resistance R', observed at current densities approximately greater than 5×10^6 amp/cm.[2] We concluded[2,3] that this increase in R' is caused by a jump in the specific resistivity R of the metal, and that energy E_j delivered to the metal prior to the instant of the jump in R is a function of the current density j. The dependence of E_j on j seemed inexplicable, and led to the assumption that high values of j produce an anomalous state in the metal. In contradiction to this assumption, it is usually stated that the explosion is due to macrosopic processes in the wires, and any talk of a special state of the metal itself is unfounded.

It is the purpose of this work to investigate the destruction of wire at currents of various densities and to check the assumption concerning the anomalous state of the metal at the instant of explosion.

1. PROCEDURE

The destruction of the wire by a current i was investigated by correlating the photographs of the wire with oscillograms of $V_R(t)$ and $V_r(t)$, which make it possible to determine, for any instant of time and particularly for the exposure time t_e, the resistance of the wire $R'(t)$ and the energy $E'(t)$ delivered to the wire during the time $t - t_1$, (t_1 is the instant the current is switched on, taken to mean hereinafter the beginning of the time measurement, and $i = (\pi d^2/4) j$, where d is the diameter of the wire).

*A detailed list of references on this problem is given in Ref. 1.

The procedure used to obtain and process oscillograms of the voltage across the wire, $V_R(t) = R'(t)\, i(t)$ and across a standard resistor $V_r(t) = ri(t)$ is discussed in Refs. 2 and 3. The electric circuit of the setup is shown in Fig. 1, where the path of the current i is shown by a heavy line.

The wires were photographed in all experiments with a 15 x magnification and a constant exposure of approximately 3 microseconds. In the photography we rotated the plane of polarization of the light with a magnetic field, and illuminated the wire with spark S. The photographic setup did not differ in principle from those given in Refs. 4 and 5.

To determine t_e, the light from the spark S was aimed on a vacuum photocell, the current i_{ph} of which was recorded with one beam of a cathode–ray oscillograph. The second beam of the oscillograph recorded the voltage $V_R(t)$. These oscillograms were used to determine the time of exposure relative to the various states of the metal as represented by the discontinuities in the curve $I = R(E)$.

2. DESTRUCTION OF WIRES AT APPROXIMATELY 5×10^5 AMP/CM^2

Figure 2 shows photographs of current–carrying wires at $j \approx 5 \times 10^5$ amp/cm^2. The current rises abruptly when the circuit is closed and is reduced gradually by 20% after 1×10^{-3} sec. Adjacent to each photograph is the oscillogram of $V_R(t)$ obtained in the same experiment. The instant of exposure t_e is determined from the start of the pip on the lower line of the oscillogram and is marked with a stroke (this pip is shown exaggerated in Fig. 2 compared with the actual duration of the exposure). In Figs. 2*a* and 2*b* the t_e marker is shown in the form of a dot under the $V_R(t)$ curve.

The photographs show that the jump in the total

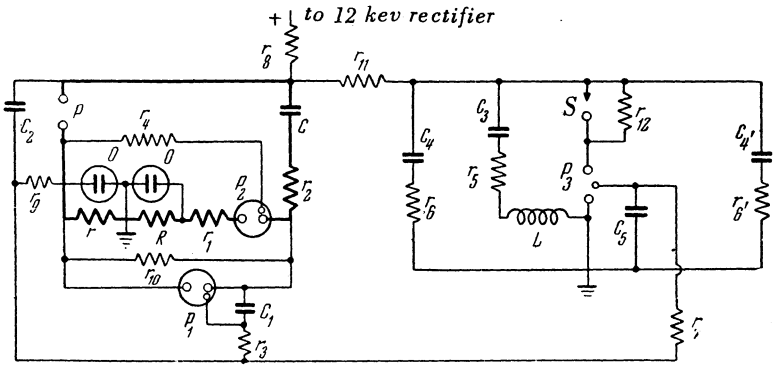

FIG. 1. Electric diagram of setup. Capacitator C— source of current i; R and r—tested wire and resistance standard; O— oscillograph; P_1, P_2, P_3 and P_4 — spark relays. Resistances r_1 and r_2 limit the current: r_3, C_1 and r_7, C_5 determine the instants the current i is shut off and the exposure is started, respectively: C_2 ($1\mu F$) ignites P_1 and P_3; C_3 ($0.25\ \mu F$) is the current source (i_3^{max} = 1000 amp) in the coil ($L = 5 \times 10^{-6}$ henry) of the Faraday shutter; $C_4 = c_4{}'$ ($0.25\ \mu F$) and C_3 are the current source for the spark S; r_8, r_9, r_{10}, r_{11}, and r_{12} insure the charging of C, C_2, C_3, C_4, and $C_4{}'$; $r_5 = 4.5$ ohm; $r_6 = r_6{}' = 7$ ohm; different values of r, r_1, r_2, r_3 and r_7 are used for each set of conditions.

wire resistance is caused by contraction and breaking. An arc flashed across the broken wire and therefore the current remains continuous (if $i \lesssim 30$ amp, the glow of this arc cannot be distinguished against the bright background, produced by the spark. The arc may evaporate part of the metal.)

Figures 2g and 2h, produced with wires of different diameter but at equal j (t) show that at equal current densities a thin wire breaks sooner than a thick one.

The nature of the variation of the breaking instant t_c with d and the length of the period of the resulting chain of droplets indicate that the breaks are caused by capillary forces.* In fact, the period of the chain produced by the capillary forces was found theoretically to be $\lambda = 4.508\ d$ (see Ref. 7, p. 591). Measurements based on Fig. 2g also yield $\lambda = 4.5d$.

Let us summarize the results of experiments in which the current i is shut off prior to the instant t_c. If the current is shut off at the instant $t_d = t_4$ at which $E(t_d) = W_h + W_m$, a wire with $d = 0.008$ cm breaks up into droplets only 3×10^{-4} — 4×10^{-4} sec after t_d (t_d is the instant at which the current is disconnected**, W_h is the energy required to heat the metal to its melting point T_m, and W_m is the melting energy). If $t_d < t_4$, the wire will of course not be completely destroyed.

The nature of the remnants of the wire depends not only on $E(t_d)$ but also on the extent to which the wire becomes deformed before its surface hardens. For example, a time interval $t_d = t_4$ is enough to break a wire with $d = 0.0077$ cm into droplets, but merely melts a wire with $d \sim 0.01$ cm. This difference is due to the longer time the capillary forces require to deform the wire surface with increasing d. If d is large enough, the capillary forces can probably no longer overcome the gravitational or electrodynamic forces.

3. DESTRUCTION OF WIRE AT APPROXIMATELY 5×10^6 AMP/CM.^{2}

Figures 3–4 show photographs of a nickel wire

*The destruction of wires by capillary forces was observed earlier. Se, forexample, Ref. 6.

**It takes about thesame time to destroy a current-carrying wire. Consequently in wires with $d \lesssim 0.008$ electrodynamic forces do not play a substantial role in the contraction.

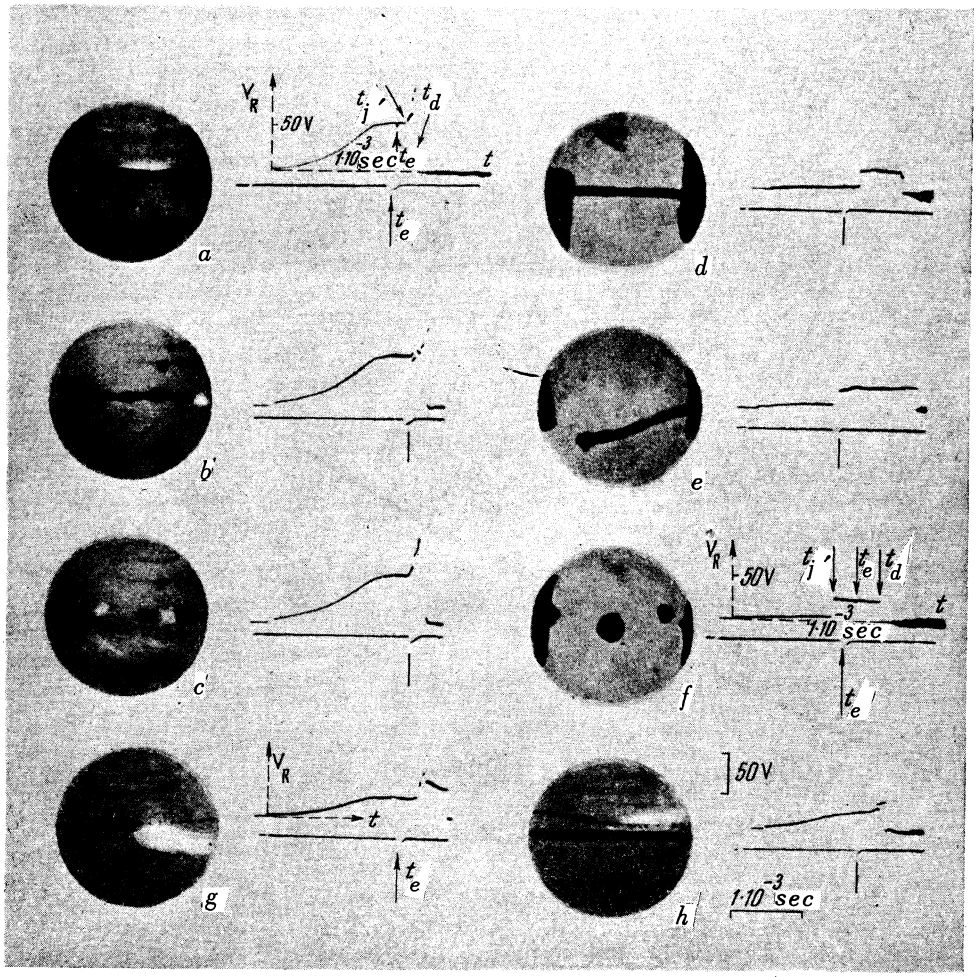

FIG. 2. Photographs (15×) and oscillograms $V_R(t)$ of wires l cm long and d cm in diameter in air at $j \approx 5 \times 10^5$ amp/cm^2; *a*, *b*, *c*— tungsten, $l \approx 1.5$; $d = 0.0077$; *d*, *e*, *f*— nickel, $l \approx 0.15$, $d = 0.008$; *g*, *h*—tungsten, $l = 0.5$, wires with $d = 0.0077$ and 0.0018 connected in parallel. In each oscillogram, the upper beam is shifted to the right by $\Delta x = 0.12$ relative to the lower beam. The scales marked on Fig. *a*, is common to Figs. *a*, *b*, and *c*; that on Fig. *f* is common to Figs. *d*, *e*, and *f*; and that on Fig. *h* is common to Figs. *g* and *h*. t_d, t_e and t_j' are the instant of current shutoff, exposure, and jump in V_r. (The bright spot of Fig. 2*g* is the drop into which the wire contracted. The tungsten drop remaining in the field of view illuminates the film through a pair of crossed polaroids).

carrying $j \approx 5 \times 10^6$ amp/cm.[2] The start of the exposure and its duration are seen from the pip on lower line of the oscillogram, the magnitude of which is proportional to the current i_{ph} (see Sec. 1).

As can be seen from the photograph, the outline of the wire does not change prior to the instant ($t = t_j$)* of the jump in V_R, except for bending. At $t = t_j$, the wire suddenly begins to expand rapidly, and the metal is exploded.

Estimating the speed of the boundary between the material of the wire and the surrounding air from Figs. 3*c* and 3*e* we get

$$V_r = [d(t_e) - d(t_c)]/2(t_e - t_c)$$
$$= 5 \cdot 10^3 - 1 \cdot 10^4 \text{ cm/sec.}$$

*At $j \gtrsim 5 \times 10^6$ amp/cm,[2] the instant at which the jump in V_R occurs is independent of the wire dimensions.

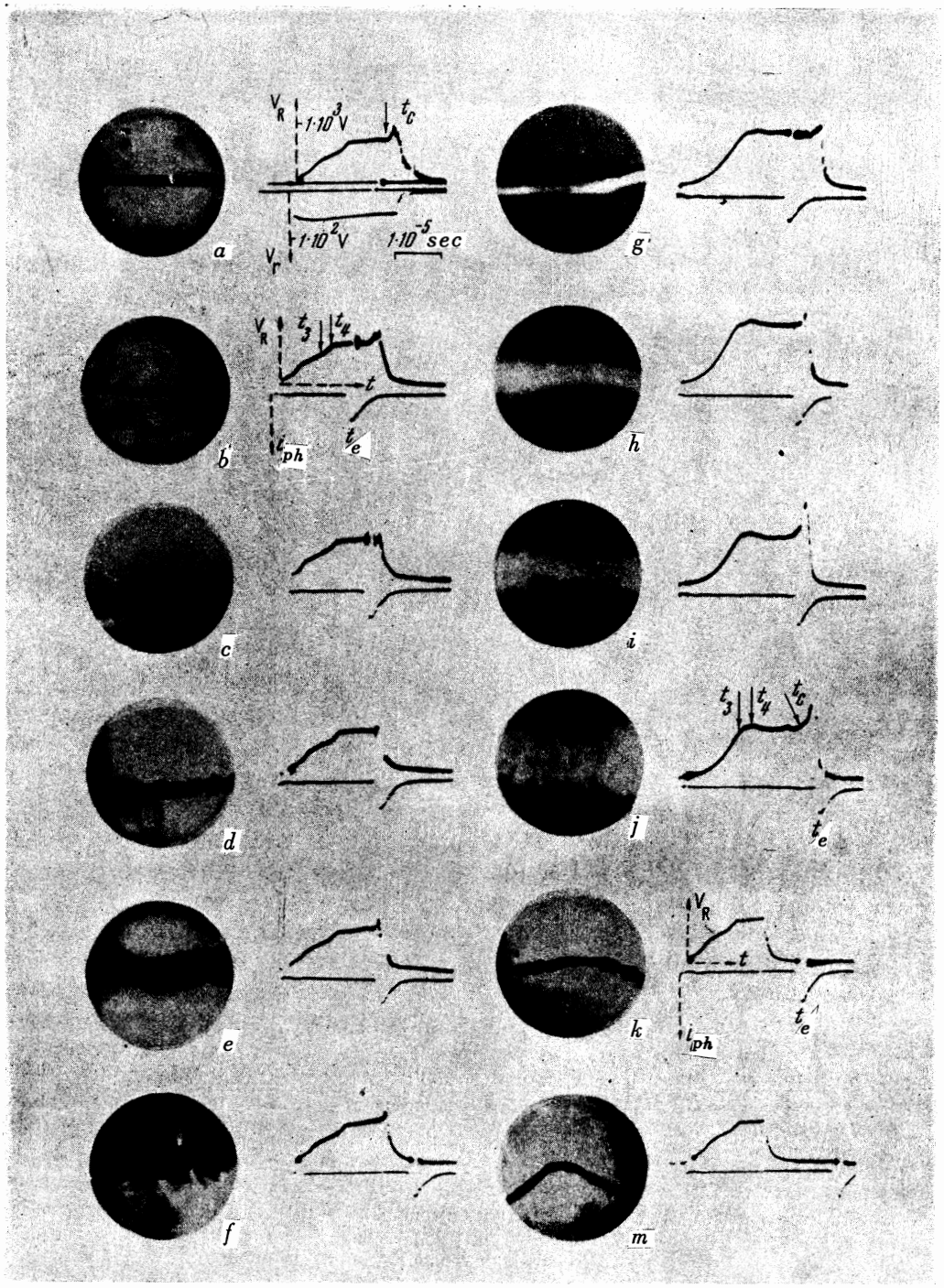

FIG. 3. Photographs (15×) and oscillograms V_R (t) of nickel wire with $d = 0.008$ cm in air ($a - f$, k, m) and of tungsten wire with $d = 0.0077$ in glycerine ($g - j$) at $j = 5 \times 10^6$ amp/cm,^{2} $l \approx 2$ cm. An oscillogram of V_r $(t) = ri$ (t) ($r = 0.45$ ohm) is shown in photograph a; a— appearance of wire before turning the current on. The dark band on photograph g is the compression wave of the glycerine. The tungsten explosion products appear bright against the background produced by the spark S; k, m — current turned off at $t < t_j$ and no explosion takes place; $\Delta x = 0.12$ cm.

Figures 3*g*–3*j* show photographs of a tungsten wire in glycerine. (In experiments with $t_d \gtrsim t_j$, the tungsten wire was placed in glycerine because a flash discharge was produced over its surface in air[3] at $E \approx W_h + 2W_m$.)

If the current is turned off at a certain instant t_s somewhat earlier than t_j, the metal will no longer explode. For example, no symptoms of an explosion are seen in the experiments with $t_j < t_s$ (Figs. 3*k*, 3*m*) even though the exposure took place later than in the experiments with $t_d \approx t_j$ (Figs. 3*e*, 3*f*). (The volume of the explosion products is always considerably greater than the initial volume of the wire after the start of the exposure.) One can judge the character of the damage to the wire from its remnants: in experiments with $t_d \geq t_j$ the metal pulverizes (glass placed near the wire becomes coated with a deposited mirror surface, but experiments with $t_d < t_s$ leave droplets measuring $\sim d$.

The fact that t_s and t_j are not exactly equal is apparently due to the inhomogeneity in the wire and to an insufficiently abrupt current shutoff.

Further reduction in t_d within the range $t_4 \leq t_d < t_s$ leaves the character of the wire destruction unchanged. Figure 4 shows photographs obtained at various time intervals after t_d in experiments with $t_4 < t_s$. These photographs show that if $t_d < t_s$, the wire is destroyed already after t_d, because it breaks by bending* and because drops are formed. The bending is apparently due to uneven distribution of pressure along the axis of the wire** caused by the rapid increase in its energy.

4. REMARKS ON THE INTERPRETATION OF PREVIOUS EXPERIMENTS WITH TUNGSTEN IN THE CASE OF SHORT PULSES, AND ON THE MELTING OF THE METAL.

From the appearance of the wire after the experiments, it was concluded in Ref. 9 that the state of the tungsten at the instant $t = t^*$, when the value of dR/dE drops*, is different for $j = 5 \times 10^6$ than for $j = 5 \times 10^6$ amp/cm^2, and that $e(t^*)$ increases and diminishes with j. However, measurements made on the oscil-

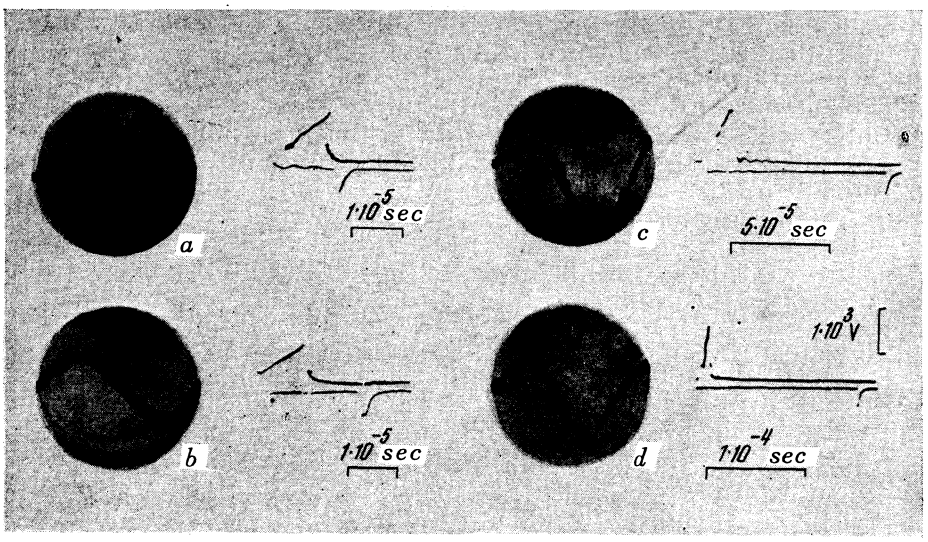

FIG. 4. Various stages of destruction of nickel wires with $d = 0.008$ cm and $l \approx 2.5$ cm in air at $t_e < t_d < t_s$; $j = 5 \times 10^6$ amp/cm^2; $\Delta x = 0.12$ cm; magnification 15×.

***The experiments in Ref. 9 were not accuaate enough to be able to distinguish the points t_3 and t_4 where the curve of $V_r(t)$ for tungsten breaks, or to determine the posttion of t_d with respect to these two points.

*Similar motion of the wire was investigated in Ref. 8.

**At $j \approx 5 \times 10^6$ amp/cm,^{2} the time required to expand the metal by heating is $\Delta t = t_3 - t_1 \approx 8 \times 10^{-6}$ sec. and the time needed to melt the metal is $\Delta t = t_4 - t_3 \approx 2 \times 10^{-6}$ sec. Therefore $u\Delta t > l$, where $u \approx 2 \times 10^5$ cm/sec is the speed of propagation of the disturbance of the metal and l is the length of the wire. At $j = 5 \times 10^5$ amp/cm,^{2} Δt is two orders of magnitude greater, add $u\,\Delta t >> l$. Consequently, the pressure along the wire will be uneven in the first case and uniform in the second case.

lograms showed no dependence of E (t^*) on j.[2,9] As was explained in Sections 2 and 3, the metal has a different microscopic motion** at $j = 5 \times 10^5$ amp/cm^2 than at $j = 5 \times 10^6$ amp/cm^2, and this determines the difference in the type of wire remnants at equal values of E (t_d). There is consequently no indication that E (t^*) depends on j.

In Reference 2 we were ableto locate*** the break points t_3 and t_4 on the curve $I = R(E)$ for tungsten (Fig. 3*k*) and to show that $E_3 = W_h$, $E_4 = W_h + W_m$, and $R_3 = R_m^s$ for all $j(t)$. The appearance of these points is naturally interpreted as the start and finish of the usual melting and we

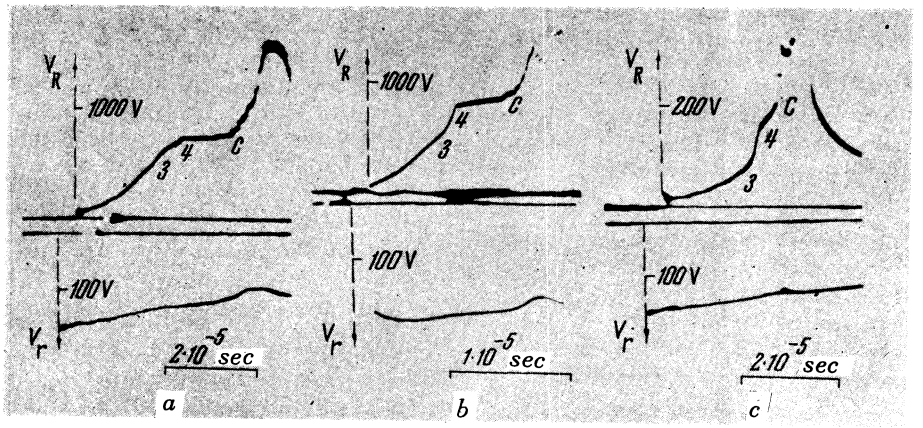

FIG. 5. Oscillograms of V_R (t) and V_r (t), $\Delta x = 0.2$ cm, *a* – Mo in glycerine, $d = 0.01$ cm, $l = 2.05$ cm, $r = 0.5$ ohm, $j^{max} = 4.6 \times 10^6$ amp/cm.^{2} *b* – Pt in glycerine, $d = 0.002$ cm, $l = 1.55$ cm, $r = 12.3$ ohm, $j^{max} = 6.2 \times 10^6$ amp/cm.^{2} *c* – Cu in air, $d = 0.008$ cm, $l =$ 1.23 cm, $r = 0.5$ ohm, $j^{max} = 7 \times 10^6$ amp/cm.^{2}

use here the following symbols: $E(t_{3,4}) = E_{3,4}$ $R(t_{3,4}) = R_{3,4}$. R_m^s and R_m^l are the values of the resistance in the solid and liquid states at T_m). However, in Ref. 9 no melting was observed in a tungsten wire in experiments with $j = 5 \times 10^5$ amp/cm^2 at $E(t_d) > W_b$. This and the values of R_3 and R_4 would apparently indicate an anomaly in the melting (R_4 of tungsten differs from R_3 much less than R_m^l differs from R_m^s of any metals, for which the values are known).

As explained now, the wires were not observed to melt at $j = 5 \times 10^5$ amp/cm^2 in Ref. 9 because the immobile molten tungsten hardened before its surface had a chance to become sufficiently deformed.

There is therefore no reason for assuming the melting of metal at large values of j to be unusual. Since the melting proceeds normally, and no contraction occurs in the wire prior to t_4, the quantities W_h, W_m, R_m^s and R_m^l can be measured from the oscillograms. Using the data of Ref. 2 for R_4/R_3, we obtained R_m^s and R_m^l for tungsten, nickel and gold. In this investigation we performed experiments

**The kinetic energy of this motion, estimated from Figure 4*b*, is less than 1% of W_h.

***For metals with large ratios R_m^l/R_m^s, the points t_3 and t_4 were already compared with the melting point in Ref. 10. However, in Ref. 10, an increase in E_3 was observed with increasing j. In Ref. 11, these points were used to measure R_m^l/R_m^s for Au and Pt at $j = 1 \times 10^6$ amp/cm.^{2} But in Ref. 11, " a shift in the breaking points towards lower energy was observed for platinum" for $j = 4 \times 10^6$ amp/cm.^{2} These data indicate the peculiar melting behavior at large values of j.

with molybdenum, platinum* and copper (Fig. 5), and repeated the measurements for tungsten and nickel. We consider experiments with copper to be the control measurements, since the quantity R_4/R_3 for copper agrees with the tabular values for R_m^1/R_m^s. The values $R_4/R_3 = R_m^1/R_m^s$ for other metals are given in the Table.

5. VERIFICATION OF CONCLUSION CONCERNING THE ANOMALOUS STATE OF THE METAL

It was confirmed in Sec. 3 that what occurs at $j \gtrsim 5 \times 10^6$ amp/cm^2 at the instant t_j is a change in the volume properties of the metal and not a rupture of the wire into parts. Consequently, our measurements of R' and E' actually make it possible to find the specific resistivity R and the internal energy E of the metal.

The dependence of E_j on j was investigated in this work over a wider range of j than in Reference 2. Here the current varied little prior to the instant t_j at $j \lesssim 5 \times 10^6$ amp/cm^2 (Figs. 3*a* and 5). But at j greater than 1×10^7 amp/cm,^{2} the time $t_4 - t_1$ became shorter and approached the duration of the current buildup that occurred after the current was turned on. The current can therefore be assumed constant only at $t_4 < t < t_j$, and the measured values of $E(t)$ and $E(t_j) - E(t_4)$ are best examined separately. For $j_{max} = 1.8 \times 10^7$ amp/cm^2 we observed, within the limits of the measurement accuracy (10%), that $E(t_4)$ equals $W_h + W_m$, and that $E(t_3)$ equals W_h. The measured values $E(t_j) - E(t_4)$ are shown in Figure 6. The maximum difference between values of $E(t_j) - E(t_4)$ for any one value of $j \gtrsim 5 \times 10^6$ amp/cm^2 does not exceed 8%. This difference increases as j drops below 5×10^6 amp/cm,^{2} owing to the increase in the dispersion of t_j (of the time $t_j - t_1$). The maximum and minimum values of $E_j - E_4$ obtained for a wire with $d = 0.008$ cm* at $j \approx 1.3 \times 10^6$ amp/cm^2 are plotted in Figure 6. The increased dispersion of t_j with diminishing j is explained by the rise in t_j to a value close to t_j, in other words, by the fact that the wire and time to become deformed by capillary forces during the time of the experiment. It is therefore impossible to estimate E_j from the jump in V_R at $j < 1 \times 10^6$ amp/cm^2 for $d \lesssim 0.008$ cm.

Thus, for $1.3 \times 10^6 < j < 18 \times 10^6$ amp/cm,^{2} according to Figure 6, the value of the internal energy of the metal E_j, at which the jump in dR/dE occurs, is a function of j.

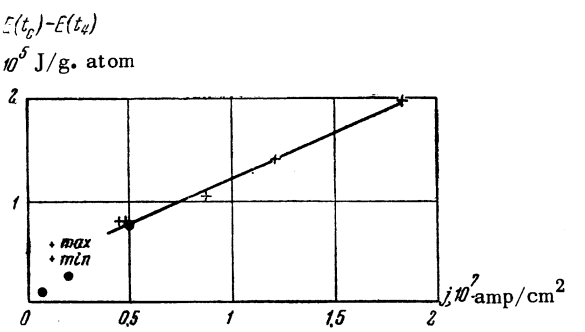

FIG. 6. Dependence of energy $E_j - E_4$ on j for nickel. Abscissas indicate the values of j at $t = t_4$; + – results of experiments with $d = 0.008$ cm and $l = 0.5 - 2$ cm; ● – results of earlier experiments [2] with defective wire 0.0015 cm in diameter.

*For Pt we obtained $R_1 = 10.2 \times 10^{-6}$ ohm. cm; $R_4 = R_m^1 = (75.6 \pm 2) \times 10^{-6}$ ohm. cm, $E_3 = W_h = (58.5 \pm 2) \times 10^3$ J/g-atom, $E_4 - E_3 = (23.2 \pm 3) \times 10^3$ J/g-atom and for $j = 6 \times 10^6$ amp/cm we obtained $E_j - E_4 = (130 \pm 3) \times 10^3$ J/g-atom. For tabular data we have for Pt at 18° C $R = 10.5 \times 10^{-6}$ ohm. cm and at 1500 °C, $R = 52.6 \times 10^{-6}$ ohm. cm[12], $W_h = 53.4 \times 10^3$ J/g-atom[13] and $= W_h = 61.5 \times 10^3$ J/g-atom[12], $W_m = 22 \times 10^3$ J/g-atom[12,13], and $T_m = 1773°$ C.[12] For Mo we obtained $R_4 = R_m = (96 \pm 2) \times 10^{-6}$ ohm. cm, $E_4 = W_h + W_m = (115 \pm 8) \times 10^3$ and $E_4 - E_3 = W_m = (40 \pm 4) \times 10^3$ J/g-atom. According to Ref. 14, we have for Mo at 2000° C, $R = 60 \times 10^{-6}$ ohm. cm, $W_m \sim 20 \times 10^3$ J/g-atom and $T_m = 2622°$ C.

*A sharp reduction in $E_j - E_4$ (black dots on Fig. 6) was observed for small j in experiments with a wire having ing $d = 0.015$ cm and containing defects; this increase is explained as follows: at large values of j, premature destruction of the wire at the defective points is concealed by the arc that is produced and produces only small dents in the oscillograms of $V_r(t)$. At small values of j, $V_r = ir$ is small and the individual wire defects cause greater jumps in V_r at $t < t_j$, i.e., at $E < E_j$.

An attempt was made to attribute the dependence of E_j on j to changes in the external conditions, by suggesting, for example, that t_j is the instant at which the metal begins to boil, and that the increase in E_j with increasing j is due to an increase in the electrodynamic pressure. But were this so, the metal in experiments 3*k* and 3*m* should boil off as soon as this pressure was removed at the instant t_d, for the value of $E(t_d)$ in these experiments exceeds the value of E_j, measured when the wire was exploded by a current with $j \approx 1.3 \times 10^6$ amp/cm^2. In fact, according to Figures 3*k* and 3*m*, the metal does not explode at $t_d < t_s$. The fallacy of the above assumption is seen also from the fact that there is no electrodynamic pressure on the surface of the wire. The surface layer would therefore boil at the same value of E at all values of j.

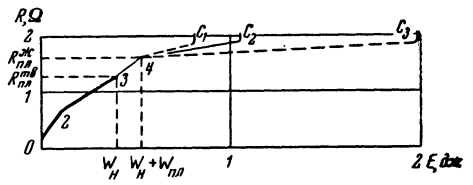

FIG. 7. Plot of $R = R(E)$ for nickel. The data were obtained for wires with $d = 0.015$ cm ($j \leq 5 \times 10^6$ amp/cm^2 and $d = 0.008$ cm (all values of j) of varying lengths and were recalculated for $d = 0.008$ cm and $l = 1$ cm. The dependence of R on E is regular up to a point 4 (heavy line). Sections $4-c_1$, $4-c_2$, and $4-c_3$ correspond to $j = 1.4 \times 10^6$, 5×10^6, and 18×10^6 respectively.

6. COMPARISON OF OUR IDEAS CONCERNING THE EXPLOSION OF METAL WITH DEDUCTIONS MADE BY OTHER INVESTIGATORS

Explosion of wires was studied by many experimenters whose interpretation of this phenomenon differs substantially from ours. For example, according to Ref. 5, the "wire breaks down into individual sections" as a result of its inhomogeneity. "The occurrence of these breaks leads to an interruption of the current and to occurrence of pauses in the current. . . During the time of the current pause, the wire particles evaporate because of the heat received during the time of current flow". Our data show, however, that at $j \gtrsim 5 \times 10^6$ amp/cm^2 a well-calibrated wire breaks up into parts because of the velocity attained by the metal during its thermal expansion, and not because of any inhomogeneities. These pieces fly apart and cool in the form of macroscopic droplets, and do not evaporate. Rather than cause the current interruption, the breaks occur after the current is shut off. Were the current not shut off prior to the instant t_j the wire would tear before the breaks would occur. Breaks are therefore observed only at $t_d < t_j$, when no explosion occurs at all.

Reference 1 gives an interpretation of the first stage of the explosion, similar to that given in Ref. 5, but the causes of the inhomogeneities* of the wire are assumed to be wire deformations caused by capillary forces. In old,[10] as well as new (Ref. 18, p. 191) investigations, the explosion is considered to be a rapid evaporation of the metal. We, to the contrary, assume the explosion to be not evaporation, but expansion of the metal over its entire volume**. An explosion differs from ordinary evaporation in that there exists an instant t_j, at which the expansion of the metal changes abruptly, and dR/dE experiences a jump. (If an attempt is made to ascribe the expansion of the image of the wire in Fig. 3 to evaporation of the metal, one must assume that the velocity of evaporation experiences a jump of one order of magnitude at $t = t_j$) That the explosion cannot be identified with rapid surface evaporation can also be seen from the fact that E_j may be less than the binding energy of the metal, as seen, for example, in experiments with nickel at $j \approx 5 \times 10^6$ amp/cm,^{2} in which the total energy delivered $E(t_d) \approx E_j = 0.43\, W_{subl}$, could not rate even half the mass of the wire (W_{subl} is the sublimation energy). Yet various photographs similar to 3*d* and 3*e*, obtained in similar experiments, show no remnants of the wire.

The mechanism of the metal explosion is still unexplained. Apparently, the increase in the thermal expansion at large values of E starts disturbing the metallic bond destroys the metallic conductivity. The energy E_j at which this occurs may

**No vapor is seen near the wire at $E(t_d) < E_j$ in Figs. 3*k* and 3*m*, but Fig. 3*e* shows for $E(t_d) = E_j$ a dense cloud with a sharp boundary, the character of which is important to the explanation of the "current pause" phenomenon[10,5,3]. Were the boundary indistinct, the cloud would be electrically weak and would immediately break down at a distance from the wire at which the density makes breakdown possible. Actually, however, if the conditions are right (Ref. 3, page 632), the cloud breakdown is noticeably later than the instant t_j, when the density in the cloud is reduced sufficiently by expansion.

be less than the binding energy of the metal. In fact, metallic conductivity disappears when the metal decomposes in particles that are smaller than the mean free path of the electron. This assumed phenomenon could also be produced by heating the metal at low current. But in our experiments heating by low current stops at a low value of E because the wire breaks by capillary forces.

Metal	$R_m^l/R_m^s = R_4/R_3$ Our data	R_m^l/R_m^s Literature data
Au	1.94±0.05*	2.28[15], 4, 335; 2**[11]
Pt	1.40±0.02	1.4[11]
Ni	1.30±0.02	1.94[16], p. 295; [15], 1, 129; 4, 335 1.3[17]
Mo	1.23±0.01	—
W	1.08±0.01	—

*See Ref. 2, p. 107, concerning the purity of the Au.

**The authors of Ref. 11 attribute the deviation of this result from 2.28 to the measurement error.

The increase of E_j with j could be caused by a change in the state of the electrons and of the metal under the influence of a strong electrical field, thus causing a change in the metallic bond. According to Fig. 7, dR'/dE' decreases with increasing j for $E' > E'_4$, apparently indicating a reduction in dR/dE. The drop in dR/dE could be interpreted as a symptom of the appearance of the "excess energy" $\mathcal{E}$ (Ref. 9, Sec. 4).

CONCLUSIONS

1. *Destruction of the Wire.* At currents $j \approx 5 \times 10^5$ amp/cm,^{2} surface tension causes the wires ($d \leq 0.01$ cm) break up into droplets after melting. At greater values of j, dE/dT ($\sim j^2$) becomes greater, and the surface tension σ does not change for a given value of E. The energy E therefore may rise enough to destroy the metal even prior to the instant (t_c) at which the breaks occur. For example, for nickel at $j \approx 5 \times 10^6$ amp/cm^2 and at $d = 0.008$ cm, the value of E (p_c,) would reach $30\,W_h \approx 4.6\,W_{subl}$, were R and σ to remain close to R_m^l and σ_m^l. But actually, at $j \approx 5 \times 10^6$ amp/cm,^{2} the wire becomes destroyed at an instant $t_j < t_j$, when $E(t_j) = 2.7\,W_h$. The destruction of the wire at the instant t_j has the nature of an explosion: there is no substantial change in d prior to t; but at $t = t_j$ the metal starts expanding rapidly, and within several microseconds it already has the shape of a cloud (even if $t_d = t_j$).

No explosion will occur if the current is shut off prior to t_j ($t_4 \leq t_d < t_s^*$) without changing the value of j. The destruction of the wire differs in this case from that occurring at low values of j only in the macroscopic motion: at $j \gtrsim 5 \times 10^6$ amp/cm,^{2} various portions of the wire acquire different velocities, causing the wire to bend and later on to break up into droplets. These velocities are apparently due to the expansion of the metal by the rapid increase in E even before the end of the melting. At $j < 5 \times 10^5$ amp-cm,^{2} dE/dt is small, the wire is not seen to bend but only to be torn by capillary forces.

Thus, the destruction of the melting wire may be of two types: *a*) a break up into macroscopic parts by external forces (if the energy has not reached the value E_j prior to the instant t_j, of this break); *b*) an explosion* due to the change in the state of the metal itself and to its pulverization (if E reaches the value E_j). The value of E_j increases with j, and at $j \leq 18 \times 10^6$ amp/cm^2 E_j is less than the sublimation energy for nickel.

2. *Dependence of R on E.* Figure 7 shows the curve $R = R(E)$ for nickel, taken from Reference 2 and supplemented by new data.

Region 1–3. As explained in Reference 2, no singularities are observed in the dependence of R on E at $j \leq 5 \times 10^6$ amp/cm^2 prior to the start of

*Usually attention is paid in the study of wire explosions not so much to the explosion of the wire itself, as to the explosive phenomena produced in its destruction products by the continuing flow of current. For example, in Refs. 4 and 5 the speed of expansion of the explosion products in the air ($V_g = 1 \times 10^5 - 2 \times 10^5$ cm/sec) was apparently measured at $i \neq 0$. In our measurements, however, we obtained $V_g = 5 \times 10^3$ to 1×10^4 cm/sec after shutting the current off.

the melting point 3).** This conclusion was confirmed in our investigation up to $j = 18 \times 10^6$ amp/cm.[2]

Region 3–4. The quantities R_3, E_3, R_4, and E_4 agree, within the limits of experimental accuracy, with R_m^s, W_h, R_m^l and $(W_h + W_m)$ respectively for all $j \leq 18 \times 10^6$ amp/cm.[2]

Region 4 – j. It was confirmed that the form of the curve $R = R(E)$ depends on j for $E > E_4$: the value $E = E_j$, at which the jump in dR/dE occurs (points C_1, C_2, C_3 on Fig. 7) increases with increasing j. For example, a metal state with energy $E > E_{j2}$ is observed only at $j > 5 \times 10^6$ amp/cm.[2] The state of the metal before the start of the explosion is different in experiments with $j = 5 \times 10^6$ amp/cm^2 (point C_2) from the state of metal with the same value of energy E_{j2} produced in experiments with $j = 1.8 \times 10^7$ amp/cm,[2] since the explosion takes place at the latter density not at E_{j3}, but at E_{j2}. This difference in states is seen also from the difference in the slopes of the curves $R = R(E)$ past point 4 in Fig. 7. However, the data on the dependence of dR/dE on j prior to the start of the explosion still require verification.

The conclusion that the metal has an anomalous state at $E > E_{jl}$ is based on the following premises: the explosion of the wire is determined by the state of the metal; if the external conditions do not change, the value of the energy E_j at the instant of explosion depends on j. Both these premises were confirmed in this investigation.

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Note added in proof. The latest work known to us[19] ascribes the explosion to inhomogeneous heating and melting of the wire.

**This result was confirmed in Ref. 18 for strongly-varying currents, reaching values $j^{max} = 6 \times 10^7$ amp/cm^2 in Ag and Cu. The $R'(E')$ curves of Ref. 18, differ from ours. Thus, our data show dR'/dE' for Pt to drop sharply at the instant melting is ended (point 4 of Fig. 5b), but according to Ref. 18 (Fig. 5, point B, corresponding to the end of the melting), dR'/dE' remains large. If the correct instant, indicated in Fig. 5, is taken for the end of the melting in Ref. 18, the resultant value of W_m is too high by approximately a factor of 2. The $R'(E')$ curves of Fig. 6 of Ref. 18 do not show at all the breaking points 3 and 4 for tungsten at $j = 1.5 \times 10^7$ amp/cm.[2]

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49