Metals during rapid heating by dense currents

S. V. Lebedev and A. I. Savvatimskiĭ

Institute of High Temperatures, Academy of Sciences of the USSR

Research on metals, particularly refractory metals, during pulsed heating by high density currents (up to $\sim 10^7$ A/cm^2) is reported. In particular, studies have been made of the specific heat and thermal expansion of metals in the liquid state, the resistivity in the liquid state as a function of the amount of energy supplied during free and confined expansion generating pressures up to $4 \cdot 10^4$ atm, the visible emission, the heat of fusion, the changes in certain properties upon melting, the dispersal of a metal during an electrical explosion, and the anomalies of the specific heat and electron emission of a metal in the solid state which stem from the high rate of Joule heating. The experimental data reported on liquid metals (Al, Cu, Mo, W) at high temperatures and high pressures (tens of kilobars) are of considerable interest for the theory of liquid metals.

TABLE OF CONTENTS

1. INTRODUCTION

Pulsed heating of metals by electric currents offers several new experimental possibilities. Data which have been obtained during rapid heating (up to $\sim 10^9$ K/s) by dense currents ($j \sim 10^6$–10^7 A/cm^2) reflect a variety of physical phenomena in metals (primarily refractory metals) in the solid state near the melting point, throughout the liquid state, and upon the disappearance of metallic conductivity. In particular, studies have been made of the specific heat and thermal expansion of a metal in the liquid state, the electrical resistance in the liquid state as a function of the energy supplied during free expansion and during expansion under pressure, the visible emission, the heat of fusion, the changes in certain properties upon melting, the dispersal of a metal during an electrical explosion, and the anomalies of the heat capacity and the electron emission of a metal in the solid state which stem from the high rate of Joule heating. In addition to studies of phenomena in the metals themselves there have been studies of the new features which are seen in the anode current in a vacuum diode at the peak of the anomalously high emission of a tungsten emitter.

The experiments which have been carried out during rapid pulsed heating supply some substantially new information about metals in two directions: First, it is possible to obtain the characteristics of states with high levels of injected energy, not accessible under steady-state conditions. Second, in all stages of an experiment it is possible to bring out those properties of a metal which are manifested only during rapid processes and cannot be observed directly under steady-state conditions.

The research on metals during rapid pulsed heating began with experiments on the explosion of conductors by electric currents of high density j. Chace[1] reports that an electrical explosion was first described in 1773. In 1920–1926, electrical explosions were used to achieve high temperatures for spectroscopic experiments.[2,3] Research on electrical explosions began to develop rapidly in the 1950s in connection with the major effort which was being undertaken in plasma research, with the result that by the end of the 1960s four international conferences had been held on this topic.[4–6]

Another explanation for the long list of studies on electrical explosions is that many of the effects involved here are of independent interest for producing intense light pulses, shock waves, and extremely fine powders; for depositing coatings; for stamping; for detonating explosives; for switching electric circuits. Many studies have been dedicated to determining the mechanism for the destruction of a conductor by an intense current. For the most part, the processes studied have been fast processes (in which the conductor is destroyed in a fraction of a microsecond, at current densities $j > 1 \cdot 10^7$ A/cm^2), since the investigators have usually attempted to pump as much specific energy as possible into the metal. If the process is too rapid, however, the state of the conductor becomes nonuniform over its cross section, mak-

ing it more difficult to obtain information about the state of the metal itself. For these reasons we will not be discussing experiments on the bulk properties of metals unless a uniform heating was arranged (Section 2), and we will not take up the mechanism of melting.

One of the factors primarily responsible for the long delay in the use of electrical explosions to study the properties of metals appears to have been the widespread belief that the explosion consists of a rapid development of macroscopic inhomogeneities in the conductor.[7-9] In Refs. 10 and 11 it was found that another effect occurs: At a high value of the specific energy injected into a metal, $w > w^*$, the metal loses its conductivity and explodes, i.e., expands rapidly. After the experiment, the metal is found not in macroscopic drops but in particles with dimensions of the order of a few hundred interatomic distances.[12,13] The energy w^* and the corresponding heating time t^* refer to a transition from a slight change in the conductivity of the liquid metal to a rapid decrease in the conductivity. Experiments have shown that before this transition begins (at $t < t^*$) all macroscopic inhomogeneities can be essentially eliminated by appropriately choosing the current density j and the cross–sectional area of the conductor. Under these conditions the time t^*, i.e., the time interval over which a metal is heated before its conductivity drops sharply, is considerably shorter than the time required for the development of macroscopic inhomogeneities. In the later stages of an experiment ($t > t^*$), however, this approach is not successful in keeping the expanding explosion products homogeneous, so that it is difficult to obtain information about the state of these products. Accordingly, studies of the properties of metals should be carried out[14] in the initial stage of electrical-explosion experiments, under conditions such that the state of the conductor is homogeneous, at $t < t^*$. We might note that with respect to homogeneity the volume heating of a condensed metal by a current is preferable to heating from a surface by, for example, a laser beam.

At current densities $j \gtrsim 5 \cdot 10^6$ A/cm^2, wires of refractory metals can be heated well above their melting point, up to the point at which the metallic conductivity disappears, by rapid Joule heating, $dw/dt \sim j^2$, so that the process is of short duration $t \lesssim 10^{-5}$ s. For times in this range several difficulties afflicting steady-state experiments on the bulk properties of metals drop out of the picture. In particular, evaporation from the surface of the conductor, all types of heat loss, and the contamination of the metal by an interaction with the surrounding medium can all be ignored. Furthermore, the experiment is too brief for a change in the shape of the molten conductor, so that crucibles can be avoided; this is an extremely important advantage, since liquid metals interact actively with the walls of a crucible at high temperatures.

Extremely few results have been obtained on liquid refractory metals in the steady state because of the serious experimental difficulties. The pulsed method allows considerable progress in this direction. In particular, experiments with rapid heating yielded the first experimental data on the heats of fusion and the jumps in the resistance upon melting for tungsten and molybdenum.[11,15] Subsequent research has yielded similar information on several other refractory metals.[16-18]

Experimental data on the properties of refractory metals during melting and in a liquid state are required for solving several physical and technological problems. Information of this type is also of considerable interest for deriving a theory of liquid metals. Particularly noteworthy is the disappearance of metallic conductivity when high energies are injected into a metal.[10,11] The results of experiments in this direction, carried out with rapid pulsed heating ($t^* \sim 10^{-5}$ s) by a current, can be explained[11,19-21] at a qualitative level by assuming that the conductivity disappears because the liquid metal is broken up by the fluctuating surfaces of microscopic discontinuities into regions whose dimensions decrease as the heating proceeds and become comparable to the mean free path of an electron in the condensed metal. The physical properties of the extremely fine metal particles which appear in these experiments (and which are also prepared by other methods) are at present the subject of active research.[22,23]

Among the phenomena characteristic of fast processes are the anomalies of the electron emission and the heat capacity which were discovered in Refs. 24 and 25, respectively. In each case the anomalies arise while the metal is still in its solid state but near the melting point, and the conditions for the heating of the metal by a dense current are the same in the two cases. The anomalies in the electron emission and the heat capacity apparently have a common physical nature. For a discussion of the reasons for the anomalies,[24,25] we cite the results of Refs. 26 and 27 on metals at high current densities in the steady state (achieved by rapidly cooling thin metal tapes with water). It was found in Ref. 27 that there are no anomalies in the state of gold, at any rate in its electrical conductivity, at current densities up to $j \sim 5 \cdot 10^6$ A/cm^2. This conclusion agrees with the theory of Refs. 28 and 29.

Pulsed experiments at high values of j differ substantially from the experiments of Refs. 26 and 27 in that the state of the metal may be largely determined not only by high values of the electric field or current density but also by a high heating rate. At current densities $j \lesssim 10^7$ A/cm^2, however, the heating time is still very long in comparison with the electron relaxation time and in comparison with the vibration period of the atoms of the crystal lattice. It might thus appear that there is no basis for expecting any significant new features in the state of the metal. This conclusion, however, is based on an ideal crystal lattice and ignores the thermal defects in a lattice, whose concentration increases dramatically as the melting point is approached. We know that diffusion of defects plays an important role in the establishment of an equilibrium defect concentration, and the diffusion rate in a metal is comparatively low. During rapid heating, the defect concentration may thus deviate from its equilibrium value. In pulsed experiments at high values of j we can thus expect changes in those characteristics of a metal for which lattice defects are important. These considerations serve as the basis for a hypothesis (Section 5) which holds that these anomalous features in the emission and heat capacity stem from a nonequilibrium defect concentration. Measurements of the emission may provide a new tool for

studying nonequilibrium defects of a crystal lattice.

The interest in nonequilibrium states is not restricted to purely physical questions. The development of high-power pulsed facilities requires an understanding of not only the equilibrium properties of a material at high temperatures but also the properties of the material during a rapid change in state. One topic involved here, for example, is the general question of the destruction of a metal by an intense energy flux. Very important in practice are the phenomena which occur in small volumes of a conductor, in particular, the electrical erosion of electrodes upon the contraction of discharges between them. The main causes of the erosion in such discharges appear to be a local Joule heating and the electical explosion of small parts of the surface layer of the electrodes.[30] Accordng to Ref. 30, the disappearance of the conductivity of a metal during an electrical explosion is the reason for the abrupt displacements of the current spot over the electrode. The disappearance of conductivity during the explosion of a metal is exploited in a variety of schemes for switching electric circuits.[31,32]

We could also cite the phenomenon which has come to be called the "explosive emission of electrons."[33-35] The special features of heating and destruction of conductors by dense currents undoubtedly play an important role in this phenomenon. Experiments carried out to produce ultrastrong pulsed magnetic fields in miniature solenoids have revealed the clearly defined features of the destruction of conductors.[36] Some of these features are similar to the "energy anomalies"[7,37] which had been observed previously to result from radial nonuniformities of the pressure (Section 4) in conductors at very high current densities. The rapid-heating method also has some extensive possibilities for studying the dependence of the high-temperature properties of a metal on its "past history." For example, it has been established reliably that wires which have and have not been annealed have different heats of fusion.

There is another pulsed method for high-temperature research which is being developed successfully.[38] This method differs substantially from that discussed above in that the pulse lengths are far greater (the time required for heating to melting is $\sim 10^{-1}$ s instead of $\sim 10^{-4}$–10^{-6} s). Slow heating has certain advantages in studies of the equilibrium properties of metals in the solid state. In the case of liquid metals, however, experiments with pulse lengths $\sim 10^{-1}$ s must still deal with the basic difficulties which are characteristic of steady-state high-temperature experiments. Long pulses are accordingly ineffective for studying liquid metals. Slow heating is also ineffective for studying the anomalies of the heat capacity[25] and the emission,[24] whose relaxation times are of the order of 10^{-4} s.

2. METHODOLOGICAL QUESTIONS

A common thread running through all the experiments discussed below is that the metal is heated by a single pulse of a very dense current. Otherwise, the experimental procedures differ substantially from one problem to the next: electrical conductivity, heat capacity, thermal expansion, visible emission, and electron emission. The arrangment shown in
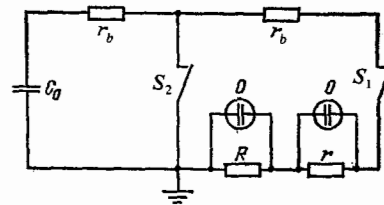

FIG. 1. Circuit for producing intense current pulses $i(t)$.

Fig. 1 is convenient for producing roughly square pulses of a high current $i(t)$. A capacitor C_0 is charged to a high voltage and used along with ballast resistances r_b and switches $S_{1,2}$. The current is delivered to the conductor under study of resistance R, and to a standard resistance r by switch S_1, and at the appropriate time t_0 this current is abruptly cut off by switch S_2. In a number of cases it is preferable to use $i(t)$ pulses of a different shape, e.g., sine half-waves. The current $i(t)$, the resistance $R(t)$, and the Joule heat evolution $dW = i^2R\,dt$ are measured by oscilloscopes O, which measure the voltage drops U_R and U_r across conductors R and r.

Circular wires and strips of foil are convenient for achieving uniform Joule heating. Uniformity is important because it allows the data obtained for the entire wire to be easily expressed in terms of a unit mass of the wire. Experiments show that at current densities $j \approx 1 \cdot 10^7$ A/cm^2 and for wires $2a \leqslant 0.1$ mm in diameter essentially no nonuniformity appears before the time t^*, the beginning of the rapid increase in the resistance R. According to Refs. 10, 11, and 39, this increase is due primarily to the pronounced decrease in the conductivity of the metal at the specific input energy

$$w \geqslant w^* = \frac{1}{M} \int_0^{t^*} i^2R\,dt,$$

where M is the mass of the wire, and the heating begins ($t = 0$) at room temperature.

Furthermore, after the current i appears, and before the stage of the rapid increase in R, the inductance of the wire, $\mathscr{L}_R$, and that of the standard resistance, $\mathscr{L}_r$, can be ignored for these values of j and a; i.e., we can assume $\mathscr{L}_R\,di/dt \ll Ri$, $\mathscr{L}_r\,di/dt \ll ri$. Figure 2a shows oscilloscope traces of

$$U_R(t) = R(t)\,i(t), \quad U_r(t) = ri(t)$$

obtained under these conditions.

The nonuniformities which appear in a wire because of the rapid thermal expansion, the skin effect, and the ponderomotive forces of the current i become progressively stronger with increasing initial wire radius a and with increasing current density $j = i/\pi a^2$. For a rough estimate of the conditions required for the appearance of nonuniformities, we show in Table I (Ref. 37) the times t^* for tungsten (the time required to heat the tungsten to the point at which the conductivity begins to drop steeply) for various values of j. These values of t^* were found from oscilloscope traces of $U_R(t)$ during the uniform heating of tungsten wires by a current pulse $j = 1 \cdot 10^7$ A/cm^2 of nearly square shape; the results have been converted to other values of j with the help of the relation $t_1^*/t_2^* = (j_2/j_1)^2$. If the heating time t^* is so short as to be less than or comparable to the time required for the
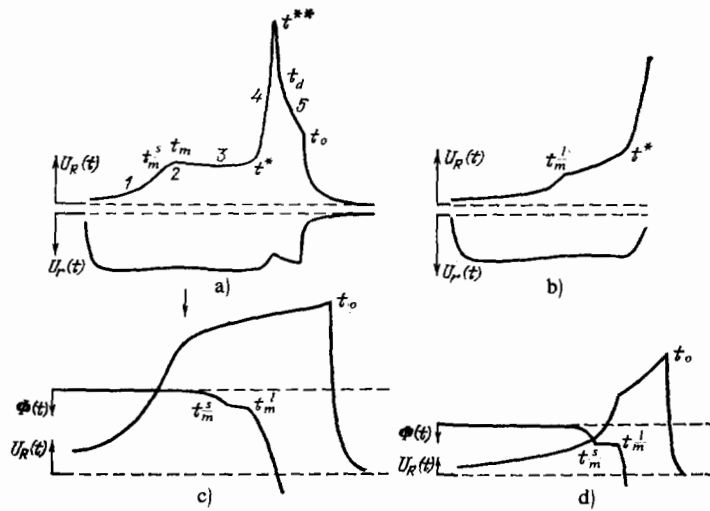
FIG. 2. Curves of $U_R(t)$, $U_r(t)$, and $\Phi(t)$ for W (a); Ref. 19); Al(b), Fe (c); Ref. 16; the arrow shows the Curie point), and Au (d); Ref. 17). t^*—Beginning of the rapid growth of the resistance; t^{**}—maximum of U_R; t_d—beginning of the discharge; t_o—time at which the current is switched off. For parts c and d, the shape of the current pulses is the same as in parts a and b. The duration of the process (along the abscissa axis) ranges from 5 to 10 μs for parts a through d.

propagation of an elastic perturbation over a distance of the order of the wire radius a, radial nonuniformities of the pressure appear in the wire. Manifestations of nonuniformities of this type were observed in Ref. 40, for example. Taking the sound velocity in the liquid metal to be $u = 1 \cdot 10^5$ cm/s, we find from Table I that in the region of metallic conductivity $(t < t^*)$ the condition for the absence of such nonuniformities, $t^* \gg a/u$, holds at radii $a \lesssim 5 \cdot 10^{-3}$ cm and current densities $j \lesssim 1 \cdot 10^7$ A/cm^2, but it does not hold at (for example) $a = 2.5 \cdot 10^{-2}$ cm and $j = 5 \cdot 10^7$ A/cm^2. At $w \gtrsim w^*$, the sharp decrease in the sound velocity u causes the nonuniformities to appear at significantly lower radii a and current densities j.

Hydrodynamic equations were used along with Ohm's law and Joule's law in Ref. 41 to determine the parameter $N = aj^2$, which is a measure of the nonuniformity of the state of the metal over the wire cross section; it was assumed there that the inertial effect is dominant. The uniformity improves with decreasing N. This condition is essentially equivalent to the inequality $t^* \gg a/u$, since $t^* \sim 1/j^2$. It was found experimentally in Ref. 41 that the curves of the wire resistance R as functions of the energy injected into the wire, W, are identical for various radii a and for various heating times t^* if the condition $N = aj^2 = $ const is satisfied. At small values of N in the region $t \gtrsim t^*$ (explosion), the derivative dR/dW is larger than at large values of N. Since the experimentally confirmed relationship between N and dR/dW was derived without allowance for nonuniformity along the length of the wire, the sharp increase in the resistance R observed at $t > t^*$ apparently cannot be attributed to such nonuniformities (which would be different for different values of a or j).

Some idea of the role played by the skin effect can be obtained by estimating the frequency ω, which appears in the familiar expression for the skin depth δ near a plane surface, from the length of the heating pulse, t^*: $\omega = \pi/t^*$. For a current density $j = 5 \cdot 10^7$ A/cm^2 and a wire radius $a = 2.5 \cdot 10^{-2}$ cm in the case of liquid tungsten, whose conductivity depends only weakly on the temperature, we find $a/\delta = 0.5$. In other words, the nonuniformity of the distribution of j over the cross section of the wire is significant. The corresponding heating nonuniformity cannot be removed by heat conduction, since over the time t^* the necessary condition for such removal, $t^* \gg a^2/\chi$, does not hold ($\chi = \varkappa/C\gamma$, where $\varkappa$ is the thermal conductivity, C the heat capacity, and γ the density). In experiments with $j \lesssim 1 \cdot 10^7$ A/cm^2 and $a \lesssim 5 \cdot 10^{-3}$ cm, however (in which case we would have $a/\delta = 1.2 \cdot 10^{-1}$ for tungsten at 20 °C and $a/\delta = 2.5 \cdot 10^{-2}$ at the melting point), it is a very good approximation to ignore the skin effect, as can be seen from the expression[42]

$$j(x) := j(0)\left[1 + \left(\frac{x}{2\delta}\right)^4\right],$$

which holds if $a \ll \delta$ (x is the distance from the wire axis).

The ponderomotive forces associated with the current flow through the conductor give rise to a pressure in the

TABLE I.

j, A/cm^2	t^*, s	j, A/cm^2	t^*, s	j, A/cm^2	t^*, s
$5 \cdot 10^5$	$2,2 \cdot 10^{-3}$	$5 \cdot 10^6$	$2.2 \cdot 10^{-5}$	$5 \cdot 10^7$	$2.2 \cdot 10^{-7}$
$1 \cdot 10^6$	$5,6 \cdot 10^{-4}$	$1 \cdot 10^7$	$5.6 \cdot 10^{-6}$	$1 \cdot 10^8$	$5,6 \cdot 10^{-8}$

conductor, which may be substantial. For a uniform current distribution over the cross section of a circular wire, the pressure in a metal in a quasisteady regime is given by (Gaussian units; c is the velocity of light)

$$p(x) = \frac{\pi a^2 j^2}{c^2}\left(1 - \frac{x^2}{a^2}\right);$$

i.e., the pressure increases from zero at the surface of the wire $(x = a)$ to a maximum value on its axis $(x = 0)$. The average pressure in the metal, $\langle p \rangle = [p(0) + p(a)]/2$, is equal to the magnetic pressure at the surface of the wire: $p_M(a) = H^2(a)/8\pi$. For a current density $j = 1 \cdot 10^7$ A/cm^2 and a radius $a = 5 \cdot 10^{-3}$ cm, we find $p(0) = 80$ atm from this expression. This pressure would not have any significant effect on the properties of a metal in a condensed state which we will be discussing below.

In Section 4 we discuss the longitudinal nonuniformities which, at $j \gtrsim 5 \cdot 10^6$ A/cm^2, form in a wire[11,39,43,44] at $t \gtrsim t^*$, i.e., after the beginning of the sharp decrease in the conductivity of the metal. Other possible causes of a nonuniform heating of wires might be imperfections of fabrication and, at low values of j, deformation by surface-tension forces after melting. In the experiments which we will discuss in this paper, the MHD instabilities of conductors[45,46] are not seen in the condensed state.

During the heating of a conductor by a dense current, a shunting discharge may arise along the surface of the conductor,[10] with the result that the current density in the metal, j, decreases sharply, and the heating of the metal nearly comes to a halt. Conditions promoting the appearance of such a discharge are a high voltage drop along the wire, $U_R = j\rho l$ (l is the length of the wire, and ρ is the resistivity of the metal), a high temperature, and a low pressure in the surrounding medium. In experiments with tungsten in air at atmospheric pressure with $j \approx 1 \cdot 10^7$ A/cm^2 and $l = 1$ cm, a shunting discharge occurs at the beginning of the liquid-state region.[19] The wire then flies apart in the form of drops. In vacuum at the same values of j and l, a tungsten wire is shunted by a discharge even before melting begins.[24] Nevertheless, the explosion of a tungsten wire in vacuum is discussed in several papers, despite the fact that under these conditions the volume heating of the wire is terminated by the shunting, and the wire either remains entirely intact or is damaged by a discharge in certain regions. In the case of the lower-melting metals (e.g., Al, Cu, and Ag), a shunting discharge does not arise in air at atmospheric pressure at these current densities at any point before the complete development of an explosion. For Fe and Ni under the same conditions, this discharge would be ignited near the time t^*. The shunting is eliminated, and the explosion of wires of refractory metals is achieved, by placing the wires in a medium with a high dielectric strength, e.g., water, oil, paraffin, or a compressed gas.[10] In vacuum, the length of the wire, l, and the current density j must be reduced markedly in order to prevent a discharge before the metal has completely melted.[24,47,48]

As the current density j becomes very large ($j \gtrsim 5 \cdot 10^7$ A/cm^2) in any medium, a shunting discharge occurs at high-er values of the injected energy. The reason for this behavior is that the time $(t \approx 1/j^2)$ required to deliver a significant amount of energy, $w \approx w^*$, to a metal (Table I) becomes comparable to the rise time of the discharge.

3. MELTING AND THE LIQUID STATE OF REFRACTORY METALS

a) Resistance and heat of fusion

Figure 2a reproduces[1] oscilloscope traces of $U_R(t) = R(t)i(t)$ and $U_r(t) = ri(t)$, which characterize the resistance $R(t)$ of a tungsten wire and the current $i(t)$ under conditions of uniform heating to the beginning of an explosion $(t \lesssim t^*)$, as discussed above. At the times corresponding to the beginning of the melting of the wire, t_m^s (the solid phase) and the end of the melting, t_m^l (liquid phase), there are slope changes on the curves of $U_R(t)$. These slope changes correspond to changes in the dependence of the resistance R on the input energy W. The beginning and end of the melting can also be determined from the emission from the wire, $\Phi(t)$ (Figs. 2c and 2d); this possibility is important for metals whose $R(t)$ curves do not have a clearly defined slope change at the time t_m^s (Au, Fe, Rh, Nb, and Ir) or at the time t_m^l (Fe). The regions of the solid state, melting, the liquid state, and the rapid drop in conductivity are labeled 1–4 in Fig. 2a. These states can be identified, in particular, by abruptly cutting off the current i in various stages of the energy input[11]: When the current is cut off in region 1, the wire remains intact after the experiment; in region 2, it is partially melted; in the beginning of region 3, the wire contracts completely into small balls, with a dimension of the order of the initial diameter of the wire that are flying apart; the products which are left from the wire after the current i is cut off in region 4 make up a finely dispersed mass. Region 5 corresponds to a discharge which occurs in these products if the current i is not cut off.

From measurements of the input energy $dW = (1/r)U_R \times U_r dt$ and the resistance $R(t) = rU_R(t)/U_r(t)$, the specific energy $dw = dW/M$ and the "reduced" resistance $\rho^0(t) = [S(0)/l(0)]R(t)$ are determined. For the solid state of a metal, this reduced resistance differs only slightly from the resistivity $\rho(t) = (S(t)/l(t))R(t)$ [M is the mass of the wire, and $s(0)$ and $l(0)$ are its original cross-sectional area and length]. Table II shows some results from such measurements[16,17] of the resistance at the melting point of a metal in the solid state, $\rho^0(t_m^s) = \rho_s^0$, and in the liquid state, $\rho^0(t_m^l) = \rho_l^0$, along with the heats of fusion, Δw_m. The errors in the results (5–10% in Δw_m, 2–3% in ρ_s^0 and ρ_l^0, and 1% in ρ_l^0/ρ_s^0) depend primarily on the clarity of the slope changes on the oscilloscope traces at the times t_m^s and t_m^l (this clarity varies from metal to metal). Some similar results, obtained without a control of the times t_m^s from the emission $\Phi(t)$, were reported in Ref. 18. It is important to compare the results of Refs. 16–18 with the results of steady-state experiments, in particular, be-

---

[1] The curves in Figs. 2–16 are drawn from oscillograms.

TABLE II.

Metal	Composition, %	Δw_m, J/g		ρ_s^0, $\mu\Omega\cdot$m	ρ_l^0, $\mu\Omega\cdot$m	$\dfrac{\rho_l^0}{\rho_s^0}$
		Pulsed heating	Magnetic levitation			
Au	99.9	70	—	0.131	0.29	2.22
Ni	Ni + Co — 99.5	318	—	0.61	0.82	1.35
Fe	C — 0.1	244	—	1.30	1.34	1.03
Pt	(Pl — 1)	128	—	0.63	0.94	1.48
Rh	99.9	257	265[54]	0.61	0.85	1.40
Ir	99.9	200	213[54]	0.70	0.92	1.31
Nb	99.7, Ta — 0.2	297	297[55]	0.95	1.08	1.14
Mo	99.96	415	408[56]	0.80	0.95	1.19
Ta	98.8; Nb ≤ 1	202	—	1.14	1.26	1.10
W	99.95	299	—	1.17	1.27	1.08

cause it is not clear at the outset whether the particular characteristics of a metal which are under study remain the same when the metal is heated by a current at a rate up to $\sim 10^9$ K/s. It was found that near the melting point in the solid state the resistances of W, Ta, and Mo found at high current densities[16,49,50] agree with the results of the corresponding steady-state measurements within experimental error (2–3%). The resistance of liquid refractory metals has not been measured by steady–state methods (the data on the jump in the resistivity during the melting of tungsten and molybdenum which have been quoted in some well-known papers[51–53] were obtained during a rapid pulsed process in Ref. 11). For Au, Ni, and Fe, within the scatter in the pulsed and steady-state data, there is so far no basis for claiming a difference between the resistances at the melting point in the two regimes.

For the heats of fusion the results of the pulsed measurements[11,16,17] lie within the scatter in the corresponding results of steady-state measurements (which is at least 6–10%). However, the results of the steady-state measurements of Refs. 54–56, which were obtained after the pulsed experiments by a method of levitation calorimetry for Rh, Ir, Nb, and Mo, agree well with the pulsed data (Table II). The heats of fusion of tungsten and tantalum have apparently not yet been measured by steady-state methods. In summary, no anomalous behavior has been found in the electrical conductivity or the heat of fusion during rapid heating by a dense current, within experimental error.

b) Resistance and thermal expansion of liquid metals; pressure dependence of the resistance

With increasing input energy w and thus increasing thermal expansion, the reduced resistance of a metal, $\rho_0(t)$, deviates progressively from the resistivity $\rho(t)$. Significantly, during rapid heating the expansion of the wire in the liquid state occurs essentially only along the radius [i.e., $l(t) = l(0)$], and the evaporation is negligible; i.e., the total number of atoms is conserved: $n_a(t)s(t)l(t) = n_a(0)s(0)l(0)$. We can therefore write

$$\rho^0(t) = \frac{n_a(t)}{n_a(0)}\rho(t) = \frac{1}{e^2 n_a(0)}\frac{m}{z\tau_e},$$

where z is the number of conduction electrons per atom; τ_e, e, and m are the relaxation time, charge, and effective mass of an electron; and $n_a(0)$ is the initial density of atoms. For a rapid process the reduced resistance thus differs from the resistivity

$$\rho = \frac{1}{e^2 n_a}\frac{m}{z\tau_e}$$

in that the varying atomic density $n_a(t)$ is replaced by the *initial atomic density* $n_a(0)$. *Under these conditions, a study of the reduced resistance* $\rho^0(t) = (s(0)/l(0))R(t)$ *immediately yields information about the quantity* $m/z\tau_e$, which is determined by the electronic structure of the metal. The resistance $\rho^0(t)$ is thus of independent interest, regardless of the resistivity $\rho(t)$, whose determination requires, in addition to measurements of $R(t)$, measurements of the thermal expansion. Figure 2 shows oscilloscope traces of $U_R(t)$, which characterizes the resistance $\rho^0(t)$ or $R(t) = rU_R(t)/U_r(t)$, for certain metals. It has been noted[20] in regard to the w dependence of the reduced resistance ρ^0 that ρ^0 usually increases only slightly upon melting and further heating for those liquid metals and alloys[16] for which it is large in the solid state at the melting point. At high input energies, the resistance ρ^0 has a value $\sim 1.3\ \mu\Omega\cdot$m before its rapid decrease for the metals which have been studied.

The experiments have shown that the reduced resistance ρ^0 in the liquid state for Al, Au, Cu, and Rh increases markedly upon the injection of energy; increases slightly for Ni, Pt, and Ir; and remains essentially constant for Fe, Mo, and Ta (Fig. 2) (i.e., we have $d\rho^0/dt \gtrsim 0$ and thus $d\rho^0/dw \gtrsim 0$). In contrast with these metals, tungsten has a derivative $d\rho^0/dw < 0$ during free expansion at atmospheric pressure after

S. V. Lebedev and A. I. Savvatimskiĭ   754

melting. With an increase in the amount of energy injected into liquid tungsten the derivative $d\rho^0/dw$ progressively increases (Fig. 2a) and becomes positive. Since the scattering of electrons by phonons intensifies with increasing w, because of the temperature rise, the negative value of $d\rho^0/dw$ indicates a decrease in the quantity $\rho^0 \sim m/z\tau_e$ during expansion, i.e., upon an increase in the average interatomic distance in tungsten at the beginning of the liquid region 3 (Fig. 2a).

Experiments on the rapid heating of wires during confined expansion, with thick-walled glass capillaries,[57] confirm this conclusion. If the confinement of the expansion begins at the beginning of the liquid region, at a comparatively high density of the tungsten, while the initial volume of the cavity in the capillary (V_c) is slightly greater than the initial volume of the wire, V_0 (Fig. 3a; $V_c/V_0 = 1.11$), then before the metallic conductivity begins to disappear, i.e., at $w < w^*$, we find a derivative $d\rho^0_{con}/dt > d\rho^0/dt$ or $d\rho^0_{con}/dw > d\rho^0/dw$, where ρ^0_{con} and ρ^0 refer to heating with a bounded volume and during free expansion, respectively. In this case, as can be seen from Fig. 3a, we have $(\partial\rho^0_{con}/\partial v)_w < 0$ ($v = V/M$ is the specific volume of the metal). If, on the other hand, the confinement of the expansion begins at a lower density, i.e., at a large value of V_c/V_0, then we find $d\rho^0_{con}/dw < d\rho^0/dw$ and $(\partial\rho^0_{con}/\partial w)_w > 0$ for tungsten and copper. Figure 3b shows the corresponding downward deviation of the ρ^0_{con} curve from the ρ^0 curve for the particular case of copper. The condition $(\partial\rho^0_{con}/\partial v)_w > 0$ is similar to that decrease in the resistance with increasing external pressure which was observed for most metals in the solid state (at room temperature) in the widely known studies by Bridgman.

The difference in reduced resistances $\Delta = \rho^0_{con} - \rho^0$ during the heating of wires in capillaries and during "free" expansion (in wax) was measured directly in Ref. 58 in a Wheatstone-bridge arrangement, with a sensitivity an order of magnitude better than that in Ref. 57. For all the metals studied (Al, Cu, Mo) the families of $\Delta(w)$ curves corresponding to several values of V_c/V_0 turned out to be qualitatively identical (Figs. 4–6). In Figs. 4–11, the specific energy pumped into the metal is calculated from the time at which the melting ends; i.e., the specific energy refers exclusively to the liquid state and is denoted by w_l (or w_l^*) instead of w. At small values of V_c/V_0, at which the confinement of the ex-

FIG. 4. Change in the electrical resistance of molybdenum, $\Delta = \rho^0_{con} - \rho^0$ (a), and ρ^0 (b) during thermal compression beginning at various metal densities.[58] a: 1—$V_c/V_0 = 1.10$; 2—1.18; 3—1.25; 4—1.34. b: Solid line—ρ^0; dashed line—ρ^0_{con} for $V_c/V_0 = 1.10$.

pansion begins at lower energies w_l, the difference Δ initially decreases with increasing w_l, goes through a minimum, and then increases (Figs. 4–6). As we go to larger values of V_c/V_0, the decrease in Δ becomes more pronounced, and we find a derivative $d\Delta/dw_l < 0$ at even higher values of V_c/V_0, over the entire range of expansion confinements studied. According to Figs. 3–6, a negative value of $\Delta = \rho^0_{con} - \rho^0$ becomes more strongly expressed as the compressibility of the metal increases (as its density decreases). This behavior is seen for each of the metals studied during a decrease in the density because of thermal expansion (the transition from lower to
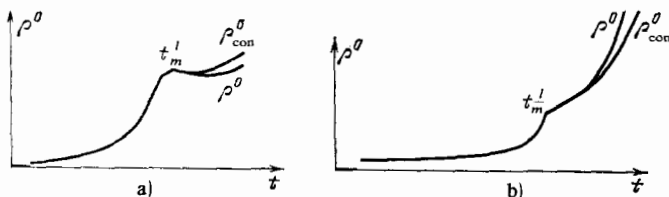

FIG. 3. Resistance of liquid W (a; Ref. 57) and liquid Cu (b). Traces of $U_R(t)$ for a nearly constant current i in the liquid region for the cases of free expansion, ρ_0, and confined expansion ρ^0_{con}, are superimposed. The initial wire diameters are 0.3 mm. The initial capillary diameters are (a) 0.316 mm and (b) 0.337 mm.
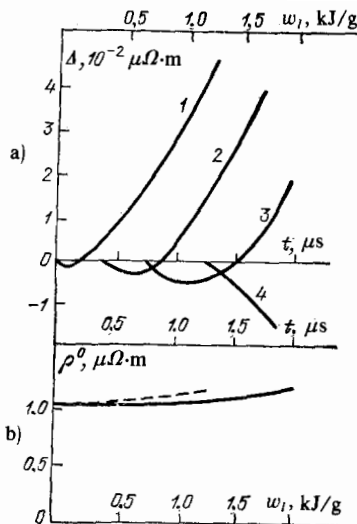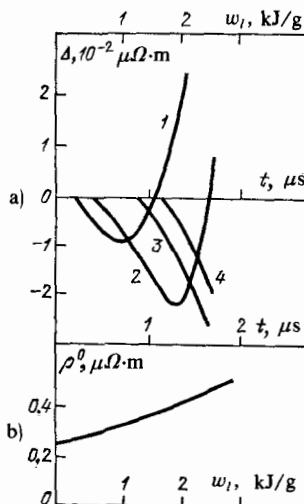

FIG. 5. Change in the electrical resistance of aluminum, $\Delta = \rho^0_{con} - \rho^0$ (a), and ρ^0 (b) during thermal compression beginning at various metals densities.[58] a: 1—$V_c/V_0 = 1.13$; 2—1.19; 3—1.28; 4—1.34.
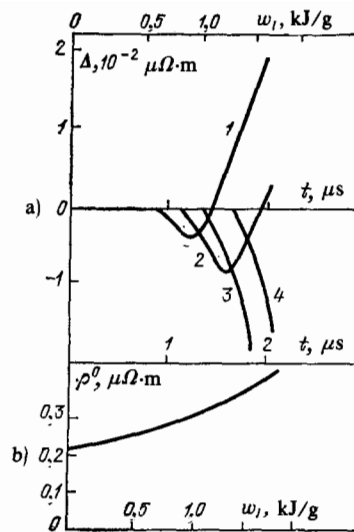
FIG. 6. Change in the resistance of copper, $\Delta = \rho_{con}^0 - \rho^0$ (a), and ρ^0 (b) during thermal compression.[58] a: 1—$V_c/V_0 = 1.22$; 2—1.28; 3—1.38; 4—1.45.

higher values of V_c/V_0) and also during the transition from denser metals to less dense metals (from W to Mo, Cu, and Al).

The preliminary results of measurements of the metal pressure in capillaries[58] show that as the energy w_l increases under these particular conditions the pressure increases monotonically during 1–1.5 μs to $\sim 4 \cdot 10^4$ atm and then decreases. Judging from these results, the w_l dependence of the difference (Δ) between the reduced resistances in the case of a limited volume, ρ_{con}^0, and during free expansion, ρ^0 (Figs. 4–6), stems from an increase in the pressure and cannot be attributed to a forcing of the liquid metal into cracks formed in the glass. The movement of a small fraction of the volume of the metal into cracks would have little effect on the resistance of the metal, R, but it would cause a noticeable pressure decrease, by virtue of the low compressibility of a liquid metal. Experimental data[59] on the development of microscopic cracks and the fracture of glass during pulsed loading are consistent with these conclusions.
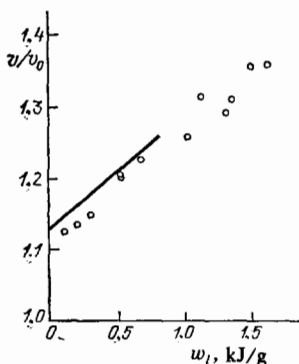

FIG. 8. Expansion of liquid copper.[63] The line shows the steady-state data of Ref. 68.

The thermal expansion of liquid metals during rapid Joule heating has been studied as a function of the input energy w_l by a variety of methods using wire samples. Measurements have been carried out for U (Ref. 60), Mo, Ta (Ref. 61), and Pt (Ref. 62) in a method which makes use of the shadow cast by a wire $2a = 1$ mm in diameter when illuminated by a laser beam. A comparatively low current density, $j \approx 4 \cdot 10^6$ A/cm^2, kept the state of the liquid metal satisfactorily uniform along the radius of the wire at input energies up to a value below w_l^*. The wire was placed in an inert gas at a pressure of $(1-2) \cdot 10^3$ atm to prevent a shunting discharge.

Similar results on the expansion dv/dw_l of metals have been obtained over a broad region in the liquid state through the use of capillaries,[63] as in Refs. 58 and 64, oscilloscope traces of the voltage $U_R(t)$ and the current $U_r(t)$, characterizing the wire resistance $R(t)$, were used to determine the change dR/dt, which occurred at the time at which the expansion of the liquid metal began to be restricted by the size of the capillary, of known diameter. The energy w_l corresponding to this time was determined directly from the oscilloscope traces. A Wheatstone bridge was used for more accurate measurements of R, as in Ref. 58. The results are shown by the circles in Figs. 7–11, which also show the results of other pulsed experiments for Mo (Refs.

FIG. 7. Expansion of liquid aluminum.[63] In Figs. 7–11, the quantity plotted along the abscissa axis is the energy (w_l) delivered to the metal after the completion of melting. The line in this figure shows the steady-state data of Ref. 67.
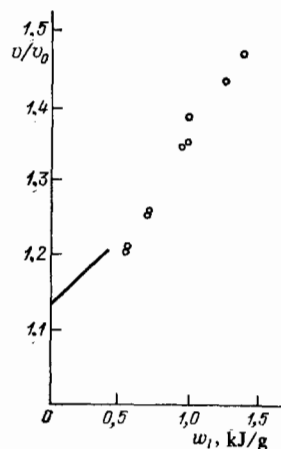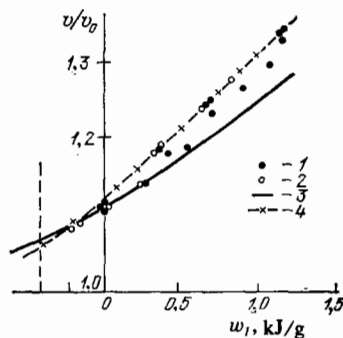

FIG. 9. Expansion of liquid molybdenum.[63] In Figs. 9–11, the vertical dashed line at the left marks the beginning of melting. 1, 2—heating times of 2 and 6 μs, respectively (the time between melting and t^*); 3, 4—pulsed data of Refs. 61 and 65, respectively.
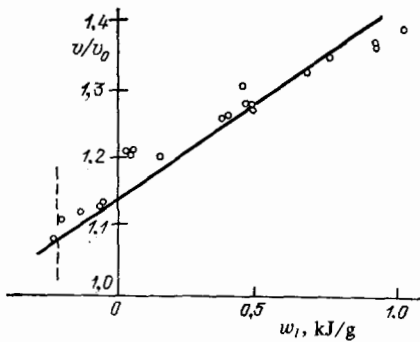
FIG. 10. Expansion of liquid tantalum.[63] The line shows the pulsed data of Ref. 61.

61 and 65), Ta (Ref. 61), and W (Refs. 65 and 66) and data from steady-state measurements for Al (Ref. 67) and Cu (Ref. 68).

In the case of liquid tungsten, in contrast with other metals, the early measurements of the expansion by different methods yielded contradictory results. The expansion dv/dw_l of liquid tungsten was measured in Ref. 66 by the same method which had been used previously for Mo, Ta, and Pt in Refs. 61 and 62. This result was confirmed by measurements of the resistance of the wire in a capillary and, for certain values of w_l, by measurements by a probe method, which was based on the occurrence of a contact between the expanding liquid metal and metal probes already in place (Fig. 11). Furthermore, the capillary experiments in the case of tungsten were supported by results which had been found previously[11] for nickel, which showed that a weak expansion at $w_l < w_l^*$ increases markedly at $w_l \approx w_l^*$.

Higher values of dv/dw_l for liquid tungsten (Fig. 11) were found in the experiments of Refs. 65 and, especially, 69. The apparent reasons for these higher values were as follows. The measurements in Ref. 65 were carried out by the same shadow method as the measurements in Ref. 66, but the wires were in water, rather than in a compressed gas. In water, a vapor layer forms near the surface of incandescent tungsten, and the refractive index in this layer is smaller than that of the water. This layer, which grows with increasing wire temperature, causes an expansion of the shadow image.
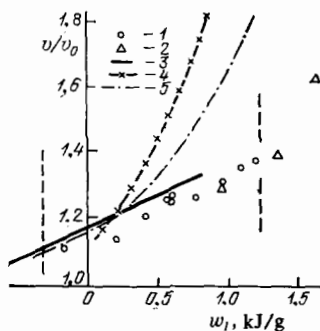

FIG. 11. Expansion of liquid tungsten.[63] The vertical dashed line at the right is the boundary of the region of the homogeneous state of the liquid metal. 1—Capillary method; 2—probe method; 3—Ref. 66; 4—Ref. 69; 5—Ref. 65.

This interpretation corresponds to experimental data which reveal no substantial difference between the results found in Ref. 65 and those found elsewhere (Figs. 9 and 11) for the less refractory metals and in the first part of the liquid region for tungsten. In a determination of the diameter of an expanding tungsten wire from its intrinsic emission in Ref. 69, it was assumed that the angular distribution of the intensity of the emission by the surface of liquid tungsten remains constant over the entire energy range. The elevated value found for the expansion dv/dw_l in Ref. 69 can apparently be attributed to a breakdown of this assumption (Fig. 11).

The expansion of exploding wires had also been studied in some earlier work. In some cases[44,70,71] the measurements were carried out by an x-ray shadow method, while in Ref. 11 shadow images were photographed in visible light at a magnification of 15x. The purpose of these studies, however, was not to measure the expansion of a uniform liquid conductor but to determine the mechanism for the electrical explosion.

Measurements in Ref. 64 (Fig. 2a) determined the density of tungsten corresponding to the time t^*, of the beginning of the rapid increase in the resistance of a wire whose heating had been carried out quite uniformly in the solid and liquid states up to $w \approx w^*$ ($2a = 0.1$ mm, $j \approx 5 \cdot 10^6$ A/cm²). The volume was measured by means of calibrated capillaries. The measurements by this method yielded $\gamma(t^*)/\gamma_0 \approx 0.5$ for the density, where γ_0 is the initial density of the tungsten wire. For a copper wire in a similar pulsed process[70] it was found by an x-ray method that "The lowest density at which liquid copper is a solid cylinder is 4.1 g/cm³." These measurements yielded $\gamma/\gamma_0 = 0.47$. According to the results of steady-state measurements for liquid mercury,[72] "At a density below 8.5–9 g/cm³ there is a change in the nature of the electrical conductivity of mercury: The conductivity ceases to be purely metallic." This density is 0.62–0.66 of the density of solid mercury. According to the experimental data, therefore, the metallic conductivity of various metals decreases sharply at a density $\gamma/\gamma_0 = 0.45$–0.65. It must be kept in mind here that the values found for $\gamma(t^*)/\gamma_0$ in the pulsed experiments are rather crude estimates because of the uncertainty in the choice of the time t^*, the rapid increase in the expansion dv/dw near the value $w = w^*$ (Fig. 2a), and the "energy anomalies" (Section 4).

4. ELECTRICAL EXPLOSION OF A METAL; DISAPPEARANCE OF METALLIC CONDUCTIVITY

There is some ambiguity in the term "electrical explosion." It is usually applied to the heating and destruction of conductors by a dense electric current in a time of 10^{-7}–10^{-5} s, but on occasion times $\sim 10^{-3}$ s are also included. Experiments show that the mechanism for the "explosion" varies with the heating current density j (the duration of the process depends on this current density, varying in proportion to $1/j^2$). While an "exploding" wire will break up into macroscopic drops of liquid metal at comparatively low current densities, at high values of j the wire breaks up into particles which are not discernible under an optical microscope.[11] As we go to higher current densities and thicker

conductors, macroscopic radial nonuniformities develop already in the liquid and the solid state (Section 2) and affect the destruction of the conductor as a whole. The picture of the electrical explosion of thin wires drawn here is as it is drawn in Ref. 21 on the basis of the experimental data available. Other aspects of the phenomena of electrical explosions are discussed in Refs. 4–6 and 73, in particular; there is a detailed bibliography up to 1955 in Ref. 8.

In some studies, investigators who have obtained objective data on the destruction of wires in a certain range of current densities have generalized the data to other values of j without adequate justification. The result was the development of several different explanations for electrical explosions which were advanced as being of universal applicability. In 1939 it was suggested[7] that an electrical explosion occurs through a rapid evaporation of metal from the surface of the wire, which becomes progressively thinner, converting into a nonconducting vapor. This picture does not agree with high-speed photographs taken of thin wires at current densities $j \sim 1 \cdot 10^7$ A/cm^2. It was concluded from such photographs in Refs. 43 that, because of nonuniformities, " . . . the wire breaks up into sections along its length. The appearance of these ruptures stops the current flow and causes a pause in the current . . . . During the pause, particles are evaporated by the heat obtained during the current flow." These particles, regions, or lengths of the wire which are formed during the explosion regime (and which are called "striations" in some studies) are called "transverse layers" of the metal in that paper.

In subsequent studies this breakup of conductors was attributed to not only existing nonuniformities but also to capillary forces,[8] inhomogeneities of the compression,[9] and MHD instabilities.[45,46] The breakup into "transverse layers" as a result of any of these factors is frequently taken, even in recent papers, to be the reason for the disappearance of the electrical conductivity of an exploding wire and the appearance of a "current pause" in the supply circuit. An opening of the electric circuit because of the breakup of the conductor into macroscopic drops can undoubtedly actually occur in comparatively slow processes, and it is illustrated by the example of the operation of fuses. There is, however, another mechanism for the breakup of a conductor: an explosion mechanism which operates at high current densities in a metal.

As we have already mentioned, at current densities $j \sim 5 \cdot 10^6 - 1 \cdot 10^7$ A/cm^2 wires $2a \approx 0.1$ mm in diameter are heated uniformly in the solid state and then in the liquid state up to a certain time t^*, which corresponds to a definite amount of specific input energy, $w(t^*) = w^*$. At $t \approx t^*$ the resistance of the wire, R, begins to rise sharply, remaining metallic up to the time[19,39] t^{**} (Fig. 2a). Furthermore, at the time t^* the wire begins to expand rapidly, so that when the heating current is turned off in stage 4 near the time t^{**} the metal has converted into a finely dispersed mass with a particle size less than 1000 Å (Refs. 12 and 13). It is this process which we will call an "explosion" below. It begins at $w \approx w^*$, when the increase in the volume of the metal reaches $v/v_0 = 1.35 - 1.45$, where v_0 is the volume of the metal at

$T = 300$ K (Fig. 11).

The pronounced decrease in the conductivity of the wire in stage 4 (Fig. 2a) occurs at an input energy not sufficient for complete evaporation of the wire. In particular, the data of Refs. 11 and 19 put the input energy w^* for nickel and tungsten at 45–60% of the sublimation energy. For this reason, the absence of macroscopic drops in the explosion products and the high strength against electrical breakdown prevented an explanation of this decrease in the conductivity being found in the conversion of the liquid metal into vapor. At present we have no experimental data which show directly how close the point on the state diagram corresponding to the beginning of the explosion of the metal, $w \approx w^*$, is to the liquid-vapor equilibrium curve (the binodal).

Martynyuk's arguments,[74] based on a superheating of the metal, put the beginning of the explosion near the spinodal (the boundary of the region of a metastable state). Baĭkov and Shestak[75] assert that during the rapid Joule heating of a wire in a capillary the state of the metal may vary along the binodal up to the critical point, and the parameters of this point can be measured. However, this method of heating a wire to the critical state could not be uniform because the condition $t^* \gg a/u$ does not hold (Section 2), since the sound velocity u falls off markedly near the critical point. We might also note that the heating of a metal along the binodal suggested in Ref. 75 would be hindered by the vapor of the material of the capillary wall which unavoidably appears. The pressure of this vapor could not be assumed small in comparison with the vapor pressure of the metal under study (W).

In an effort to develop a model-based explanation for the rapid expansion of a metal and the disappearance of its conductivity at $w = w^*$, it was suggested in Ref. 11 that only some of the metallic bonds are ruptured in this stage of the process, so that the liqud metal breaks up into microscopic regions. The metal-bond rupture surfaces which separate these microscopic regions in the liquid metal are naturally identified with the fluctuating surfaces of microscopic discontinuities whose appearance in an expanding liquid metal was discussed by Frenkel'.[76] The expansion increases in the course of the heating, and there is a corresponding increase in the number of bond rupture surfaces per unit volume; the average distance (L) between these surfaces decreases. According to the suggestion in Ref. 11, the conductivity should decrease sharply when L decreases to the point where it is equal to the mean free path of an electron in the metal, Λ.

It was later found[12] with the help of an electron microscope that the finely dispersed products which remain after the explosion of the metal constitute a sol in which the bulk of the particles have a size $L_{sol} = 0.02$ μm. The mean free path (Λ) of electrons in a condensed metal with an energy $\sim w^*$ is not known, but the conductivity remains the same in order of magnitude throughout the region of the liquid state after the completion of the melting and before the time (t^*) at which the explosion begins (the volume of the conductors increases by $\sim 20–30\%$, while their total resistance increases by no more than a factor of two or three—considerably less for refractory metals[20]). If the conductivity changes

only slightly, we would naturally expect that the changes in the mean free path Λ would also be slight. We can estimate Λ for liquid metals at the melting point from the data of Ref. 77: $158d$ for Na, $177d$ for K, $6d$ for Al, $18d$ for Ag, and $13d$ for Cu, where $d \sim 3$ Å is the interatomic distance. The value $L_{sol} = 200$ Å found in Ref. 12 is thus not far from Λ in order of magnitude. The energy injected into the conductor was not measured in Ref. 12, and the sol was interpreted as a product of the condensation of a vapor which had formed beforehand, in the spirit of the widespread belief that the metal evaporates during the explosion. It was shown later[13] that the products of the explosion of tungsten in a liquid medium do constitute a sol of roughly the same size as the sol found in Ref. 12 in the explosion of lower-melting metals in a gas. The results found in Refs. 13 and 19 supported the earlier conclusion[11] that the total amount of energy supplied to the conductor is insufficient for a preliminary evaporation of a metal which converts into a sol. There is accordingly reason to interpret the sol as evidence of a breakup of the liquid metal into the microscopic regions mentioned above.

Chace[78] has also linked the explosion to a definite state of the material of the conductor; he also took into account the appearance of a sol directly from the liquid metal. His interpretation of the explosion, however, differs from that outlined above in two respects: 1. Chace[78] attributes the beginning of the rapid increase in the wire resistance R to the appearance of a nonconducting vapor, rather than to the breakup of the liquid metal into microscopic regions of size $L \sim \Lambda$. 2. Chace assumes,[78] in contradiction of the data of Refs. 19–21, that the dispersal of the liquid metal results from superheating energy which accumulates in the metal before the time t *, rather than from the Joule heat which is evolved in the metal during the rapid increase in the resistance, in the time interval t ** $- t$ *.

This idea of a superheating of the metal is the basis for Martynyuk's interpretation[74] of the electrical explosion.

Grevtsev et al.[79] believe that the explosion " . . . occurs in two stages: First, the local volume vapor formation which results from the spatial and temporal nonuniformity of the energy injection during rapid heating by the current causes the formation of striations, which in turn cause a loss of conductivity. The decay of the current and the removal of the magnetic pressure then cause a violent boiling of the superheated metal and the formation of an aerosol." This explanation of the mechanism for the explosion, which uses the arguments of Refs. 43 and 78, is not convincing. In a typical explosion of a wire $2a \approx 0.1$ mm in diameter at a current density $j = 5 \cdot 10^6$ A/cm^2, the pressure produced in the metal by the ponderomotive forces associated with this current is, even at the axis, $p(0) = 20$ atm. At the surface of the wire, this pressure is $p(a) = 0$ and thus could not impede the destruction of the wire from the surface. Furthermore, the explosion begins at an energy $w \approx w^*$, regardless of the instantaneous value of the total current,[10] $i(t$ *), which determines the pressure p. According to the data of Refs. 11 and 39, the conductivity is lost, and the current i is cut off, not because of the separation of the exploding conductor into macroscopic striations but because of a breakup of the liquid metal into

microscopic regions of size $L \approx \Lambda$. The breakup itself, i.e., the loss of some of the metallic bonds near the time t *, is a necessary condition for the occurrence of transverse stratification. The appearance of the sol is thus one of the reasons for the formation of the striations; it is not a matter of striations forming and giving rise to a sol through the cutoff of the current and the elimination of the magnetic pressure.

Many investigators[43,74,78,79] have assumed superheating in the sense that the dispersal of the conductor and the sharp increase in its resistance R at $t \gtrsim t$ * occur because of the energy stored in the metal before the time of the explosion, t *. This assumption is at odds, in particular, with the following experimental data: During the rapid increase in R (in the time interval t **$-t$ *; Fig. 2a) an energy $\Delta W \approx 0.2 W$ ** is injected[19] into a wire $2a \approx 0.1$ mm in diameter at a current density $j \approx 1 \cdot 10^7$ A/cm^2. When the current i is cut off abruptly in an early stage of the rapid increase in R near the time t *, the acoustic effect is considerably weaker, and the size of the sol particles which form is greater than when the current is cut off near the time t **. That the energy ΔW supplied to the wire from the external circuit has a decisive effect on the sharp increase in the resistance of the wire can also be seen from the results of Ref. 41, discussed in Section 2 of the present review (dR /dW varies with the value of the parameter $N = aj^2$ at a given current density).

During the explosion, the breakup of the conductor into "transverse layers," i.e., macroscopic regions of condensed metal and regions of a low density, occurs even if the heating current i is turned off at the very beginning of the rapid increase in the resistance, while these longitudinal inhomogeneities are still not visible.[11] According to Refs. 11, 20, and 39, the appearance and growth (after the cutoff of the current i) of these inhomogeneities can be explained qualitatively by two factors: the rupture of some of the bonds in the liquid metal and the presence in the liquid metal of longitudinal elastic waves, which arose in the earlier stages of the heating. If the heating current i is cut off before the beginning of the rapid increase in the resistance, while the rupture of bonds is still insignificant (as can be seen from the absence of a sol from the explosion products), then inhomogeneities of an entirely different nature—liquid drops—appear, and this occurs over a time an order of magnitude greater than the time required for the formation of the "transverse layers" (see Figs. 3 and 4 in Ref. 11).

In the course of the electrical explosion the transverse layers gradually increase in diameter and decrease in thickness. Discharges occur between them. Budovich and Kuzhekin[80] and Abramova et al.[81] believe that the total voltage drop across these discharges is the reason for the cutoff of the current in the circuit of the wire. In contradiction of that assumption, it is assumed in the explosion scheme which we are discussing here,[11,19–21] in accordance with the results of Ref. 39, that the discharges between the transverse layers make only a small contribution to the total resistance R of the exploding wire.[2] The marked increase in R in the time

---

[2]This position also corresponds to the experimental results reported by Ivanov[41] (Section 2), which show that the effect of longitudinal inhomogeneities of the wire on the rapid increase in the wire resistance R can be ignored.

interval $t^* < t < t^{**}$ is caused by a decrease in the metallic conductivity of the condensed metal in the layers. The energy $w(t^{**})$ [more precisely, $w(t_d)$; Fig. 2a] at which the conductivity of the condensed metal essentially disappears, and the heating of the metal stops,[19] is low (insufficient for a complete evaporation).

As we have already mentioned, the vanishing of the conductivity of the liqiud metal in stage 4 (Fig. 2a) is due, according to Refs. 11 and 19–21, to the appearance of a fluctuating grainy structure with $L \sim \Lambda$ in the metal. This structure is produced by the surfaces of microscopic discontinuities. Since these discontinuities sever or greatly weaken the bonds between the metal particles which they separate, these particles can fly away from the surface of the layers. (While the microscopic discontinuities have expanded only slightly, it is natural to assume that the sol particles which form have a thermal velocity. Assuming a temperature $\sim 1 \cdot 10^4$ K, we then find a velocity ≈ 70 cm/s for the particles, each consisting of 10^6 tungsten atoms, and the time required for the expansion of a microscopic discontinuity by an amount on the order of 10 Å would be $\sim 1 \cdot 10^{-9}$ s. These numbers refer to the mean square velocity, although it is possible that faster particles play an important role.) The beginning of the rapid expansion of the metal is related to the decrease in its conductivity because of the size of the sol particles. At $t < t^*$, while the average size of these particles is large in comparison with the electron mean free path in the metal ($L > \Lambda$), the thermal dispersal velocity of these particles from the surface of the transverse layers of the wire is still low, since it is proportional to $L^{-3/2}$. Experiments show that as we approach the time t^* (at $t < t^*$) the contours of the wire become indistinct, and we would naturally attribute this effect to a slow dispersal of large sol particles. In other words, the expansion velocity, like the rate of increase of the resistance R (Fig. 2a), should change not abruptly but smoothly over some transition region near t^*, which corresponds to a decrease in the average size of the sol particles to $L \sim \Lambda$. Since the dispersal of the sol particles from the surface of the conductor begins while the size of these particles is still considerably greater than Λ, the appearance of vapor in the expanding gaps between the particles may play a substantial role in the disappearance of the conductivity of the metal near the surface. The dispersal of the sol particles from the interior of the wire is delayed by the presence of outer regions. During this delay, the interior regions continue to rise in temperature, so we would expect the disappearance of the conductivity in the interior of the conductor to result from a decrease in the size of the sol particles to $L \sim \Lambda$. Consequently, the state of the conductor in region 4 is inhomogeneous not only along the length of the wire (because of the breakup into transverse layers) but also along its radius. This inhomogeneity along the radius can explain the larger size of the particles ($L \sim 1000$ Å instead of 200 Å for the bulk of the particles) whose appearance has been detected on the basis of the scattering of light[82] directly during the explosion, in stage 4. This scattering apparently occurred in the outer regions of the column of explosion products, since the density of the column is still high in stage 4.

In this mechanism for the explosion there is no substantial superheating of the metal in the sense that the conversion of the metal into a sol results from energy stored in the metal before the beginning of this conversion. The more rapid heating due to a pressure increase is a different matter. This effect, which corresponds to the state diagram, is demonstrated by experiments in capillaries.[64] When a high pressure is produced by means of a glass capillary, the energy which can be pumped into the metal after melting before the metal leaves the liquid state and loses its metallic conductivity is 70% higher than at atmospheric pressure. The conductivity begins to disappear only when the capillary is broken. In other words, the input energy w^* required for the beginning of the explosion of the metal increases with increasing pressure. From the standpoint of the model of a sol, this effect is explained on the basis that the capillary wall restricts the expansion of the liquid metal and prevents the appearance of new microscopic discontinuities in it; i.e., it prevents the breakup of the metal into microscopic volumes $\sim \Lambda$ in size.

Like the capillary wall, the outer parts of the wire can restrict the expansion of the inner parts. This is the case if the current density j is high or if the radius a is large, so that the conditions $a/u \ll t^*$ does not hold (Section 2). For the regions of the wire relatively close to the axis which are compressed in this manner, the energy w^* at which the metal begins to explode is greater than for the outer regions. As a result, the transition from the liquid state (region 3 in Fig. 2a) to the rapid increase in the resistance of the wire becomes smoother overall and shifts toward higher energies.[37] This increase in the energy averaged over the volume, $\overline{w}^*$, with increasing current density was observed a long time ago,[7,11,15] and it was labeled an "energy anomaly" because of the difficulty in explaining the effect. Other reasons for the effect of the current density on the "explosion energy," associated with the different definitions of this term used in different studies, were discussed in Ref. 37. We stress that no dependence on the current density j has been found for the energy w^* at which the explosion of the metal begins, in contrast with the average energy $\overline{w}^*$ at which a large-diameter wire begins to explode. This result argues against the interpretation that the dispersal of the metal which begins at $w \approx w^*$ results from a superheating energy; the accumulation of such an energy would be more likely at large values of $dw/dt \sim j^2$.

This interpretation of the electrical explosion[11,19–21] differs from other explanations in that the disappearance of the conductivity of the conductor as a whole is attributed to the disappearance of the conductivity of the metal due to the appearance of microscopic inhomogeneities with $L \sim \Lambda$ in it. These arguments agree qualitatively with all the experimental data available on the question, including the results on the explosion products. The state of these products has usually not received the attention it deserves (in Ref. 46, for example, it is simply noted that the conductor disperses and "disappears").

Let us summarize the data on the destruction of conductors in the various heating regimes. In the "fuse" regime ($j \gtrsim 5 \cdot 10^5$ A/cm^2, wire diameter of 0.1 mm) the conductor does not explode, and after melting it becomes deformed and

breaks up into macroscopic drops. In particular, a thin wire contracts into a chain of drops because of surface-tension forces.[11] The conductivity of macroscopic drops of a liquid metal is still high, so that the chain can cut off the current only because of gaps between the drops. Under certain conditions the conductor may bend and fly apart in drops because of the momentum acquired during the rapid expansion or as a result of electromagnetic forces (see Fig. 4 in Ref. 11).

An electrical explosion occurs at high current densities ($j \gtrsim 5 \cdot 10^6$ A/cm^2 for a wire 0.1 mm in diameter), at which the heating is so rapid that an energy $w \gtrsim w^*$—the energy at which the conductor loses its conductivity and forms a sol, is evolved in the metal before the conductor has time to deform. Since the time required for the deformation of a molten conductor depends on its diameter, the current density required for the explosion regime also depends on the diameter. In the stage in which the conductivity disappears, the conductor becomes radially inhomogeneous. Along its length, the conductor breaks up into "transverse layers" of condensed metal and regions of low density, across which the voltage drop increases because of the decrease in metallic conductivity, and discharges occur. The conductivity of these discharges is substantially higher than that of the transverse layers,[39] so that the conductivity of the conductor as a whole disappears because of the disappearance of the conductivity of the macroscopic layers, due to the appearance of microscopic discontinuities in them. So far, there has been no experimental test of the suggestion[20,39] that an exploding conductor breaks up into transverse layers under the influence of longitudinal elastic waves after some of the metallic bonds have been ruptured in the liquid metal near the time t^*.

At intermediate values of the current density, or in the case of current pulses of varying amplitude, a wire may become deformed and explode at necks which form. The final products contain both macroscopic drops and a sol. As we go to current densities $j > 1 \cdot 10^7$ A/cm^2 and diameters $2a > 0.1$ mm, these radial inhomogeneities become progressively more noticeable and may cause a marked increase in the energy for explosion of the wire as a whole. In certain studies, the energy delivered from the current source to the products of the destruction of the wire after the occurrence of a discharge in these products is included in the energy of the electrical explosion.

5. THERMIONIC EMISSION

a) Anomalies of the thermionic emission

Anomalies were discovered in the electron emission during the heating of a metal by single current pulses of high density ($j > 10^6$ A/cm^2) in Refs. 24 and 83 and were studied further in Refs. 15, 47, 48, and 84–87. These anomalies are seen as an unusually intense emission and also a deviation from equilibrium. In the experiments of Ref. 24, the emission of a tungsten emitter which had not melted was found to be 100 times its tabulated value for the melting point T_m, and a similar effect was observed for a nickel emitter in Ref. 15, where the factor was ~50. The deviation from equilibrium is

seen in the circumstance that after the heating current is abruptly cut off the emission current decays sharply before the cooling of the emitter could become significant. Over a time $\tau \sim 5 \cdot 10^{-4}$ s, the emission nearly reaches the equilibrium value corresponding to the given temperature.[86] (In research on the anomalous emission and heat capacity, the "temperature" is understood as the quantity found from the emission and the electrical resistance of the metal by the same operations as are used to determine the temperature in the early stages of the experiments or during slower processes, when there is no basis to assume a nonequilibrium state.)

These anomalies become significant only during intense heating of the emitter, and they grow as the emitter is heated further, up to the melting point. In the early stage of pulsed heating (for tungsten, at $T < 2600$ K $= 0.7T_m$), the emission is normal. The nature of the increase in the anomalous emission (and the nature of its decrease after the sharp cutoff of the heating current) is the same for the metals which have been studied, in particular, for tungsten and nickel, although the normal emission of these metals at their melting points differ by eight orders of magnitude. The peak value of the current in the anomalous-emission pulse, $I_{em}(t)$, continues to exceed by a large factor the value $I_{em}(t + \tau)$ to which this current falls after the end of heating when the heating pulses $i(t)$ are repeated, until the emitter is destroyed. The number of pulses which an emitter can withstand decreases as the maximum temperature of the emitter approaches the melting point T_m. In Ref. 86, yttrium emitters remained intact after a hundred repeated pulses, which raised the temperature of the metal to ~$0.92T_m$ and which produced $I_{em}(t)/I_{em}(t + \tau) \approx 10$. While this ratio is conserved, the values of both $I_{em}(t)$ and $I_{em}(t + \tau)$ at the beginning of the series decrease from pulse to pulse, because, according to Ref. 86, of a purification of the surface layer of yttrium. The experiments with the tungsten emitters were usually carried out with 10–30 repeated pulses of intense heating after a preliminary outgassing.

Conclusions regarding the anomalies are drawn from the anode current pulses $I(t)$ in a vacuum diode whose cathode is the wire emitter under study, of radius a and length l. In these experiments, particular attention is paid to satisfying the requirement of a low ion current $I_i(t)$, i.e., to satisfying the condition $I_i(t) \ll I(t)$; under this condition, the anode current $I(t)$ is equal to the emission current $I_{em}(t)$ or is less than it because of the electron space charge. For yttrium and nickel emitters we have $I(t) = I_{em}(t)$ even at low anode voltages so that the average measured emission current $j_{em}(t) = I(t)/2\pi a l$ can be compared directly with the equilibrium emission $\bar{j}_{em}$ corresponding to the given emitter temperature or that corresponding to its melting point, $\bar{j}_{em}^m$. In the case of tungsten at $I(t) < I_{em}(t)$, i.e., under the condition $I(t)/2\pi a l < j_{em}$, the conclusion regarding an anomalously high value of j_{em} is drawn[24] from the inequality $I(t)/2\pi a l > \bar{j}_{em}^m$.

Figure 12 illustrates these features in the anomalous-emission current of yttrium. At the time t_o, the time at which the heating pulse $i(t)$ ends (before the beginning of melting),
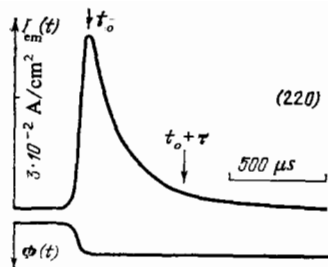
FIG. 12. The emission current $I_{em}(t) = 2\pi a l j_{em}(t)$ and the photocurrent $\Phi(t)$ for an yttrium emitter.[86] The heating pulse $i = \pi a^2 j(t)$ is turned off before melting begins $(t_o < t_m^s)$. The emitter diameter is $2a = 0.01$ cm; the emitter length is $l = 0.5$ cm; and the current density is $j = 8.2 \cdot 10^5$ A/cm^2. The numbers in parentheses in Figs. 12 and 14–16 show the order of the given pulse in the total number of pulses passed through the given emitter.

the rapid increase in the current $I_{em}(t)$ gives way to a decrease, during which $(\tau \sim 5 \cdot 10^{-4}$ s) the photocurrent $\Phi(t)$, used in determining the emitter temperature from its visible emission, remains essentially constant. Estimates confirm that the change in the emitted temperature over the time τ is an order of magnitude smaller than the value which would explain the observed decrease in the emission current, $I_{em}(t_o)/I_{em}(t_o + \tau) \approx 10$, in accordance with Richardson's law.

Figure 13 demonstrates (for a nickel emitter) that the anomalies in the anode current $I(t)$ are due to the state of the metal, and not to ionization. During the heating pulse $i(t)$, which continues up to the time (t_m^l) at which the melting of the emitter ends, the current I before the beginning of the melting increases to an anomalously high value. When the melting begins, at t_m^s, this current begins to decrease, and it approaches its normal value, although the current i does not change, and none of the interelectrode voltages change. In other words, the anode current I decreases when the conditions for ionization and for the burning of the discharge do not become less favorable, and the only change is in the state of the emitter: The emitter temperature stops rising, and the emitter begins to melt. In this experiment, the ignition of a discharge near the emitter was ruled out, even during rupture of the emitter, because of the comparatively low heater current density, $j \approx 1 \cdot 10^5$ A/cm^2. A rupture at the time $t \approx t_m^l$ cuts off the current i; the only event is a brief spark, which produces a peak on the $I(t)$ oscilloscope trace.

Since there are no anomalies in the emission in the early stages of the pulsed heating of the emitter, the anomalies cannot be due to contaminants in the metal. In particular, this is true of those contaminants which might have settled on the surface of the emitter before the beginning of the pulse
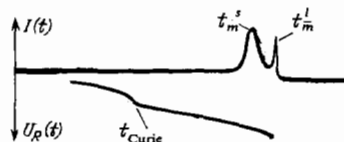

FIG. 13. The anode current $I(t)$, which is equal to the emission current $I_{em}(t)$ (except at the time $t \approx t_m^l$), and the voltage $U_R(t) = R(t)i(t)$ for a nickel emitter.[15]

(after the end of the preceding pulse) and lowered the work function of the emitter. The question of contaminants of this type was studied experimentally in Ref. 84.

Specific difficulties in detecting anomalous emission stem from the high density of the heating current, j, and a very high emitter temperature, $T \gtrsim 0.9 T_m$, which corresponds to an equilibrium vapor pressure $p \gtrsim 1 \cdot 10^{-3}$ torr of the metal.[88] Under these conditions, an elevated voltage near the emitter gives rise to a discharge. This discharge serves as a prolific source of electrons and thus prevents measurements of the emission of the metal. We should first consider the possibility that the discharge is ignited because of the voltage drop along the emitter, U_R, which can be large. In Ref. 89, for example, for a tungsten emitter of length $l = 3$ cm, at $T \approx T_m$ and $j = 3.8 \cdot 10^7$ A/cm^2, this voltage drop was $U_R = 1.3 \cdot 10^4$ V. In most studies of the emission the voltage does not exceed a few tens or hundreds of volts, so that short emitters are used ($l = 1$ cm down to 0.015 cm) along with comparatively low current densities j, which, however, still give rise to anomalies ($j \sim 5 \cdot 10^5$ A/cm^2). In certain cases,[47,48] measurements have been taken during the relaxation of the anomalous emission, after the cutoff of the heating current, under the condition $U_R = 0$. In addition to the discharge along the emitter, a discharge can occur between the emitter and the anode at a high anode voltage U_a in the diode. The voltage U_a is determined by the voltage U_+ of the anode power supply. If the voltage drop satisfies $U_R \gtrsim U_+$, we need to take into account the difference in the values of U_a for different parts of the emitter.

Another factor complicating detection of the emission from the anode current $I(t)$ is the magnetic field produced by the intense pulsed heating current $i(t) = \pi a^2 j(t)$. This field prevents the emitted electrons from reaching the anode if the anode voltage U_a is below a critical value U_{cr}, which is very high if the current i is. [For a coaxial system with an anode of radius b and an emitter of radius a, the critical voltage is $U_{cr} = 1.9 \cdot 10^{-2} i^2 [\log(b/a)]^2$, where U_{cr} is expressed in volts, and i in amperes. In Ref. 89, for example, at a current density $j = 3.8 \cdot 10^7$ A/cm^2 and with diameters $2a = 0.01$ cm and $2b = 0.1$ cm, the critical voltage was $U_{cr} = 1.7 \cdot 10^5$ V, while in Ref. 47, with $j = 6.9 \cdot 10^5$ A/cm^2, $2a = 0.0077$ cm, and $2b = 1$ cm, it was $U_{cr} = 86$ V.]

Another very important aspect is that the emission can be studied near the melting point only by using repeated and intense heating pulses $i(t)$. In the steady state the emitter cannot withstand the heating which performs the necessary cleaning of its surface layer, especially near melting points.

In contradiction of the results of these experiments, it was concluded in Ref. 89 that there is no anomalous emission. The experiments of Ref. 89 were carried out on tungsten emitters with a diameter $2a = 0.01$ cm and a length $l = 3$ cm at a very high current density, $j = 3.8 \cdot 10^7$ A/cm^2, for which the voltages U_R and U_{cr} were estimated above. At such values of U_R and U_{cr} a discharge arises in the diode and prevents measurements of the emission using the anode current; before this discharge appears, the anode current is cut off by the magnetic field. In addition, long pulses $i(t)$ were used in Ref. 89, and each pulse destroyed the emitter. For

this reason, a preliminary annealing of the emitter under working pulse conditions was ruled out. The experiments of Ref. 89 thus tell us nothing about the emission, and the conclusion that there are no anomalies in the emission is not justified. These questions are discussed in more detail in Ref. 87.

b) Phenomena in a diode with a tungsten emitter

Since the equilibrium emission of tungsten at its melting point is very high, $\tilde{j}_{em}^m = 480$ A/cm^2, during anomalous emission exceeding $\tilde{j}_{em}^m$ by two orders of magnitude[24] the electron density n near the emitter surface must be very high. Under these conditions, phenomena associated with deviation of the electron gas from ideality may occur in the diode. Table III (Ref. 91) shows the electron densities n, the nonideality parameter α, and the ratio f/nkT, where f is the fraction of the pressure which depends on the distance between the particles (it was calculated in Ref. 90 as a small correction to the pressure of the electron gas) for normal and anomalously high emission of tungsten.

It was found in Ref. 24 that during the anomalous emission of a tungsten emitter the anode current $I(t)$ in a vacuum diode exceeds the value I^* corresponding to the Langmuir law for the limitation of this current by the electron space charge. According to the data of Ref. 83, the reason why I exceeds I^* is not a neutralization of the space charge by ions but very intense emission. In Fig. 14a, the Langmuir value of the anode current, I^*, corresponds to the flat region which precedes the anomalous increase in $I(t)$ before the time t_o at which the heating pulse $i(t)$ ends. After this point, the anomalies in the anode current disappear over a time during which the cooling of the emitter could not be responsible for a manyfold decrease in the normal emission.

Figure 14c illustrates the case of a zero voltage from the anode power supply, $U_+ = 0$, at which the anode voltage U_a is approximately zero. The anode current I is cut off by the magnetic field of the heating current $i(U_a \ll U_{cr})$ and appears (abruptly) only at the time t_o at which this current is cut off. Figure 14b was obtained under the same conditions at a slightly greater value of t_o, but after the length of the emitter was reduced from $l = 0.5$ cm to $l = 0.015$ cm and the sensi-
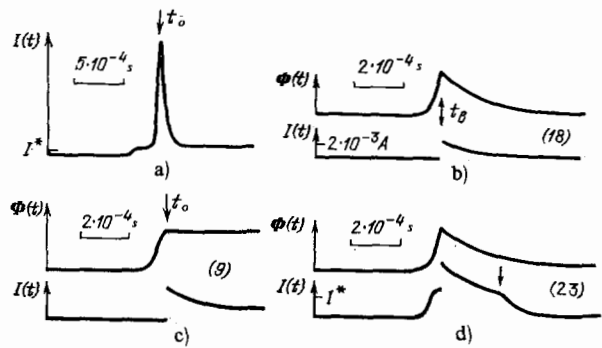

FIG. 14. Deviation from the Langmuir law for a tungsten emitter. Here $I(t)$ is the anode current, and $\Phi(t)$ the photocurrent. a—According to Ref. 83. The anode supply voltage is $U_+ = 200$ V; plane anode; $2a = 0.01$ cm; $l = 0.5$ cm; average current density $j = 5.5 \cdot 10^5$ A/cm^2; b–d—according to Ref. 47. The anode is a semicylinder of radius 0.5 cm; $2a = 0.0077$ cm; $j = 6.9 \cdot 10^5$ A/cm^2; b—$l = 0.015$ cm, $U_+ = 0$; c—$l = 0.55$ cm, $U_+ = 0$; d—$l = 0.015$ cm, $U_+ = U_a = 400$ V.

tivity of the measurement of the current I was increased. For such a short emitter, the cooling by heat conduction at the ends becomes important. The decrease in the anomalous anode current $[I(t_o) \gg I^*]$ is of the same nature in the two cases (Figs. 14b and 14c), although the temperature of the long emitter remains nearly constant, while that of the short emitter decreases, as can be seen from the photocurrent $\Phi(t)$. Consequently, the anomalously high anode current I is also observed in the case of a very short emitter, for which the voltage drop along the emitter, U_R, does not exceed 1.2 V at any time during the experiment. This voltage drop is lower than the ionization potential of tungsten vapor by a factor of more than six. The anode voltage is also low, $U_a \ll U_R$. Under these conditions, the anomalous anode current cannot be explained in terms of ionization.

At anode voltages $U_a > U_{cr}$ in experiments with a very short emitter, the rapid cooling of the emitter makes it possible to detect a bend on the $I(t)$ curve corresponding to the value $I = I^*$ not only during the increase in the emission but also during its decrease (see the arrow in Fig. 14d). In Ref. 91 the reason for the deviation from the Langmuir law was perceived to be a deviation of the potential of the electron gas from ideality outside the metal in the region of the retarding field between the emitter surface and the minimum-potential surface. This complicated question was not solved rigorously.

In a diode with a tungsten emitter yet another effect is observed at the peak of the anomalous emission: Before the metal begins to melt $(t = t_m^s)$, the anomalous anode current I goes through a "cutoff" value $(U_a < U_{cr})$ of the magnetic field. This effect cannot be explained on the basis of an interaction of electrons with metal vapor or with gases evolved from the metal, since the I pulse decays rapidly after the time t_m^s, when the density of the vapor and evolved gases does not decrease, but there is a sharp decrease in the anomalous emission. The pulse of the anode current I which appears during the flow of the current I under the condition $U_a \ll U_{cr}$ is seen in Fig. 15a at $t \approx t_m^s$; a discharge is ignited at a later time, at $t \approx t_m^l$. The cutoff of the current I by the magnetic

TABLE III.

$\tilde{j}_{em}$	T, К	$n = \frac{j_{em}}{e}\sqrt{\frac{2\pi m}{kT}}$, cm^{-3}	$\alpha = \frac{e^2 n^{1/3}}{kT}$	$\frac{\pi^{1/2}\alpha^{3/2}}{3}$
$0.01\,\tilde{j}_{em}^m$	2840	$3.6 \cdot 10^{12}$	0.009	—
$0.1\,\tilde{j}_{em}^m$	3200	$3.4 \cdot 10^{13}$	0.017	—
$\tilde{j}_{em}^m$	3655	$3.2 \cdot 10^{14}$	0.031	0.003
$10\,\tilde{j}_{em}^m$	Ditto	$3.2 \cdot 10^{15}$	0.067	0.010
$100\,\tilde{j}_{em}^m$	» »	$3.2 \cdot 10^{16}$	0.145	0.033

*The density n is estimated without allowance for the reflection coefficient, for which no data are available at $j_{em} > \tilde{j}_{em}^m$.
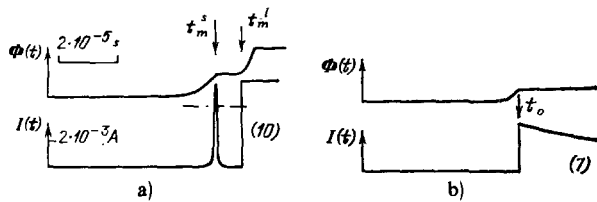
FIG. 15. a—The pulse of anode current, $I(t)$, and the emission $\Phi(t)$ of a tungsten emitter in a "cutoff" magnetic field $(U_a < U_{cr})$; b—the same emitter during a shorter preceding heating pulse $i(t)$. $j = 2.1 \cdot 10^6$ A/cm^2; $2a = 0.0077$ cm; $l = 0.26$ cm; the anode is a semicylinder of radius 0.5 cm; $U_+ = 0$. The dashed lines in Figs. 15 and 16 are the boundaries on the linear detection of the current $I(t)$ (Ref. 48).

field at low temperatures is demonstrated by Fig. 15b, which shows that the current I arises only after the current i is cut off, at $t_o < t_m^s$.

An anode current can appear in the presence of a "cutoff" magnetic field if the high density results in an interaction between emitted electrons which disrupts their motion in Larmor orbits. A necessary condition for this situation is $\Lambda_{ee} \ll a_L$, where a_L is the Larmor radius of the electron in the magnetic field of the current i, and Λ_{ee} is the mean free path with respect to electron-electron collisions, which is related to the electron density n and the emission current density j_{em}. For the experiment to which Fig. 15b corresponds an estimate of the value of j_{em} required to satisfy the equality $\Lambda_{ee} = a_L$ near the emitter surface yields[48] $j_{em} \approx 10^3$ A/cm^2, i.e., a value roughly twice the emission of tungsten at the melting point, j_{em}^m. Consequently, during the anomalous emission of tungsten, when j_{em} reaches $10 j_{em}^m - 100 j_{em}^m$, the condition $\Lambda_{ee} \ll a_L$ should be satisfied. (In this case, the radius a_L near the emitter surface is ~ 10 times smaller than the emitter radius a. In the gap between the electrodes the electron density depends not only on the anode voltage, the magnetic field, and the space charge of the electrons themselves but also on the interaction of the electrons with metal vapor and with the gas evolved from the emitter.)

The interaction of the electrons with the vapor (and, analogously, with the gas), whose density increases during the heating of the metal, along with an increase in the anomalous emission, is manifested under certain conditions in a decrease in the anode current I near the onset of melting[48] (Fig. 16a). The current I falls below the Langmuir value I^*
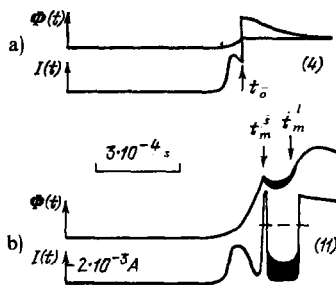

FIG. 16. The weakening of the anode current $I(t)$ by tungsten vapor in a magnetic field at $U_a > U_{cr}$. a—The heating current $i(t)$ is cut off before melting begins $(t_o < t_m^s)$; b—the same emitter, for $t_o > t_m^l$ (Ref. 48). $j = 6.2 \times 10^5$ A/cm^2; $2a = 0.0077$ cm; $l = 0.34$ cm; $U_+ = 100$ V; the anode is a semicylinder of radius 0.5 cm.

instead of increasing, as it does during the anomalous emission at a slightly lower current i or a higher anode voltage U_a. This decrease in the current I stems from the effect of the magnetic field of the current i, which reduces the diffusion coefficient of electrons in the vapor:

$$D_M = \frac{D_0}{1 + (\Lambda_{ea}/a_L)^2},$$

where D_0 is the diffusion coefficient in the absence of a magnetic field, and Λ_{ea} is the mean free path of an electron with respect to collisions with vapor atoms. At the time t_o at which the current i is cut off, and at which the magnetic field vanishes, the diffusion coefficient increases from D_M to D_0, while the anode current jumps abruptly to a value $I > I^*$. At $U_a > U_{cr}$, these jumps can be seen in Figs. 16a and 14d. If, on the other hand, the current i is not cut off (Fig. 16b), the anode current I continues to decrease, but subsequently the decrease is replaced by a sharp and brief increase up to the time t_m^s corresponding to the peak of the anomalous emission. This spike-shaped increase in the electron current to the anode at a low diffusion coefficient D_M is naturally attributed to sharp changes in the electron density gradient caused by the very rapid increase and decrease of the anomalous emission before and after the time t_m^s. In experiments with $U_a < U_{cr}$ (Fig. 15a), the anode current appears at $t \approx t^{sm}$, despite the combined effects of the metal vapor and the "cutoff" magnetic field. These changes in the anode current $I(t)$ near the time t_m^s at a constant current are unrelated to the onset of a discharge. A discharge occurs only in a later stage of the experiment, at $t \approx t_m^l$, and leads to an increase in the anode current, and this current now does not decrease until the current i is cut off (Figs. 15a and 16b).

We thus see that the metal vapor, whose equilibrium pressure for tungsten at $T = T_m$ is[88] $2 \cdot 10^{-2}$ torr, can act in two ways. At low voltages U_a or U_R —at values too low to ionize the vapor—the electron currents are weakened in the case of small values of D_M. At high values of U_a or U_R, the vapor can be ionized. In this case the currents, which initially are carried exclusively by the emission electrons, intensify and ignite a discharge. This discharge is not quenched unless there is a pronounced decrease in the voltage U_R or U_a.

c) Thermionic field emission

It was suggested in Refs. 48, 85, and 86 that the anomalously high thermionic emission results from a lowering of the work function of the metal as it is heated by the dense current. If this is the case, then we should find anomalously high values for not only the thermionic emission but also the field emission (if a high current density prevails in the interior of the field emitter), since field emission intensifies markedly upon a decrease in the work function φ:

$$j \approx \frac{e^3 E^2}{16\pi^2 \hbar \varphi} \exp\left[-\frac{4\sqrt{2m}}{3\hbar} \frac{\varphi^{3/2}}{eE} \theta\left(\frac{\sqrt{e^3 E}}{\varphi} \right) \right];$$

here e and m are the charge and mass of the electron, $\hbar$ is Planck's constant, E is the electric field, and $\theta(y)$ is the Nordheim function.[3]

---

[3] At the fields E ordinarily used, the function $\theta(y)$ varies slowly with its argument $y = \sqrt{e^3 E}/\varphi$ (Ref. 95).

An anomalously high electron current from the tip of a field emitter was first detected in Ref. 92 during microsecond pulses of an elevated anode voltage. It was found in Refs. 92–95 that the heating of the tip by the field-emission current itself causes a conversion to thermionic field emission, which intensifies in an avalanche manner with a further heating of the tip, to the point at which it melts. Comparison of data on the emission of fine tips during microsecond pulses with data on the anomalous thermionic emission of wires has revealed[85] some common features in the anode current $I(t)$ in the two experimental situations. In each case, the onset of melting of the emitter is preceded by an abrupt and pronounced increase in the emission current and by the transition of this current into a vacuum arc (in the case of high anode voltage). For the tip, the sharp increase in the field-emission current is preceded by a region in which the current is constant or even decreasing.[96] A similar behavior of the current $I(t)$ is observed during anomalous emission, in which case this decrease may be either pronounced (Fig. 16b) or weak, depending on the anode voltage U_a.

According to Ref. 97, this sharp increase in the anode current from a tip cannot be attributed to a continuation of the growth of thermionic field emission which begins earlier. It was suggested in Refs. 96 and 97 that the sharp growth of the current I "... results from processes analogous to the explosion of thin wires. ... The isolation of a dense plasma during the explosion will make it possible to resolve the problem of the formation of the medium in the vacuum gap unambiguously." Pursuit of these ideas led to a picture of explosive emission[33–35] which portrayed not so much the metal as its interaction with the plasma by the mechanism outlined in Ref. 98: "The explosion of the tip of an emitter ... leads to a sharp increase in the conductivity of the gap because of the purely electron component of the current. The electron current arises from an interaction of dense, highly ionized plasma with the surface of the cathode, which is suffering damage. Electrons are emitted from the front of the plasma and are replaced by electrons arriving from the surface of the cathode by a tunneling mechanism. A strong field near the cathode surface is produced by the positive space charge of the polarized plasma."

This picture does not make it possible to identify the phenomena of explosive emission and anomalous emission. The anomalous emission can be observed repeatedly from the same wire emitter before it begins to melt, and this phenomenon is clearly unrelated to an explosion of the metal. This picture of explosive emission[98] is not consistent with results on the explosion of conductors, particularly the following point: Experimental data show that the specific input energy w^* at which the metal begins to explode is more than three times (in the case of tungsten) the corresponding energy required for the beginning of melting. On the other hand, it is known[92–95] that in the case of microsecond pulses a sharp increase in the electron current and a melting of the tip require only a slight increase in the input energy beyond the initial value of the energy at which the tip does not yet melt. The anode voltage has to be changed by only 1% to make the switch between these two regimes. Consequently, the sharp

increase in the current from the tip, on the one hand, and the vacuum arc, on the other, during microsecond pulses do not appear during the explosion of the metal but before or at the time of the beginning of melting, just as in the case of wires at high anode voltages U_a or at high voltage drops along the wire, U_R.

The anomalous emission from the wire has not been studied during a more rapid heating, in contrast with the field emission from a fine tip and the associated phenomena, for which voluminous information was obtained in Ref. 33, in particular, for shorter pulses. These phenomena are discussed in detail in the reviews of Refs. 34, 35. There are also some questions which pertain equally well to microsecond and nanosecond processes. It is not clear how we are to reconcile the idea of explosive emission with the fact that the metal loses its conductivity during an electrical explosion. The disappearance of conductivity is attributed to the familiar "current pause," i.e., a temporary disappearance but not an increase in the current through the exploding metal. In the case of explosive emission[33,98] the sharp increase in the current from the tip due to the appearance of a cloud of explosion products should begin at the value of this current corresponding to a preexplosion liquid state of the metal, not a solid state. In a preexplosion state the temperature is ~ 3 times the melting temperature of the metal, and the metal is in the stage in which the metallic conductivity is beginning to disappear. We have no experimental data on the emission properties of the metal in such a state. Furthermore, outside the metal the emission current must flow through metal vapor. The equilibrium pressure of this vapor exceeds atmospheric pressure, since the temperature of the metal before the explosion is higher than its normal boiling point. For these reasons, we could hardly generate reliable estimates of the field-emission current from a tip either just before or after its explosion. These difficulties remain when we try to explain the high electron current during explosive emission as a consequence of a rise of the emitter temperature to tens of thousands of degrees.[99,100]

If it is assumed that the anomalies in the thermionic emission which are seen during the intense heating of wires by a dense current result from a lowering of the work function of the metal, φ, then the phenomena observed during dense current pulses in the tips of thermionic field emitters could be pictured as follows: When the metal is heated nearly to the melting point the rate of increase of the thermionic field emission should increase dramatically because a new factor comes into play[85]: a lowering of the work function φ. At the very end of the tip the current density j and the rate of energy evolution, dw/dt, increase markedly. There is a corresponding contraction ($\sim 1/j^2$) of the time interval over which the metal melts and the liquid metal is heated to the explosion point; i.e., the time at which melting begins, t_m^s, and the time at which the explosion begins, t^*, lie close together and are difficult to distinguish when the entire experiment lasts only 10^{-7}–10^{-8} s [the ratio $(t^* - t_m^s)/t_m^s$ becomes even smaller if the current in the tip rises because a discharge is ignited]. In this picture, in contrast with the picture of explosive emission,[33,98] the metal explodes after

rather than before the beginning of the rapid increase in the current from the tip.

Reasons for the emission anomalies

In accordance with the hypothesis of nonequilibrium defects[48,85,86] of the metal lattice which we mentioned in the Introduction, we could imagine the following simple mechanism for the lowering of the work function near the melting point. The equilibrium density of vacancies in a metal, which increases rapidly with increasing temperature,[4] cannot reach a steady state during rapid pulsed heating. The reason is that the bulk of the vacancies are generated at the surface of the metal and at other boundaries of the single-crystal grains, and they diffuse comparatively slowly into the interior of the metal (the Schottky mechanism). Until this diffusion is completed, there should be an excess (greater-than-equilibrium) density of interstitial atoms in the interior of a crystal because of the deficiency of vacancies, since the annihilation of these atoms with vacancies is reduced. The interstitial atoms may appear in a more rapid process by leaving lattice sites, i.e., in a process which involves the simultaneous appearance of vacancies (a Frenkel' defect). The excess density of interstitial atoms will presumably deform the lattice, thereby changing the state of the electrons in the meal (the Fermi level will rise). As a result, the work function decreases, and the emission therefore increases. The transition of the emission to an equilibrium value can be attributed to the establishment of an equilibrium defect concentration in the surface layer of the metal. It is difficult to make estimates for these processes[86] in the absence of reliable data on the characteristics of defects near the melting point. It is possible that in addition to Frenkel' defects we should consider the binary defects mentioned in Ref. 102, which are of the same type but have a shorter lifetime and a lower formation energy.

Experiments with yttrium[86] revealed a regular dependence of the height of the $(n + 1)$st anomalous-emission pulse, I_{n+1}, on the height of the preceding heating pulse, i_n. From the standpoint of the hypothesis of a nonequilibrium defect concentration this dependence would naturally be explained as resulting from quenching, which leaves "frozen" vacancies in the cold metal. The concentration of these vacancies increases with the intensity of the preceding heating. These frozen vacancies lower the anomalous emission by absorbing the interstitial atoms which arise during the rapid heating of the emitter during the following pulse, i_{n+1}. Consequently, after a "weak" heating pulse i fewer frozen vacancies remain in the cooled metal, so that during the next pulse, i_{n+1}, a higher concentration of interstitial atoms is reached, so that the amplitude of the anomalous emission, I_{n+1}, is higher than after an intense preceding heating pulse.

The experiments in Ref. 86 also included a study of the dependence of the anomalous and normal electron emission

---

[4]According to the estimates available, the number of vacancies near the melting point of a metal does not exceed a few tenths of 1% of the number of atoms. Working from the experimental data of Ref. 101 for tungsten, we find $\sim 3\%$.

of yttrium on volume contaminants (impurities), whose concentration decreases as the emitter is raised to a high temperature. The effects observed in this situation can be described qualitatively under the assumption that these impurity atoms intensify the emission of yttrium in basically the same way that interstitial yttrium atoms would. The actual picture of the decrease in the work function φ may of course be considerably more complicated than this primitive outline. It may be that a decisive role is played not by the interstitial atoms, vacancies, and impurity atoms directly but by complexes of these simple defects.

Working from the Richardson law

$$j_{em} \sim T^2 \exp\left(-\frac{\varphi}{kT}\right),$$

we can attribute the emission anomalies to either a lowering of the work function φ or a rise of the temperature T due to overheating of the electron gas (overheating of the metal as a whole could not be detected from its resistance R). The possibility of overheating of the electron gas fell into disfavor after it was learned that the relaxation time of the anomalous emission is very long $(\tau \sim 1 \cdot 10^{-4} - 5 \cdot 10^{-4}$ s).

It should be noted that, by analogy with the emission of thoriated tungsten, which has been studied quite well in the steady state, we might attempt to explain the anomalous emission as resulting from the appearance on the surface of the emitter of a monomolecular film of impurities, even if the impurity concentration in the interior is low. Such a film might form through the diffusion of the impurity from the interior of the emitter during its cooling after a preceding pulse (a thick film does not form in the case of thoriated tungsten, since thorium atoms evaporate more readily from a thick film of thorium than from tungsten). The decrease in the emission from $I(t_o)$ to $I(t_o + \tau)$ after the time (t_o) at which the heating current i is turned off (Fig. 12) might result from the evaporation of this film at the high temperature $T(t_o)$ reached at the time t_o (at a high temperature, the film may evaporate more rapidly than it is replenished by diffusion).

However, the assumption that there is a film of this type does not agree with the results of the pulsed experiments which we have been discussing, as can be seen most easily in the case of tungsten, since tungsten can be purified quite well by annealing. In Ref. 84, which we mentioned earlier, a check revealed that there was no film which greatly intensified the emission from the tungsten emitter. It was found in Ref. 84 that during pulsed heating the emission is initially (under the condition $T < 2600$ K $\approx 0.7T_m$) the same as the corresponding value in the steady state and that the anomalous increase in the emission begins only during more intense pulsed heating. Over the time required to heat the emitter from $T = 0.7\,T_m$ to $T(t_o)$, however, it would be unrealistic to expect the appearance of a film: In the experiments of Ref. 84, this time was $\lesssim 10^{-5}$ s, and furthermore at $T = T(t_o)$ a film of this sort should not have formed but evaporated, since the emission decreases at the temperature $T(t_o)$ after the time t_o. The temperature $T(t_o)$ could be varied.

Let us list the main experimental results on which our interpretation of the anomalous emission is based: 1) the unusually high electron emission and its decrease to the equi-

librium value with essentially no change in emitter temperature (W, Ir, Ni); 2) the effect of "quenching" of the emitter on the anomalously high emission (Ir); 3) the deviation from Langmuir's three-halves law for a vacuum diode with a tungsten emitter, for which the anomalous emission is particularly high; 4) the passage of the anomalous-emission current of tungsten at its peak value through the cutoff magnetic field; 5) the sharp increase in the rate of increase of the current in pulsed thermionic field emission and the ignition of a vacuum arc before the field emitter begins to melt.

6. SPECIFIC HEAT

The specific heat of refractory metals during rapid heating by an electric current was studied in Refs. 25, 49, 103, and 104 at pressures near atmospheric. The heat supplied to the metal was determined from Joule's law by the method described in Section 3. Two methods were used to determine the temperature T. One was based on measurements of the resistance R of the conductors and the use of the ordinary temperature dependence of R; no deviations from this ordinary dependence are observed under these heating conditions. The tabulated melting temperature of the given metal is assigned to the time (t_m^s) at which the conductor begins to melt, found from the slope change on the oscilloscope trace of $U_R(t) = i(t)R(t)$ (Fig. 2a). The resistance and the Joule heat supplied were determined with respect to this change in slope for various times $t < t_m^s$ on the same oscilloscope traces, $U_R(t)$ and $U_r(t)$. This procedure was used only for the solid state, since the temperature dependence of the resistance has not been studied for liquid refractory metals. The other method suitable to determine the temperature, which can be used in both the liquid and solid states, makes use of Planck's law for the spectral brightness of the thermal emission of a blackbody, $b_\lambda[T]$. The visible emission of a conductor, which intensifies with increasing temperature $T(t)$, was detected with a photoelectric detector and an interference filter and recorded as oscilloscope traces of the photocurrent $\Phi(t) = K\varepsilon_\lambda[T(t)]b_\lambda[T(t)]$. Here K characterizes the experimental apparatus, and $\varepsilon_\lambda[T]$ is the emissivity of the emitter.

In the first experiments[25] on the specific heat near the melting point it was assumed that in a narrow temperature interval ΔT for the solid state the emissivity of the metal surface, ε_λ, remains the same as at the beginning of melting (at the time t_m^s), while for the liquid state ε_λ remains the same as at the end of melting (at the time t_m^l). For such time intervals ΔT we have $b_\lambda[T(t)] = b_\lambda[T_m]\Phi(t)/\Phi(t_m^s)$ in the solid state and $b_\lambda[T(t)] = b_\lambda[T_m]\Phi(t)/\Phi(t_m^s)$ in the liquid state. In the determination of $b_\lambda[T(t)]$, the quantities $\Phi(t)/\Phi(t_m^s)$ and $\Phi(t)/\Phi(t_m^s)$ were determined from oscilloscope traces of $\Phi(t)$, with allowance for the slope changes at t_m^s and t_m^l. The tabulated melting point of the metal was used for T_m. These results were used along with ordinary tables for $b_\lambda[T]$ to determine $T(t)$ are various times t. The Joule heat was determined from the oscilloscope traces of $U_R(t)$ and $U_r(t)$. The accuracy of this optical method deteriorates with distance from the melting point in either direction along the temperature scale.

In Refs. 103 and 104 the temperature range over which this method could be used was broadened greatly by replacing the wires by strips of foil rolled into tubular blackbody models $(\varepsilon = 1)$. One end of the tube was pinched, and the radiation was coupled out of the cavity at the other end with the help of a cylindrical light-guide with a blackened lateral surface. This model was used up to the time t', while the voltage drop across the model, $U_R(t)$, was the same as that across a wire of the same material and the same length at the same heating current density. In the experiments of Ref. 103, the model could be heated to a temperature ~ 4000 K by the time t', while in the experiments of Ref. 104 it could be heated to ~ 5000 K. The apparent reason for the discrepancy between the $U_R(t)$ curves at $t > t'$ is the development of a preexisting roughness on the surface of the foil. Pulsed x-ray photographs showed that there was no significant deformation of the model as a whole up to the time t' and beyond, up to the beginning of the explosion of the metal.

The results of these experiments can be summarized as follows. During heating by a dense current in that region of the solid state in which anomalies are observed in the electron emission, an elevated specific heat is also observed. Near the melting points of the metals studied (W, Ta, Mo, Nb), the specific heat exceeds the corresponding equilibrium value by some tenths—outside any possible experimental error. In the preceding heating stages, i.e., at lower temperatures, there are no anomalies in the specific heat. In the liquid state near the melting point the specific heat is near its value just before the beginning of melting; later on, this specific heat decreases. The anomalous behavior of the specific heat $C_p(T)$ near the melting point in the solid and liquid states remains the same as the heating rate is varied by a factor ~ 150, i.e., as the current density is varied over the range $j \approx 8 \cdot 10^5 - 1 \cdot 10^7$ A/cm^2 (Refs. 25 and 104). (At a lower heating rate, the heat loss would have to be taken into account.)

Some of the results are shown in Fig. 17. The circles are experimental points found in Ref. 49 for the specific heat of tungsten during pulsed heating ($j \approx 5 \cdot 10^6$ A/cm^2) in measurements of the temperature dependence of R. At $T \gtrsim 3300$ K these points lie above the solid curve, which was obtained for the slow process in Ref. 101. [According to data from other investigators, in particular, Ref. 105, the curve of $C_p(T)$ for tungsten during the slow process near T_m lies slightly below the solid curve.] At $T \gtrsim 3500$ K, an elevated
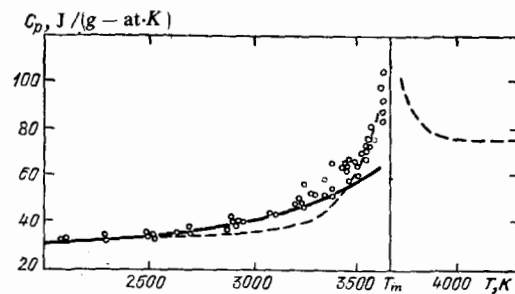

FIG. 17. Measurements of the specific heat of tungsten.[25,49]

specific heat during the fast process also emerges from the experiments of Ref. 25, where the temperature was determined from the emission of the surface of the wires under study. The results of these measurements for the solid and liquid states are shown by the dashed curve. With distance from the melting point in either direction along the temperature scale, this line does not describe the actual behavior of $C_p(T)$ because of the change in the emissivity $\varepsilon(T)$ of the wire surface.

Figure 18 shows that the specific heat during rapid heating for tantalum is higher than the corresponding specific heat in a slow process. In the fast process (the heavy line) the specific heat was measured for both the solid and liquid states in Ref. 103 with the help of a blackbody model at $j \approx 5 \cdot 10^6$ A/cm^2. For the slow process we have taken data from Refs. 101 and 106 (light lines 1 and 2, respectively). The dashed line is the specific heat found for liquid tantalum in Ref. 66 during rapid pulsed heating at a pressure of $1 \cdot 10^3$ atm in a determination of the temperature from the emission of the surface of a wire. These results well into the liquid region are considerably higher than the results of the measurements with the blackbody model.

The specific heat of niobium during the rapid process was measured in Ref. 104; in the solid state, the temperature was determined from the temperature dependence of R at a comparatively low current density, $j = 7 \cdot 10^5$ A/cm^2. The liquid state was studied at $j = 5 \cdot 10^6$ A/cm^2 with a blackbody model. The results of these pulsed measurements are shown by the circles in Fig. 19. Solid lines 1–3 show data from Refs. 101, 107, and 108, respectively, on the slow process. The dashed line shows the measurements of C_p in Ref. 66 at a pressure of $2 \cdot 10^3$ atm in a fast pulsed regime; the temperature is determined from the emission of the wire surface. It can be seen from Figs. 18 and 19 that for niobium, as for tantalum, the results found from measurements of the specific heat on the basis of the emission from the wire surface well in the liquid region are high in comparison with the data found for the blackbody model. As mentioned above, this difference can be explained in a natural way on the basis of a change in the emissivity of the metal surface, ε.

For tungsten, measurements[25] of the temperature from the surface emission also yield an unnaturally high specific heat at $T \gtrsim 4000$ K (Fig. 17); these measurements were carried out at atmospheric pressure. During a single heating pulse, a change in ε may result not only from an increase in the temperature of the metal but also from an evaporation of
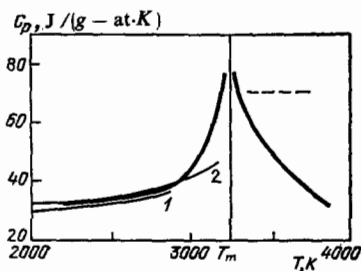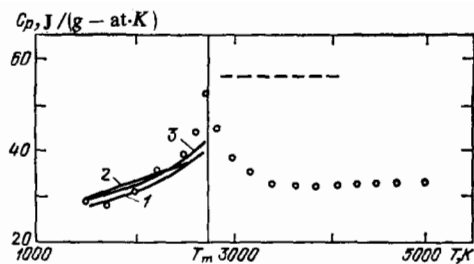

FIG. 18. Measurements of the specific heat of tantalum.[103]

FIG. 19. Measurements of the specific heat of niobium.[104]

contaminants from its surface.

This discussion of data on the specific heat of liquid refractory metals is limited by the lack of corresponding data for the steady state. The reasons for the anomalies in the specific heat of the metal in the solid state which occur during the fast process have not been finally resolved, and the same is true of the mechanism for the anomalous emission. With regard to the hypothesis of nonequilibrium defects in the metal we can offer the following comments. We know that as a metal is heated slowly in its solid state, and the melting point is approached, the specific heat will increase. This increase can be explained in a natural way as resulting from an expenditure of energy on the formation of thermal lattice defects.[101] The nonequilibrium nature of the defects could therefore be expected to be manifested as features in the specific heat, and these features would appear near the melting point, where they are in fact observed. The suggestion that the anomalies in the specific heat are of the same physical nature as those in the electron emission agrees with the fact that the anomalies are seen in the same state of the metal in the two cases and under the same heating conditions. There has been no study of the specific heat of low-melting metals during rapid heating by a current ($j \gtrsim 10^6$ A/cm^2).

7. CONCLUSION

1. We have seen that in pulsed experiments with very dense currents it is possible to obtain information about the properties of metals which is fundamentally different from that which can be obtained by steady-state methods.[109,110] This information is required primarily for metals at the high temperatures inaccessible to steady-state methods. When a pulsed method is used, however, it is necessary to determine whether this method yields equilibrium values of the measured properties. This important question is resolved in control experiments where it is possible to compare directly data obtained in pulsed and steady-state regimes, i.e., at relatively low temperatures or for the less refractory metals. It should be kept in mind that the pulsed method discussed here (in contrast with the steady-state method) is equally suitable for metals with all melting points.

Control experiments have shown that pulsed and steady-state measurements yield essentially the same results for several properties (in particular, the heat of fusion, the electrical conductivity in the liquid and solid states at the melting point, and the thermal expansion in the first part of the liquid region). It is thus possible to find the equilibrium

values of these properties within the accuracy of experiments by the pulsed method. A convincing example is the measurement of the heat of fusion of niobium, where a value of 297 J/g was found[111] in a fast ($\sim 10^{-5}$ — s) pulsed process, and 290 J/g was found[112] in a slow ($\sim 10^{-1}$ — s) pulsed process. Measurements by a magnetic levitation method yielded[55] 297 J/g. The heat of fusion which had been predicted for niobium before these experiments was[113] 355 J/g. Nonequilibrium phenomena—anomalies in the emission and the specific heat—have been observed in pulsed experiments only in a comparatively narrow temperature interval near the melting points of the metals.

The only studies of the liquid state of a metal which have been carried out at high input energies have been in the pulsed regime, so that it is not yet possible to compare the results of pulsed and steady-state measurements for such states.

In most studies of the properties of metals during fast pulsed heating the results are presented as functions of the energy supplied to the metal. The complicated problem of measuring the high temperatures under these conditions can be approached by using a blackbody model which will be destroyed as the ("exploding") metal test sample (Section 6). Such a model is exceedingly useful for high-temperature experiments with liquid metals, since the emissivities of the surfaces of liquid metals and the temperature dependences of their other properties have not been studied.

2. Rapid heating by an electric current opens up some broad possibilities for obtaining experimental data in a region which has received little study: that of high temperatures and high pressures. Obviously, it is much easier to produce a high pressure in a metal for a brief time by pulsed heating than in a steady state. Pulsed thermocompression is a promising method (Section 3), and corresponding studies have already begun. In particular, the electrical conductivity of liquid metals (Al, Cu, Mo, and W) has been studied[57,58,114] at pressures up to $\sim 4 \cdot 10^4$ atm, generated by pulsed thermocompression. It was found in Ref. 64 that the amount of energy which can be pumped into a metal sample is significantly higher if the volume into which it can expand is limited than in the case of free expansion. The conductivity of a liquid metal (tungsten) changes only very slightly in a restricted volume. An even higher pressure can be achieved, and even more energy can be injected into a metal in a condensed state, in the thermocompression method by increasing the density of the heating current (i.e., increasing the heating rate) or by also imposing an external pressure.

3. Studies of the physical mechanism for the anomalies in the electron emission and specific heat are interesting, as is a study of the suggested relationship between these anomalies and thermal defects in a metal. These questions have not been finally resolved and require further study. Without going into the concrete reasons for the anomalies in the electron emission and the specific heat, we can imagine the following general scheme for the occurrence of nonequilibrium phenomena in pulsed experiments: As a metal is heated quite rapidly, certain features of its original state (a comparatively low-temperature state) may be carried along to the higher

temperatures. Here we mean, on the one hand, the equilibrium features of the original state (the concentration of thermal defects, for example) and, on the other, nonequilibrium features of the original state which resulted from a preliminary treatment of the metal. There is thus an analogy (an inverse analogy) with ordinary quenching, in which the features of the state of the metal characteristic of high temperatures are carried down to low temperatures through a rapid cooling.

Despite the short life of the nonequilibrium phenomena which result from the pulsed heating of the metal to a high temperature, these phenomena may play an important role in fast processes (according to Ref. 86, the relaxation time of the anomalous emission is $\sim 5 \cdot 10^{-4}$ s).

According to this general picture, the proposed explanation for the anomalous emission in terms of nonequilibrium thermal defects is (Section 5) the transfer of a negligibly low equilibrium vacancy concentration corresponding to the original temperature up to high temperatures, where the equilibrium vacancy concentration would be far higher. From this standpoint, the dependence of the amplitude of the anomalous-emission pulse on the rate of cooling of the emitter after a preceding pulse which was discovered in Ref. 86 could be explained in a natural way as the result of the transfer to the high-temperature region of nonequilibrium features of the original low-temperature state (i.e., features which reflect the "prehistory" of the metal). The same could be said regarding the dependence of the heat of fusion of a metal during rapid heating on the particular features of the preceding treatment, mentioned in the Introduction. Significantly, these features can be controlled or eliminated through a sufficiently slow preliminary heating or a preliminary annealing.

4. The disappearance of the conductivity of a metal and the conversion of a metal into a sol which are observed during pulsed heating at high input energies (Section 4) can be discussed in a natural way in connection with the general problem of metal-nonmetal transitions.[115]

The questions and experimental results which we have reviewed here obviously do not exhaust the possibilities for obtaining information about the properties of metals through rapid pulsed heating by an electric current, in particular, at high pulsed pressures. More information could be obtained by studying other metals (including amorphous metals) and other conducting materials (e.g., carbon and, especially, various alloys). Pulsed heating also holds promise for studying the strength characteristics of metals and alloys near the region of the transition to the liquid state. It would be particularly interesting to study other physical phenomena and the relationships between them. We make particular note of thermoelectric phenomena, where we could expect to find some distinctive features under anomalous-emission conditions.

[1]W. G. Chace, Phys. Today 17(8), 19 (1964) [Russ. Transl., Usp. Fiz. Nauk 85, 381 (1965)].

[2]J. A. Anderson, Astrophys. J. **51**, 37 (1920).

[3]J. A. Anderson and S. Smith, Astrophys. J. **64**, 295 (1926).

[4]W. G. Chace and H. K. Moore (editors), Exploding Wires, Vol. 1, Plenum Press, N. Y. (1959) [Russ. Transl. IL, M., 1963].

[5]W. G. Chace and H. K. Moore (editors), Exploding Wires, Vol. 2, Plenum Press, N. Y. (1962) [Russ. Transl. Mir, M., 1965].

[6]W. G. Chace and H. K. Moore, Exploding Wires, Vol. 3, Plenum Press, N. Y., 1964; Vol. 4, 1968.

[7]J. Wrana, Arch. Elektrotechn. **33**, 656 (1939).

[8]W. M. Conn, Z. Angew. Phys. 7, 539 (1955).

[9]I. F. Kvartskhava, A. A. Plyutto, A. A. Chernov, and V. V. Bondarenko, Zh. Eksp. Teor. Fiz. **30**, 42 (1956) [Sov. Phys. JETP **3**, 40 (1956)].

[10]S. V. Lebedev and S. É. Khaǐkin, Zh. Eksp. Teor. Fiz. **26**, 629 (1954).

[11]S. V. Lebedev, Zh. Eksp. Teor. Fiz. **32**, 199 (1957) [Sov. Phys. JETP **5**, 243 (1957)].

[12]F. G. Carioris, B. R. Fish, and G. W. Royster, in: Exploding Wires, Vol. 2 (ed. W. G. Chace and H. K. Moore), Plenum Press, N. Y. (1962), p. 299.

[13]S. V. Lebedev, B. V. Lukin, A. E. Rautbort, and A. I. Savvatimskǐ, Teplofiz. Vys. Temp. 7, 1020 (1969).

[14]S. V. Lebedev, Teplofiz. Vys. Temp. **6**, 157 (1968).

[15]L. N. Borodovskaya and S. V. Lebedev, Zh. Eksp. Teor. Fiz. **28**, 96 (1955) [Sov. Phys. JETP **1**, 71 (1955)].

[16]S. V. Lebedev, A. I. Savvatimskǐ, and Yu. B. Smirnov, Teplofiz. Vys. Temp. **9**, 635 (1971).

[17]S. V. Lebedev, A. I. Savvatimskǐ, and Yu. B. Smirnov, Zh. Tekh. Fiz. **42**, 1752 (1972) [Sov. Phys. Tech. Phys. **17**, 1400 (1972)].

[18]M. M. Martynyuk, V. I. Tsapkov, O. G. Panteleǐchuk, and I. Karimkhodzhaev, Issledovanie fizicheskikh svoǐstv metallov metodom impul'snogo nagreva (Pulsed-Heating Studies of the Physical Properties of Metals), UDN im. P. Lumumby, M., 1972.

[19]S. V. Lebedev and A. I. Savvatimskǐ, Teplofiz. Vys. Temp. **8**, 524 (1970).

[20]S. V. Lebedev and A. I. Savvatimskǐ, Fiz. Khim. Obrab. Mater. No. 1, 6 (1976).

[21]S. V. Lebedev, Teplofiz. Vys. Temp. **18**, 273 (1980).

[22]I. D. Morokhov, V. I. Petinov, L. I. Trusov, and V. F. Pervukhin, Usp. Fiz. Nauk **133**, 653 (1981) [Sov. Phys. Usp. **24**, 295 (1981)].

[23]Yu. I. Petrov, Fizika malykh chastits (The Physics of Small Particles), Nauka, M., 1982.

[24]S. V. Lebedev and S. É. Khaǐkin, Zh. Eksp. Teor. Fiz. **26**, 723 (1954).

[25]I. Ya. Dikhter and S. V. Lebedev, Teplofiz. Vys. Temp. **8**, 55 (1970); I. Ya. Dikhter and S. V. Lebedev, High Temp. High Press. **2**, 55 (1970).

[26]P. W. Bridgman, Phys. Rev. **19**, 131 (1922).

[27]H. M. Barlow, Philos. Mag. **9**, 1041 (1930).

[28]L. Nordheǐm, Helv. Phys. Acta 7, Suppl. II, 3 (1934) [Russ. Transl., Usp. Fiz. Nauk **15**, 800 (1935)].

[29]V. L. Ginzburg and V. P. Shabanskǐ, Dokl. Akad. Nauk SSSR **100**, 445 (1955).

[30]V. E. Il'in and S. V. Lebedev, Zh. Tekh. Fiz. **32**, 986 (1962) [Sov. Phys. Tech. Phys. 7, 717 (1963)].

[31]V. A. Glukhikh, in: Voprosy atomnoǐ nauki i tekhniki (Questions of Atomic Science and Engineering), Nos. 1-2, M., 1978, p. 113.

[32]V. V. Andrianov, V. P. Baev, S. V. Lebedev, and A. I. Savvatimskǐ, Dokl. Akad. Nauk SSSR **256**, 1119 (1981) [Sov. Phys. Dokl. **26**, 216 (1981)].

[33]G. A. Mesyats and D. I. Proskurovskǐ, Pis'ma Zh. Eksp. Teor. Fiz. **13**, 7 (1971) [JETP Lett. **13**, 4 (1971)].

[34]S. P. Bugaev, E. A. Litvinov, G. A. Mesyats, and D. I. Proskurovskǐ, Usp. Fiz. Nauk **115**, 101 (1975) [Sov. Phys. Usp. **18**, 51 (1975)].

[35]E. A. Litvinov, G. A. Mesyats, and D. I. Proskurovskǐ, Usp. Fiz. Nauk **139**, 265 (1983) [Sov. Phys. Usp. **26**, 138 (1983)].

[36]A. M. Andrianov, S. P. Anan'ev, N. N. Gennadiev, V. F. Demichev, and P. A. Levit, Pis'ma Zh.Tekh. Fiz. **8**, 240 (1982) [Sov. Tech. Phys. Lett. **8**, 106 (1982)].

[37]S. V. Lebedev and A. I. Savvatimskǐ, Teplofiz. Vys. Temp. **19**, 1184 (1981).

[38]A. Cezairliyan, High Temp. High Press. **11**, 9 (1979).

[39]S. V. Lebedev, Teplofiz. Vys. Temp. **19**, 301 (1981).

[40]R. J. Reithel and J. H. Blackburn, in: Exploding Wires, Vol. 2 (ed. W. G. Chace and H. K. Moore), Plenum Press, N. Y. (1962), p. 21.

[41]V. V. Ivanov, Teplofiz. Vys. Temp. **21**, 146 (1983).

[42]L. D. Landau and E. M. Lifshitz, Élektrodinamika sploshnykh sred, Nauka, M., 1982, p. 292 [Engl. Transl. of earlier edition, Electrodynamics of Continuous Media, Pergamon, N. Y., 1974].

[43]N. N. Sobolev, Zh. Eksp. Teor. Fiz. **17**, 655, 987 (1947).

[44]K. S. Fansler and D. D. Shear, in: Exploding wires, Vol. 4 (ed. W. G. Chace and H. K. Moore), Plenum Press, N. Y., 1968, p. 185.

[45]K. B. Abramova, V. P. Valitskǐ, Yu. V. Vandakurov, N. A. Zlatin, and B. P. Peregud, Dokl. Akad. Nauk SSSR **167**, 778 (1966) [Sov. Phys. Dokl. **11**, 301 (1966)].

[46]K. B. Abramova, N. A. Zlatin, and B. P. Peregud, Zh. Eksp. Teor. Fiz. **69**, 2007 (1975) [Sov. Phys. JETP **42**, 1019 (1975)].

[47]S. V. Lebedev, Zh. Eksp. Teor. Fiz. **50**, 509 (1966) [Sov. Phys. JETP **23**, 337 (1966)].

[48]S. V. Lebedev, Teplofiz. Vys. Temp. **8**, 252 (1970).

[49]S. V. Lebedev, A. I. Savvatimskǐ, and M. A. Sheǐndlin, Teplofiz. Vys. Temp. **14**, 285 (1976).

[50]S. V. Lebedev and G. I. Mozharov, Teplofiz. Vys. Temp. **14**, 1266 (1976).

[51]N. E. Cusak, Rep. Prog. Phys. **26**, 361 (1963).

[52]A. R. Ubbelohde, Melting and Crystal Structure, Oxford Univ. Press, N. Y., 1965 [Russ. Transl. Mir, M., 1969].

[53]J. R. Wilson, Met. Rev. **10**, 560 (1965).

[54]V. Ya. Chekhovskoi and S. A. Kats, High Temp. High Press. **13**, 611 (1981).

[55]A. E. Sheindlin, B. Ya. Berezin, and V. Ya. Chekhovskoi, High Temp. High Press. **4**, 611 (1972).

[56]G. Betz and M. G. Frohberg, High Temp. High Press. **12**, 169 (1980).

[57]V. V. Ivanov, S. V. Lebedev, and A. I. Savvatimskǐ, Teplofiz. Vys. Temp. **20**, 1093 (1982).

[58]V. V. Ivanov, S. V. Lebedev, and A. I. Savvatimskǐ, Teplofiz. Vys. Temp. **21**, 390 (1983).

[59]A. P. Sukhotin and S. D. Viktorov, in: Razrushenie i deformirovanie tverdoǐ sredy vzryvom (Destruction and Deformation of Solids by Explosions), ed. V. N. Rodionov, Nedra, M., 1976, p. 55.

[60]G. R. Gathers, J. W. Shaner, and D. A. Young, Phys. Rev. Lett. **32**, 70 (1974).

[61]J. W. Shaner, G. R. Gathers, and C. Minichino, High Temp. High Press. **9**, 331 (1977).

[62]G. R. Gathers, J. W. Shaner, and W. M. Hodgson, High Temp. High Press. **11**, 529 (1979).

[63]V. V. Ivanov, S. V. Lebedev, and A. I. Savvatimskǐ, J. Phys. F **14**, 1641 (1984).

[64]S. V. Lebedev and A. I. Savvatimskǐ, Teplofiz. Vys. Temp. **16**, 211 (1978).

[65]U. Seydel and W. Kitzel, J. Phys. F **9**, L153 (1979).

[66]J. W. Shaner, G. R. Gathers, and W. M. Hodgson, in: Proceedings of the Seventh Symposium on Thermophysical Properties, Nat. Bur. Stand., Gaithersburg, 1977.

[67]E. I. Gol'tsova, Teplofiz. Vys. Temp. **3**, 483 (1965).

[68]W. D. Drotning, High Temp. High Press. **13**, 441 (1981).

[69]S. V. Lebedev, A. I. Savvatimskǐ, and N. V. Stepanova, Teplofiz. Vys. Temp. **16**, 67 (1978).

[70]V. M. Kul'gavchuk and G. A. Novoskol'tseva, Zh. Tekh. Fiz. **36**, 549 (1966) [Sov. Phys. Tech. Phys. **11**, 406 (1966)].

[71]K. W. Henry, D. R. Stephens, D. J. Steinberg, and E. B. Royce, Rev. Sci. Instrum. **43**, 1777 (1972) [Russ. Transl. Prib. nauch. issled. No. 12, 42 (1972)].

[72]I. K. Kikoin and A. P. Senchenkov, Fiz. Met. Metalloved. **24**, 843 (1967).

[73]V. A. Burtsev, N. V. Kalinin, and V. N. Litunovskǐ Élektricheskǐ vzryv provodnikov (Electrical Explosions of Conductors), NIIÉFA, Leningrad, 1977.

[74]M. M. Martynyuk, Zh. Tekh. Fiz. **44**, 1262 (1974) [Sov. Phys. Tech. Phys. **19**, 793 (1974)].

[75]A. P. Baǐkov and A. F. Shestak, Pis'ma Zh. Tekh. Fiz. **8**, 1457 (1982) [Sov. Tech. Phys . Lett. **8**, 626 (1982)].

[76]Ya. I. Frenkel', Kineticheskaya teoriya zhidkosteǐ, Nauka, L., 1975. [Engl. Transl. of earlier edition, J. Frenkel', Kinetic Theory of Liquids, Dover, N. Y., 1955].

[77]T. Faber, in: The Physics of Metals (ed. J. M. Ziman), Cambridge Univ. Press, 1964 (Russ. Transl. Mir, M., 1972, Vol. 1, p. 317).

[78]W. G. Chace, in: Exploding Wires, Vol. 1 (ed. W. G. Chace and H.K. Moore), Plenum Press, N. Y., 1959, p. 7.

[79]N. V. Grevtsev, V. D. Zolotukhin, Yu. M. Kashurnikov, V. A. Letyagin, and B. I. Makhorin, Teplofiz. Vys. Temp. **15**, 362 (1977).

[80]V. L. Budovich and I. P. Kuzhekin, Zh. Tekh. Fiz. **46**, 737 (1976) [Sov. Phys. Tech. Phys. **21**, 428 (1976)].

[81]K. B. Abramova, V. L. Budovich, I. P. Kuzhekin, and B. P. Peregud, Zh. Tekh. Fiz. **46**, 1465 (1976) [Sov. Phys. Tech. Phys. **21**, 834 (1976)].

[82]F. N. Weber and D. D. Shear, J. Appl. Phys. **40**, 1969 (1969)

770   Sov. Phys. Usp. **27** (10), October 1984

S. V. Lebedev and A. I. Savvatimskǐ   770

[83]S. V. Lebedev, Zh. Eksp. Teor. Fiz. **27**, 487 (1954).

[84]I. L. Ivantsova and S. V. Lebedev, Teplofiz. Vys. Temp. **9**, 1168 (1971).

[85]S. V. Lebedev, Teplofiz. Vys. Temp. **11**, 986 (1973).

[86]S. V. Lebedev and N. V. Stepanova, Poverkhnost' No. 5, 101 (1982).

[87]S. V. Lebedev, Teplofiz. Vys. Temp. **19**, 203 (1981).

[88]S. Dushman and J. M. Lafferty, Scientific Foundations of Vacuum Technique, Wiley, N. Y., 1962 [Russ. Transl., Mir, M., 1964, p. 614].

[89]S. M. Karakhanov, Zh. Tekh. Fiz. **48**, 1474 (1978) [Sov. Phys. Tech. Phys. **23**, 832 (1978)].

[90]A. Isihara, Statistical Physics, Academic Press, N. Y., 1971 [Russ. Transl., Mir, M., 1973, p. 140].

[91]S. V. Lebedev, Teplofiz. Vys. Temp. **15**, 1099 (1977).

[92]W. P. Dyke and J. K. Trolan, Phys. Rev. **89**, 799 (1953).

[93]W. P. Dyke, J. K. Trolan, and E. E. Martin, Phys. Rev. **91**, 1054 (1953).

[94]W. P. Dyke, J. P. Barbour, E. E. Martin, and J. K. Trolan, Phys. Rev. **99**, 1192 (1955).

[95]M. I. Elinson and G. F. Vasil'ev, Avtoélektronnaya émissiya (Field Emission), Fizmatgiz, M., 1958.

[96]I. L. Sokol'skaya and G. N. Fursei, Radiotekh. Elektron. **7**, 1474 (1962).

[97]G. N. Fursei and P. N. Vorontsov-Vel'yaminov, Zh. Tekh. Fiz. **37**, 1880 (1967) [Sov. Phys. Tech. Phys. **12**, 1377 (1968)].

[98]G. N. Fursei, Author's Abstract, Doctoral Dissertation, Novosibirsk, 1973.

[99]M. M. Martynyuk, Zh. Tekh. Fiz. **48**, 1482 (1978) [Sov. Phys. Tech. Phys. **23**, 837 (1978)].

[100]E. A. Litvinov, G. A. Mesyats, and A. G. Parfenov, Dokl. Akad. Nauk SSSR **269**, 343 (1983) [Sov. Phys. Dokl. **28**, 272 (1983)].

[101]Ya. A. Kraftmakher, in: Issledovaniya pri vysokikh temperaturakh (High-Temperature Research) (ed. I. I. Novikov and P. G. Strelkov), Nauka, Novosibirsk, 1966.

[102]V. M. Koshkin and Yu. R. Zabrodskii, Dokl. Akad. Nauk SSSR **227**, 1323 (1976) [Sov. Phys. Dokl. **21**, 203 (1976)].

[103]S. V. Lebedev and G. I. Mozharov, Teplofiz. Vys. Temp. **15**, 53 (1977).

[104]G. I. Mozharov and A. I. Savvatimskii, Teplofiz. Vys. Temp. **19**, 954 (1981).

[105]A. Cezairliyan and J. L. McClure, J. Res. Nat. Bur. Stand. **A75**, 283 (1971).

[106]A. Cezairliyan, J. L. McClure, and C. W. Beckett, J. Res. Nat. Bur. Stand. **A75**, 1 (1971).

[107]L. P. Filippov and R. P. Yurchak, Inzh.-Fiz. Zh. **21**, 561 (1971).

[108]A. Cezairliyan, J. Res. Nat. Bur. Stand. **75**, 565 (1971).

[109]V. A. Alekseev, A. A. Andreev, and V. Ya. Prokhorenko, Usp. Fiz. Nauk **106**, 393 (1972) [Sov. Phys. Usp. **15**, 139 (1972)].

[110]A. R. Regel' and V. M. Glazov, Periodicheskii zakon i fizicheskie svoistva élektronnykh rasplavov (The Periodic Law and the Physical Properties of Electrically Melted Materials), Nauka, M., 1978; Fizicheskie svoistva élektronnykh rasplavov (Physical Properties of Electrically Melted Materials), Nauka, M., 1980; Zakonomernosti formirovaniya struktury élektronnykh rasplavov (Regularities in the Formation of the Structure of Electrically Melted Materials), Nauka, M., 1982.

[111]A. I. Savvatimskii, Teplofiz. Vys. Temp. **11**, 1182 (1973).

[112]A. Cezairliyan, Faraday Symposia of the Chemical Society No. 8, 30 (1973).

[113]J. L. Margrave, High Temp. High Press. **2**, 583 (1970).

[114]V. V. Ivanov, Author's Abstract, Candidate's Dissertation, Moscow, 1983.

[115]R. Evans and D. A. Greenwood (editors), Liquid Metals, Am. Inst. Phys., N. Y. (1977) (Russ. Transl. ed. V. M. Glazov, Metallurgiya, M., 1980).

Translated by Dave Parsons