ELEMENTARY AND THERMOPHYSICAL PROPERTIES AT THE CATHODE IN THE CASE OF A POWERFUL PULSE DISCHARGE

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The equilibrium conditions for cathode processes are investigated in the high-temperature region by simultaneous consideration of evaporation and the thermal autoelectronic emissions as the cooling effect acting on the cathode surface.

In discharge the cathode functions simultaneously as an electron emitter and a positive-ion collector, in which connection the current density j_c at the cathode surface is made up of the electron (j_e) and ion (j_i) components, so that we can write

$$j_c = j_i + j_e, \quad j_i/j_e = \psi,$$

$$j_i = [\psi/(1+\psi)]\, j_c, \quad j_e = [1/(1+\psi)]\, j_c. \qquad (1)$$

The density of the heat flow to the cathode, generated by the ion current j_i can be determined in this case from the expression

$$F_i = (j_i/e)\, q_i = [\psi\, j_c/(1+\psi)\, e]\, q_i = (\psi\, j_e/e)\, q_i, \qquad (2)$$

where e is the electron charge, and q_i is the energy transmitted to the cathode by an individual ion.

The ion goes from the plasma to the region of the cathode potential drop with an energy $2kT_i$, where T_i is the ion temperature of the plasma at the boundary with the cathode region. On passage of the cathode-drop potential U_c the ion receives additional energy eU_c, recombining as it approaches the cathode to a distance of 6–10 Å; however, since the formed excited atom covers the remaining distance in a time that is explicitly inadequate for spontaneous emission (10^{-12} sec), according to [1], it reaches the cathode in the excited state and imparts the excitation energy eU_{exc} to the cathode. Thus the ion reaches the cathode with the energy $q' = eU_c + 2kT_i + eU_{exc} = (1 + \eta + \nu)eU_c$ and imparts to the cathode only that portion $q_i = q' - q''$, where q'' is the energy with which the atom leaves the cathode surface. In view of the equality between the mass of the bombarding atom and the atom of the wall (discharge in the vapors of the cathode material), according to Levin [2] q'' is identical to the energy of the evaporating atom, i.e., we can assume that $q'' = 2kT$, where T is the cathode-surface temperature.

The accommodation factor μ and the energy q_i transmitted by the ion to the cathode can be expressed by the equations

$$\mu = (q' - q'')/q' = 1 - 2kT/(1+\eta+\nu)\, eU_c, \qquad (3)$$

$$q_i = \mu(1+\eta+\nu)\, eU_c. \qquad (4)$$

The relative coefficient $\nu = eU_{exc}/eU_c$ can be evaluated on the basis of the ion-neutralization mechanism described by Oliphant and Moon [3], and subsequently acknowledged by Morgulis [4], Shekhter [5], Granovskii [1], Massey, and Barhop [6]. On the basis of these descriptions, the ion approaching the metal surface sets up a field sufficiently strong for the field emission from the metal of an electron, recombination with which leads to the formation of an excited atom; the greatest emission probability in this case is exhibited by the electron whose energy level in the metal coincides with or is very close to one of the quantum levels of atom excitations, which corresponds to the equation

$$\varepsilon_0 + \varphi - \varepsilon = eU_i - eU_{exc}, \qquad (5)$$

where ε_0, ε, φ, and eU_i are, respectively, the electron energy at the Fermi level, the energy of the emitting electron, the work function, and the ionization energy.

If the atom exhibits an excitation level to which an electron with energy $\varepsilon = \varepsilon_0$ in the metal can pass under isoenergy conditions, as follows from (5), in this case

$$\nu = (eU_i - \varphi)/eU_c = \nu_0. \qquad (6)$$

However, in the remaining recombination cases in which $\varepsilon \neq \varepsilon_0$, we have the conditions: $\nu < \nu_0$ where $\varepsilon < \varepsilon_0$ and $\nu > \nu_0$ where $\varepsilon > \varepsilon_0$. Neutralization is clearly possible for $\nu \leq \nu_0$ when $T \geq 0$, whereas neutralization for $\nu > \nu_0$ is possible only when $T > 0$, when electrons with an energy $\varepsilon > \varepsilon_0$ appear in the metal.

Table 1

Values of U_c, φ, U_i, and ν_0 for Various Metals

metal	U_c, V	φ, eV	U_i, V	ν_0	metal	U_c, V	φ, eV	U_i, V	ν_0
Cu	16.0	4.0	7.72	0.234	Sn	12.0	4.0	7.34	0.278
Ag	15.3	4.3	7.57	0.214	Mo	16.0	4.3	7.10	0.174
Au	15.5	4.4	9.22	0.312	W	16.1	4.5	7.98	0.216
Zn	10.0	3.5	9.39	0.589	Fe	15.1	4.5	7.87	0.223
Cd	9.8	3.7	8.99	0.541	Co	15.2	4.4	7.86	0.228
Al	14.4	3.5	5.98	0.172	Ni	15.0	4.8	7.63	0.189

In Table 1, together with the quantities U_c, φ, and U_i, taken from [7, 8, 9], we present the coefficient ν_0 for several metals, these having been calculated from the same data.

As follows from [9], the metal atoms, as a rule, have excitation levels at which ion neutralization according to condition (5) is possible for $\nu \approx \nu_0$; however, the coefficient ν_0, as we can see from Table 1, for most metals exhibits values substantially smaller than unity.

The relative coefficients $\eta = 2kT_i/eU_c$ account for the effect of the ion temperature of the plasma adjacent to the cathode region on the thermophysical cathode processes. There are no data whatsoever with regard to the temperature of precisely this cathode region, i.e., at the beginning of the relaxation zone, and this makes difficult the determination of an exact estimate for η; however, assuming that the ion temperature here does not exceed the temperature in the experimentally more accessible sections of the channel—said temperature, as is well-known, reaching values of 30 000–40 000° K—the coefficient η can be optimally evaluated at 0.1–0.2.

The evaluation of μ follows from the evaluations of ν and η, as well as from the values of U_c (Table 1). As follows from (3), for any real cathode-surface temperatures all the way to $T \approx 10^{4\circ}$ K, the accommodation factor remains very close to unity, which corresponds to the Bauer conclusion [10] regarding the value $\mu \approx 1$ with respect to heavy ions.

From (2) and (4) we finally find that

$$F_i = \mu(1+\eta+\nu)U_c j_i = [\psi\mu(1+\eta+\nu)/(1+\psi)]U_c j_c = \psi\mu(1+\eta+\nu)U_c j_e, \quad (7)$$

whence it follows that in expressing F_i in terms of j_c or j_e, the evaluation of the coefficient ψ assumes particular importance.

The electron emission from the cathode surface is associated with the cooling of the latter; the specific power of the emission process can be determined, in this case, from

$$F_e = (j_e/e)\,q_e = [j_c/(1+\psi)\,e]\,q_e = (j_i/e\psi)\,q_e, \quad (8)$$

where q_e is the energy loss by the cathode per one emitter electron. The value of this quantity is a strong function of the nature of electron emission.

The basic factors determining the density of the electron-emission current j_e are the electric field E at the cathode surface and the cathode temperature T. The relationship $j_e = f(E, T)$ is exceedingly complex and is presently known in the form of individual expressions, each of which has its own area of applicability within the range of the limited values of E and T, and namely:

$$j_{e,\,(N.F.)} = (1.55\cdot10^{-6}E^2/\varphi)\exp[-6.85\cdot10^7\varphi^{3/2}v(y)/E], \quad (9)$$

$$j_{e,\,(R.D.)} = 120\,T^2\exp(-\varphi/kT), \quad (10)$$

$$j_{e,\,(R.D.S.)} = j_{e,\,(R.D.)}\exp(4.39\,E^{1/2}/T), \quad (11)$$

$$j_{e,\,(M.G.)} = j_{e,\,(R.D.S.)}\,\xi/\sin\xi, \quad (12)$$

$$j_{e,\,(M.G.)} = j_{e,\,(N.F.)}\,\varkappa/\sin\varkappa, \quad (13)$$

$$j_{e,\,(M.G.)} = 5.2\,E[Tt(y)]^{1/2}\times \exp[-1.16\cdot10^4\varphi/T + 5\cdot10^{-5}E^2\theta(z)/T^3], \quad (14)$$

$$j_{e,\,(G.M.)} = \{1.55\cdot10^{-6}E^2/v^2(y)\,\varphi + 241\,T^2[(1-\alpha^2)^{-1} - \beta^2\varepsilon_1(\beta^2-\alpha^2)^{-1}]\}\exp[-6.85\cdot10^7\varphi^{3/2}v(y)/E], \quad (15)$$

where $y = 3.62\cdot10^{-4}E^{1/2}/\varphi$; $\xi = 1.64\cdot10^{-2}E^{3/4}/T$; $\varkappa = 2.8\cdot10^4 t(y)\varphi^{1/2}T/E$; $z = 2.94\cdot10^4 T^2/E^{3/2}$; $\alpha = 8.813\cdot10^3 v(y)\varphi^{1/2}T/E$; $\beta = 1.852$; $\varepsilon_1 = 0.1775$; v(y), t(y), and $\theta(z)$ are tabulated functions [11, 12]. The quantities j_e, E, and φ in each of these expressions are given, respectively, in the following units: A/cm^2; V/cm; and eV.

The well-known Nordheim-Fowler equation (9) and the Richardson-Dashman equation (10) pertain, respectively, to the autoelectronic and thermoelectron emissions and are valid in directly opposed situations; the former is valid when E > 0 and T = 0; the second equation is valid when T > 0 and E = 0. The remaining equations, i.e., (11)–(15), pertain to the conditions of simultaneous effect of E and T and describe the thermal autoelectronic emission. Among these, Eq. (11) is the Richardson-Dushman-Schottky equation; Eqs. (12), (13), and (14) are the Murphy and Good equations [12, 13] (in writing the latter together with the quantities ξ, $\varkappa$, and z we changed from the dimensionless expressions of j_e, φ, kT, and E in the original to the dimensional values of these quantities on the basis of the conversion factors cited in [12]: $2.37\cdot10^{14}$ A/cm^2 for j_e; 27.2 eV for φ and kT; $5.15\cdot10^9$ V/cm for E); and finally, Eq. (15) is the simplified version of the Guth and Mullin equation [14], derived by Andreev [15]. Equations (12) and (13) are valid for relatively small values of ξ and $\varkappa$ [12], while Eq. (15) is valid for $0.2 \le \alpha \le 0.9$ [15].

Although we know of attempts in the literature to treat cathode processes on the basis of Eqs. (9) or (10), as correctly pointed out by Rakhovskii, Levchenko, and Teodorovich [16], these are based on extremely dubious grounds, because it is highly unlikely that such extreme conditions as T = 0 where E > 0 or E = 0 where T > 0 can be satisfied in powerful arc or pulse discharges. This suggests a need for an analysis of cathode processes on the basis of thermal autoelectronic emissions, which is precisely what is being undertaken here. This is the approach taken by Bauer [10], as well as by Lee and Greenwood [17], and the further development of this approach is extremely promising for the understanding of cathode processes.

There is no emission cooling of the cathode in the case of autoelectronic emission ($q_e = 0$), while in the case of thermoelectronic emission it reaches a maximum and, according to [1], it is defined by

$$q_e = \varphi + 2kT, \tag{16}$$

where T is the cathode temperature. With thermal autoelectronic emission—when the intensity of the tunnel electron yield remains relatively weak with a drop in the potential barrier, which is possible under high-temperature conditions and fields that are not too strong, i.e., under conditions in which Eqs. (11) and (12) are applicable—the quantity φ in (16) can be replaced by the effective work function $\varphi^* = \varphi - (e^3E)^{1/2}$ so that

$$q_e = \varphi - (e^3E)^{1/2} + 2kT. \tag{17}$$

However, if the intensity of the tunnel electron yield becomes relatively great with a drop in the potential barrier, the expression for q_e will be more complex. Thus, under conditions in which Eq. (15) is applicable, according to [15],

$$q_e = [(\beta - \alpha)/(1-\alpha)]\, kT. \tag{18}$$

Thus, for high cathode temperatures (T > 4000° K), accompanying a powerful pulse discharge, we can limit ourselves to the expression for the specific power of the emission process which follows from (8) and (17):

$$F_e = \frac{\varphi - (e^3E)^{1/2} + 2kT}{e}\, j_e =$$

$$= \frac{\varphi - (e^3E)^{1/2} + 2kT}{(1+\psi)\, e}\, j_c = \frac{\varphi - (e^3E)^{1/2} + 2kT}{e\psi}\, j_i. \tag{19}$$

One of the unavoidable consequences of pulse discharge is the intensive vaporization of the cathode. This phenomenon is manifested in the appearance of a strong cathode flame and is an experimentally undisputed fact.

The intensive vaporization of metal under the action of a powerful light flux (a laser beam), as demonstrated in [18], satisfies the Frenkel mechanism [19] quite well. The present author adopted this mechanism [20, 21] in studying the thermophysical processes occurring at electrodes, since the thermal effect of pulse discharge is competitive in terms of efficiency with a powerful laser beam.

The outstanding feature of this paper involves the consideration of elementary cathode processes in the case of a pulse discharge on the basis of a thermal autoelectronic emission in conjunction with the Frenkel mechanism of vaporization in the high-temperature zone (4000–8000° K).

According to [19], the rate of atomic vaporization $G_n = dn/ds\, dt$ is a function of the atomic bonding energy q_n and of the temperature T of the vaporization front; this is determined from

$$G_n = G_0 \exp(-q_n/kT) = G_0 \exp(-T_m/T). \tag{20}$$

The vaporization of the cathode is accompanied by its cooling, and the specific power of this process, as follows from (20), is given by

$$F_n = G_n q_n = F_0 \exp(-T_m/T). \tag{21}$$

Table 2 shows the values of q_n and G_0 for several metals, and these values have been calculated from the data in [22, 23]. For the values of G_0 in the table, the vaporization front penetrates into the electrode at a speed

$$v = v_0 \exp(-T_m/T), \tag{22}$$

where v_0 is the speed of sound in the material of the cathode.

Assuming that the quantities F_i, F_e, and F_n are fundamental to the development of the continuing thermophysical process from the instant at which the melting point t_1 is reached at the cathode surface, on the basis of [21, 24], we can formulate the one-dimensional problem relating to the movable vaporization front:

$$\frac{\partial T(x,\, t)}{\partial t} =$$

$$= a\, \frac{\partial^2 T(x,\, t)}{\partial x^2} + v_0 \exp[-T_m/T(0,\, t)]\, \frac{\partial T(x,\, t)}{\partial x} +$$

$$+ c_V^{-1} \rho_{melt} \{1 + \alpha [T(0,\, t) - T_{melt}]\} \times$$

$$\times j_c^2(0,\, t) \exp(-\delta x), \tag{23}$$

$$-\frac{\partial T(0,\, t)}{\partial x} = (ac_V)^{-1} (F_i - F_e - F_n),$$

$$\frac{\partial T(\infty,\, t)}{\partial x} = 0; \tag{24}$$

$$T(x,\, t_1) \approx T_0 + (F_i/\lambda) \times$$

$$\times \{(at_1/\pi)^{1/2} \exp(-x^2/4at_1) - x \operatorname{erfc}[x/2(at_1)^{1/2}]\},$$

$$0 \leqslant x \leqslant \infty;\ t_1 \leqslant t \leqslant t_{ev}. \tag{25}$$

The penetration of the vaporization front into the electrode is responsible for the transition of the process into a steady regime with within a very brief transition time, particularly in the case of high pulse power [21]. Integrating (23) over the coordinate in the semibounded region with boundary conditions (24), for

Table 2

Values of Limit Vaporization Rates and Atomic Bonding Energies for Various Metals

Metal	q_n, eV	G_0, cm² · sec⁻¹	Metal	q_n, eV	G_0, cm² · sec⁻¹	Metal	q_n, eV	G_0, cm² · sec⁻¹
Cu	3.45	$3.08 \cdot 10^{28}$	Cd	1.14	$1.16 \cdot 10^{28}$	W	8.60	$2.70 \cdot 10^{28}$
Ag	2.90	$1.48 \cdot 10^{28}$	Al	2.34	$3.02 \cdot 10^{28}$	Fe	4.00	$4.07 \cdot 10^{28}$
Pb	2.02	$5.35 \cdot 10^{27}$	Sn	3.31	$9.90 \cdot 10^{27}$	Co	3.62	$4.35 \cdot 10^{28}$
Zn	1.16	$2.86 \cdot 10^{28}$	Mo	6.80	$2.25 \cdot 10^{28}$	Ni	3.62	$4.50 \cdot 10^{28}$

the steady regime we obtain the equation

$$v_0 [n_0 q_n + c_V (T - T_0)] \exp(-T_m/T) = \mu (1 + \eta + \nu) U_к j_i - \{[\varphi - (e^3 E)^{1/2} + 2kT]/e\} j_e + \{\{\rho_{melt} [1 + \alpha (T - T_{melt})]\}/\delta\} j_c^2, \quad (26)$$

which under these conditions expresses the law of the conservation of energy. Here j_i, j_e, j_c, and T are steady values for the current densities and the temperature at the vaporization front; n_0 is the number of atoms per unit cathode volume and δ is the reciprocal of the microlune depth.

Equation (26) determines the thermophysical process at the cathode. This process must be in equilibrium with the thermal autoelectronic emission. However, the latter is determined, on the one hand, by the temperature which satisfies Eq. (26), while on the other hand, it is determined by the electric field of the ambipolar current at the cathode surface, and this can be expressed from the McKeown equation [25]:

$$E^2 = 7.57 \cdot 10^5 [(m_i/m_e)^{1/2} \times j_i - j_e] U_c^{1/2}. \quad (27)$$

Thus, to calculate the conditions of equilibrium for the thermophysical and elementary processes at the cathode for the thermophysical and elementary processes at the cathode, we must simultaneously solve Eqs. (26) and (27), as well as the equation of the thermal autoelectronic emission, for which it is best to

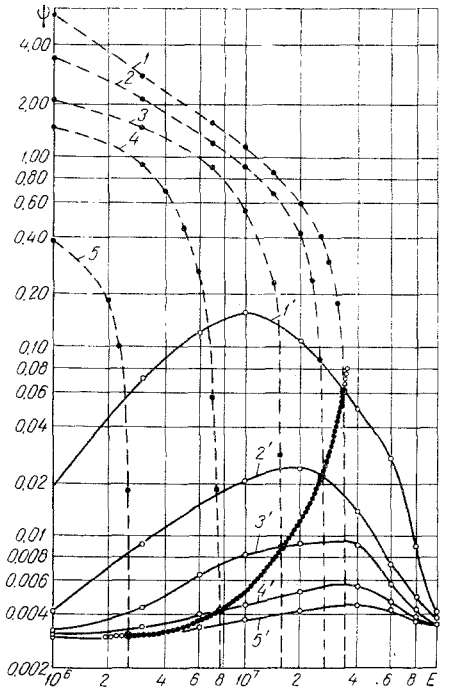

Fig. 1. Determination of equilibrium values of coefficient ψ from intersection of curves 1) 1', 2) 2', 3) 3', 4) 4', 5) 5' (E, V/cm).

take Eq. (12) in the high-temperature region. Having expressed the current j_i and j_c in terms of j_e on the basis of (1), (7), and (19), and turning to numerical data, we can represent this system of equations in the case of copper when $\delta^{-1} \approx 10$ μm, $\nu \approx 0.234$,

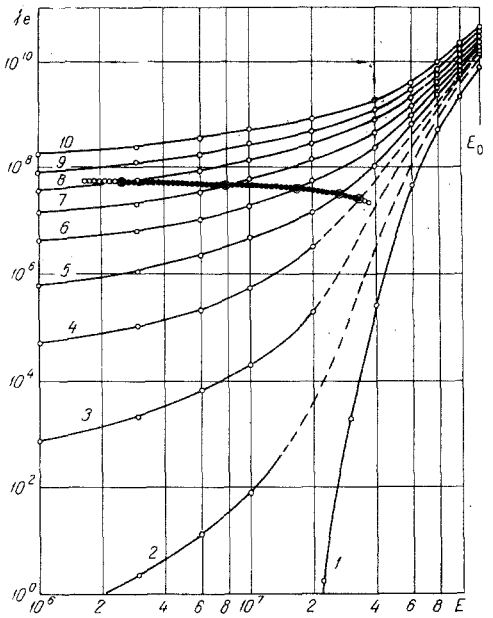

Fig. 2. Equilibrium density of cathode emission current against a background of current densities of thermal autoelectronic emission (j_e, A/cm^2, E, V/cm): 1) 0° K; 2) 2000; 3) 3000; 4) 4000; 5) 5000; 6) 6000; 7) 7000; 8) 8000; 9) 9000; 10) 10 000.

$\eta \approx 0.1$, and $\mu \approx 1$ in the following form:

$$j_e = 120 T^2 \exp[(4.39 E^{1/2} - 1.16 \cdot 10^4)/T] \times \times \frac{1.64 \cdot 10^{-2} E^{3/4}/T}{\sin(1.64 \cdot 10^{-2} E^{3/4}/T)}, \quad (28)$$

$$\psi = 3 \cdot 10^{-3} + 7.45 \cdot 10^{-10} E^2/j_e, \quad (29)$$

$$[1.44 \cdot 10^{-17} (1020 + T) j_e^2] \psi^2 + [1.68 \cdot 10^{-5} j_e + 2.88 \cdot 10^{-17} (1020 + T) j_e] \psi + [1.44 \cdot 10^{-17} (1020 + T) j_e^2 - (14100 + T) \exp(-40200/T) - 1.68 \cdot 10^{-5} (1.88 \cdot 10^{-1} + 1.71 \cdot 10^{-5} E^{1/2} + 8.1 \cdot 10^{-6} T)] = 0. \quad (30)$$

Here j_e, E, and T are expressed in A/cm^2, V/cm, and ° K; Eq. (28) has been derived from (12); Eq. (29) is derived from (27); and Eq. (30) is derived from (26).

Curves 1, 2, 3, 4, and 5 (broken) in Fig. 1 have been calculated from (28) and (29); curves 1', 2', 3', 4', and 5' (continuous) have been calculated from (28) and (30); these calculations have been carried out for temperatures of 4000, 5000, 6000, 7000, and 8000° K; respectively, the points of intersection for these curves determining those values of E and ψ for a given T which simultaneously satisfy all three equations, i.e., (28), (29), and (30); consequently, a curve constructed on the basis of these points is a curve showing the equilibrium between the thermophysical and elementary processes at the cathode.

Figure 2 shows $j_e = f(E, T)$, this function corresponding to the system of emission equations (9)–(15)

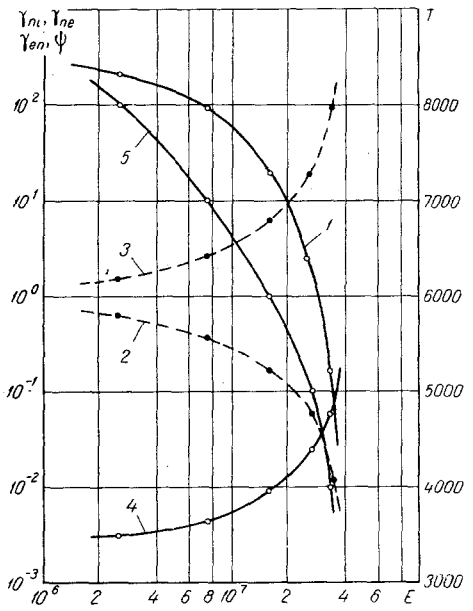

Fig. 3. Equilibrium values of main cathode-process characteristics: 1) γ_{ni}; 2) γ_{ne}; 3) γ_{en}; 4) ψ; 5) T. (E, V/cm; T, ° K).

in the temperature interval between 0 and 10 000° K and fields of 10^6–10^8 V/cm. The same curve shows the equilibrium density of the emission current—satisfying Eqs. (28)–(30)—which, as we can see from the figure, increases very weakly with a rise in temperature, approaching the level $j_e \approx 10^8$ A/cm^2, whereas the equilibrium value of ψ with a rise in temperature within the same range drops sharply, approaching a level of 0.003 (Fig. 1).

Figure 3 shows the yield factors γ_{ni}, γ_{ne}, and γ_{en}, as ψ and T as functions of the field E in the range 10^6–10^8 V/cm for equilibrium cathode processes. Here $\gamma_{ni} = G_n/G_i$ is the number of vaporized atoms per single ion ($G_i = j_i/e$); $\gamma_{ne} = G_n/G_e$ is the number of vaporized atoms per single emitted electron ($G_e = j_e/e$); and, finally, $\gamma_{en} = G_e/G_n$ is the number of emitted electrons per single vaporized atom ($\gamma_{en} = \gamma_{ne}^{-1}$). As we can see from the graph, in the region of weak fields and their correspondingly high temperatures, the coefficients $\gamma_{ni} \gg 1$, $\gamma_{ne} \approx 1$, $\gamma_{en} \approx 1$, $\psi \to 0.003$. However, in the strong-field region and the correspondingly low temperatures we have $\gamma_{ni} < 1$, $\gamma_{ne} \ll 1$, $\gamma_{en} \gg 1$, and $\psi \to 1$.

It follows from the calculations that we have carried out that when the cathode processes are analyzed on the basis of the Frenkel mechanism of vaporization and thermal autoelectronic emission, equilibrium is possible over the entire range of fields and the corresponding temperatures; no conclusion can be drawn in connection with the selection of any specific value for these quantities from the actual equilibrium condition. This can be achieved only from some additional condition such as, for example, the limitation which should be imposed on the yield factors. Thus, when $\gamma_{ni} < 1$, the occurrence of discharge in the vapors of the cathode material is impossible and, consequently, the value of $\gamma_{ni} < 1$ in the case of a pulse discharge cannot be accepted. When $\gamma_{ni} = 1$, the discharge in the vapors of the cathode material becomes possible, but the formation of a powerful cathode flame—as observed in the experiment—remains impossible. It is therefore reasonable to assume that under conditions of pulse discharge with a powerful cathode flame we have $\gamma_{ni} > 1$, or even possibly $\gamma_{ni} \gg 1$.

With high values for γ_{ni}, e.g., when $\gamma_{ni} = 100$ ($E = 8 \cdot 10^6$ V/cm, T = 7100° K), the coefficient $\gamma_{en} = 2.5$. This means that the neutral generated by the cathode spot (with most of this neutral participating in the flame) may be rather highly ionized, since under these conditions we have 2.5 emitted electrodes per single vaporized atom; with the cathode drop in potential, each of these emitter electrons exhibits energy fully adequate for ionization. However, this problem should be studied separately and in greater detail. The information derived in this case on the value of any of the coefficients γ_{ni}, γ_{ne}, and γ_{en} would make it possible from the data of Fig. 1 to define E and T uniquely.

The data of Fig. 1 quite adequately serve to explain, in addition, the evolution of the cathode spot. It begins its existence as a cold emitter in the case of a rather strong field, in the absence of cooling effects ($F_n \approx 0$, $F_e \approx 0$), and with coefficients $\psi \approx 1$, $\gamma_{ni} \ll 1$. At this stage ($\psi \approx 1$) a rather strong ion heat flux F_i reaches the cathode, and with the additional effect of the bulk heat source ρj_c^2, under the influence of the ion heat flux there is a development of temperature in the surface layer of the cathode. However, the development of the temperature changes the cathode spot from a regime of a cold emitter to one of hot emitter, with the simultaneous "slippage" of the process into the region of weak fields and values of $\psi \ll 1$ and $\gamma_{ni} \gg 1$, at which the function of the cathode spot as a collector of positive ions is markedly diminished. Under these conditions, the quantities F_e and F_n increase in conjunction with the corresponding rise in the power of the bulk heat source ρj_c^2, whereas F_i diminishes, and this means that F_i now becomes inadequate to ensure two such high-energy processes as vaporization and thermal autoelectronic emission at the high-temperature level; these processes now take place under the action of the bulk heat source.

Thus the change in the cathode spot from a regime of a cold emitter to a regime of a hot emitter is accompanied by a parallel transition of the predominant efficiency in the thermophysics of the cathode from the surface (ion) heat source to the bulk heat source. However, given the predominating effectiveness of the latter, even during the existence of the cathode spot, we find volume overheating—the predominance of the volume temperature over the temperature of the front. This phenomenon may result in an explosive effect capable of ending the existence of the cathode spot and leading to its migration to another region of the cathode surface.

Consequently, among the various other reasons usually employed in interpreting the migration of the

cathode spot, we should also give consideration to the reason offered here, since it is based on a rather convincing physical foundation.

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