# The cathode spot of a vacuum arc

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In this review we analyze the current state of experiments and theory relating to the cathode spot of a vacuum arc. We discuss technical features of the experimental study of the near-cathode region of a vacuum arc with high time and space resolution. We discuss in detail the experimental data on such basic parameters characterizing the cathode spot as velocity, nature of motion, and lifetime of the spot, the current to the spot, current density, cathode fall, charge-transfer coefficient, vapor-jet velocity, charged-particle concentration, and electron temperature. We evaluate the reliability of the results obtained by various authors. A classification of cathode spots is proposed, and conditions for the existence of various types of spots and the behavior in the transition from one type to another are described. On the basis of the experimental data considered, we propose the explosive and diffusion models which provide qualitative and sometimes quantitative descriptions of cathode spots of various types.

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CONTENTS



## 1. INTRODUCTION. EXPERIMENTAL STUDY OF CATHODE SPOTS

The term "cathode spot" is usually associated with a certain small, highly luminous region on the cathode surface, through which transfer of current between the cathode and the interelectrode space is accomplished in an arc discharge. Several forms of arc discharge are known (vacuum arcs, arcs which burn at normal pressure in various gases, high-pressure arcs, hot-cathode arcs, etc). Without going into physical definitions of the various forms of arc discharge, we note only that in all of them there is a cathode spot.[1-3]

The concept of the cathode spot unites two physically different regions—the metal surface, which can be heated in the vicinity of the spot to temperatures well above the boiling point, and the near-cathode plasma, which is formed in the process of producing the spot or is continuously generated as the result of evaporation. The near-cathode plasma is characterized by extremely high parameter values which depend on the type of spot and the form of the discharge.

Various theoretical estimates and experimental results on determination of the physical parameters of the near-cathode plasma of a vacuum arc lead to the following values: particle concentration $n \sim 10^{17}-10^{20}$ $cm^{-3}$, degree of ionization $\alpha \sim 10-100\%$, electron temperature $T_e = 1-2$ eV, heavy-particle temperature $T \sim 0.5-2$ eV. Naturally, a near-cathode plasma with such parameters cannot be in equilibrium; it is moving away from the region of the spot, and the vapor-jet velocities measured at some distance from the cathode are of the order $10^6$ cm/sec.

The appearance of the cathode spot in the course of formation of an arc discharge is due to the necessity of transport of large currents ($10-10^4$ A) through the surface of a cold and practically nonemitting conductor. This possibility is realized in the cathode spot as the result of the high concentration of energy in a small region on the electrode surface (the chacteristic size of a cathode spot is $r \sim 10^{-4}-10^{-2}$ cm). Here the current transport is accomplished both by ions coming from the near-electrode plasma and by electrons, which are

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emitted from the metal in the vicinity of the cathode spot as the result of the high surface temperature and the electric field produced by the space charge in the near-cathode plasma.

A simple description of the cathode spot and the plasma parameters present in it already shows that it is an extremely unique physical object. If we further consider that arc discharges have great practical significance, we can understand why the cathode spot has become the object of unceasing attention and of numerous investigations, beginning at the start of the twentieth century. Nevertheless at the present time the problem of the cathode spot is still far from being solved.

The difficulties in the experimental study of the cathode spot are due to the fact that its size and lifetime at a given location are extremely small (the velocities of travel of the spots over the cathode surface reach values of $10^4$ cm/sec). For this reason, until recently only certain external characteristics of the cathode spot were studied—the size of the luminous region, the nature of the track left by the spot on the metal surface, the time of existence of the discharge and the time characteristics which were identified with properties of the cathode spot, and so forth. However, even these measurements were often inaccurate as the result of technical difficulties. Ideas regarding the physical processes occurring in the spot were based on this experimental information and on rather crude theoretical evaluations, which as a rule did not take into account the parameters of the near-cathode plasma. Here it was tacitly assumed that all cathode spots are identical in their properties.

Only very recently, with the aid of specially developed complicated methods of measuring cathode-spot parameters, has it been possible to trace the dynamics of cathode-spot development and to make direct measurements of a number of parameters of the near-cathode plasma. These measurements have made it possible to establish, first of all, that cathode spots can differ substantially in their properties—the idea of cathode spots of different types arose. On the basis of measured parameters of the near-cathode plasma, it has been possible to evaluate the role of individual physical processes in maintaining the conditions for existence of the spot. Nevertheless there remain open for investigation at the present time many problems having fundamental significance in understanding the processes which accompany the formation, development, and existence of the cathode spot.

The present review has the purpose of drawing the attention of a broad and assorted group of physicists to this complex problem, which is at the meeting point of the physics and dynamics of plasma and solid-state physics. In the first part of the review, after a critical analysis of experimental methods, we present experimental facts and data which, from the point of view of the authors, are reliably established. Here we have attempted to describe all known qualitative effects and to present numerical values of the principal parameters characterizing cathode spots of various types. It appears to us that this information in its entirety will be necessary to anyone who attempts to interpret or describe the set of physical processes which determine a cathode spot. In some sections of this part of the review, we give a critical analysis of the existing attempts to explain various effects. This analysis has the purpose of directing attention toward certain important problems associated with some of the experimentally established facts.

In the second part of the review we systematically set forth the latest and, as it appears to us, the best justified approaches to physical and mathematical descriptions of certain types of cathode spots. In the text we consider individual problems in this area, whose solutions would have fundamental importance for the theory of cathode spots.

### a) Types of Cathode Spots and Their Qualitative Characteristics

Even the first observations of mercury arcs made by Stark and Reich[7] revealed a rapid chaotic motion and division of a "bright luminous region near the cathode" which Stark[8] called a cathode spot and which subsequently has frequently been called the near-cathode region of the discharge.

At the present time there is no clear physical definition of a cathode spot; this is apparently due to the fact that its physical properties have not yet been studied with sufficient completeness. Nevertheless, we always associate with this idea a small region on and near the electrode surface, through which the arc current is transported to the cathode.

In some cases we understand the cathode spot to mean only the portion of the electrode surface with which we associate definite laws of emission, erosion, supply of charged particles and so forth, and in this way we identify it as the portion of the surface in which transfer of current from the metal to the interelectrode plasma is accomplished. However, such a definition cannot be physically complete, since the physical processes which occur on the electrode surface in the region of the spot are closely connected with the processes occurring in the plasma near the surface and with its parameters. In this respect the electrode surface in the vicinity of the spot and the plasma adjacent to it are indivisible physically and the combination of the two regions is naturally discussed as a single physical object—the cathode spot.[1)]

The boundary of the cathode spot *on the electrode surface* is arbitrary, since a continuous distribution of the parameters determining the current-transfer process exists along the surface. However, as the result of the rapid dependence of the emission and degree of ionization of the plasma on temperature, this boundary can be rather distinctly determined both experimentally and theoretically.

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[1)]In the course of the discussion, in those cases when it is convenient to separate these two ideas, we will use for them the designations "electrode surface in the spot" and "near-cathode plasma."

The characteristic size of the cathode spot in the direction normal to the electrode surface, which determines the volume of the near-cathode plasma, is by definition related to the maximum length of the elementary process which affects the physical processes on the electrode surface in the spot. The theoretical and experimental study of the near-cathode plasma has been started comparatively recently. The information obtained does not yet permit us to construct a complete physical model of the near-cathode plasma or of the spot as whole. Therefore the boundary of the cathode spot toward the interelectrode plasma cannot yet be clearly defined (appropriate estimates for existing models of the spot will be given in Chapter 2).

We emphasize that in terms of this definition the cathode spot can be substantially inhomogeneous (the specific distribution of the parameters in a spot naturally depends on the type of spot). The experimental determination of the distributions of the physical parameters in the spot encounters fundamental difficulties related to the capabilities of the optical systems recording the radiation of the spot itself.

Limitations related to aberrations of the optical system which projects an image of the spot and which has the necessary minimal depth of field do not permit a real spatial resolution of better than $10^{-4}$ cm to be obtained with use of such systems.[82] However, estimates show that the characteristic size of inhomogeneities in the spot can be substantially smaller. Therefore the establishment of the substructure of the spot from its measured integral parameters and the parameter distributions remote from it and on its outer boundary is a problem of the theoretical (physical and mathematical) models of the spot. This is the reason for the great instructive value of such models and at the same time for the difficulty in constructing them.

It was long assumed that the properties of the cathode spot of a vacuum arc do not depend on the discharge current, the nature of the electrode surface, the duration of the discharge, or on other characteristics of the discharge. The term cathode spot has been identified with a certain physical object with which the entire set of experimental data has been associated.

However, as recent studies[24,29,33,49] have shown, cathode spots can differ substantially in their properties.

It has been established that in the initial stage of a discharge, rapidly moving cathode spots arise on all metals (spots of the first type). These spots exist independently of each other and produce insignificant erosion of the surface.[2)] Most of the experimental information accumulated in the course of many years obviously applied just to this type of spot.

Sometime after ignition of the discharge, the nature of the cathode spots on the electrode surface changes. At first, in addition to spots of the first type, there appear individual spots of large size which have a substantially smaller velocity of their motion (spots of the second type). With passage of time, the number of these spots increases and eventually only spots of the second type remain on the surface.

The time of transition from spots of the first type to spots of the second type depends on the discharge current and the thermal properties of the electrode material. At low currents, under the conditions of the experiments of Kantsel' *et al.*,[49] spots of the second type are generally not observed.

Spots of the second type produce substantially greater erosion than spots of the first type. These spots easily form clusters—grouped spots—in which erosion is maximal.

Analysis of the experimental data leads to the conclusion that the erosion in spots of the second type (and in grouped spots) is of a thermal nature. With a specially prepared and outgassed electrode surface the erosion is determined by the evaporation which occurs at the high temperature in these spots.

On the other hand, the experimental data and also physical estimates show that the erosion in spots of the first type has a nonthermal nature and is apparently due to successive explosions of microinhomogeneities on the electrode surface.[3)]

It is necessary to emphasize that the number of experimental investigations in which the type of spot has been determined is very limited. Therefore it not excluded that, under certain conditions of the discharge, cathode spots of other types will be observed.

### b) Some Technical Features of the Investigation of the Near-Electrode Regions of a Vacuum Arc

The main technical difficulties arising in experimental study of cathode spots (particularly rapidly moving spots of the first type) are due to the fact that the spot occupies a random location on the electrode surface which is moving rapidly ($v$ is ~$10^4$cm/sec) and has a small size ($r \sim 10^{-3}$ cm). These features of a cathode spot as a physical object and the limitations of experimental techniques until recently have not permitted reliable information to be obtained on the local characteristics of the metal surface in the spot and the near-cathode plasma. The principal results have been related to observation of the dynamics of cathode spots.

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[2)]Numerical values of the principal parameters describing the spot will be given below in the appropriate sections for spots of various types. In this section we give a qualitative description of spots to facilitate the reading of the text which follows.

[3)]The mechanism of erosion in spots of the first type has not yet been finally clarified. While it is due to successive explosions of microinhomogeneities, this process is due to accommodation of the thermal energy of the currents flowing in the microinhomogeneities, and in this sense it is also of a thermal nature. Nevertheless, here and in what follows we shall use for convenience the term "thermal" to refer only to spots of the second type, in which the erosion is due to evaporation. All other erosion mechanisms will be referred to as nonthermal.

ment of the near-electrode regions of a vacuum arc and, in particular, of a cathode spot the problem arises first of all of determining the shape and characteristic size $r$ of the spot.

At the present time two methods are mainly used for this purpose. In one method the size of the spot, which is assumed to be a circle, is identified with some characteristic dimension of the track left by the spot on the electrode surface (the autograph method)[9-14] and in the other method it is identified with the characteristic size of the region of illumination (the high-speed detection method).[18,19,22-25,29] In determining the spot size by the autograph method a certain arbitrariness arises in selection of the characteristic dimension of the track. In fact, it is impossible to establish from the track through which particular one of the thermal effect regions (oxidation zone, recrystallization zone, melting zone, microcrater zone, etc.) the current flowed and how it was distributed.

A problem of this type was encountered for the first time by Somerville *et al.*,[15] who completely failed to observe the tracks of the spot in a study of the surface of a copper cathode, as the result of use of insufficient magnification. Subsequently, with use of higher magnification, tracks were observed. Use of more refined optical equipment does not permit removal of this arbitrariness, but only brings out new possibilities for establishing the characteristic size of the spot. This is illustrated by the work of Basharov *et al.*[14]

In order to establish a definite relation between the characteristic size of the track and the size of the spot and in this way to justify the correctness of the autograph method, it is necessary to study the nature of the erosion in spots of different types. Such investigations carried out recently show that the autograph method can apparently provide both correct and incorrect results.

For example, at the present time we can consider it established that the erosion in a rapidly moving spot of the first type is of a nonthermal nature [see Section (c) and also Ref. 136] and that the dimensions of the damaged surface of the electrode in such spots are much less than the dimensions of the region of current transfer (the spot) [see Section (h)]. Naturally in this case the autograph method cannot be used to determine the spot size, and the structure of the track is interesting only for estimation of the rate and nature of erosion.

On the other hand, calculations[184] for grouped spots in which the erosion is determined by evaporation have shown that the characteristic size of the region bounded by the isotherm at which the temperature is equal to the melting temperature does not differ greatly from the size of the spot if the lifetime of the spot is $\tau \lesssim 1$ sec. Consequently, for spots of this type the autograph method can be used to estimate the spot size if we take as the characteristic track size the size of the melting isotherm. It is clear from general considerations that in this case the autograph method will give better results in metals with low thermal conductivity and high heat of phase transitions. In determination of spot size by recording the size of the luminous region on the cathode, questions arise as to whether it is legitimate to identify the current-carrying channel with the luminous region, and also questions of the reliable determination of its size. The latter question is particularly important in the study of rapidly moving spots.

Analysis of the spectrum of a cathode spot, which is discussed in Section (i), shows that the luminous region on the cathode consists of vapor of the electrode material at a high pressure and highly ionized. Here the boundary of the luminous region should not differ greatly from the boundary of the near-cathode plasma.

Corresponding estimates show that for spots of the second type the ion current from the near-cathode plasma to the electrode can be comparable with the arc current (see Chapter 2). In spots of the first type the ion current cannot contribute appreciably to the arc current, but the ions of the near-cathode plasma determine the electric field at the cathode and hence the necessary level of electron emission. In both cases in view of the accepted definition [see Section (a)] the boundary of the cathode spot should correspond to the boundary of the near-cathode plasma, and, consequently, should be determined by the boundary of the luminous region on the cathode. It is just this quantity which is determined in the high-speed detection method.

In analyzing measurements of cathode-spot size by the high-speed detection method,[18,19,22-25] it is easy to see that with decrease of the exposure in photography of cathode spots the recorded size of the cathode spot decreases. At first glance, later experiments (with better time resolution) appear more reliable, since with decrease of the exposure the size of the luminous region exposed in one frame is less distorted by motion of the spot during the exposure. However, the decrease of the time leads also to loss of information, since for very short exposures the light flux in the detecting equipment decreases and if the sensitivity of the equipment is insufficient, a reduced spot size corresponding to the brightest points of the luminous region will be determined.[4)]

In order to determine reliably the size of the luminous spot, it is necessary first of all to have adequate time resolution and, secondly, to have a high sensitivity of the detecting apparatus such as to permit photographs of the spot with very short exposures. Most studies of the motion and size of cathode spots have not met these requirements, since use was made of apparatus with inadequate time resolution[1,15,22,23,26] or apparatus which, while having adequate time resolution, did not have the necessary sensitivity.[18,24,25]

In order to avoid these deficiencies, we developed[29] a special technique. This technique permitted achievement of ultrafast recording of cathode spots by means of an image amplifier with a time resolution of $5\times10^{-8}$ sec and a spatial resolution (resulting from the use of an appropriate optical system) as low as $10^{-3}$ cm (Fig.

[4)] The case is possible in which an extraordinary decrease of exposure makes it completely impossible to record an image of the spot. For example, with exposures of $1\times10^{-7}$ sec Froome[25] could not observe the spot on a copper cathode in his experiments, utilizing a Kerr cell.

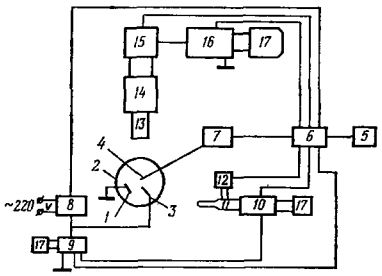


FIG. 1. Block diagram of experimental apparatus for study of rapidly moving cathode spots.[29] 1—cathode, 2—experimental tube, 3—anode, 4—ignition electrode, 5—control circuit, 6—synchronization circuit, 7—ignition circuit, 8—power supply, 9—oscilloscope recording discharge current and voltage drop across discharge, 10—image amplifier, by means of which the near-cathode region is photographed frame by frame, 11—microscope attachment, 12—reticule projector, 13—microscope attachment, 14—spectrograph, 15—image-amplifier detector of spectral line shape, 16—oscilloscope, 17—Polaroid cameras or television cameras.

1). Control experiments and evaluations specially carried out showed[187] that the size of the region of illumination coincides with the size of the cathode spot, since the decrease in the exposure time is compensated by the presence of the necessary amplification of the light, and microphotometry of the cathode-spot images with the spatial resolution used did not reveal significant inhomogeneities of illumination within the spot,[5)] and the dynamic range of contrast of the image amplifier permitted the entire spot to be seen under selected conditions of photography. Thus, the high-speed detection method with the necessary time and spatial resolution and adequate sensitivity (see for example Ref. 29) permits the characteristic cathode-spot size $r$ to be determined with adequate accuracy.

In study of slowly moving spots (spots of the second type and grouped spots), such high time resolution is not required and a high-speed photodetector can be used to determine the spot parameters.

The technique developed, which has been described elsewhere,[29,154,187] permits simultaneously recording, in addition to the spot size, a number of other parameters. In particular, it is possible by means of a specially developed instrument[60] MRS-1 to record directly on an oscilloscope screen (Fig. 2) the dynamics of the change in the contours of spectral lines. Here the number of sweeps of the contours of the portions of the spectrum studied corresponds to the number of frames recorded by the image amplifier. Recording the dynamics of variation of the contours of atomic and ionic lines in the near-cathode region with a spatial resolution $\sim 10^{-3}$ cm and a time resolution $5 \times 10^{-8}$ sec has permitted determination on the basis of Stark broading of the concentration of charged particles $n_e$, and on the basis of the ratio of the line intensities—their temperature $T_e$. In addition, determination of the concentration of charged particles can be carried out on the basis of the ratio of intensities of allowed and forbidden lines.[27]

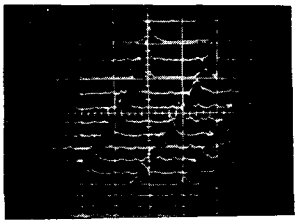

FIG. 2. Sweep of portion of spectrum of near-cathode region of a vacuum arc burning on copper. Time resolution $10^{-7}$ sec.

In experiments carried out with the described apparatus, the nature and rate of the electrode erosion produced by the action of the spot has been studied. For this purpose before the experiment the cathode surface was polished, and after action of a single discharge the track (Fig. 3) left by the cathode spot was photographed with the necessary magnification. The track area was determined from the photograph. The depth of the track was determined either by means of the profile (Fig. 4) recorded on a contact profilograph with a sensitivity of $10^{-5}$ cm, or by means of an optical profilograph, or from photographs with an electron microscope. Knowing the area and depth of the track and the parameters of the discharge, it was possible to determine the rate of erosion $\gamma$ in g/sec or the electrical transport coefficient $\varkappa$ in g/Coul.

The size and shape of the cathode spots were determined from photographs taken with image amplifiers. The rate of displacement of the spots was determined as the quotient obtained by dividing the distance between the centers of the spots by the time between frames. The current density was determined as the ratio of the instantaneous current value determined by an appropriate time marker to the instantaneous value of the spot area determined from the image-amplifier photograph. The lifetime of the spot was determined from direct observations of spots of a given type under various conditions of burning of the arc discharge.

Specific results obtained by the techniques described will be presented below in the appropriate sections. Unfortunately, only copper electrodes have been investigated in detail by this technique.

### c) Nature of the Motion of a Cathode Spot

It was shown some time ago by Schmidt,[28] who was the first to study the nature of the displacement of a cathode spot on mercury by means of high-speed motion pictures which recorded the trajectory of the spot, that the mean square displacement of a cathode spot is directly pro-

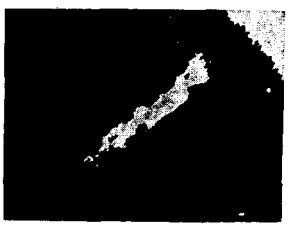

FIG. 3. Photograph of track left by a spot of the second type on a copper cathode. Magnification 150.

[5)] Use of higher spatial and time resolution[82] permitted observation inside the spot of finer inhomogeneities of illumination—fragments.

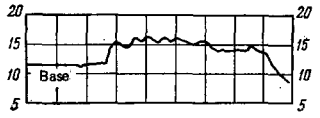


FIG. 4. Profilogram of erosion track left by a spot of the second type on a copper cathode.

portional to the time of its motion, i.e., he directly established the random nature of the motion of rapidly moving cathode spots. On increase of the current to 450 A, a directed motion was superimposed on the random motion of the spot, the former becoming more and more noticeable as the current was increased, which evidently could be explained by the effect of the intrinsic magnetic field of the current and magnetic field of the current leads.

The results of a rather complete study of the motion of a cathode spot on mercury and other metals are given in Refs. 1 and 26. They were obtained by the method of sweeping the spot image by a rotating mirror. The track left by the discharge in such a study has the form of a branching line.[1,22,26] It is usually assumed (see for example Ref. 1) that the different branches correspond to cells (independent cathode spots) which emit current and create the medium necessary for sustaining their own existence.[6)] The existence of several branches indicates the simultaneous existence of several spots.

At currents close to some minimum value called the threshold current, the entire current is concentrated in one spot. As the current is increased a steadily increasing tendency for division of this single spot is observed. Here, beginning at some current, the probability of simultaneous existence of two or more spots asymptotically approaches unity.[1]

In a stationary state of the arc (a specified current) spontaneous decay of spots is observed. However, in view of the constancy (on the average) of the number of spots at a given current, simultaneously with the decay formation of spots occurs by division of existing spots. A spot has its maximum stability[1] at a current to the spot equal to twice the threshold current.[7)]

In the literature there are many studies devoted to explanation of the mechanism of division of the spot and its random motion. Il'in and Lebedev[30] suggest that in view of the explosion of emitting portions of the spot surface there is a pause in the current due to the destruction of the surface, and the spot jumps to a new location. Similar ideas were expressed by Rothstein[31]; Grakov and Hermoch[24] suggested that rapidly moving spots have a high current density and therefore exist mainly at places where the field enhancement factor is high: on projecting faces of crystallites, microirregularities, and so forth. In view of the melting of these microirregularities the field enhancement factor drops and the spot moves to another place. This also results in significantly more stable burning of an arc with a rapidly moving spot on solid cathodes than on liquid cathodes.[1,24] Observations of the motion of a cathode spot on oxidized surfaces[11] have led to attempts to explain its random motion by destruction of the film as a consequence of ion bombardment in the vicinity of the spot and a deterioration of the conditions for emission in view of the removal of the Malter effect (Ref. 32).[8)]

The often noted fact of division of spots has led to a wide range of hypotheses regarding their mutual repulsion.[9)] In Ref. 1 on the basis of analysis of the motion of a spot in a magnetic field it was established that the displacement of the spot occurs in the direction of the maximum of the magnetic field. This property of a spot is used by the author[1] to explain the repulsion of spots after division and their random motion. It is assumed that at the beginning of the division there are formed within a single spot two "current centers" (the causes of formation of these centers are not discussed). The magnetic field due to the arc current will be less between the centers than on the outside, and as a result of the established effect of displacement of the spot toward the maximum of the field this should lead to repulsion of the centers and formation of two spots. Sena[186] explains the mutual repulsion of spots by a force of interaction between them, determined by the attraction of parallel flowing currents and the repulsion of the space charges above the cathode spots.

Study of the nature of the motion of cathode spots of the first type on a massive cathode by means of apparatus with high time and space resolution[29] has permitted observation of a number of new features of the dynamics of their development which were not observed in previous studies.[1,5,24]

The macroscopic displacement of these spots is usually the result of an anisotropic increase of the spot size, appearance of a new spot on its periphery, and a dying out of the initial spot. On division of a spot the initial spot does not die out, and this leads to formation of two independent spots. Division of a spot sets in during the course of its expansion on reaching some minimum current density with a practically constant current to the spot. Increase of the distance between

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[6)] According to the terminology of Ref. 1 a cathode spot is defined as the entire set of individual cells at a given current. It appears logical to us to identify a cell with an individual cathode spot. This terminology is adopted in what follows.

[7)] This fact, and also many other regularities in the behavior of cathode spots, were established by Kesaev[1] in experiments with film cathodes. It has been assumed that the properties of spots on massive cathodes and on film cathodes (for a film thickness $d \sim 1-1.5\ \mu$) are identical. However, this statement is not obvious to us, since the type of spot (which was not determined in Ref. 1) on a massive cathode and on a film cathode may be different, and the thermal properties of the film material may differ from those of the massive cathode (on this point see Ref. 182). The properties of cathode spots on film cathodes are not considered below. Those interested in this question are referred to the very fine book by Kesaev.[1]

[8)] The term Malter effect is usually used to mean the appearance of field emission under the influence of the electric field of ions condensed on a thin dielectric film covering the cathode surface.

[9)] We note that the repulsion of spots occurs by no means always; we have directly observed very frequent fusion of spots.[29]

spots after division is due to the cessation of current flow at a definite part of the surface, and not to displacement as the result of repulsion of the daughter spots after division, as was proposed by Kesaev.[1] Fusion of spots has been established as well as division. The rate of expansion of spots of the first type appreciably exceeds the rate of propagation of the thermal front in the body of the electrode and is apparently determined by the speed of outward motion of heavy particles in the near-cathode plasma. Whether the spots exist separately after division or are again combined into one spot is determined by the preferential direction of dispersion of the plasma away from the near-cathode regions of the spots which arise after the division.

The rate of displacement of spots of the first type depends weakly on the electrode material (it is higher in materials with low thermal conductivity and melting temperature) and amounts to $\sim 10^3$–$10^4$ cm/sec. It rises sharply as the surface density of microirregularities on the cathode increases.

The observed characteristic features of the macroscopic random motion of a cathode spot can be explained in terms of the explosive model[33,121,187] of a spot of the first type.[10)]

The essence of the model is as follows. At the moment of appearance of a spot, current can flow between the electrodes at the expense of the residual plasma formed in the breakdown or as the result of the decay of a previously existing spot. Here, as the result of enhancement of the local field strength at microinhomogeneities of the cathode surface, field-emission current can flow through a microinhomogeneity; this current has sufficient density ($> 5\times10^7$ A/cm$^2$) to lead to explosion of the point as the result of resistive heating and the Nottingham effect. The plasma which arises in this case, propagating along the cathode surface, enhances the field at microinhomogeneities on the cathode surface and results in appearance of field-emission current. However, in view of the sharp drop in field strength after appearance of a discharge channel, the field strength and current density from the micropoints are such that they do not lead to their explosion. As the result of the diffusion and cooling of the plasma which arose at the explosion, its conductivity drops and the potential fall near the cathode rises, and at some moment an explosion again occurs at a suitable microinhomogeneity—the cycle is repeated. In this way heavy particles necessary to assure current transport in the near-cathode region are regenerated in the explosion of micropoints at the moment of initiation of the spot.[121] Transport of current is accomplished mainly as the result of field emission from microinhomogeneities of the cathode at current densities much less than the explosive current density, providing an average current density in the spot of the order $5\times10^4$ A/cm$^2$.

The model described for the appearance and development of a spot of the first type permits qualitative explanation of a number of experimental facts. The absence of displacement of a spot of the first type in a single crystal and its fixation by "reference lines" located at a distance greater than the spot size are explained by the absence of microinhomogeneities. With deterioration of the surface quality (transition from a single crystal to a single crystal with "reference lines" located closer than the spot size,[121] transition from a polished surface to surfaces prepared more poorly) the rate of displacement of the spots increases and the time of transition to spots of the second type also increases.[5,154]

Representation of the displacement of a spot as a succession of explosions (or breakdowns at the periphery of the spot) permits easy explanation of the high displacement velocity of spots, which is determined by the rate of diffusion of the plasma, and also permits explanation of oscillations in the voltage on the arc with a frequency commensurate with the reciprocal of the mean life of the spot.[1,97] Since the appearance of conditions for a subsequent breakdown on diffusion of the plasma is random in nature, the motion of the spot over the cathode surface should be random, and after division the individual spots can either separate from each other or merge into a single spot. All these facts are observed experimentally.[33,187]

The rate of displacement of spots of the second type lies in the range 10–100 cm/sec. These spots have a tendency to fuse and to form grouped spots. The number of spots in a group is of the order of ten, and they are located at distances of the order of the diameter of the individual spots.

The causes leading to displacement of a spot of this type and to formation of grouped spots are not clear at the present time. There is no discussion of this point in the literature.

### d) Retrograde Motion of a Cathode Spot in a Magnetic Field

Over a period of many years, one of the most disturbing puzzles regarding cathode spots has been the so-called retrograde motion of the cathode spot in a magnetic field. The essence of the phenomenon is that the cathode spot of a vacuum arc in a magnetic field tangential to the cathode surface moves in the direction opposite to the direction of the Ampere force, as was pointed out for the first time by Stark.[21] This effect has been studied in a large number of metals[34–36,39] and in the presence of various residual gases.[34,36,38] The following facts have been established.

The directed velocity of the retrograde motion of a cathode spot increases with the magnetic field strength $H$ mainly as the result of straightening of the trajectory.

[10)] Description of a cathode spot as a sequence of explosions has been undertaken repeatedly.[30,48,57,83,134] However, these attempts were made without regard to the properties of spots of a definite type and, as a rule, have not been confirmed to a sufficient degree by experimental data. The model presented below corresponds qualitatively, and in some cases quantitatively, to the experimental data.[33,187] Nevertheless, as can be seen below, it is far from having been perfected, i.e., it is not reduced to relations permitting calculation of all of the parameters of a cathode spot.

In individual portions of the trajectory, the rate of displacement of the cathode spot is constant and equal to the random value. At sufficiently high fields ($H \sim 10^3$ Oe) the directed velocity becomes practically equal to the random velocity.[1,46] At magnetic fields $H \sim 10^4$–$2 \times 10^4$ Oe a discontinuous increase in velocity is observed.[39]

When the residual gas pressure is increased, the velocity of the retrograde motion decreases and at some value $P = P_{cr}$ the spot begins to more in the opposite direction. $P_{cr}$ increases with increase of $H$ and decrease of the current and, depending on these parameters, varies over a wide range.[34,36,38,39]

Providing conditions which facilitate appearance of a thermionic-emission spot (heating of the cathode) leads to transfer from retrograde to direct motion.[3]

The velocity of the retrograde motion increases with deterioration of the quality of processing of the surface.[5,187]

Many attempts have been made to explain the retrograde motion of the cathode spot (see for example Refs. 1, 40–48). However, at the present time not only is there no systematic quantitative theory, but also there is not even a qualitative model of the retrograde motion of the cathode spot of a low-pressure arc.

In the attempts to explain the direction of motion of a spot in a magnetic field in the direction opposite to the electrodynamic force acting on the arc column, the terms "anomalous direction," "reverse direction," "astonishing fact," and so forth are frequently used. Here the impression can be created that the displacement of a spot in a direction opposite to that observed experimentally would be natural and would not require explanation. In actual fact the direction of action of the forces in the arc column may not have a direct relation to the physical processes on the electrode surface and in the immediately adjacent plasma layers, which actually determine the direction of motion of the spot. Therefore it is more correct to speak of the phenomena which lead to the displacement of the spot and of the influence of them of the magnetic field.

On the other hand, in explaining the mechanism of spot displacement, frequent use is made of "kinetic" reasoning, discussing the motion of individual particles in a more or less plausible force field and then, on the basis of the qualitative form of the particle trajectory, drawing conclusions regarding the spot displacement (see for example Refs. 43 and 47), invoking at this stage some assumptions regarding the properties of the spot as a whole (the nature of the emission, the relation of the emission to the concentration of ions, and so forth). This approach has produced a diversity of explanations of the motion of a spot in a magnetic field but has not led at the present time to a solution of this problem, since none of these explanations describe the complete set of experimental data, and some simply contradict elementary physical ideas.

Reviews of various attempts to discover the mechanisms leading to the motion of a spot in a magnetic field, and criticism of these attempts, are contained in Refs. 1, 5, and 39. Recently two studies have appeared[1,47] which present new reasoning in an attempt to explain the motion of the spot.

Kesaev[1] proved experimentally that the spot moves in the direction of the maximum of the magnetic field and that the duration of the discharge $\theta$ increases with increasing magnetic field strength. On the basis of the latter fact he gives the following explanation of the mechanism of spot displacement. It is assumed that the spot can be represented as a set of "active emission centers" whose lifetime depends on the magnetic field strength. Here the displacement of the spot is represented as the dying out of centers in the region of weak fields and the creation of new centers in the region of stronger fields. It follows from this that the spot should be displaced in the direction of increase of the magnetic field, which is observed experimentally.

This type of logic is characteristic of many studies. In the first place, an undefined concept, active emission centers, is introduced; secondly, a fact established for some phenomenon (the increase of $\theta$ with increase of the field) is ascribed to the concept introduced (active centers) and then physical conclusions are drawn. It appears obvious that the reasoning presented does not explain the causes of the motion of the spot.

Nevertheless, Kesaev's experiments,[1] which were carried out in magnetic field of a complex configuration, show quite convincingly that the spot moves into the region of increase of the combined field (external field plus the field due to the arc itself). This fact, named by Kesaev the principle of maximum field, can be considered established experimentally, and it must be taken into account in constructing any theoretical model of spot motion. Kesaev[1] attempted to prove that the maximum field in the spot corresponds to the maximum concentration of charged particles, and he attempted to use this fact to explain the motion of the spot. However, this proof is mathematically incorrect.

The work of Sena[47] is based on analysis of the trajectories of ions near the edge of the spot. It is assumed that as the result of action of the space charge of the central region of the spot on the ions located near its edge, the latter acquire velocities directed away from the center of the spot. If these velocities are substantial, then as the result of Larmor rotation an ion, moving in a planar drift path, will on one side of the spot approach the cathode surface and on the other side it will move away from it. On this basis it is considered likely that a zone of increased ion concentration is formed in the location where the trajectory of the ions considered approaches the surface. From this fact, assuming that emission increases with increase of the ion concentration, it is concluded that there is a continuous appearance of new emitting regions near the edge of the spot, where the ion concentration is increased. A simple analysis shows that if this effect exists, the spot should be shifted in the direction which corresponds to the experimental data.

Sena's approach[47] is characteristic of many studies

in this area. The main question is left aside—how effective is the considered mechanism against the background of other mechanisms whose action either is not considered or is replaced by the force pattern chosen. In particular, in regard to the situation considered in Ref. 47, we can say the following. Near the electrode surface there is a region of space charge, the structure of which at the edge of the spot is unknown and cannot be known until some model of the spot as a whole is adopted. It is clear, however, that near the edge of the spot there is a zone of electric fringing field and, consequently, the particle will participate in two motions in the course of its orbit in the presence of the magnetic field—rotation in a circle (this is the motion studied in Ref. 47) and drifting in the direction of the vector $\mathbf{E}\times\mathbf{H}$ (this component of the motion is not considered in Ref. 47).

It is easy to see that in the situation studied in Ref. 47 the drift of a particle in the presence of a real electric field will lead to effects qualitatively opposite to the conclusions of Sena, and this places in doubt the explanation proposed in his work for the nature of the spot motion.

In concluding this section we emphasize that elucidation of the reasons leading to the directed motion of the spot in a magnetic field and, equally, of the reasons for its random motion in the absence of a field, is an extremely attractive and important problem both for theoretical and experimental study. It appears to us, however, that the theoretical solution of this problem is impossible without use of a rather complete physical model of the cathode spot as a whole.

### e) Lifetime of a Cathode Spot

It was remarked above that for a long time a cathode spot as a physical object was inseparably associated with an arc. In this case it is natural that some properties of the arc were associated with the properties of the spot. In particular, the lifetime of the spot has been identified with the duration of the discharge.[1]

The study of the duration of a discharge at a cold cathode led to an empirical rule[1] according to which the number of arcs $N_t$ existing for a time $t$ is

$$N_t = N_0 e^{-t/\theta}, \qquad (1.1)$$

where $N_0$ is the total number of arcs investigated and $\theta$ is the average duration of existence of an arc. The quantity $\theta$ increases exponentially with increase of the discharge current $I$.

In Kesaev's opinion[1] the ratio $\theta/t$ indicates existence of a special property of vacuum arcs, named by him "intrinsic instability," which characterizes the constant tendency of the arc to go out.

Since at the present time it has been established[1,5,29,33,187] that the lifetime of the discharge can greatly exceed the lifetime of a spot, as the result of division of the spots or of their appearance and disappearance [see Section (c)], it is natural that the quantity $\theta$ cannot characterize the cathode spot as a physical object. This applies also to the case in which, at a small current to the cathode, at each moment of time only one spot exists.

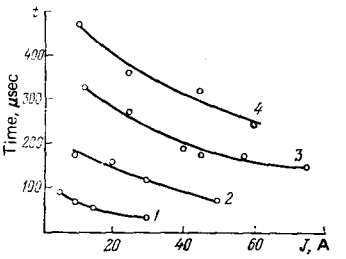


FIG. 5. Time of transition from spots of the first type to spots of the second type as a function of cathode material and discharge current. 1—zinc, 2—iron, 3—copper, 4—silver.

In order to determine the laws governing the lifetime of an individual cathode spot on a massive cathode, special studies were undertaken by means of an image amplifier.[29,33,187] It turned out that the time of existence of a spot of the first type, i.e., the time between two successive divisions, does not depend on the current and increases with increasing rate of rise of the current. For a copper cathode at $dI/dt = 10^5$ A/sec the lifetime of a spot is 7.5 μsec, at $dI/dt = 6\times10^5$ A/sec it is 10.2 μsec, and at $dI/dt = 6\times10^6$ A/sec it is 20 μsec. For the same rate of rise of current the number of spots of the first type changes in proportion to the current. Here the value of the current per spot $J$ does not depend on $I$ for a constant $dI/dt$ and varies from 6.9 A to 14–17 A as $dI/dt$ increases within the limits indicated.

In addition, the investigations carried out have shown that at the beginning of the discharge and for small currents, only spots of the first type exist at the cathode. The duration of the regime of burning of the arc in which only spots of the first type are observed at the cathode depends on the thermal parameters of the cathode material and on the discharge current (Fig. 5). Experiments[49] have shown that this time increases with increase of thermal conductivity and decrease of the vaopor pressure of the cathode material and of the discharge current. At currents less than a certain value, rapidly moving spots are preserved during the entire duration of the discharge ($\theta \sim 1$ msec). The value of this current depends on the thermal parameters of the cathode material. At large currents after the indication time has elapsed (see Fig. 5) slowly moving spots of the second type appear; at first these spots coexist with the rapidly moving spots, and then they are observed in the absence of the latter. The lifetime of these spots depends weakly on the electrode material and varies from 500 μsec to one and a half milliseconds. As a rule, spots of the second type arise at the place of most frequent occurrence of spots of the first type. The dependence of the time of transition on the thermal properties of the material, and the relation between the place of appearance of spots of the second type (and grouped spots) and the location of the spots of the first type, suggest a thermal nature of the phenomenon of transition from the first to the second type of spots.

Spots of the second type readily form a grouped spot containing up to twenty individual spots located at distances comparable with the spot diameter, the lifetime[11)] of such a grouped spot on materials with high

[11)]This time was limited by the duration of the discharge. It appears likely that a grouped spot can exist for a significantly longer time.

thermal conductivity (copper, silver, and so forth) reaching several milliseconds.[154]

Grouped spots do not arise at currents less than some critical value $I_{cr}$ (for copper, for example, $I_{cr} \sim 100$ A).

As a consequence of the low rate of displacement of grouped spots, thermal processes are established in them on materials with high thermal conductivity (for example, copper) in a time $t_* \sim 10^{-3}$ sec (Ref. 184). Consequently, a spot of this type for $t > t_*$ can be considered a stationary spot.

The lifetime of grouped spots on tungsten in the experiments of Refs. 49 and 154 did not exceed $5 \times 10^{-5}$ sec. Here thermal processes in the spot are not established ($t_* \sim 10^{-4}$ sec) and consequently it is possible that these spots have a different nature from that found with copper and other high-conductivity materials. The grouped spots on tungsten in the experiments of Lukatskaya[89] were observed for small interelectrode spacings. Here it is possible to have an increase of the vapor pressure and the appearance of spots characteristic of arcs in an inert-gas atmosphere. In general the question of the type of the grouped spots on tungsten and their physical nature is in need of further investigation.

### f) Value of current in a spot

Studies carried out by various experiments have shown that the value of the current in a cathode spot depends substantially on the cathode material, the type of cathode spot, the rate of rise of the current, the conditions of burning of the discharge, and a number of other factors. It apparently makes sense to distinguish two concepts—the minimum current value at which the cathode spot and consequently the arc can still exist (the threshold current $J_*$) and the statistical average value of the current per spot $J_n$.

Attempts to determine the threshold current have been made repeatedly by a number of workers. Various physical methods have been used: Lee *et al.*[50] identified the threshold current with the average value of the extinction current of an alternating current arc before passing through zero (the cutoff current); Malcolm[51] and Pleesse[52] identified it with the minimum current for transition from a glow discharge to an arc; a number of other workers[1,54-56,58] identified it with the minimum current for appearance of an arc in vacuum between breaking contacts. It appears natural that the values of $J_n$ obtained by different methods are quite different. This is due to the fact that the physical processes which determine the appearance or disappearance of a spot are different under the measurement conditions mentioned. Accordingly, it is clear that the concept of threshold current requires refinement.

We note an interesting empirical fact established by Kesaev[1] which is that the minimum current of a breaking arc in vacuum is connected with the thermal constants of the material by the relation

$$J_* = 2.5 \cdot 10^{-4} T_b \sqrt{\lambda_T}; \qquad (1.2)$$

$T_b$ is the boiling temperature, and $\lambda_T$ is the thermal conductivity. The experimental points lie satisfactorily on the curve calculated with this formula, although appreciable deviations are observed in the case of ferromagnetic metals. The physical meaning of Eq. (1.2) is not yet clear.

TABLE I. Current in a rapidly moving cathode spot as a function of the rate of rise of current in the discharge circuit.

| $J_n$, A | $dJ/dt$, A/sec | Reference | $J_n$, A | $dJ/dt$, A/sec | Reference |
|---|---|---|---|---|---|
| 75 | 0 | 58 | 6.9 | $10^5$ | 29 |
| 3.5 | 0 | 1 | 10.2 | $10^6$ | |
| 100 | $10^5$ | 5 | 17 | $6 \cdot 10^6$ | |

Experiments[1] on determination of the average current per spot $J_n$ led Kesaev[1] to conclude that there is a universal relation between this quantity and the threshold current,

$$J_n = 2J_*. \qquad (1.3)$$

We note that this result was obtained in experiments with film cathodes, but is widely used at the present time also to estimate the current per spot on massive cathodes. However, systematic study of spots of the first type on a massive copper cathode[5,29,49] have shown that Eq. (1.3) is not satisfied for them. In fact, it was found that the current per spot under these conditions varies over a wide range and depends on the rate of rise of the current (Table I). Here the current per spot exceeds the value $J_* = 1.6$ A (Ref. 1) by a factor of three or four for $dI/dt < 10^5$ A/sec and by a factor of up to ten for $dI/dt \sim 6 \times 10^6$ A/sec.

Thus, Eq. (1.2) cannot be considered universal and it is of interest to determine the limits of its applicability, both as to type of spot and as to arc parameters.

The study of slowly migrating cathode spots on various materials[29,154] has shown that in a single spot of the second type the current is two to four times greater than in a rapidly moving spot.

Results of measurements of $J_n$ for grouped spots on various metals are given in Table II. The numbers in the Table correspond to the spots most frequently observed in the experiments.[24,49,154] At the same time spots were observed with a current per spot differing appreciably from the value given in Table II. For copper, for example, grouped spots were recorded with a current per spot of 100–500 A (Refs. 49 and 154). It is possible that the average current per grouped spot de-

TABLE II. Value of current in quasistationary cathode spots and electrical transport coefficients according to the data of various authors.

| Metal | $J_n$, A | $\varkappa$, g/Coul | Reference |
|---|---|---|---|
| Cu | 200 | $1 \cdot 10^{-4}$ | 49, 154, 187 |
| Ag | 150 | $1.3 \cdot 10^{-4}$ | 5, 154, 62 |
| W | 300 | $1.3 \cdot 10^{-5}$ | 49 |

pends on the discharge current. Unfortunately, there are no experimental studies on this point. However, data on erosion in group spots, discussed in Section (h), apparently indicate that there is such a dependence.

### g) Current Density in a Cathode Spot

The current density in a cathode spot can be determined if the current per spot and its characteristic size are known. We report below results obtained by methods based on determination of the spot size as the size of the luminous region; see Section (b).

At the present time the cathode material which has been studied in greatest detail is copper. Measurements of the current density in rapidly moving cathode spots on copper have been carried out by us[33,49,187] for rates of rise of the current of $5\times10^5$, $5\times10^6$, and $6\times10^6$ A/sec in the range of currents from 5 to 4000 A. The average current density calculated from the current in the spot and the size of the luminous region varied from $2\times10^4$ A/cm$^2$ to $7\times10^4$ A/cm$^2$. The maximum current density ~$10^5$ A/cm$^2$ was observed usually immediately after division of a spot, and the minimum value (~$10^4$ A/cm$^2$)—immediately before division.

Holmes and Djacov[58] observed that a spot has a substructure, which they called fragments, and that the current density evaluated from the size of a fragment varied from $10^5$ to $5\times10^7$ A/cm$^2$. As in Ref. 33, an appreciable decrease of the current density was observed immediately after division of a spot. We suggest that the higher current densities observed in Ref. 58 are due to the fact that those authors did not use sufficient light amplification and therefore did not see the true spot size. The fragments observed by them are most likely spots of the first type which were not resolved in Ref. 58.

Investigation of the current density in slowly moving spots (spots of the second type) and grouped spots has led to values $5\times10^4$–$10^5$ A/cm$^2$ for copper.[49]

The existing results on measurement of current density in various cathodes, obtained by various methods, are given in Table III.

TABLE III. Current density in cathode spots on various metals from data in the literature.

| Metal | Discharge current, $I$, A | Current density in cathode spot $J$, A/cm$^2$ | Reference | Remarks |
|---|---|---|---|---|
| Hg | 2.6 | $2\cdot10^5$ | 11 | Photographic scanning method |
| | 3 | $3\cdot10^1$ | 8 | Visual determination of spot size |
| | 10 | $4\cdot10^3$ | 33 | Photograph by chamber using rotating mirror |
| | 35 | $1.7-2.1\cdot10^3$ | 70 | Visual observation |
| | 90—440 | $3\cdot10^5-3\cdot10^4$ | 118 | Photograph by chamber using rotating mirror |
| | 150 | $10^6$ | 18 | Photographed with Kerr cell |
| | $8\cdot10^3$ | $2\cdot10^6$ | 59 | Photographed with single-stage image amplifier |
| Cu | 2.6 | $1.2\cdot10^5$ | 11 | Measured by autograph method |
| | 1—5 | $4\cdot10^4-6\cdot10^4$ | 122 | High speed photography of spot |
| | 60 | $3\cdot10^6-10^7$ | 12 | Autograph method |
| | 200 | $2\cdot10^3-10^4$ | 122 | Ditto |
| | 2—200 | $1.5\cdot10^5-7.7\cdot10^6$ | 123 | Calculated on the basis of calorimetric data |
| | 3000 | $2.5\cdot10^4$ | 20 | High speed photorecording |
| | 5—4000 | $3\cdot10^4-10^5$ | 29 | Photographed with multistage image amplifier |
| | 5000 | $1.2\cdot10^6-1.2\cdot10^8$ | 14 | Autograph method |
| | 16 000 | $8\cdot10^5-8\cdot10^7$ | 14 | Ditto |
| Al | 20 000 | $5\cdot10^6$ | 124 | » » |
| Zn | 2.6 | $2.9\cdot10^4$ | 11 | Photographic scanning method |
| Mg | 20 000 | $1.6\cdot10^6$ | 124 | Autograph method |
| W | 20 000 | $1.6\cdot10^6$ | 124 | » » |
| | 2.6 | $7.7\cdot10^4$ | 11 | Photographic scanning method |
| | 50 | $10^5$ | 125 | » » |
| | 150 | $10^6$ | 10 | Photograph method |
| | 1000 | $10^3$ | 3 | » » |
| | 300 000 | $7.5\cdot10^3-2\cdot10^4$ | 13 | » » |
| Oxidized $W$ | 2 | $10^6$ | 93 | |
| Bronze | 2—80 | $4.5\cdot10^6$ | 126 | » » |
| Stainless steel | 80 | $4.1\cdot10^7$ | 126 | » » |
| Na—K (Alloy) | 150 | $10^6$ | 18 | Photographed with Kerr cell |

### h) Erosion of Cathodes of Vacuum Arcs

1. *Erosion in the vapor phase.* Erosion of an electrode under the action of a cathode spot can occur in the vapor phase and also in the form of drops and individual particles of metal moving away from the region of the spot. However, if the electrode is well outgassed before the experiment and the rate of rise of the current is relatively small ($dI/dt < 10^6$ A/cm$^2$), erosion occurs mainly in the vapor phase.[5]

Study of erosion damage in outgassed cathodes[5,24,29,49] has shown that the rate of erosion is completely determined by the type of cathode spot. A convincing proof of the decisive role of the type of spot in the destruction of the cathode is given by the results of Kantsel' *et al.*,[49] who showed that the minimum erosion rate occurs in the case when during all or most of the burning time of the discharge the regime of existence of spots of the first type is preserved. A change of the conditions of burning of the discharge, leading to appearance of grouped spots or spots of the second type, results in an appreciable increase in the rate of erosion.

Rapidly moving cathode spots of the first type leave on the electrode a track in the form of a characteristic Christmas tree, which has been observed repeatedly by a number of workers.[1,5,15,24,49] Careful study of this track[187] by means of scanning and ordinary electron microscopes has shown that it consists of craters whose average diameter is ~$1\times10^{-4}$ cm with an average depth of the order of the crater radius. As a rule, these craters are concentrated in an area less than the area of the cathode spot. The surface between the craters and groups of craters is practically undamaged (Fig. 6). Comparison of the area occupied by craters and by the spot directly before extinction or division shows that the former area is of the order of 1% of the latter.

Since in spots of this type the current per spot does not depend on the arc current (for a constant $dI/dt$), the number of spots increases with increase of the current and, consequently, the erosion increases linearly.[29,60,61] It follows from this that the electrical transport coefficient $\varkappa = \gamma/J$, where $\gamma$ is the erosion rate in g/sec, should remain constant over the range of cur-

FIG. 6. Photograph of erosion track left by a cathode spot of the first type on a copper anode. Magnification 6000.

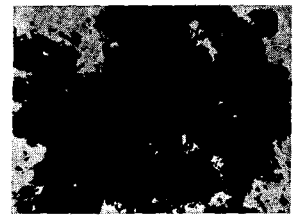

FIG. 7. Photograph of erosion track left by a grouped spot on a copper cathode.[187] Magnification 50.

rents in which only spots of the first type exist on the cathode. This conclusion is confirmed by experiment[187]: for example, for copper we have $\varkappa = 0.45$ μg/Coul.

After the appearance of spots of the second type, the erosion of the cathode is determined mainly by the action of just these spots or of a grouped spot. The action of the individual spots in a grouped spot is traced also in the photograph of an erosion track shown in Fig. 7. The grouped clusters of spots of the second type produce the most intense erosion; there remain of the latter melted tracks having an area $\sim 10^{-3}$–$10^{-2}$ cm$^2$ with depth up to $10^{-2}$ cm, and the average depth of destruction as the result of burning of single spots amounts to $(2-5)\times 10^{-3}$ cm.

Values of the electrical transport coefficient for grouped spots on various metals are given in Table IV.

In an experimental investigation of the dependence of erosion on arc current, the total erosion during the entire discharge time is usually measured. This value naturally depends on the relative duration of the regimes with spots of different types during the discharge time studied. Since a transition from one type of spot to another depends substantially on the thermal parameters of the electrode material and on the arc current, a dependence of the erosion rate on the thermal constants of the cathode material, the arc current, and the discharge time should be observed.

Experiments[64,65] (Fig. 8) confirm the existence of this dependence. Analysis of these data in terms of the electrical transport coefficient shows that the latter varies rather weakly (see Tables II and IV[12)]) in the range of currents studied ($I = 100$–$700$ A). A dependence of the electrical transport coefficient on arc current in this range of current has been observed also in other experiments[62,79,128] (see Table IV).

We can see that the difference in the values of the electrical transport coefficients in the current range 100–400 A is of the order of the spread of the data in one series of experiments and also of the spread in the results obtained by different workers. This fact has led to the frequently expressed conclusion that the electrical transport coefficient does not depend on the arc current in the range of currents for which grouped spots exist on the electrode.[2,188] We note that this conclusion would be valid if the average current per grouped spot did not depend on the arc current. However, analysis of the experimental data[64,65] (Fig. 8) shows that the assumption that the average current per grouped spot does not depend on the arc current [for example, $J = 200$ A, as discussed in Section (f)], on appropriate recalculation of erosion on the basis of the electrical transport coefficient for $J = 200$ A, leads to a discrepancy of several times with the actually measured erosion for $J > 200$ A. Since this discrepancy substantially exceeds the possible experimental error, there is a great likelihood that the average current per grouped spot depends on the arc current and increases with increase of the latter. However, there is no direct experimental proof of this statement.

The measured erosion values have frequently been used to estimate the temperature of the metal $T_W$ in a cathode spot. The current density (or spot size) was used for this purpose and it was assumed that the specific erosion rate is determined only by the temperature in the spot and is equal to the rate of evaporation in vacuum $mW$:

$$G = mW = mCT_W^{1/2}e^{-B/T_W},$$
$$\gamma = \pi r^2 G = \frac{I}{j}G; \qquad (1.4)$$

here $m$ is the mass of the atom and $B$ and $C$ are constants of the material.[173] Since the rate of evaporation physically corresponds to the flux of atoms leaving a unit of the metal surface per unit time, the first relation of (1.4) is valid, strictly speaking, when there is no reverse current of atoms to the metal. This condition is not satisfied in the cathode spot and the difference between $G$ and $mW$ can be substantial (see below). Therefore the first relation of (1.4) is unsuitable for calculation of the erosion.[133]

On the other hand, if the spot size and total erosion are known (for example, have been measured in the same experiment), then the relations (1.4) can be used to estimate the temperature in the spot, since, as the result of the strong dependence of the evaporation rate on temperature, the temperature value calculated from (1.4) will not differ greatly from the true temperature

TABLE IV. Electrical transport coefficient as a function of discharge current.

| I, A | Our data[29] for $\varkappa$, g/Coul | Data from literature on $\varkappa$, g/Coul | Reference |
|---|---|---|---|
| 100 | $1.34\cdot10^{-4}$ | $1.15\cdot10^{-4}$ | 128 |
| | | $0.7\cdot10^{-4}$ | 2 |
| 200 | $1.055\cdot10^{-4}$ | $0.9\cdot10^{-4}$ | 62 |
| 300 | $1.1\cdot10^{-4}$ | $1.3\cdot10^{-4}$ | 79 |
| | | $2.05\cdot10^{-4}$ | 62 |
| 400 | $1.29\cdot10^{-4}$ | $0.8\cdot10^{-4}$ | 62 |

[12)]The values of the electrical transport coefficient given in Tables II and IV were obtained from analysis of erosion data on the assumption that the entire current (for 100–400 A) is concentrated in a single spot (the number of spots which actually existed in these experiments was not determined).

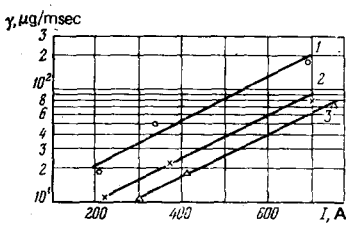


FIG. 8. Rate of erosion as a function of cathode material and discharge current. 1—copper, 2—nickel, 3—tungsten.

even if there is a large difference between $G$ and $mW$ (for example, for copper for $T_W \sim 3500°$ K the rate of evaporation changes by a hundred times with a change of temperature of ~400°). It is obvious that the accuracy of such an estimate in uncertain and depends on the difference between $G$ and $mW$.

2) *Cathode vapor jets.* The existing experimental data, discussed in Section (i), and also theoretical estimates[5,109,136] show that in the vicinity of the cathode spot of a vacuum arc there are high concentrations of the electrode material vapor, $10^{17}$–$10^{20}$ cm$^{-3}$. Since in vacuum there are no forces capable of holding a high-pressure vapor cloud near the electrode, the vapor should flow out of this region; the fact that a cathode spot serves as the source of a high-speed vapor jet was first observed by Tanberg[69] in 1929. Since then a large number of studies of the parameters of cathode jets have been carried out,[70,71,75,76,79,80,116,111,112,127] and the following facts have been established.

It has been established that there are fluxes of heavy particles emitted by the cathodes of vacuum arcs, which have velocities significantly greater than thermal velocities ($v \sim 10^6$ cm/sec).

The force of reaction of the vapor jet on the cathode varies, depending on the cathode material, from ten to several tens of dynes per ampere.

The velocity of cathode jets usually increases as the vapor pressure of the cathode material decreases (Table V).

In jets of metals with high vapor pressure (for example Cd, Zn, Pb) singly charged ions are dominant and the degree of ionization amounts to about 25%. In jets of low-vapor-pressure material (for example, Cu, Ag, Ni) the degree of ionization varies from 50 to 100%, and the plasma contains up to 50% of doubly charged ions and an appreciable amount of triply and quadruply charged ions.

With increase of the current density the velocity of the ions and the content of multiply charged ions have a tendency to decrease.

We note that most of the experimental data have been obtained at relatively low currents ($I \lesssim 100$ A), and therefore they evidently apply to spots of the first type. The work of Plyutto *et al.*[79] is an exception; their measurements by the pendulum method apparently refer to grouped spots.

For measurement of the velocities and other parameters of the jets, use has been made of pendulum measurements.[69,75,79] measurement of the reaction force on the cathode,[69,70,75] and measurements of the energy dissipated by the jet in the target.[73,111,112]

TABLE V. Cathode vapor jet velocities measured by various experimental methods.

| Cathode material | Discharge current $I$, A | Jet velocity, cm/sec | Recording method | Reference |
|---|---|---|---|---|
| Cu | 18 | $1.91 \cdot 10^6$ | * | 69 |
| | 32 | $1.35 \cdot 10^6$ | $r$ | 69 |
| | 115 | $1.25 \cdot 10^6$ | * | 75 |
| | 300 | $7.8 \cdot 10^5$ | * | 79 |
| | 18.5 | $1.62 \cdot 10^6$ | * | 73 |
| | | $3.7 \cdot 10^6$ | $c$ | 73 |
| | 100 | $1.6 \cdot 10^6$ | M | 127 |
| | 100 | $8.4 \cdot 10^5$ | $e$ | 79 |
| Mg | 50 | $1.23 \cdot 10^6$ | $e$ | 79 |
| | 55 | $2.74 \cdot 10^5$ | * | 75 |
| | 170 | $8.8 \cdot 10^5$—$1.5 \cdot 10^6$ | * | 79 |
| Ag | 100 | $7.54 \cdot 10^5$ | $e$ | 79 |
| | 166 | $9.7 \cdot 10^5$ | * | 75 |
| | 300 | $8.4 \cdot 10^5$ | * | 79 |
| | 100 | $10^6$ | M | 127 |
| Au | 53 | $4.06 \cdot 10^5$ | * | 75 |
| Ca | 40 | $1.56 \cdot 10^6$ | M | 127 |
| | 100 | $1.36 \cdot 10^6$ | M | 127 |
| Zn | 20 | $5.79 \cdot 10^5$ | $e$ | 79 |
| | 57 | $5.31 \cdot 10^5$ | * | 75 |
| | 100 | $4.5 \cdot 10^5$ | $e$ | 79 |
| | 300 | $2.9 \cdot 10^5$ | * | 79 |
| Cd | 43 | $1.64 \cdot 10^5$ | * | 75 |
| | 50 | $3.09 \cdot 10^5$ | $e$ | 79 |
| | 100 | $2.92 \cdot 10^5$ | $e$ | 79 |
| | 170 | $1.8 \cdot 10^5$ | $e$ | 79 |
| Hg | 30—40 | $1.6$—$4.3 \cdot 10^6$ | $r$ | 70 |
| | 30—50 | $7.5 \cdot 10^5$ | $c$ | 112 |
| | | $0.2$—$1 \cdot 10^5$ | | |
| | 10 000 | $0.8 \cdot 10^5$ | o | 71 |
| Al | 110 | $6.95 \cdot 10^5$—$1.84 \cdot 10^6$ | $e$ | 75 |
| | 100 | $1.37 \cdot 10^6$ | $e$ | 79 |
| | 300 | $6.5 \cdot 10^5$ | $e$ | 79 |
| | 100 | $1.8 \cdot 10^6$ | M | 127 |
| C | 73 | $3.58$—$1.73 \cdot 10^6$ | * | 75 |
| | 100 | $2.34 \cdot 10^6$ | M | 127 |
| Pb | 20 | $1.34 \cdot 10^5$ | $e$ | 79 |
| Sn | 60 | $1.19 \cdot 10^5$ | * | 75 |
| Zr | 100 | $1.3 \cdot 10^6$ | M | 127 |
| | 200 | $1.28 \cdot 10^6$ | M | 127 |
| Ta | 150 | $1.1 \cdot 10^6$ | M | 127 |
| Mo | 150 | $1.47 \cdot 10^6$ | M | 127 |
| | 200 | $1.47 \cdot 10^6$ | M | 127 |
| | 50—300 | $1.3 \cdot 10^6$ | $p$ | 80 |
| | 135 | $2.72 \cdot 10^6$ | * | 75 |
| W | 50—300 | $1.3$—$7.10^6$ | $p$ | 80 |
| | 30—1000 | $1.2 \cdot 10^6$—фронт | | |
| | | $1.3 \cdot 10^5$—спад | $p$ | 80 |
| Fe | 142 | $8.8 \cdot 10^5$ | * | 75 |
| Ni | 100 | $10^6$ | $e$ | 79 |
| | 300 | $7 \cdot 10^5$ | * | 79 |
| | 200 | $1.29 \cdot 10^6$ | M | 127 |

Designations of recording method: $r$—measurement of reaction forces, $c$—calorimetric measurements, o—optical measurements of front velocity, $p$—probe measurements of front velocity, M—mass-spectrographic measurements, $e$—electrostatic analyzer, *—data of pendulum measurements.

A major advance in the latter method was achieved by Eckhardt,[111,112] who used a calorimeter consisting essentially of a black body. In addition, in front of the calorimeter he established a special gate which per-

mitted passage into the calorimeter either of the total flux of particles (ions and atoms) or only the flux of neutral atoms, or only the radiation from the cathode spot. The accuracy in measurement of the power dissipated in the calorimeter was $7\times10^{-2}\%$. At the present time there is no theory which could describe even qualitatively the experimental facts presented above. Furthermore, the literature does not even contain opinions regarding the mechanism of acceleration of the vapor to such high velocities. The principal difficulty here is due to the fact that the heavy-particle energy, calculated from the measured velocity and converted to electron volts, sometimes exceeds by several times not only the cathode fall, but also the potential fall in the arc.

Compton[74] and Rich and Ludi[76] assumed that the only mechanism of energy transfer to particles of the vapor involved acceleration of ions into the space-charge layer at the cathode. Here two difficulties arose: in order that particles with energy exceeding the cathode fall be produced, it is necessary to assume the presence of multiply charged ions; it is necessary to indicate a mechanism of energy transfer from ions accelerated along the direction to the cathode to the particles of the vapor (ions and neutral particles) which are traveling away from the cathode. The explanations proposed in this connection, which are based on smallness of the ion-energy accomodation coefficient, high efficiency for ejection of ions from the cathode by bombarding ions, and so forth, appear unlikely.[5]

In order to avoid these difficulties, later studies[79,128] have proposed the idea of a potential hump. It is assumed that in the near-cathode plasma there is a nonmonotonic potential distribution, and that the maximum of the potential at the hump corresponds to the average energy of the particles in the jet.

The idea of a potential hump is extremely artificial. In proving the possibility of formation of a potential hump and estimating its magnitude, the authors of Refs. 79 and 128 employ a number of assumptions which essentially replace the single assumption that such a potential distribution exists.

In contrast to the attempts described above to explain the high velocities of vapor particles in the jet on the basis of "drift" acceleration of ions in an electric field, Ecker[81] discusses the possibility of gas-dynamic acceleration of the vapor. Here the acceleration of the vapor is due to the action of magnetohydrodynamic forces and the hydrodynamic momentum equation is used to estimate the velocity of the jet.

However, one of us[185] has shown recently that the apparent possibility of reconciling the theoretical formulas[81] with the experimental data is due to the presence in these formulas of a physically undetermined quantity: the average density of the gas in the jet. Direct estimates[185] lead to the conclusion that acceleration of the vapor in the jet cannot be provided by magnetohydrodynamic forces.

In spite of these deficiencies of Ref. 81, its basic idea of gas-dynamic acceleration of the vapor in a jet is correct. We have shown[183] that such acceleration can be provided from the energy point of view as the result of the flow of energy from the electric field to the jet outside the zone of the cathode fall, and to obtain the experimentally observed velocities a potential drop in the jet $U_n \sim 1$ V is sufficient.

This fact becomes evident if we turn to the energy equation for the jet as a whole, which with reasonable assumptions can be reduced to the form[183]

$$\gamma\frac{u_2^2}{2}=IU_n=I(U-U_c), \tag{1.5}$$

where $\gamma$ is the consumption of gas in the jet, $u_2$ is the velocity in the jet far from the cathode, measured experimentally, $U$ is the voltage across the arc, and $U_c$ is the cathode fall.

Hence we obtain for the energy of the heavy particles

$$U=m\frac{u_2^2}{2eU_n}=\frac{mI}{\gamma e}\equiv\alpha^2 \tag{1.6}$$

($m$ is the mass of the atom and $e$ is the charge of the electron).

It is evident that the particle energy can substantially exceed the potential drop in the jet (and even the drop in the arc) if we have $\alpha^2\gg1$. Evaluation of this parameter from the data of Refs. 69, 79, 111, and 112 leads to values $\alpha^2\sim10$–200. It is clear that the possibility of accelerating heavy particles as the result of small potential drops in the jet with the gas-dynamic mechanism of acceleration is due to an efficient mechanism of energy transfer from the electrons (the flux of which exceeds by a factor of ten the heavy-particle flux) to the heavy particles by collisions.

In Fig. 9, taken from Ref. 183, we have shown the straight line corresponding to Eq. (1.6) and the experimental points of Plyutto *et al.*[79] for various cathode materials. It is evident that Eq. (1.6) describes the experimental data reasonably well.

### i) Concentration and Temperature of Particles in the Cathode Spot

Until recently there were no reliable data on the parameters of the near-cathode plasma.

The concentration of heavy particles in cathode spots was usually determined quite crudely. In such determinations the investigators proceeded from more or less reasonable estimates of the pressure of cathode-material vapor in the spot and of the temperature of the heavy particles.

In view of the fact that the increase of the pressure of the surrounding gas produces an inversion of the

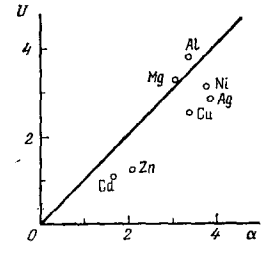


FIG. 9. Vapor velocity in a cathode jet as a function of electrode material.

retrograde motion of rapidly moving cathode spots[1,5,39] in a magnetic field and a decrease in the slope of the curve of arc duration as a function of current,[1] we can suggest that the pressure of cathode-material vapor in the near-cathode region should be of the order of the pressure at which these effects are observed.

To determine the concentration of heavy particles, in addition to the pressure, which is usually assumed to be reliably measured in experiments, information on the temperature of the heavy particles is necessary. However, estimates of the temperature, even in the case of the most carefully studied mercury cathode, are distinguished by a substantial spread. In fact, if we assume that the temperature of neutral atoms is equal to the cathode temperature, then according to the existing data the latter lies in the interval from 700 to 3360° K (Refs. 84–86).[13)]

Another estimate of the concentration of heavy particles in the spot can be made on the basis of the assumption that it corresponds to the saturated vapor pressure at the temperature of the cathode surface. In this case for a mercury cathode with the maximum obtainable (critical) temperature we obtain $1.7\times10^{22}$ cm$^{-3}$. An attempt at determining the temperature of the cathode spot on copper by means of a pyrometer[88] led to values 240–3300° K, which gives a particle concentration, estimated from the equilibrium vapor pressure, $3\times10^{17}$–$1.5\times10^{19}$ cm$^{-3}$.

Very interesting measurements of the pressure of electrode-material vapor in short arcs with practically no column[4] have been carried out with carbon[117] and metallic electrodes.[4] In both cases the arc burned between contacts pressed together by springs with a definite force. As the result of initiation of a discharge on passage of relatively small currents (about 90 A)[117] the contacts moved apart and remained in that position during the entire burning time of the arc. Assuming that the force is applied at the region of the cathode and anode spots, and knowing the area of these spots and the magnitude of the compressive force, it is possible to estimate the vapor pressure in the near-electrode regions and then, assuming that the heavy-particle temperature is equal in order of magnitude to the temperature of these particles in the plasma of the column of an arc burning between these electrodes under ordinary conditions, it is possible to find also the concentration of heavy particles in the spot. Here for carbon electrodes it turned out that $n\sim1.5\times10^{20}$ cm$^{-3}$.

Determination of the concentration of neutral particles in the near-cathode region from the attentuation of an electron beam[89] in the case of a vacuum arc on an iron cathode led to a concentration of $1\times10^{16}$–$2\times10^{17}$ cm$^{-3}$.

Direct measurements of the charged-particle concentration in the near-electrode regions of a copper arc have been made only very recently.[29,33,61] The characteristic feature of these measurements has been that

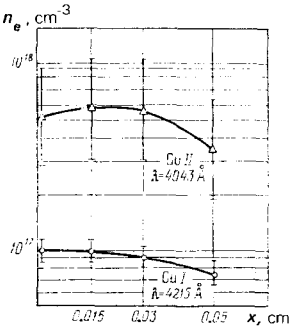


FIG. 10. Concentration of charged particles in near-cathode plasma as a function of distance from the cathode surface.

measurements were carried out simultaneously with high spatial resolution (~$10^{-3}$ cm) and high time resolution (~$5\times10^{-8}$ sec) both of the concentration and of the temperature of charged particles (on the basis of the Stark broadening and the ratio of the intensities of atomic and ionic lines, respectively).[14)]

The measurements made showed that the concentration of charged particles in spots of the first type attains values of $6\times10^{17}$ cm$^{-3}$ (Refs. 33 and 61) and has a weakly expressed maximum (Fig. 10). The presence of relatively low concentrations of charged particles in the immediate vicinity of the cathode confirms the existence of the low current density observed in rapidly moving spots. Similar measurements carried out in the grouped-spot regime led[29] to values of $5\times10^{17}$ cm$^{-3}$.

It is interesting to note that in the spectrum of spots of the first type, lines of doubly charged copper ions were observed; these lines have been observed also in mass-spectrometric studies of vacuum arcs.[79, 127] Similar lines have not been observed in the spectrum of grouped spots.

Measurements of the electron temperature in spots of the first type on the basis of the ratio of intensities of ionic lines have led to values $T_e\sim2$ eV, and measurements on the basis of the intensities of atomic lines have led to $T_e\sim0.8$ eV. Apparently these measurements correspond to the temperatures in the internal and peripheral regions of a cathode spot of the first type.

Measurement of the electron temperature in a grouped cathode spot on the basis of the ratio of intensities of atomic lines gave values $T_e\sim1$ eV.

The measured distribution of concentrations (Fig. 11) in a cathode spot of the first type shows that the concentration of charged particles varies weakly at distances from the cathode $10^{-3}\lesssim1\lesssim10^{-2}$ cm. If we assume that

[13)]We note that the critical temperature for mercury, according to the data of Senchenkov,[86] is 1720 °K, which agrees satisfactorily with the previously obtained data of Birch.[87]

[14)]The constants of the Stark broadening of ionic and atomic lines were calculated in the approximation of the nonstationary theory of Vaĭnshteĭn and Sobel'man[90] in the case of an atomic line and by the method of quasiclassical scattering phase shifts with allowance for the curvature of the trajectories of the perturbing electrons in the impact approximation.[91] For use of the Ornstein method it is necessary to be assured that the Boltzmann distribution and ionization equilibrium can be established in a time less than the time of existence of a rapidly moving cathode spot. Estimates by means of Griem's formula[92,118] have shown that these requirements are satisfied for the lines chosen.

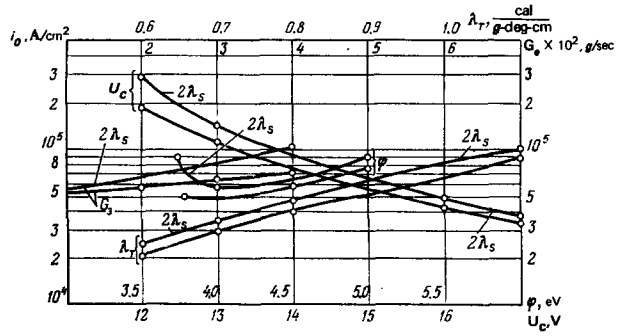


FIG. 11. Principal parameters of a cathode spot as a function of the numerical values of the constants used in calculation with the model described.

this region corresponds to temperatures $T_e \sim 2$ eV (measurements based on ionic-line intensity ratios), it is easy to show that in this region ionization equilibrium should be realized. Here the degree of ionization in this region will be close to unity with practically complete double ionization. If we assume, on the other hand, that this region corresponds to a temperature $T_e = 0.8$ eV (measurements on the basis of atomic-line intensities), the plasma will be in ionization equilibrium for a degree of ionization of the order of 0.3.

An estimate of the relaxation time $t_*$ of the electron and heavy-particle temperatures for the condition $T_e \sim 2$ eV leads to a value $t_* \sim 10^{-8}$ sec. However, comparison of the Joule heating and the energy transferred by electrons to heavy particles shows that under the conditions considered these terms in the energy equation for electrons are comparable. It follows from this that the temperatures of the plasma components in a cathode spot of the first type can differ substantially. To estimate the temperature of the heavy particles one needs a deeper analysis of the energy equations of the components and a more detailed model of the cathode spot.

### j) Cathode Fall of Potential

Measurement of the potential fall near the electrodes is a very complex problem, in view of the small extent of the near-cathode and near-anode regions along the discharge axis. At the present time two methods are principally used to measure the cathode fall $U_c$. One of them—the probe method—consists of measuring the potential drop between the cathode and a probe located as close as possible to it (~0.01 cm). The quantity measured is identified with the cathode fall. Another method consists of measuring the burning voltage of a short arc $U_a$. Here it is assumed that $U_c$ can be obtained by extrapolation of the relation $U_a = f(l)$ to $l = 0$, where $l$ is the distance between the electrodes.

Use of the probe method involves a substantial perturbation of the near-cathode plasma, a relatively cold probe, complications in determining the true probe potential, and the necessity of using rapidly moving probes.[94,95] Use of the short-arc method of measuring the cathode fall is complicated by the need of separating the cathode and anode falls. An attempt to make this separation on the basis of the difference in the electrode temperature in direct and alternating current was made by Finkelnburg and Segal.[93] In most studies it is assumed that the anode fall in a vacuum arc is small[1,2,56] and the potential drop in a short arc is identified with $U_c$ although, as far as we know, no reliable measurements of the anode fall exist.

TABLE VI. Cathode fall at cathodes of various materials.

| Element | Cathode fall $U_c$, V | | | | | | |
|---|---|---|---|---|---|---|---|
| | Ref. 107 | Ref. 130 | Ref. 131 | Ref. 106 | Ref. 32 | Ref. 2 | Ref. 26 |
| Li | 11.1—11.7 | | | | | | |
| Na | 8.7—9.0 | | | | 4—5 | 11.0 | 16.0 |
| K | 6.7—7.4 | | | | | | 7.2 |
| Cs | 6.2 | | | | | | |
| Cu | 14.7—15.4 | 12.6 | 8.5 | 13.0 | 8.0—9.0 | 21.0 | 16.0 |
| Ag | 12.1—13.6 | 12.3 | 8.0 | 12.0 | | 16.5 | 13.0 |
| Be | 18.6—19.2 | 12.5 | | | | 12.0 | 17.0 |
| Mg | 11.6—13 | | | 10.0 | | | 12.5 |
| Ca | 10.8—11.4 | | | | | | |
| Sr | 8.4—9.2 | | | | | | |
| Zn | 9.8—11.1 | 10.9 | 9.0 | 10.5 | | 11.0 | 10.0 |
| Cd | 8.6—10.2 | 9.8 | | 11.0 | 9.0 | 10.0 | 11.0 |
| Hg | 8.0—9.5 | | | | 7.0—10.0 | 8.0 | 8.0 |
| Al | 17.2—18.6 | 18.3 | | 14.0 | | 16.5 | 15.5 |
| Ga | 15.0 | | | | | | 15.0 |
| In | 9.5—11.9 | | | | | | 13.0 |
| Tl | 10.5—11.5 | | | | 6.5 | | 10.5 |
| Ti | 16.8—17.6 | | | 20.0 | | | |
| Zr | 17.7—18.5 | | | | | | |
| C | 15.2—18.9 | | | 13.5 | 12.0 | | 12.5 |
| Sn | 10.6—13.0 | | | 9.6 | 9.6 | | 10.0 |
| Pb | 8.8—10.2 | 9.1 | 7.5 | | | | |
| V | 17.3—18.0 | | | | | | |
| Nb | 19.9—21.6 | | | | | | |
| Ta | 16.8—21.4 | | | | | | |
| Bi | 8.4—8.7 | | | | | | |
| Sb | | | | | | 8.1 | 9.0 |
| Cr | 16.7—17.4 | | | 16.0 | | | |
| Mo | 16.6—17.2 | | | 17.0 | | 15.0 | |
| W | 16.2—22.6 | 15.2 | 10.0 | 15.0 | | 50.0 | |
| Te | 11.0—12.4 | 3.0 | | | | | |
| Fe | 17.1—18.0 | | 8.0 | 13.0 | 8.0—12.0 | 53.0 | 17.0 |
| Co | 16.8—17.7 | | | 15.0 | | | |
| Ni | 16.3—17.3 | | 8.0 | 14.0 | | 15.0 | 16.0 |
| Pt | | 15.3 | 13.5 | 17.5 | | | 18.0 |

The two methods of measuring $U_c$ do not permit study of the potential distribution inside the region of the cathode fall, the extent of which is estimated[5,96] not to exceed the mean free path of an ion ($10^{-5}$–$10^{-6}$ cm). The most reliable and complete measurements of the cathode fall have been made by Kesaev[1] and Grakov[56] by the short-arc method (Table VI).

The first measurements of the cathode fall already revealed the presence of oscillations, the maximum amplitude of which may vary by a large factor, while the minimum value does not fall below some value determined for each material.[97] The oscillations themselves are a superposition of two types of oscillations with different periods (for example, for mercury $4 \times 10^{-6}$ sec and $10^{-4}$ sec). Increase of the current leads

to a decrease of the amplitude of oscillations to roughly one volt.

The observed frequencies of oscillation of the cathode fall (the voltage on the arc in the experiments of Refs. 1 and 56) are explained on the basis of the model of a spot of the first type, as discussed in Section (c). In fact, in these experiments the arc current did not exceed several tens of amperes and consequently only spots of the first type apparently were present on the electrode. In this case the oscillations of the voltage are due to the increase of the cathode fall during the period of existence of the spot (escape of the plasma) and to the sharp drop in potential at the moment of formation of a new spot (breakdown). This, the oscillation period is determined by the lifetime of the spot [for copper $\tau \sim 10^{-5}$ sec; see Section (e)], which agrees with the experimental data.

Kesaev[1] called attention to the fact that $U_c$ is minimal for metals of the second group of the periodic table, which have metastable $^3P_{0,1,2}$ levels with an excitation potential close to half of $U_i$. This led him to suggest a dominant role of step ionization in the burning of an arc in these metals.[15)] Direct measurements which have been made of the cross section for excitation of the $^3P_0$ metastable level of Hg (Ref. 99) and of the cross sections for step ionization of Cd (Ref. 98) have confirmed this idea.

In view of the fact that the cathode fall is the main source of energy which makes possible the existence of the spot, we can expect that its magnitude should depend on the thermal properties of the cathode material. This is confirmed by the data of Refs. 1 and 2, in which it is established that there is a universal dependence of $U_c$ on the quantity $\xi = T_b\lambda_T$ or $\xi = T_b\sqrt{\lambda_T}$ ($T_b$ is the boiling point and $\lambda_T$ is the thermal conductivity), i.e., the measured values of $U_c$ for various metals lie on a single curve in the $U_c$, $\xi$ plane. The physical meaning of this dependence and its relation to the type of spot are not clear at the present time.

A number of qualitative attempts to explain the principal observed relations for the cathode fall[101,102,106] have been based on the idea that $U_c$ should be sufficient for ionization by electron impact and for heating of the cathode to temperatures at which thermionic emission becomes appreciable. At the present time there are no reliable methods of calculating the cathode fall (see Chapter 2).

[15)]The suggestion that existence of a metastable level leads to step ionization and consequently to a reduction of the cathode fall is an indication that the current density in the cathode spot should be rather low. Otherwise step ionization, occurring through a resonance level, would take place also for other metals. For example, for copper, according to a rough estimate, absence of step ionization is possible only for $j \gtrsim 10^4$ A/cm$^2$ (Ref. 100). Thus, the existence of an appreciable cathode fall ($U_c \sim U_i$) in a copper arc, which indicates absence of step ionization, argues in favor of low current densities, which have been observed experimentally.[29,33]

## 2. THEORETICAL DESCRIPTION OF A THERMAL CATHODE SPOT

### a) Introduction

In spite of the fact that vacuum arcs have been intensively studied for more than a hundred years, there is up to the present time no satisfactory description of the physical processes occurring in the cathode spot. This is due to the fact that in the near-cathode region complicated and varied phenomena occur which it has become possible to understand and describe physically only now when important results have been achieved in plasma physics, solid state physics at high temperatures, gas dynamics, and so forth.

A cathode spot is therefore one of the puzzles of nature, and the history of the development of theoretical ideas regarding the near-cathode region of a vacuum arc can easily be compared with the history of development of plasma physics and solid state physics, whose achievements are always used in the attempts to describe a cathode spot. We do not propose to describe this history, or to recall all of the models and ideas, sometimes extremely ingenious, involved in description of a cathode spot.[16)]

Our principal attention will be devoted to a presentation of current ideas regarding the physical processes in the cathode spot and to their mathematical description. Here we shall attempt also to bring out in a natural way those questions which require further investigation and refinement.

We note at once that, in spite of the great qualitative diversity of cathode spots and the phenomena which accompany their development, all models for a cathode spot which have existed till very recently have essentially been stationary. Therefore, in principle they cannot explain the causes of the appearance, disappearance, or division of a spot or the physical regularities and parameters in rapidly moving spots.[17)] The entire development of the theory of cathode processes reduces essentially, although there is no clear understanding of this, to construction of a model of a thermal spot, i.e., a spot in which generation of the vapor is accomplished as the result of evaporation (this includes grouped spots and possibly spots of the second type). The content of the present section is devoted to this subject.

To make the exposition which follows specific we present here without details or justification a qualitative picture of a thermal spot.[18)] A fixed or slowly moving cathode spot on a metal surface is a highly heated region. As a result of the high temperature, the metal in this region evaporates, forming a vapor jet flowing

[16)]Those interested in a complete bibliography on this question are referred to the reviews and books of Refs. 1, 5, 81.

[17)]Here we are not considering studies of the phenomenon of breakdown. One of the latest models of rapidly moving spots was described in Section (c).

[18)]The characteristic parameter values given here correspond to a cathode spot on copper.[109,136]

into the interelectrode space and in which the pressure is close to zero. The high temperature of the surface at the spot is maintained by the energy brought in mainly by ions arriving at the electrode surface from the near-cathode plasma. Under stationary conditions this energy is expended in compensation of losses of various types (heat flow into the electrode by thermal conduction; loss by radiation; energy loss associated with electron emission, and so forth) and in generation of the necessary amount of vapor.

Near the metal surface in a region of the order of an ion mean free path ($l_i \sim 10^{-5}-10^{-6}$ cm) a space-charge layer is formed in which there is a substantial (~10 V) potential drop (the cathode fall) and there are strong electric fields ($\sim 10^6-10^7$ V/cm). This layer is the main source of energy which assures the existence of the spot.

Ions of the near-cathode plasma are accelerated into the space-charge layer along the direction towards the electrode surface, acquiring kinetic energy which they transfer to the metal surface on collision. This energy, together with that liberated in neutralization of the ion, comprises the main flow of energy to the metal surface. On the other hand, as a result of the high temperature of the electrode surface in the spot and the strong electric field in the space-charge layer, the electrode emits electrons. These electrons are accelerated into the space-charge layer and form a high-energy beam which enters the near-cathode plasma.

The energy carried into the near-cathode plasma by the emitted electrons is expended in the beam-relaxation zone on ionization and heating of the plasma components. The physical processes and dynamics of the relaxation region determine, in particular, the ion flux to the electrode surface. The extent of the beam-relaxation zone (or ionization zone) is determined by the plasma parameters ($l_p \sim 10^{-4}-10^{-3}$ cm), but as a result of the high pressure of the vapor near the electrode and the large cross section for ion-atom collisions it turns out to be much greater than the ion mean free path, and consequently also much greater than the extent of the space-charge layer. For this reason the electric field strength in the relaxation zone is relatively low. Beyond the relaxation zone there extends a broad region of the jet itself, in which flow of the multicomponent plasma occurs.

### b) Emission Laws

The question of the mechanisms of electron emission from the metal in a cathode spot has been subjected to the greatest amount of discussion in connection with attempts to describe a cathode spot theoretically. Ideas regarding the emission mechanisms in the spot have changed fundamentally as experimental data have been accumulated on the current density in the spot (see the reviews of the corresponding theories in Refs. 1, 5, and 81). Estimation of the possible density of electron current in the spot represents the first natural attempt to understand the physics of the processes occurring in the near-cathode region, which can provide an idea of the orders of magnitude of a number of physical parameters. However, all attempts up to the 1950's to reconcile the experimental data with the calculations based on one emission mechanism or another (thermionic emission, field emission, and so forth) failed to provide satisfactory results, since they led to contradictory and often unlikely results (high temperatures in the spot, the impossibility of satisfying the energy balance equation, and so forth). This circumstance has stimulated many studies devoted to consideration of various types of hypothetical mechanisms capable of providing the yield of electrons from the metal (for example see Refs. 31, 57, 137–140). Here, as a rule, there have been no theoretical or experimental confirmations that conditions exist in the near-cathode region for occurrence of the various processes. The density of the electron emission current from the metal $j_p$ can be calculated with the formula given by Bethe and Sommerfeld[141]

$$j_p = e\int_0^\infty n(\varepsilon_x)\, D(\varepsilon_x, E)\, d\varepsilon_x = f(T_W, E). \qquad (2.1)$$

Here $e$ is the electronic charge, $T_W$ is the temperature of the metal surface in the spot, $n(\varepsilon_x)$ is the density of states of the electrons in the metal, $D(\varepsilon_x, E)$ is the transmission coefficient of the potential barrier at the boundary of the metal, and $E$ is the average value of the electric field normal to the surface.[19)]

Various approximations for the functions $n$ and $D$ are given in the literature.[142-144,147,170,171] The most complete calculations with these formulas for the conditions of a cathode spot have been carried out by Lee and Greenwood,[145,146] whose work has had fundamental significance in shaping contemporary opinion regarding the mechanism of emission in the cathode spot.

This view can be formulated as follows: the mechanism of thermionic field emission [Eq. (2.1)] can provide the current density $j \sim 10^5$ A/cm$^2$ observed in experiments in grouped spots, without leading to substantial inconsistencies in the order of magnitude of the parameters of the near-cathode region.

### c) Temperature of the Metal Surface in a Spot

From the point of view of the temperature distribution in the body of the electrode, the cathode spot on its surface, which occupies a very small portion of the electrode, can be represented as a point source (if we are interested in temperatures far from the source) or as a distribution of sources (if we are interested in the distribution of temperature near the spot and at its boundaries). Since the electron emission depends sub-

[19)] Investigation of the influence of the individual fields of ions on emission and determination of the limits within which it is possible to use the average field values in the emission law (2.1) was begun in Refs. 148 and 149. However, in these studies the problem was not completely solved, since an undetermined parameter—the neutralization distance—was introduced. A complete solution of this problem is contained in Refs. 150 and 151, where it is shown that in calculation of the density of the thermionic field emission current ($j_p \leq 10^7$ A/cm$^2$), which is of interest for thermal spots, use of the average field in Eq. (2.1) does not lead to substantial errors.

stantially on the temperature, for a quantitative description of a cathode spot it is important to know rather accurately the temperature distribution on the surface of the electrode in the spot.

In thermal calculations the cathode spot is usually modeled either as a circle of radius $r$ within which the energy flow to the electrode surface is constant and outside it is zero (see for example Refs. 146, 152, 4, and 153) or as a circle whose effective radius is determined by specifying a normal distribution law for the energy flux (Refs. 16, 17, 136, 2):

$$dq_T = \frac{Q_T}{\pi r^2} e^{-\xi^2/r^2} \xi \, d\xi \, d\varphi, \qquad Q_T = \int dq_T, \tag{2.2}$$

where $q_T$ and $Q_T$ are the density and total influx of energy carried away by thermal conduction, and $\xi$ and $\varphi$ are cylindrical coordinates. Both approaches are based on the fact that experimentally the spot, which is identified with the luminous region, has rather sharp boundaries. The assumption of a circular shape of the spot is introduced to simplify the problem; the actual shape of spots is quite exotic.[18,19,29,49,154]

Beĭlis and Rakhovskiĭ[155] have shown that when evaporation is taken into account the temperature distribution at the boundaries of the spot (a circle of radius $r$), obtained from a thermal calculation with use of Eq. (2.2), turns out to be close to the uniform value $T = T_W$ = const, where the temperature $T_W$ does not greatly differ from that which is obtained at the center of the spot in the absence of evaporation,

$$T_W = \frac{q_T \sqrt{\pi}}{\lambda_T} r, \tag{2.3}$$

where $\lambda_T$ is the thermal conductivity of the electrode material.[20)]

### d) The Space-Charge Layer and the Total-Current Equation

Modeling of the cathode spot as a circle within which the metal surface temperature $T_W$ is constant permits construction (see below) of a model of the near-cathode region with parameters which are constant within the cathode spot.

In such a model the current density $j$ is related to the total current $J$ going through the spot by the expression

$$J = \pi r^2 j. \tag{2.4}$$

The quantity $j$ in Eq. (2.4) is the density of current at the surface of the spot. It is made up of the current density of emitted electrons $j_p$ given by Eq. (2.1) and the current densities $j_e$ and $j_i$ of electrons and ions incident on the electrode surface from the plasma:

$$j = j_p - j_e + j_i. \tag{2.5}$$

The quantities $j_e$ and $j_i$ in this expression, and also the electric field strength $E$ in the emission law (2.1), are determined by the state of the near-cathode plasma, and calculation of them presents the principal difficulty in the theory of the cathode spot. The first attempt at such a calculation and at formulation of a complete system of expressions for calculation of the parameters of the cathode spot was made by K. T. Compton at the beginning of the 1930's.[159] However, both in his work and until very recently the calculation could not be carried through to a conclusion, as a result of the lack of an adequate amount of experimental data on the parameters of the near-cathode plasma which would permit evaluation of the contributions of individual elementary processes and would permit formulation of the corresponding plasma-physics problem.

Under the conditions characteristic of a cathode spot the thickness of the space-charge layer $h$ is given by

$$h \ll \min (l_i, \; l_e, \; l_{em}) \tag{2.6}$$

(here $l_i$, $l_e$, and $l_{em}$ are the mean free paths of the ions and electrons of the plasma and of the emitted electrons, respectively). The potential drop in this layer is equal to the cathode fall $U_c \sim 10$ V.

If the average energy (temperature) of the plasma electrons $kT_e$ is much less than the energy of the cathode fall $eU_c$, the plasma electrons are reflected from the outer part of the potential barrier of the space-charge layer. Consequently, the concentration of plasma electrons in the space-charge layer and their flow to the electrode surface $j_e$ can be neglected.[21)] Here instead of Eq. (2.5) we obtain

$$j = j_p + j_i. \tag{2.7}$$

Since the ions and emitted electrons move without collisions in the space-charge layer and there are no plasma electrons, the electric field distribution in this layer can be calculated from Langmuir's formulas.[160] Here we have for the electric field strength at the electrode surface and the space-charge layer thickness the relations[161]

$$E^2 = 16\pi \left(\frac{mU_c}{2e}\right)^{1/2} j_i, \tag{2.8}$$

$$h = \frac{U_c^{3/4} (2e)^{1/4}}{3\sqrt{\pi} \, j_i^{1/2} m_i^{1/4}}; \tag{2.9}$$

here $m_i$ is the mass of the ion and $e$ is the electronic charge.

Equations (2.7) and (2.8) are used in all theories of the cathode spot.

### e) Energy Balance at the Electrode Surface

With the assumptions formulated above regarding the structure of the space-charge layer, it is easy to calculate the energy $Q$ arriving at the electrode surface

[20)] In these calculations and in deriving Eq. (2.3) we have neglected the dissipation of Joule heat in the body of the electrode. The latter effect can be important only at very high current densities. In this regard see Refs. 152 and 156. In the calculations carried out in those studies, Joule heat has a substantial effect on the temperature distribution for $j \gtrsim 10^7$ A/cm$^2$.

[21)] Beĭlis *et al*.[109,136] have shown that for $T \gtrsim 2$ eV the flow of electrons from the plasma cannot be neglected, and Ecker[165] has shown that in a number of cases the concentration of electrons at the outer boundary of the space-charge layer is important in calculation of the thickness of this layer.

from the near-cathode plasma if we know the state of the near-cathode plasma; the energy influx from the plasma to the electrode surface as the result of thermal conduction and radiation, and the corresponding coefficients of particle accomodation and ion neutralization[22] depend on this state. Since in the cathode region of a vacuum arc there is contact between the metal and its vapor, we can assume that the corresponding accomodation and neutralization coefficients are close to unity. A more or less accurate estimate of the energy transferred to the metal surface from the plasma as the result of radiation and thermal conduction is impossible without solution of the problem of escape of vapor from the cathode-spot region.[23] On the other hand, the energy $\varepsilon \sim eU_c$ acquired by ions in the region of the cathode fall where they move without collision, as well as the ion flux $j_i$, are quite large. Accordingly it is natural to assume that the energy transferred to the electrode surface in the vicinity of the cathode spot is determined mainly by the ion energy, which is made up of the kinetic energy of the ions and the energy liberated in their neutralization[24]:

$$q = j_i (U_c + U_i - \varphi_*), \quad Q = \pi r^2 q; \tag{2.10}$$

here $U_i$ is the ionization potential of the atoms of the metal and $\varphi_*$ is the effective work function.

We note that the total energy flow $Q$ to the spot (2.10) differs from that carried away by thermal conduction, and the difference between these quantities is determined by the energy loss at the metal surface in the spot, which occurs as the result of evaporation, radiation, electron emission, and destruction other than in the vapor phase[25] (crumbling, ejection of droplets, and so forth):

$$\frac{Q-Q_T}{\pi r^2} = q - q_T = \lambda_s G + \sigma T_W^4 + W_e + \ldots, \tag{2.11}$$

where $q$ is the average heat (energy) flux to a unit surface of the spot, $\lambda_s$ is the heat of evaporation, $\sigma$ is the constant in the Stefan-Boltzmann law, and $G$ is the flux density of evaporated material, which is related to the total loss (erosion) of electrode material per unit time $\gamma$ by the expression

$$\gamma = \pi r^2 G.$$

In Eq. (2.11) we have taken into account only the surface loss by evaporation, radiation, and electron emission $W_e$. The article by Lee[157] is devoted to calculation of the energy loss due to electron emission $W_e$. This quantity is easily calculated in the two limiting cases of thermionic emission and field emission: $W_{eT} = \varphi j_i$ ($\varphi$ is the work function of the metal), and $W_{ea} = 0$.

In the more general case of thermionic field emission (*field* emission of electrons *above* the Fermi level) the quantity $W_e$ depends in a complicated way on the temperature $T_W$ and electric field $E$ (Ref. 157). On the basis of the work by Beĭlis[158] it is assumed, however, that for grouped spots

$$W_e = \varphi_* j_i, \quad \varphi_* = \varphi - \sqrt{e^3 E}.$$

Equation (2.11), together with appropriate definitions of the quantities which enter into it, represents the energy balance at the metal surface in the spot. In writing down the equation (2.11) and its individual terms a number of assumptions are made regarding the relative importance of the various mechanisms of energy transfer and regarding the specific values of the thermal constants. In addition, this equation contains a number of quantities (for example $G$, $j_i$, $T_W$, etc.) which can be determined only as the result of a complete solution of the problem of the near-cathode region. Until recently the parameters of the near-cathode region were determined extremely roughly. Furthermore, in the literature there is no information on the thermal constants of the cathode-material vapor under the conditions which occur in the near-cathode region. These circumstances have resulted in the point of view (see Refs. 1, 5, and 81) that the energy balance equation (2.11) can be used in a theoretical discussion only for rough estimates.

However, recent studies carried out on the basis of a closed system of equations [including Eq. (2.1) for the near-cathode region[109,136]] have shown that a substantial variation of the thermal constants and other prameters specified in the calculation leads to a rather weak change of the parameters of the near-cathode region (Fig. 12). This fact, it appears, permits us to make a new evaluation of the energy balance equation (2.11). With the level of ideas existing today regarding the parameters and physical processes in the near-cathode region it is possible to write down the energy balance equation (2.11) with an accuracy sufficient for use in a system of equations for the near-cathode region. The principal uncertainty in this equation remains the energy expended in destruction of the material other than in the vapor phase. This uncertainty is unimportant for explanation of physical experiments on specially prepared

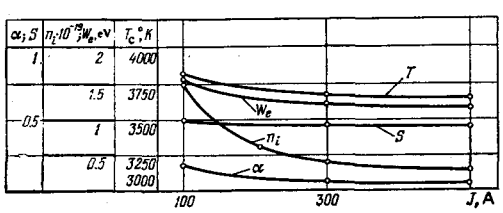


FIG. 12. Principal parameters of a cathode spot as a function of the current in the spot.

[22] The accommodation coefficients for the ion and atom energy and the neutralization coefficients for ions of energy ~10 eV have been studied relatively little. Most of the existing data refer to interaction of a metal with atoms and ions of various gases, and not with the vapor of the metal itself, and to the high-energy region (see for example Ref. 181). A discussion of the choice of these coefficients under cathode-spot conditions and a review of the corresponding literature is given in Refs. 5 and 81.

[23] Extremely crude estimates of these quantities are given in Refs. 165 and 169.

[24] It is usually assumed that the entire energy liberated in neutralization is transferred to the metal, although this conclusion is not obvious.

[25] With special preparation of the electrode material (see Ref. 5) these forms of loss can be reduced to a minimum, since erosion of the metal will occur only in the vapor phase.

electrodes, but it is important for calculation of the parameters of cathode spots in technical devices.

Equations (2.1), (2.3), (2.4), (2.7), (2.8), and (2.11), their modifications, or certain of the these equations are used in all theories of the cathode spot. Here the quantities $J$, $U_c$, and $\gamma$ are as a rule specified.

### f) Parameters Specified in the Calculation

It seems natural to specify the total current $I$ of a discharge in constructing a theoretical model of a cathode spot, and this quantity is specified in all theories and is varied over wide ranges, $I \sim 1-10^4$ A. However, the experimental data presented above show that at large currents several grouped spots are formed on the electrode, the current per grouped spots are formed on the electrode, the current per grouped spot being $J \sim 100-500$ A, and spots with $J = 200$ A are the most stable.[5,154] It is evident that in the theoretical calculations of a cathode spot it is necessary to specify $J$—the total current per spot (grouped), and not the total discharge current $I$, if $J \neq I$. As a result the calculations existing in the literature for high-current spots (see for example Refs. 84 and 4) hardly correspond to reality.

For the cathode fall $U_c$, experimental data are usually used. The value of the cathode fall for various metals has been reliably measured[1,56] at low currents [see Section (i)]. In short arcs $U_c$ practically coincides with the voltage between the electrodes and consequently can be measured in each experiment.

Calculation of the cathode fall is an important and interesting problem which at the present time has not been solved or correctly formulated.

The relation proposed in Refs. 1, 106, and 107 for calculation of $U_c$, although it reflects the experimentally determined dependence of $U_c$ on the atomic weight of the electrode material, does not involve calculation of the space-charge layer. It is in a certain approximation the energy equation for the near-electrode plasma. Therefore in any model of the near-electrode plasma, free parameters will remain in this relation if the cathode fall is not specified.

The problem of calculating the cathode fall involves calculation of the space-charge layer at the cathode. The zeroth order approximation for this solution will be the relations[161] for the layer traversed. Here the equation for $U_c$ is obtained from (2.9) if in that equation we equate the layer thickness $h$ to the ion mean free path $l_i$:

$$U_c = (3\sqrt{2})^{4/3} j_i^{2/3} \left(\frac{m_i}{2e}\right)^{1/3} l_i^{4/3}. \tag{2.12}$$

However, this relation is inapplicable for practical calculations of the cathode fall, since from a physical point of view there is an uncertainty in the condition $h = l_i$ due to calculation of the region of infrequent collisions.[26)] In this connection the main problem is calculation of infrequent collisions for the space-charge layer and combination of these solutions with the solution of the hydrodynamic equations far from the cathode.

In theoretical models of the cathode spot in which electrode evaporation is taken into account in Eq. (2.11) (see for example Refs. 50, 66, 67, and 81) it is assumed as a rule that the quantity of electrode material is carried away from the region of the cathode spot in the form of vapor (per unit time and per unit area) $G$ is determined only by the temperature of the metal surface in the spot and is equal to the rate of evaporation in vacuum[173]:

$$G = mW = mcT_W^{1/2} e^{-B/T_W}, \tag{2.13}$$

where $C$ and $B$ are constants of the material.

It is interesting to note that in addition to Eq. (2.13) in estimation of the pressure in the near-cathode region it is always assumed that it is equal to the saturated vapor pressure $p_0$ at $T = T_W$ (see for example Refs. 160, 154, 81, 163 and 165).

The question of the consumption of gas in the cathode jet and the hydrodynamical parameters in the near-cathode region has been investigated relatively little at the present time. Solution of the problem of evaporation in vacuum[68,164,174] shows that the velocity of the vapor at the outer boundary of the Knudsen transition layer, whose thickness is of the order of the mean free path for the evaporating atoms, is equal to the velocity of sound $V_T$, that the consumption of vapor does not differ greatly from Eq. (2.13), and that the gas parameters differ quite substantially from the equilibrium values[68]:

$$\begin{aligned} T &= 0.65T_W, \quad n = 0.31n_0, \quad p = 0.2p_0, \\ u &= 0.8V_T, \quad G = 0.82Wm, \end{aligned} \tag{2.14}$$

where $u$ is the velocity of the plasma at the cathode surface; $n_0$ and $p_0$ are the equilibrium values of concentration and pressure.

It would appear that these relations can be accepted for estimation of the hydrodynamical parameters of the near-cathode plasma and the gas consumption in the jet. However, analysis of the experimental data on electrode erosion, together with the equations for the near-cathode plasma,[109] shows[133,136] that it is possible to have conditions for which

$$G \ll mW, \quad u \ll V_T, \quad p = p_0. \tag{2.15}$$

The difference of these parameters from the values (2.14) may be due to the fact that in the cathode jet the flow into the vacuum is not free (in the jet a significant energy is liberated and electromagnetic forces are acting).[27)] It is obvious that under these conditions the parameters of the near-cathode plasma and the consumption of gas will be determined by the dynamics of escape of the jet. The problem of vapor escape under

[26)] In general there is no solution of the type (2.12) if the electron and ion temperatures are different.[190]

[27)] The idea that the measured value of material consumption $G \neq mW$ and that possibly in the near-cathode region $G \ll mW$ existed long ago in the literature.[159,36] Nevertheless until very recently calculations were usually performed with Eq. (2.13).

the conditions considered has not been formulated at the present time, but its solution presents great interest for the theory of the cathode spot. The question of to what extent the parameters of the near-cathode plasma differ from the equilibrium values and how they depend on the vapor consumption in the cathode jet remains open.

Nevertheless, taking into account the reliability of the experimental data on electrode erosion (consumption in the jet), one of us has proposed[133] use in theoretical calculations of the experimentally measured values of vapor consumption in the jet $\gamma$, and calculation of the near-cathode plasma parameters according to the relations

$$G=\frac{\gamma}{\pi r^2}, \quad T=T_W, \quad p=p_0, \quad n=n_0, \quad u=\frac{G}{mn_0}. \tag{2.16}$$

As will be evident from what follows, calculation of the cathode spot parameters with use of Eq. (2.16) gives satisfactory agreement with the experimental data.

### g) Calculation of parameters of the near-cathode plasma

It is easy to see that the system of equations (2.1), (2.3), (2.4), (2.7), (2.8), and (2.11), supplemented by one of the relations for material consumption (2.13) and (2.14) or a value specified from experiment, for specified $U_c$ and $J$, is not closed. It contains one free parameter: the equations involve the quantity $j_i$ associated with the state and dynamics of the near-cathode plasma (instead of $j_i$ one frequently introduces the quantity

$$S=\frac{j_p}{j_i+j_p}, \tag{2.17}$$

which is called the fraction of the electron current). Therefore if $j_i$ (or $S$) is specified on the basis of some additional assumptions, the system of equations obtained for determination of the distributions of parameters in the electrode body and on its surface in the spot will be closed and independent of the parameters of the near-cathode plasma.

This circumstance has led to a number of studies devoted to investigation of the parameters of the spot and the distribution of temperature[28)] with various specifications of $S$ (see for example Refs. 153, 159, 156, and 155) or with introduction of certain additional physical relations for the purpose of closing the system of equations. As such an additional relation, the surface temperature of the spot is often used (see for example Refs. 1, 67, and 152), where as a rule it is assumed equal to the melting point of the metal. In some studies in analyzing the effect of various factors on the spot parameters, a portion of the system of equations indicated above is used, rather than the entire set. Here the missing equations are replaced by relation associated with the physical model of the spot (see for example Refs. 153, 175, and 176).

In the studies cited above, useful information on the effect of various factors on the spot parameters has been accumulated, but the quantitative data contained in these studies must be approached with caution in view of the fact that the quantity $S$ depends strongly on the results of the calculation by Beĭlis.[136] Here, depending on the assumptions made, it is possible to obtain values of the cathode spot parameters (temperature, current density, etc.) which both agree and strongly disagree with the experimental data.

Among the studies which involve specifying an additional relation to close the system of equations in the near-cathode region, we note the work of Lee and Greenwood.[146] These authors introduce certain "limiting relations" to close the system of equations. The meaning of these relations is that on the basis of simple physical reasoning an upper or lower limit of some quantity is estimated, and then this limiting value is used to close the system of equations. For example, it is obvious that the density of the ion current from the plasma cannot exceed the flux density of neutral atoms from the surface. Therefore as an additional relation Lee and Greenwood assume[146]

$$j_i = eW. \tag{2.18}$$

A natural development of this approach is the method of constructing "regions of existence of a solution" proposed by Ecker.[81,162]

The idea of this method is to use certain limiting relations instead of some of the equations, which are given above and which are related to definite physical laws. Here it is shown that an appropriate procedure separates on the $j$, $T_W$ plane the region of values of these parameters in which the exact solution of the problem must lie.

The method of regions of existence can be useful in evaluating the results of approximate approaches to solution of the problem of the cathode-spot parameters. It also permits rather simple estimation of the qualitative influence of individual effects on the value of the current density and temperature in the spot (the velocity of the spot motion, roughness of the surface, variation of accommodation coefficients, etc.). However, the size of the region of existence for the currents characteristic of grouped spots ($J \gtrsim 100$ A) turns out to be rather substantial (for copper, for example for $J=200$ A we obtain for the current density $10^4$ A/cm$^2 \leqslant j \leqslant 10^6$ A/cm$^2$). This does not permit use of this method for comparison with experimental data on current density. Essentially the method discussed also does not give estimates of other spot parameters (except the temperature and current density).

At low currents $J \sim 10$ A the corresponding existence regions turn out to be very narrow (at some current $I_{typ}$ the region contracts to a point) and it appears at first glance that there is a possibility of rather accurate evaluation of the spot parameters. This circumstance has been used[146,191] to compare the results obtained with the experimental data, in particular, for comparison of $I_{typ}$ with the minimum current for existence of the spot [see Section (f)]. However, such a comparison, even if it gives good results, cannot be regarded as

[28)] In discussion of moving spots[156] or problems of spot development[136,175,176] instead of Eq. (2.3) the problem of a nonstationary temperature distribution in the body of the electrode is solved.

convincing, since in this range of currents only spots of the first type exist on the cathode, and these are not described by the stationary relations which form the basis of the method discussed.

It remains an open question whether it is possible to use the method of existence regions for estimation of the parameters of slowly moving spots of the second type [see Section (a)], since the nature of these spots and consequently the system of equations describing the parameters are not definitively known. At attempt to calculate the parameters of these spots on the basis of the relations described above [with inclusion of the slow motion of the spot in Eq. (2.11)], supplemented by the equations for the near-cathode plasma,[109] showed that for the currents and displacement velocities characteristic of spots of the second type the corresponding system of equations does not have a solution. On the other hand, for the same conditions there is a finite "region of existence."

Thus, at the present time the existence-region method can be used with confidence only to estimate the parameters of a grouped spot. The possibilities and limits of applicability of the method have also been analyzed by Beĭlis and Lyubimov.[177]

The foregoing analysis should have convinced the reader that not only a quantitative calcualtion, but even an understanding of the physical processes in the near-cathode region are impossible without study of the state and dynamics of the near-cathode plasma. Studies in this direction began to appear at the beginning of the 1960's (Refs. 81, 106, 108, 109, 145, 162, 163, 165–168, 175, 176). A natural first step in the direction of solution of this problem is to analyze the physical processes in the immediate vicinity of the metal surface. In this region intense ionization occurs and a flux of ions to the electrodes forms which to a large extent (if not entirely) determines the energetics of the cathode spot. However, separation of some region in the vapor jet for analytic study always involves (although this is not always stated) definite assumptions which in essence postulate either a model of the jet flow or values or distributions of the hydrodynamical parameters in the region specified for investigation.

Beĭlis *et al.*[109] establish a physical and mathematical model of the relaxation region in the near-cathode plasma. The extent of this region is determined by the relaxation length of the beam of emitted electrons. It is shown that for parameter values characteristic of cathode spots,

$$\begin{gathered} n \sim 10^{19}-10^{20}\ \text{cm}^{-3}, \\ n_i = n_e \sim 10^{18}-10^{19}\ \text{cm}^{-3}, \\ j \sim 10^5\ \text{A/cm}^2,\ \frac{j_i}{j_p} \sim 0.1-1,\ T = T_W \sim 0.5\ \text{eV}, \\ T_e \sim 1\ \text{eV},\ u \sim 10^3\ \text{cm/sec}, \end{gathered} \tag{2.19}$$

the problem of determining the state of the plasma in the relaxation region can be separated from the problem of escape of the plasma jet if it is assumed that the hydrodynamical parameters ($n$, $T$, $u$) do not change in this region. The extent of the relaxation region under the conditions considered is $l_p \sim 10^{-4}$ cm. The region of parameter values (2.19) corresponds to the results of the calculation by Beĭlis[136] on the basis of a model of the near-cathode plasma[109] and to the experimental data.

The physical picture of the relaxation region is determined by the relative value of the cross sections for elementary processes in the plasma, which under the conditions considered are of the following order (for copper):

$$\sigma_i \sim 10^{16}\ \text{cm}^2,\ \ \sigma_{Cb} \sim 10^{-15}\ \text{cm}^2,\ \ \sigma_{ia} \sim 10^{-14}\ \text{cm}^2,\ \ \sigma_C \sim 10^{-13}\ \text{cm}^2; \tag{2.20}$$

here $\sigma_i$ is the cross section for ionization of copper by electrons with energy ~15 eV, $\sigma_{Cb}$ and $\sigma_C$ are the Coulomb cross sections for collisions of beam electrons and the electrons and ions of the plasma, and $\sigma_{ia}$ is the cross section for resonance charge exchange for copper.

The cross sections (2.20) and concentrations (2.19) determine the characteristic lengths of the elementary processes (for definiteness we take $n \sim 10^{20}$ cm$^{-3}$ and $n_i/n \sim 0.1$):

$$\begin{gathered} l_{ia} \sim 10^{-6}\ \text{cm},\ \ l_{ie} \sim l_{ee} \sim 10^{-6}\ \text{cm}, \\ l_{pa} \sim l_{pi} \sim 10^{-4}\ \text{cm},\ \ l_i \sim 10^{-4}\ \text{cm}. \end{gathered} \tag{2.21}$$

Here $l_{\alpha\beta}$ are the corresponding mean free paths, $l_i$ is the ionization length of the emitted electrons, and $l_{p\alpha}$ and $l_{pi}$ are the relaxation lengths for beam electrons in atoms and ions.

The relations (2.21) show that the emitted electrons accelerated in the space-charge layer [with the parameter (2.19) it follows from Eq. (2.9) that $h \lesssim l_{ia}$] relax in the near-cathode plasma at distances $l_p \sim 10^{-4}$ cm (at lower concentrations $l_p$ may reach values ~$10^{-3}$ cm) as the result of impact ionization of atoms and scattering by atoms and charged particles. The extent of the relaxation region greatly exceeds the mean free paths of the ions and electrons of the plasma. Therefore we can assume that the motion of the plasma components in the relaxation region is described by the equations of multicomponent diffusion.[109] In addition to the elementary processes mentioned above, thermal ionization and charged-particle recombination occur in the relaxation region. The ions formed in the relaxation region diffuse to the surface, the effective diffusion coefficient being determined by the charge-exchange process, and the concentration gradient by the rate of the ionization-recombination process. Estimates[109] show that the electric field in the relaxation region is small and exerts a small effect on the diffusion of the ions and on the energy of the electron gas.

The system of equations corresponding to the physical picture described above,[109] supplemented by the relations described earlier for the space-charge layer and the electrode body, form a closed system for determination of the cathode-spot parameters.

For illustration we present some results of calculation of the parameters of the near-cathode region.[136] In Fig. 12 we have shown the principal parameters of a stationary cathode spot as a function of the total current into the spot. It can be seen from this figure that the parameters of the near-cathode region do not change greatly as the current to the spot changes from 100 to

500 A. We call attention to the fact that the orders of the quantities obtained as the result of the calculation correspond to the region of values (2.19), for which the simplification of the system of equations was carried out.[109]

Analysis of the curves shown in Fig. 12 shows that the parameters obtained from the calculation agree reasonably well with the experimental data for grouped spots [see Section (h) of Chapter 1].

All the results presented above were obtained with the tabulated values of the material thermal constants $\lambda_S$ and $\lambda_T$ measured at room temperature, a work function $\varphi = 4.5$ V, and also for specified values of $\gamma$ (Ref. 5) and $U_c = 15$ V (Ref. 56).

The information on thermal constants at high temperatures is very limited.[178] In addition, at the present time there are no accurate data on the state of the metal in the region of the cathode spot and its influence on the work function. The experimental data on erosion and particularly on the cathode fall [see Section (j) of Chapter 1] may also be inaccurate. In this connection we made an analysis of the influence of the values of the constants specified in the calculation on the result of calculation of the parameters of the near-cathode region. Figure 11 illustrates the results of this analysis. The curves in this figure show the variation of the current density in the spot for $J = 200$ A. On the basis of the data shown in Fig. 11 it can be concluded that variation within reasonable limits of the constants specified in the calculation does not lead to a catastrophic change of the calculated parameters (for example, the change of the current density lies within the experimental error in determination of this quantity).

In conclusion we emphasize again that, in spite of substantial progress which has been achieved in recent years in the experimental and theoretical study of cathode spots, a complete understanding of this physical phenomena does not yet exist. It appears to us that this field is extremely attractive for further physical investigations.

In the list of references we have given a number of additional sources which may be useful to readers: Refs. 20, 21, 37, 53, 72, 77, 78, 103–105, 110, 114, 115, 118–120, 129, 135, 141, 172, 179, 180, 182, and 189.


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