MINIMUM POTENTIALS OF AN ARC DISCHARGE AND THE QUESTION OF TWO FORMS OF AN ARC WITH A COLD CATHODE

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Abstract

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MINIMUM POTENTIALS OF AN ARC DISCHARGE AND THE QUESTION OF TWO FORMS OF AN ARC WITH A COLD CATHODE

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In the theory of the electric discharge there still remains an ambiguity as to by what physical processes, in an arc with a cold cathode, high charge concentrations are produced in the region of the negative glow. On the basis of a number of data the author has come to the conclusion that, according to the character of the processes of ionization of metal vapors at the cathode, metallic arcs must be divided into two groups, belonging in essence to different forms of discharge ([1]). One of them, with predominantly stepwise ionization of metal atoms by electrons in the region of the negative glow, must serve as the principal form for cathodes whose metals belong to group II of the periodic system of elements. The main feature of a "stepwise arc" is the low value of the cathode fall U_c relative to the ionization potential U_i, satisfying the condition

$$U_c \approx U_i. \tag{1}$$

The other form, maintained predominantly by direct ionization of metal vapors by electrons, should be observed on metals of groups I and III, for which the schemes of atomic energy levels are less favorable for stepwise ionization. For brevity, it is convenient to call this form an "elementary arc." The most reliable feature of the elementary arc should be considered the relatively high value of the cathode fall in comparison with the ionization potential of the cathode metal, namely

$$U_c \geqslant 2U_i. \tag{2}$$

The latter follows from the fact that ionization functions attain the high values necessary for the realization of an elementary arc only at electron energies exceeding the ionization potential by a factor of 2–3.

These conclusions are fully confirmed by the results, given below, of measurements of the minimum arc-burning potentials $U_{g\,\min}$ for various cathode materials. The measurements were carried out with pure and especially pure metals both under conditions of a short vacuum arc ($d = 2$—5 mm), and directly in air at atmospheric pressure. Vacuum arcs are, in most cases, sharply unstable, which is expressed in the short duration of their burning even at relatively large currents, and also in considerable fluctuations of the voltage at the electrodes. The difficulties arising from this are easily overcome by using the compensation method of measuring the burning potential (1), which does not require prolonged maintenance of the discharge and permits determination of the minimum values of U_g. The method of observation is considerably simplified in the presence of an air medium, which sharply increases the stability of the arc. In this case the procedure reduces to determining the burning potential of a stationary discharge at the smallest possible distances between the electrodes. A natural source of errors in measurements in air is possible oxidation of the cathode metal. By means of parallel measurements of the minimum potentials

Table 1

Group	Atomic number	Element	U_{res}, V	U_{met}, V	U_i, V	$U_{g\,min}$, V (air)	$U_{g\,min}$, V (vacuum)	$U_{g\,min}/U_i$ (air)	$U_{g\,min}/U_i$ (vacuum)	Boiling point, °C
I	29	Cu	1.4—3.8	–	7.68	20	16	2.6	2.1	2310
I	47	Ag	3.7	–	7.54	13	13	1.7	1.7	2193
I	79	Au	–	–	9.18	17	14.5	1.85	1.58	2700
II	4	Be	–	–	9.28	10—11	17	1.1—1.2	1.83	2770
II	30	Zn	4—5.8	4	9.36	10	10	1.07	1.07	908
II	48	Cd	3.8—5.4	3.7—3.9	8.96	9.5	11	1.1	1.22	767
II	80	Hg*	4.9—6.7	4.7—4.5	10.39	–	9.5	–	0.9	357
II	80	Hg	4.9—6.7	4.7—4.5	10.39	–	8	–	0.77	
II	80	Hg fixed	4.9—6.7	4.7—4.5	10.39	–	7	–	0.7	
III	13	Al	3.1—4	0.0	5.96	18—20	–	3.2	–	2330
III	31	Ga*	3—4.2	0.1	5.97	12—13	15	2.1	2.5	2100

Group	Atomic number	Element	U_{res}, V	U_{met}, V	U_i, V	$U_{g\,\text{min}}$, V (air)	$U_{g\,\text{min}}$, V (vacuum)	$U_{g\,\text{min}}/U_i$ (air)	$U_{g\,\text{min}}/U_i$ (vacuum)	Boiling point, °C
III	49	In	3–4	0.27	5.76	10.5	13	1.8	2.26	2100
III	81	Tl*	3.3 – 4.9	1	6.07	–	11.5	–	1.9	1460
III	81	Tl	3.3 – 4.9	1	6.07	–	10	–	1.65	
IV	82	Pb*	–	–	7.38	–	11	–	1.5	1750
IV	82	Pb	–	–	7.38	10	10	1.35	1.35	
V	83	Bi	–	–	8	–	9	–	1.1	1470
Scandium series and refractory metals	24	Cr	–	–	6.74	20	–	3	–	2200
Scandium series and refractory metals	26	Fe	–	–	7.83	20	17	2.6	2.17	2450
Scandium series and refractory metals	27	Co	–	–	7.81	17	16	2.18	2.05	3000

Group	Atomic number	Element	U_{res}, V	U_{met}, V	U_i, V	$U_{g\,\mathrm{min}}$, V (air)	$U_{g\,\mathrm{min}}$, V (vacuum)	$U_{g\,\mathrm{min}}/U_i$ (air)	$U_{g\,\mathrm{min}}/U_i$ (vacuum)	Boiling point, °C
Scandium series and refractory metals	28	Ni	–	–	7.61	15	18	2	2.36	3000
Scandium series and refractory metals	42	Mo	–	–	7.35	16	18	2.18	2.45	4800
Scandium series and refractory metals	74	W	–	–	8.1	16	20	2	2.47	>5000

for vacuum and atmospheric arcs; this provides the necessary mutual check of the data obtained under the two sets of experimental conditions.

The measurement results for various cathodes are collected in Table 1, together with the values of the critical potentials of the atoms of the corresponding metals and their boiling temperatures (^{2}) (U_{res} and U_{met} are, respectively, the energies of the resonance and metastable levels of the atoms). Asterisks mark reports relating to metals in the liquid state. For the mercury cathode, the minimum arc potential with a cathode spot fixed near the boundary of wetting of the molybdenum strip by mercury is given additionally.

The most essential regularity in the table is that the metals of group II of the periodic system stand out by their low arc potentials relative to U_i. Whereas

Fig. 1

Figure 1: Fig. 1

for metals of groups I and III the ratio $U_{g\,\min}/U_i$ lies within the range from 1.7 to 3, for group II it varies approximately from 0.7 to 1.3. The values of $U_{g\,\min}$ measured under vacuum-arc conditions most often prove to be different from those in air. In individual cases, as, for example, for Ag, they coincide. The discrepancy between the values of the ratio $U_{g\,\min}/U_i$ derived from measurements in air and in vacuum, as a rule, does not exceed 20%, which is much less than the changes that these quantities undergo on going from metals of group II to metals of neighboring groups. In addition to the dependence on the group number of the metal, the figures given reveal a dependence on atomic weight and on the state of the cathode. The burning voltage of an arc with a solid cathode, and also for heavy atoms, is usually lower (by 1–2 V) than for an arc with a liquid cathode and light atoms. Especially low voltage values can be obtained under conditions of an arc with a cathode in the form of a thin film of liquid metal wetting a metal substrate, as occurs in a mercury arc. The indicated secondary circumstances make the principal dependence of the voltage on the ionization potential and on the group number of the cathode metal less distinct.

The values of the minimum arc potentials given in Table 1 must be sufficiently close to the values of the cathode fall for the corresponding metals and, thus, describe the regularities of the cathode fall itself in metallic arcs. But then we are entitled to conclude that the value U_c is determined primarily by the group number of the cathode metal and by its critical potentials. The dependence we have established of the cathode fall on the group number of the metal finds a simple explanation when account is taken of the peculiarities of the schemes of atomic energy states of the elements of group II and of neighboring groups, which determine the character of the ionization process in the cathode region of the arc. Whereas the schemes of groups I and III are represented exclusively by terms of even multiplicity (doublets), the scheme of atomic states of elements of group II represents a combination of singlet and triplet terms, shown in its main features for metals of the Hg type in Fig. 1. The lowest of the triplets ($2^3P_{0,1,2}$) forms, by virtue of the intercombination prohibition and other selection rules, two metastable levels ($2^3P_{0,2}$) with excitation potentials close to half the ionization potential. The third level (2^3P_1) is resonant. The properties of this term, especially its large statistical weight, the presence in it of two metastable levels, and also its position relative to U_i, sharply favor stepwise ionization of vapors of metals of group II. Excitation of metastables in the present case may proceed by the mechanism of electron exchange.

Fig. 1

The probability of such a process reaches maximum values at electron energies exceeding the critical value for the given level by only 1–2 V. Thus, for Hg the maximum of the excitation function for the level 2^3P_0 lies near 6–7 V. Thus, the probability of stepwise ionization must reach a maximum at electron-energy values somewhat smaller than U_i. Accordingly, in particular, in a mercury arc the value of the cathode fall U_c must lie near 7 V, which is indeed the case for an arc with a fixed spot. Under the influence of secondary effects depending on the state of the cathode, U_c may increase somewhat in comparison with this lower level, as is seen in the example of the mercury arc.

It is easy to see that the schemes of atomic states of elements of groups I and III do not present such possibilities for stepwise ionization. For the elements of group I, in general, the absence of metastable levels is characteristic. As for the elements of group III, their metastable level $2^2P_{3/2}$ is located too low and cannot play an essential role. Only for thallium does its energy reach a relatively high value (~ 1 V), with which the low cathode fall of the thallium arc, compared with the arc in In and Ga vapors, may be connected. Stepwise ionization in the vapors of metals of these groups can occur only with the participation of diffusion of resonance radiation, but such a path is, apparently, ineffective under the conditions of the cathode region of the arc because of its small dimensions. The role of metastables as the main source of the observed deviations in the behavior of the metals of group II is clearly visible in the table, since it is precisely by metastables that these metals stand out from the general mass of metals of the first three groups, and not by resonance potentials. From the character of the terms of the most typical metals of groups IV and V one may assume that, on passing to these metals,

the role of stepwise processes should again increase, as is also indicated by the low values of U_c for Pb and Bi.

The special features of Group II metals include low boiling points. Since they are also characterized by low voltage drops in the arc, a tendency toward an increase in voltage should be observed upon transition to refractory metals. It does not follow from this, however, that there is an unambiguous causal relation between the cathode drop and the thermal constants of the cathode ([3]). Although an increase in the boiling point and in the thermal conductivity of the metal should be accompanied by a decrease in the stability of the arc and in this way promote an increase in the average voltage drop in the arc, the minimum voltage required for a given cathode is determined by the character of the ionization process and should depend chiefly on the critical potentials of the atoms. These conclusions are confirmed by the data on the existence of two groups of cathodes, for which the values of the cathode drop satisfy conditions (1) and (2).

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REFERENCES

1. I. G. Kesaev, *Cathode Processes of the Mercury Arc and Questions of Its Stability*, Ch. II, 1961.

2. U. Chailds, *Physical Constants*, 1961.

3. M. P. Reece, *Nature*, **181**, 475 (1958).

Note: Figure translations are in progress. See original paper for figures.