THE DIFFUSION OF ELECTRONS AGAINST AN ELECTRIC FIELD IN THE NON-OSCILLATORY ABNORMAL LOW VOLTAGE ARC

By K. T. Compton and Carl Eckart

Abstract

Oscillatory abnormal low voltage arc in pure helium.—Experiments with a tube provided with an anode and a hot filament cathode, built and used with elaborate precautions for excluding mercury vapor, disproved the suggestion that traces of mercury vapor as an impurity play an essential role in permitting arcs in helium to operate at abnormally low voltages.

Non-oscillatory low voltage arc.—It has been found that, under certain conditions, arcs may be maintained at abnormally low voltages (below the lowest critical potential) and without oscillations, in helium, mercury vapor and argon, this type of arc being particularly striking and easy to obtain in argon. An arc tube, provided with a movable exploring electrode which was used according to Langmuir's method, enabled measurements of potential, of ion concentration, and of average energy to be made in all parts of the arc. With arcs operating on about 6 volts, the *cathode drop* was invariably very near to 11.5 volts (the minimum radiating potential of argon), so that there was a *reverse field* of about 5 volts existing throughout the greater part of the arc. The fact that the arc current of almost an ampere flows against this field is due to the effect of diffusion arising from the large concentration gradient. The *electron concentration* varied from the order of 10^{12} per cc just outside the cathode to about 10^{10} near the anode. The reverse field is due to the difference between the mobilities of electrons and of positive ions and is therefore most pronounced in the case of argon, in which electron free paths are abnormally long. The most interesting single feature of this research is the proof of the importance of *ion diffusion in low voltage arcs*.

Introduction

IT IS well established that arcs may be maintained in gases or vapors at voltages as low as their ionizing potentials, or, in cases where cumulative ionization is possible, as low as their radiating potentials, provided a hot cathode is used as a source of electrons. Considerable discussion has been occasioned by arcs which have been maintained at still lower voltages,[1] since at such voltages the electrons are known not to effect either partial or complete ionization of the molecules with which they collide.

Recently Bär, v. Laue, and Meyer[2] and, independently, the present writers[3] have shown that some of these arcs, notably those in helium,

[1] Compton, Lilly, and Olmstead, Phys. Rev. **4**, 282 (1920).
[2] Bär, v. Laue and Meyer, Zeit. f. Phys., **20**, 82 (1923)
[3] Eckart and Compton, Phys. Rev. **24**, 97-112 (1924)

may be accounted for by the existence of electrical oscillations,[4] the peak voltages of which always exceed the lowest radiating potential of the gas. An experimental and theoretical study of these oscillations has shown them to be in the nature of current interruptions occasioned by the rise in current and consequent drop in voltage occurring when the ionization is sufficient to create a positive space charge around the filament. Under such conditions there is nothing to prevent a rise in current to its saturation value. The increased potential drop in the series resistance, which accompanies this rise, reduces the voltage across the arc to such a value that no further excitation of molecules can occur. Ionization, however, continues for some short time, until the supply of previously excited atoms is exhausted. During this period, the current through the arc is dropping, and the voltage consequently rising, until finally excitation of atoms begins again, whereupon the cycle is repeated. Reactance is not essential to the maintenance of the oscillations on this theory. This has been confirmed by experiment.

It has been suggested that the abnormal low voltage arc in helium, instead of being due to the causes considered in the authors' theory, is in some way to be explained by an effect of minute, sub-spectroscopic traces of mercury vapor present as an impurity in the helium. We have performed the following experiment which appears definitely to disprove this suggestion. An experimental tube and system of traps were built of new G702 P glass. The nickel anode and leads were first suspended in an exhausted bulb, protected from mercury vapor by two liquid air traps, and given a prolonged heat treatment at a bright red heat by an induction furnace. Then, when the experimental tube was constructed, it was protected from the first from the introduction of mercury vapor by a liquid air trap and ten feet of glass tubing ($\frac{3}{8}''$). After a second heat treatment by the induction furnace and thorough baking out of the glass parts to about 300° C, liquid air was also added on four additional traps, one containing cocoanut charcoal and another gold foil, adjacent to the experimental tube. Spectroscopically pure helium was then introduced through the trap system, slowly, through a capillary, to avoid carrying

[4] There is some discussion as to priority in observing these oscillations. (See Marshall, Astrophys. J **60,** 246, 1924 et al.). Oscillations in arcs and discharge tubes have been known for some time, and it would indeed be strange if such oscillations had not been observed in tubes filled with helium at an early date. The authors make no claim to priority on this point. So far as they are aware, however, Bär, v. Laue and Meyer, and they themselves, were the first to offer the existence of oscillations as an explanation of the abnormal low voltage arc. The theory of oscillations about a critical potential, as developed by the present authors, also differs considerably from any previous theory.

over traces of mercury vapor. Neither then, nor after standing for several days with the liquid air continuously applied, was there any difficulty in securing the oscillatory abnormal low voltage arc. We believe, therefore, that any effect which the mercury may have must be a secondary effect, probably due to its easy ionization and the effect of its positive ions in permitting larger currents from the cathode.

Our theory fully accounts for one type of abnormal low voltage arc, which may be called the oscillatory type. Holst and Osterhuis[5] have found a non-oscillatory type which requires an entirely different explanation, as will be shown in this paper. They have maintained steady arcs in neon at 7.5 v, and in argon at 3.5 v, whereas the lowest critical potentials for these gases are 16.7 and 11.5 v respectively. They have also proposed a rather elaborate theory involving collisions of the second kind to explain their results.

This type of arc had also been found in helium and in mercury vapor by the present authors. This type is illustrated in the oscillogram, Fig. 7 of our previous paper,[3] in which it is seen that the arc persists at about 16 volts *after the oscillations have ceased.* Uncertainty regarding the interpretation of this phenomenon prevented its discussion, pending the experiments recorded in the present paper. The following experiments with argon, in which gas this type of arc is very pronounced, have shown that the potential of the gas very near the cathode is always about 11.5 volts (the radiating potential) higher than the potential of the cathode. As the anode is only 3 to 6 v higher than the cathode, *most of the gas is at a potential considerably higher than the anode.*

Experimental Methods

The arc tube was constructed as shown in Fig. 1. A is a sheet-nickel anode; B a movable exploring electrode, details of which are shown in Fig. 2. C is the filament cathode, taking 16.5 amp. at 3.0 v. The anode was made quite large (4×6 cm) as this seemed favorable for the non-oscillatory type of abnormal arc.

The method of using a cold exploring electrode, recently developed by Langmuir,[6] to determine gas potential, average energy of electrons and electron concentration, was used. A brief summary of the theory of this method may not be out of place.

[5] Holst and Osterhuis, Physica **4**, 42 (1924)

[6] Langmuir, General Electric Review **26**, 731 (1923); Langmuir and Mott-Smith, ibid **27**, pp. 444-538 (1924)

If V is the potential of the gas a small distance away from the exploring electrode, v the potential of the electrode itself, and V_0 the average energy of the electrons in the gas, three cases may be distinguished:

1. $v < V$ and $V - v >> V_0$
2. $v < V$ and $V - v$ comparable to V_0
3. $v > V$

Case I. Electrons are repelled, positive ions are attracted to the electrode. Since the wire emits no electrons, the current is carried by

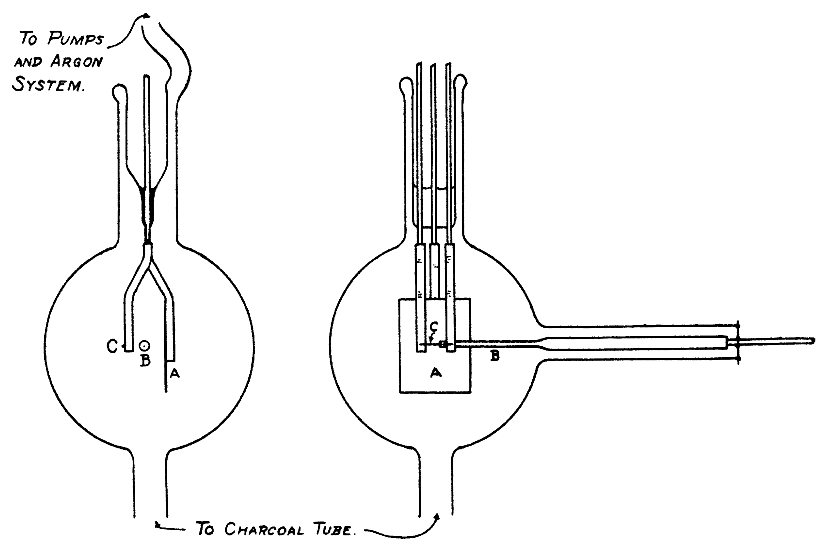


Fig. 1. The arc tube

positive ions only. If currents carried to the wire by electrons are designated as positive, this current is $-i_p$. It is limited to a very small

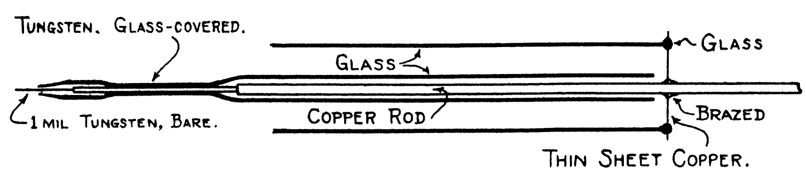


Fig. 2. The exploring electrode.

and nearly constant value by its space charge action. Many of the ordinary formulas for currents carried by positive ions between concentric cylinders can be applied to phenomena observed in this case, but, for reasons not clearly understood, it is impossible to obtain reliable estimates of the positive ion concentration in the gas from them.

Case II. As $(V-v)$ approaches V_0, some of the faster electrons are able to penetrate the retarding field and reach the electrode. This causes an algebraic increase in the current i to the electrode. If it is assumed that the distribution of velocities among the electrons is Maxwellian (an assumption which must be justified for each separate case), the following formula for this current can be derived:

$$i+i_p=A\epsilon^{3(v-V)/2V_0}, \qquad (1)$$
$$A=Nea\sqrt{eV_0/3\pi m},$$

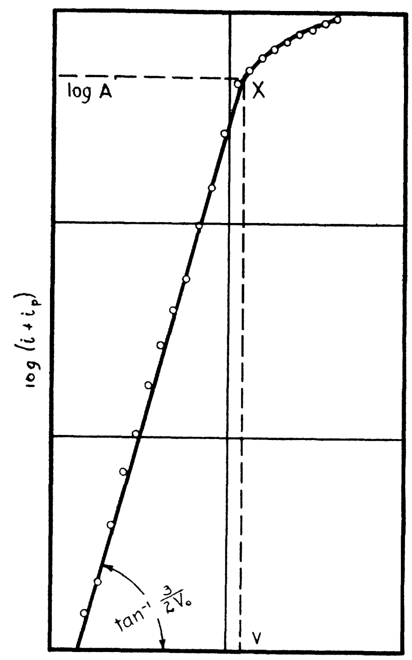


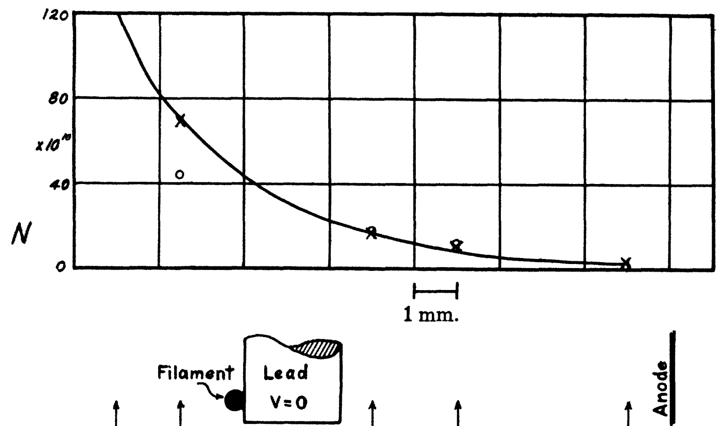
Fig. 3. Current-voltage characteristic of the exploring electrode.

where N is the number of electrons per cc, a is the area of wire electrode and e,m are the charge and mass of electron. If the assumption is justified, a straight line graph should result on plotting log $(i+i_p)$ against v. Fig. 3 is such a graph constructed from data taken with the tube of Fig. 1.

Case III. When v becomes greater than V, conditions change abruptly. Electrons are now attracted and positive ions repelled. The abrupt change in the curvature of the graph (Fig. 3, X) determines V accurately to a few tenths of a volt. The area of the electrode being known from actual measurements of the exposed wire, this value of V enables the calculation of N and V_0 from Eq. (1) by methods which are obvious.

Results and Conclusions

The experimental data are summarized in Fig. 4. The curve indicates the electron concentration in various parts of the arc space. The electrodes are drawn in diagrammatically beneath. The tables give the



						Anode	Current
V		10.5	7.5	8.0	5.6	5.8	.40 a.
V_0		4.2	3.8	3.6	2.5		
N		44×10^{10}	18.5×10^{10}	11.9×10^{10}	2.1×10^{10}		
V	10.6	9.7	9.7	7.0	6.2	5.2	.45 a.
V_0	3.4	4.2	3.9	3.3	2.3		
N	122×10^{10}	70×10^{10}	18×10^{10}	10.5×10^{10}	2.5×10^{10}		
V	10.6					6.2	.45 a
V_0	3.3						
N	112×10^{10}						
V	11.6					8.2	.78 a.
V_0	2.3						
N	480×10^{10}						

Fig. 4. Summary of data.

values, at the points indicated by the arrows, of V (the potential of the gas), V_0 (average energy of electrons), and N (concentration of electrons). The horizontal groups of data were taken under the same conditions of anode voltage (which is given beneath the anode) and of arc current (which is indicated in the last column).

It is seen that gas potential,[7] electron energies, and electron densities

[7] That such a phenomenon might exist and would explain the low voltage arc, was suggested to the authors by Dr. Langmuir.

all increase as the distance from the anode toward the cathode increases. The voltage increases even behind the cathode, reaching a maximum of approximately 11 volts about 3 mm away from the filament. Excitation apparently takes place in this region and is produced only by those electrons that have reached it without inelastic collision. The excited atoms may then be ionized in any of the various possible ways. This is borne out by the fact that the intensity of radiation is very great in this same region.

The apparent difficulty which arises from the fact that the electron current (which is practically the entire arc current) flows against an opposing field, disappears on consideration of the concentration gradient of electrons which is shown by the graph. It is obvious from general considerations based on ionic and electronic mobilities, that this concentration gradient is the equivalent of an electromotive force. J. J. Thomson has called attention[8] to this force which is given by

$$E=\frac{\mu_- - \mu_+}{\mu_- + \mu_+}\ \frac{e}{KT}\log\frac{N_1}{N_2}$$

where E is the potential difference set up between two regions of ion concentrations N_1 and N_2, μ_- and μ_+ are the mobilities of electrons and positive ions and $(3/2)KT$ is the average kinetic energy of the ions. (It is assumed that this is the same for electrons and positive ions. If this is not true, the equation is more complicated, but the underlying features are similar.)

Usually this force has been considered as negligible in comparison with that due to the applied electric field. Under suitable conditions, however, it may become of primary importance. The favorable conditions are a long free-path for the electrons and a high concentration gradient. The first of these conditions is realized to an unusual degree in argon and probably accounts in the case of this gas for the persistance of the non-oscillatory low voltage arc and the unusually large reverse field in the gas. In helium the authors have observed it only occasionally, and in mercury vapor it is also less clearly defined than in argon. In these gases the maximum observed reverse field was three or four volts. Measurements in mercury showed concentration gradients similar to those reported here for argon.

The high concentration gradient of electrons is probably built up during a transient period of oscillations when the arc is started. While no definite experiments have been performed to confirm this, the following observations suggest a connection between the two.

[8] J. J. Thomson, Conduction of Electricity through Gases, p. 85 (1906)

If a Braun tube is connected so as to indicate the voltage across the arc and the series resistance gradually decreased, the luminous spot passes through the successive stages of Fig. 5.

Stages 1 and 2 correspond to the normal low-voltage arc, where the ionization occurs by cumulative action. Stages 3 to 6 correspond to the oscillatory abnormal arc, with positive potential gradient at all times and parts of the discharge. In stages 7 to 9, the arc is obviously in a transition state, where the negative gradient is present during certain parts of the cycle at least. It is not yet stabilized, however, so that the oscillations persist. Stages 10 to 13 represent the non-oscillatory state in which the negative gradient has become stable.

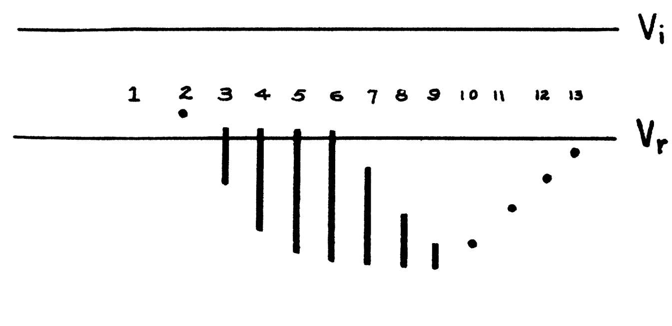


Fig. 5. Successive stages of the arc indicated by the Braun tube oscillograph.

The conditions for stability of the negative gradient have not yet been thoroughly investigated.

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Princeton, New Jersey,
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