THE ELECTRIC ARC.

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Last summer the writer had occasion to make a review of recent researches on the electric arc. After writing the results of this investigation it seemed that it would not be out of place to present them to the readers of SCHOOL SCIENCE AND MATHEMATICS.

The writer does not lay any claim upon a complete review of the arc, but wishes to present simply the results obtainable from sources of information accessible at the time the paper was written.

The electric arc, ever since its discovery by Davy in 1810, has been the object of spasmodic investigations. In recent years the purpose of these has been to verify the various theories that have been presented to show the nature of the arc, as well as to increase its efficiency as a light producer. It is the work spent upon the theory of the arc that I wish to present in this review.

At first thought the arc may appear to be a simple phenomenon; but when we consider in how many ways it may be varied—by using different electrodes, current strengths, different media through which it may take place, variable pressures, and injecting salts of various kinds into it, and then considering that each of these conditions has its own characteristics, there is no wonder that investigators, although they have learned much concerning its practical points, have not yet reached very definite conclusions as to what is really going on in the arc itself and the space immediately surrounding it.

In 1898 N. H. Brown succeeded in photographing the arc produced by an alternating current. This was done by rapidly rotating the film and obtaining a lengthened picture of the arc, which showed two light fronts. The one from the cathode started sooner than the one from the anode, but it moved much more slowly than did the latter. Of course this at once started speculation as to the cause.

It was while studying the results of these photographs that C. D. Child of Colgate University was led to the conclusion that the current, in part at least, was carried by ions—positive ions traveling to the cathode and negative ions to the anode. To explain some of the characteristics of the arc, he assumed the

positive ions to have the faster rate of travel. Both of these statements are only assumptions derived from the photographs of Brown which showed that there is a movement of some sort from the anode to the cathode and vice versa. These light fronts seemed also to move with a variable speed and that just where the positive moved most slowly the negative gained in speed. If we are justified in assuming ions, and of these, the positive to move the faster, by this assumption some of the phenomena of the arc ought to be explained.

We know that there is a greater fall in potential at the electrodes when compared with the fall between the carbons. We also know that the resistance of the arc is not altogether ohmic. It is often said that there is a back electromotive force due to the Thompson and Peltier effects, but it cannot be detected when the current is turned off, even though the conditions for its detection are of sufficient duration. There may be some cause similar to the Thompson effect, but just what it is is not yet known. Will ion carriers of electricity explain any of these things happening in the arc?

Suppose intense heat causes the dissociation of gases of the arc into positive and negative ions, which move to opposite poles. There would be an excess of positive ions at the cathode and an excess of negative at the anode. Now if in addition we assume the positive ions to be the most rapid we would have a scarcity of them between the poles which would lower the potential of the intervening gas. There would also be a greater fall at the anode than at the cathode, which we know to be the case.

J. Paley Yorke in his book of Applied Electricity, however, says this extra fall at the anode may be due to the extra energy consumed in vaporizing the carbon. This, however, cannot be proved absolutely until a method for determining the heat of vaporization of carbon is found.

It is also known that with an alternating current the average potential of the gas is not zero. The faster movement of the positive ions will account for this because the space between the electrodes would then be charged with the more abundant negative ions which would not have time to get out of the field.

When the current is increased the resistance of the arc is apparently decreased. This is due to a more rapid process of dissociation due to the heat.

C. D. Child, the supporter of this theory, experiences some difficulty, because in other cases already examined the negative ions were the ones that outstripped their partners. When ions were drawn from a flame to charged plates and the velocity of each kind calculated it was learned that the negative were the faster. For a potential gradient of one volt per centimeter their speed was 2.6 cm. per second and that of the positive only 2 cm. per second. When a similar experiment was performed with the arc, however, the faster ions were found to be positive, no matter how the conditions were varied. The rate of discharge increased with increased current. The ratio of the speeds was 2 : 1. In the vapor of the arc, though, the negative were the faster. This may be due to a falling off in speed as the positive go farther and farther from the center.

So far only the most rapid ions of each class had been compared. But when the slower ions were considered the following results were obtained:

- (1) The fastest positive ions surpassed the fastest negative ions.
- (2) The slowest positive lagged behind the slowest negative ions.

The performer of these experiments then turns his attention to the discharge of hot platinum wires and of hot carbon and concludes that particles are emanated from the platinum and carbon. These particles when settling upon the negative ions retard their motion. His researches led to the belief also that the process of ionization may begin within the metal or the carbon itself. Perhaps occluded gases have something to do with it, and the arc in partial vacua also was studied. Without going into detail concerning the apparatus and its management, the results may be represented in Fig. 2

Fig. 1.

—the irregular line showing a larger drop at the anode, a uniform fall in the space between the carbons and another abrupt fall at the cathode somewhat less than that at the anode.

During these experiments an exhaust pump was connected (as shown) and pressures ranging from 730 to 2 mm. of mercury were obtained. The relative fall was always as indicated in the figure; but the drop at the negative carbon was greatest at a pressure of 100 mm. No explanation was found for this strange behavior. Thus it is seen that the conditions controlling the fall at the anode are different from those controlling that of the cathode. The electric force through the arc, moreover, was found to decrease as the pressure in the tube was lowered.

Fig. 2.

Concerning the temperature of the arc it was learned that a platinum wire .31 mm. in diameter could be melted at a pressure of 4 mm. of mercury. One .11 mm. in diameter could be melted at a pressure of 2 mm., and one that was said to be .01 mm. in diameter broke down when a pressure of .5 mm. was reached, showing that even at low pressures the temperature of the

arc is very high; also proving that the value of this method of determining the exact temperature of the arc is very low.

With the same form of apparatus Child measured the rate of discharge of positive and negative ions to a surrounding cylinder and it was found that in a pressure of one atmosphere the positive ions were the faster and in very low pressures the negative ions were the more rapid.

These data present many difficulties and permit of no definite conclusions concerning what is really taking place in the arc. Yet the very fact that there are variations in the deportment of the ions under different conditions may some day lead to discoveries very valuable.

J. J. Thomson, after experiments with the discharge from platinum wires, considers ions produced within the cathode as the essential phenomenon. He says: "The essential feature in the discharge is the hot cathode, as this has to supply carriers for the electricity through the arc." Now, although a hot cathode is necessary, Weintraube has shown that in case of the mercury arc or between mercury and graphite the temperature of the mercury is far too low for the production of ions within it. It

was shown in the experiments of Child and Weintraube that no arc could be formed without a hot cathode and that there could not be two cathodes in multiple.

Now it may be that ions are formed at the boundary surface between the cathode and the surrounding gas, and that this gas boundary may be the thing that is hot, instead of the cathode itself.

It was Thomson's idea that the anode played an important role in the arc, but Weintraube proved that the part taken by it is insignificant. Thomson took it for granted also that there was no ionization going on between the carbons, but the statement is made by Child that the only way to account for the change in electrical force at the anode is to assume an increase of ions in the middle of the arc. There has been some speculation as to the cause of this extra ionization.

In atmospheric pressure the mean free path of the molecules is too small to permit of ionization by impact. In this case the high temperature must develop extra ions. In a vacuum, however, the mean free path is larger and the molecules could be broken up by impact, the temperature at the same time being lower. Again, the increase of ions at the center of the arc may be due to a change of electric force into some other form of energy.

Continuing his experiments further, Child substituted graphite terminals for the carbon. At a certain pressure, dependent upon the length of the arc used, there appeared a glow similar in appearance to the canal rays. The current seemed to emanate from the bright spot on the cathode. When a piece of platinum was introduced between the electrodes the glow always appeared, but no shadow was cast as in the case of the cathode rays. When a piece of platinum with a hole cut in it was placed close to the anode the glow seemed to pass through the opening toward the cathode, as if ions were being projected from the positive graphite terminal. The conductivity of the arc was greater when there was no glow.

When a magnet was brought near the arc at a pressure of .7 mm. or less, the gas in all parts of the tube became luminous and bright streams appeared to run from the arc to the magnet in the magnetic lines of force. Then a magnet bent into the form of a nearly completed circle was brought near and the lines then ran between the poles of the magnet. In this case the most luminous part was in the strongest magnetic field.

Thomson says: "There is a tendency for ions to follow magnetic lines of force."

Thus it is seen that the phenomena of the arc depend largely upon the electrodes used and conditions of pressure, length of arc, strength of current, and other seemingly minor details.

Besides all these, any explanation that does not consider the presence of chemical reactions would not be complete. Some years ago, and preceding the work of Child, while at Cornell University, Dr. Arthur L. Foley conducted some investigations which indicated an electrolytic action of the arc. Briefly stated these experiments were as follows: Some calcium chloride was introduced into a hollowed-out negative carbon. The anode was a plain arc carbon. The arc was allowed to operate for one minute, then the cathode was removed and after a plain carbon was substituted, the arc was again started by bringing a third carbon between the electrodes (as was done in the first case also). A photograph of the spectrum was then made which showed only those calcium lines which are in every arc due to the metal in the carbon as an impurity. The horizontal arc was used to avoid the misleading results due to convection currents. Next, the calcium chloride was inserted into the anode, the cathode being a plain carbon, and the arc was allowed to pass for one minute. On replacing the anode by a plain carbon and taking a photograph of the spectrum thus caused, numerous calcium lines were found at the cathode, due to the latter being impregnated with calcium while the salt was in the anode. The voltage was higher when the salt was in the negative pole.

The work of Dr. Foley was mainly on the "Spectra of the Arc" but these experiments show its electrolytic action.

Most of the work by Weintraube has been done in connection with mercury as a cathode and the arc in partial vacua. In many respects the conclusions reached are similar to those of other workers. He shows that besides starting the arc in the usual ways of contact and separation of electrodes and by very high voltages, it may be started also in the following ways: 1. By bringing the cathode, if mercury, in contact with an already active cathode. 2. By the cathode coming in contact with ionized vapor. 3. By mere mechanical agitation of the mercury. Like the others he shows that the cathode plays the important part in the process of ionization and that the properties of the arc are independent of the anode.

When iron, graphite or other solids are made the cathode and mercury the anode, the solid cathode always rapidly disintegrates.

This disintegration is probably intimately connected with the ionization process. "The most probable assumption," he says, "is that the current leaves the graphite in the form of carbon ions and is carried through the arc by means of mercury ions. The question whether ions after reaching the anode become positively charged and move back toward the cathode must be left undecided."

Fig. 3.

In the beginning of the year 1909 at King's College in London a series of experiments was begun by J. Nicol with the rotation of the arc in a radial magnetic field. The apparatus is illustrated in Fig. 3 and Fig. 4.

Figure 3 shows an iron rod, A, at the middle of which a magnetic pole is made by the coils B, B. F is an insulated block of wood carrying holders E, E which are supports for the copper

cylinders D D, between which the arc takes place. A top view of E is shown separately. SS are the binding screws by which the current enters and leaves DD. The apparatus is so arranged that the parts can be taken down readily for the insertion of clean copper cylinders.

The arc was started with the magnetic field already in action by inserting a carbon pencil between the copper plates D, D. Carbon terminals would permit of only a few revolutions of the arc. Iron-iron and iron mercury electrodes also were unsatisfactory. The copper cylinders were taken out and cleaned often.

To determine the number of revolutions of the arc per second a photographic method involving the use of a rotating mirror was employed. The mirror was fixed not quite normally on the end of a small motor shaft (Fig. 4). When the mirror was in

motion therefore a point source was drawn out into a circle of light and if the point source was intermittent, this circle was made up of as many dots as the number of times the source became luminous in one revolution of the mirror. The intermittent source was obtained by placing a slit in front of the arc. This was illuminated once for every rotation of the arc, and the image of the slit was photographed by an ordinary camera. The camera shutter was adjusted so that the dots overlapped a little in order that fractions of revolutions could be estimated to the nearest tenth.

Let K be the velocity of drift of an ion along the arc due to unit electric force. Then if X represent the electric force the velocity is XK . This motion of an ion in a magnetic field causes a transverse electric force of $H \times K$ to act on the ion, H being the strength of the magnetic field. This electric force gives the ion a velocity of $H \times K^2$. Hence the transverse displacement of an ion while it is passing from one electrode to the other is this transverse velocity XHK^2 , multiplied by the time to cross the

arc which is $\frac{l}{XK}$ where l is the arc length. This division gives $H K l$. The velocity of the two ions not being the same the arc will not remain parallel to the electrodes, but the two ends will eventually move at the same speed, and their position will be given by $y_1=vt$ for the anode end, $y_2=a+vt$ for the cathode end. The positive ion starting from the anode and moving to the cathode in a time $\frac{l}{HK_1}$ must travel a transverse distance of

$$a + \frac{vl}{XK_1} \dots\dots\dots(1)$$

Similarly a negative ion travels a distance transversely of

$$-a + \frac{vl}{XK_2} \dots\dots\dots(2)$$

Equating (1) and (2) to the expression above ($H K l$) we have:

$$a + \frac{vl}{XK_2} = K_2 l X \text{ which gives } v = H X K_1 K_2 \text{ or } K_1 K_2 = \frac{v}{H X}$$

This may also be written $K_1 K_2 = \frac{2\pi r n}{H X}$ where r is the radius of the electrode and n is the number of revolutions the arc makes per second.

This product was obtained and Nicol makes the assumption that the negative ion is an electron. By calculation then the positive ion was found to be about nine hundred times the negative ion or about the mass of a hydrogen atom. "The positive ions then cannot be either copper or air molecules, but may be the same as the carriers of positive electricity detected by J. J. Thomson in the canal rays," says the author.

The product of the two velocities is directly proportional to the temperature. But the experiments show that the product is trebled by a rise in the current from two to nine amperes. This indicates a temperature change from 1,000° to 3,000° which is larger than probable. If the positive ions are copper or air molecules the rise in temperature could be accounted for by the dissociation of these groups.

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