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ROTATIONS IN THE IRON ARC.

By W. G. Cady.

§ 1. Reference has been made in previous papers[1] to a peculiar type of rotations found at the anode of the iron arc in air. Subsequent experiments have shown that the phenomenon is more complicated than was at first supposed. Stated briefly, if the anode is sufficiently oxidized so that a smooth molten globule of oxid is formed, the positive base of the arc tends to fall into a circular motion, producing the appearance of a minute ring of light at the anode. As the current is increased from about 1.5 to 2.5 amperes, four characteristic types of rotation may be observed in succession, the transition from one type to the next being marked by a distinct and sudden change in diameter and frequency of rotation. This is not the result of artificial conditions, but the *normal sequence of events* in the iron arc as the current increases.

Apparatus and Method.

§ 2. Since we are dealing with an effect that depends essentially upon the anode, any substance that does not, by distilling across the arc, change the chemical nature of the anode, may serve as cathode. An iron cathode serves fairly well, but the wandering of the negative base is troublesome. I have secured the best results by using as cathode a cored carbon half an inch in diameter. Apparently the traces of salt in the carbon tend to hold the negative base steadier at the small currents with which we have here to do. Care must however be taken not to let the arc take place directly from the core, as the metallic salts from the core change the form of the discharge to a glow at the anode, so that the first stage[2] persists even for currents over five amperes. It was found best to remove the core, leaving a bore through the center of the carbon. The

[1] Am. Jour. Sci., 24, p. 405, 1907; Phys. Rev., 24, p. 381, 1907, and 35, p. 77, 1912; Phys. Zeitschr., 8, p. 890, 1907.

[2] Cady and Arnold, Am. Jour. Sci., 24, p. 384, 1907.

negative base of the arc occupied only a small spot on the side or end of the carbon. No advantage was found from impregnating solid carbons with various salts. The anode may be either above or below, in the form of an iron rod from 3 to 6 mm. in diameter with oxidized end, or a small bead of oxid resting in a depression on the end of a carbon holder. The length of arc in the present experiments varied between 3 and 10 mm.

Most of the experiments recorded here were performed with the brass water-cooled lamp shown in Fig. 1. As this apparatus has been found useful in various lines of work, the following brief description is given. It consists of an inner vertical cylinder TT of brass 18 × 9 cm., with flat top and bottom, completely inclosed in an outer brass jacket. Water is kept flowing in at A and out at B. C and D are brass tubes for inlet or outlet of gases. E is a round horizontal brass disk on the end of a vertical brass stem with hard rubber handle G, which can be rotated about a vertical axis by means of a ground glass joint. The stem is sealed into the lower member of the joint at M. The upper member of the joint, N, is sealed into a brass tube, which is soldered to the inner and outer jackets. The joint is thus kept cool. The disk E carries six brass sockets (two of which are shown), in which various electrodes may be fastened. A convenient interchange of electrodes is thus made possible without opening the lamp. For the present purpose this was an important consideration, since the rapid and irregular wearing away of the carbon cathodes made frequent changes necessary. F is the upper electrode, controlled by a rack and pinion movement. The stem for turning the pinion passes through a horizontal glass joint (not shown) similar to that at E. In front is a round opening passing through the inner and outer cylinders, indicated by a dotted line in Fig. 1. A glass window can be screwed tightly over this.

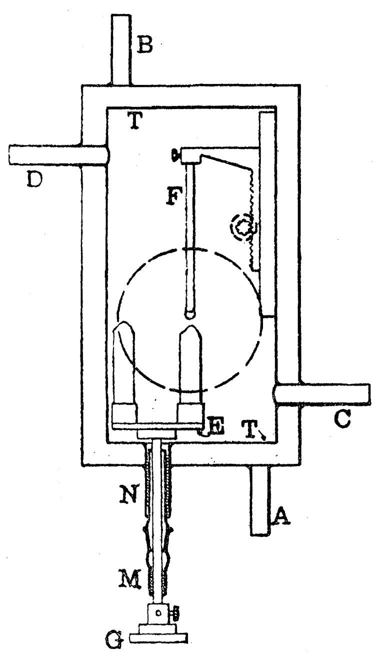

Fig. 1.

For the experiments in free air the window was generally left open. But since the rings are best observed when disturbing air-currents are eliminated, it was sometimes necessary to close the opening and to draw a slow current of air through the lamp, in order to maintain the supply of oxygen.

In order to make the rings visible from the front, the cathode was generally brought into such a position as to cause the arc to take place from a point on the front of the anode globule.

§ 3. The following methods were employed, singly or together, in studying the appearance of the anode and the accompanying oscillations.

1. A large image of the arc was projected on to a screen.

2. The frequency of the oscillations could be approximately determined by comparing with a tuning fork the high-pitched whistle that accompanied the rotations.

3. To detect small periodic effects, especially when there were disturbing noises, a high-resistance telephone receiver, shunted by about one ohm, was connected in series with the arc. The receiver responded to the small fluctuations in current which, as will be seen, always accompany the rotations.

4. By reflecting the image from a rotating mirror, the movements of the positive base could be roughly examined. Although no stationary image could be obtained in this way, still valuable knowledge of the character of the movements was gained.

5. The fluctuations in current and potential drop were recorded with a Duddell high-frequency oscillograph and rapidly moving film.

6. A somewhat enlarged image of the arc was in some cases photographed on the moving film, alone or simultaneously with the oscillograph records.

All the characteristic phenomena can be observed with a supply of 110 volts, but in general from 150 to 300 volts were used, as the arc was then more stable. A liquid resistance was used for fine regulation of current.

Description of the Rotations.

§ 4. *Type A*.—Up to about 1.5 amp. the anode globule, though brightly incandescent, is not vaporizing, *i. e.*, the arc is on the first stage with a glow discharge at the anode. At about 1.5 amp. the change to the second stage generally occurs, when the current increases abruptly one or two tenths of an ampere. The positive base of the discharge then concentrates itself upon a spot similar to that at the cathode, and a hissing sound is heard, due to the vaporization. A close examination of the magnified image, however, reveals the fact that the positive base is in the form of a ring with dark center, about 0.4 mm. in diameter, while under favorable circumstances a faint wavering high-pitched note can be heard.

This is the first of the four types of rotation referred to above. For brevity we will call it "Type A," or "Ring A." The measured frequency f and diameter δ of this as well as of the other three types are shown in Fig. 2. The data for this figure are mostly taken from a single photo-

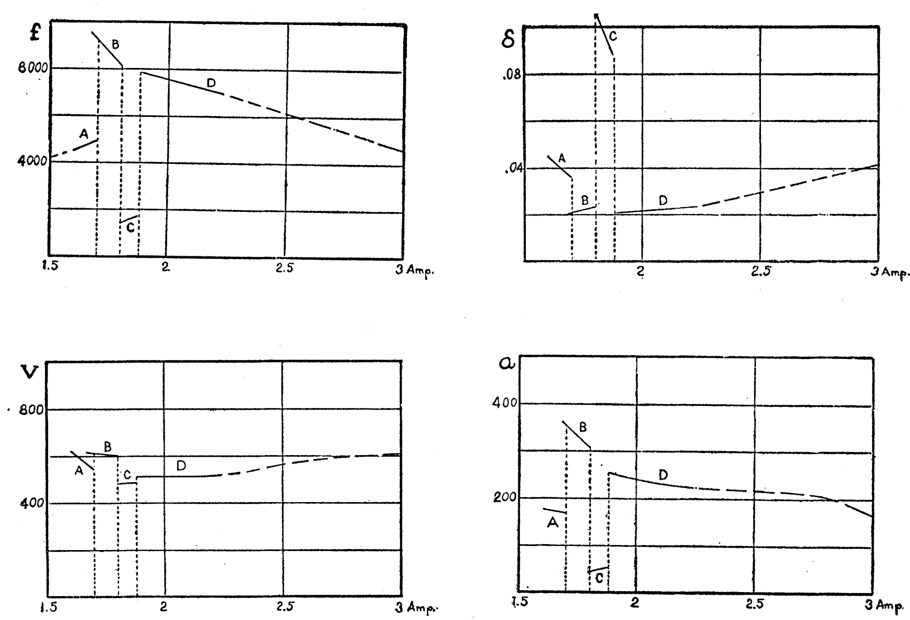

Fig. 2.

Dependence of frequency f (cycles per sec.), diameter of ring δ (cm.), linear velocity v (cm. per sec.), and normal acceleration a, upon the current, for the four types of rotation.

graphic film. The drum carrying the film was kept turning at the rate of 10 rev. per sec. during the operation. The "life history" of all four types was recorded as a practically continuous record about eleven feet long on this film. This was done by gradually decreasing the resistance in the arc circuit, while simultaneously the lens that projected the image of the positive base on to the film was moved sidewise by hand at as uniform a rate as possible. The values here shown were confirmed by other observations, photographic and visual, and may be taken as representative of the normal phenomena, except that the changes on this film took place at somewhat smaller currents than is commonly the case. In single instances, more or less wide departures from these values must be expected, for while the *relative* values of f and δ in any experiment are generally in agreement with Fig. 2, still the *absolute* values may differ very widely. Hence averages from different tests are sometimes untrustworthy.

The broken lines in Fig. 2 are based on other data gathered at different times.

§ 5. *Type B.*—Between 1.67 and 1.73 amperes the second type of rotations, which we will call Type B, begins to assert itself. This ring, as seen in Fig. 2, has a smaller diameter and higher frequency than Type A. It appears on the film first in short trains interjected at intervals in the midst of Type A. This is seen in the first curve in Fig. 3. The long waves are Type A, the short ones Type B; for each type, the frequency is higher than that shown on Fig. 2. Neither type is as steady here as when it exists by itself alone. As the current increases, the trains of waves from Type B become longer and the intervals (Type A) shorter, until at 1.73 amp. (Fig. 2) Ring A ceases altogether and Ring B

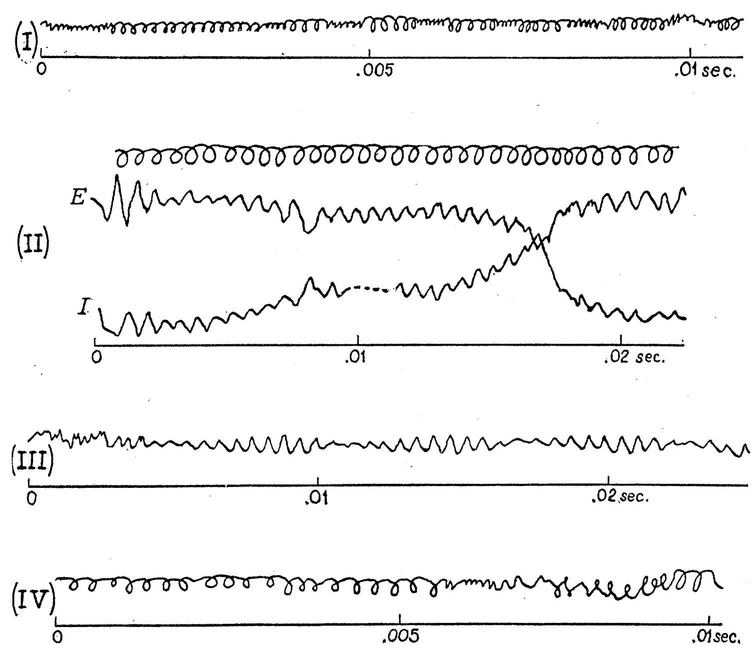

Fig. 3.

I. Photograph of positive base on moving film. Types A (large) and B (small) alternating. Mean diameter of ring, Type A, 0.3 mm. Current, 1.75 amp.

II. Oscillograph records of p.d. and current, together with image of positive base similar to (*I*). Type C, frequency 1,600. In *E* curve, 1 mm. = 1.34 volts; in *I* curve, 1 mm. = 0.013 amp. Diameter of ring, 0.9 mm. Current, 2.05 amp.

III. Oscillograph record of p.d., Type C, frequency 1,670. 1 mm. = 1.23 volts.

IV. Photograph of positive base, Type D. 1 mm. = 0.206 mm. at anode of arc. Current, 2.75 amp.

alone is seen. Direct examination with the rotating mirror reveals the same effect. The data for Fig. 2 are not taken from the films shown in Fig. 3.

The audible pitch falls gradually in a peculiar manner while the transition from Type A to Type B is in progress. This, I think, is due to slowing down of the column of entrained gas, which, as long as Type B alternates with Type A, fails to keep in step with either ring. The sound of course proceeds from the moving vapor and not alone from the positive base of the arc.

§ 6. *Type C.*—On the film on which Fig. 2 is based, Type B lasts only up to 1.80 amperes, when quite suddenly it gives place to the third type. Here the diameter is much larger and the frequency correspondingly lower. This, by far the most conspicuous of the rotations, is the one referred to in the earlier papers. Occasionally Type C fails to appear, or at most it comes in a few irregular trains. This is especially the case when the arc is disturbed or when the gas contains an insufficient supply of oxygen. The range of current over which Type C prevails is often very limited, in the present case only from 1.80 to 1.88 amp. Under normal conditions, Type C begins at about 2 amperes and lasts until 2.3, or even 2.5, amperes, at which point Type D begins.

The audible tone due to Type C, which may be heard at a considerable distance from the arc, varies in the manner indicated by the frequency curve in Fig. 2. The absolute values of f and δ are nearly the same, at whatever current the ring first appears.

In Fig. 4 may be seen a charcoal drawing of the arc between an iron anode and carbon cathode, based upon a photograph. Owing to very unequal light distribution, the photograph did not lend itself to direct reproduction. The diameter of Ring C was 0.91 mm., current 2.12 amp.

Simultaneous records of current and voltage, together with the image of the positive base for Type C, are shown in the second group of curves, Fig. 3. The long-period fluctuations in the oscillographic records, which are very evident on the complete film (only a part of which is here shown), are due either to swaying of the arc or to wandering of the negative base. Whatever the cause, it is evident that the movement of the positive base was undisturbed. Curve *III* of Fig. 3 is a voltage record for Type C, showing irregular fluctuations at the beginning, as well as the appearance of beats (cf. § 10).

§ 7. *Type D.*—At 1.88 amp. the film under discussion shows a sudden change to the fourth type of rotation, Type D. This, the final type, lasts in air at atmospheric pressure up to about 5 amp. The frequency falls and the diameter increases with increasing current (Fig. 2). Beyond 3 amp., however, the motion becomes very irregular. Still, up to 5 amp. the rotating mirror still shows detached trains of large waves in the midst of the irregular wandering of the positive base; at about this point the movement ceases somewhat suddenly, as explained in § 22. From then on, no tendency to wander has hitherto been observed.

The appearance of Ring D, as revealed by the moving film, is seen in Curve *IV* of Fig. 3. The disturbed state characteristic of large currents is here in evidence.

As has been stated, the currents for this particular film were smaller than those usually encountered. In general, one may look for the four types at about the following values of current: Type A, from 1.4 to 1.8 amp.; Type B, from 1.8 to 2.0 amp.; Type C, from 2.0 to 2.5 amp., though very often Type B or Type D encroaches widely on this interval; Type D, from 2.5 to 5 amp.

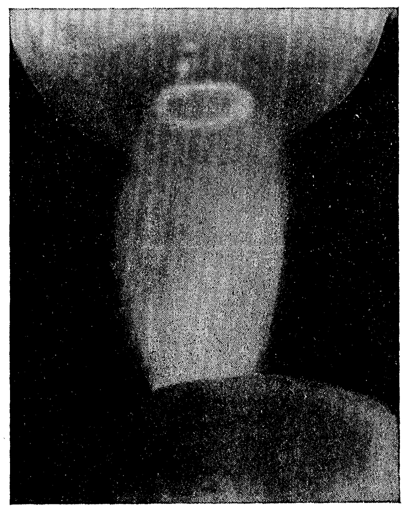

Fig. 4.

Iron arc rotations, Type C. Below: Carbon cathode. Above: Iron oxide anode. Current, 2.12 amp. Diameter of ring, 0.91 mm.

§ 8. *Remarks on Type C.*—The vapor of the arc for a distance of several millimeters from the anode seems to partake of the motion. At any rate, the arc becomes diffuse, and the envelope of yellow flame surrounding it, which is due chiefly to the oxidation of the iron vapor, flickers convulsively the moment the ring appears. If the arc is shortened to about 2.5 mm., the negative base is also affected by the rotation and the anode ring is less distinct. With still shorter arcs, Type C fails to appear, though the other types are still in evidence. It would appear from this that only about 2.5 to 3 mm. of vapor, at the anode end of the arc, is affected by Type C, and that the vapor is even less influenced by the other types. Type C generally passes through a very disturbed state at largest currents, just before the change to Type D takes place. Sometimes the arc appears to divide into two or more parallel arcs. The anode sometimes becomes so cooled at such times that in spite of the large current the change from second to first stage (non-vaporizing anode) occurs. Over this part of the characteristic curve accurate observations of current and p.d. are impossible.

On diminishing the current, the observations on all four rings are repeated in reverse order. Whenever Type C begins, whether on increasing or decreasing current, the drop across the arc always increases 1 to 2 volts while the current decreases slightly. This is probably due to the lengthening of the arc.

The tendency of both ends of the arc to wander over the surfaces of the electrodes is a most exasperating feature of the work, rendering precise observations utterly impossible. Various remedies, such as steadying the arc by holding a bar magnet near it, have been tried without success. Ring C is the hardest form to obtain. It is seen generally only for a few seconds at a time, though under good conditions it may last a full minute.

§ 9. *Refraction of Light by the Column of Hot Vapor.*—The surface of the iron oxid globule, which under normal conditions is brightly incandescent, is extremely smooth, giving a distinct reflected image of the column of vapor and of the negative end of the arc, especially when a carbon cathode is used. If the globule is viewed from such an angle that the negative crater is reflected from a point near the positive base of the arc, a curious distortion takes place: the image sends out a line pointing toward the positive base, and sometimes a second fainter image appears close to the main one, in a direction away from the positive base. This condition is shown close to the ring in Fig. 4.

The first of these effects is probably due to refraction of the light from the crater by the hot vapor of the arc. The second image seems to result from a deformation of the surface of the globule, caused by the mechanical pressure which the arc is known to exert upon the molten surface.

No distortion of the image of the negative crater is seen on the first stage of the arc, as the positive base is then very diffuse and no vaporization of the anode takes place.

A similar distortion of the reflected image was observed with anodes of other metals and oxides (§ 26).

§ 10. *Observations with the Oscillograph.*—It seemed desirable to study the variations in voltage and current produced by the rotations. A Duddell high-frequency oscillograph with rapidly moving film was used. In some cases an image of the anode of the arc was projected on to the film, in addition to the oscillograph spots. A part of one such record is shown in Fig. 3, *II*.

Owing to the high frequencies involved, it was not possible to secure oscillographic records showing accurately the wave-form of the current and voltage curves. Indeed, except at the lowest frequencies, variations accompanying Types A, B and D could not be seen at all. Type C was always found to be accompanied by oscillations in arc voltage amounting to ± 1 to 3 volts, and in current amounting to ± 0.01 to 0.03 amperes. The cause of these fluctuations lies probably in periodic changes in length and temperature of the arc, especially since in taking the photographs the electrodes were moved out of vertical alignment in order to bring the positive base as far over on to the side of the globule as possible.

On some films the amplitude of the oscillograph curves varies periodically, reaching a minimum every ten to twenty cycles, or even passing through a zero value and suffering a phase displacement of 180°, as in Fig. 3, *III*. This at once suggests beats, and indeed it is not impossible that such were present, since once in a while two tones could be heard at once during Type C. The appearance of beats, moreover, would be produced if, owing to air currents or other cause, the entire ring swayed from side to side over the surface of the globule. Direct evidence of such swaying was sometimes furnished by the blurred appearance of the ring. This might account for the production of two musical notes, especially through the action of the Doppler effect.

On the whole, the determination of current and voltage relations does not seem to be of particular value in the study of these rotations, except in so far as it throws additional light upon the periodicity. These observations with the oscillograph serve, however, to explain the nature of the oscillations in the iron arc current which Arnold and the writer[1] found always to be present on the second stage.

Self-inductances (transformer windings) were at times connected in series with the arc on both sides, but they were without effect upon the period or sound of the rotations.

Theory of the Rotations.

§ 11. It is well known that in both glow and arc discharge, rotation of the positive column can be produced by a radial magnetic field. It is conceivable that in the present case, a magnetic field perpendicular to the plane of the ring might maintain the circular motion by virtue of its component at right angles to the arc stream. The writer thought at one time that this would prove to be the cause of the rotations. That

[1] Cady and Arnold, *l. c.*, pp. 405, 409.

such is not the case became clear when it was found that the period and amplitude of the rotations are independent of the direction of the arc in space, and that the direction of rotation often reverses itself spontaneously. Moreover, I have placed the arc in a magnetic field whose direction and intensity were varied through wide limits, without detecting the slightest influence on the rotations.

Dufour[1] found that the irregular wandering of the cathode base of the mercury arc, caused by excess of vapor pressure, can be made to resolve itself into a circular motion. This cannot, however, be the controlling cause of the iron arc rotations, since, as will be seen (§ 24), the presence of oxygen is the prime requisite for their maintenance.

Trotter[2] observed a rotation of the bright spot at the anode of the carbon arc just before the beginning of the hissing stage. This was later shown to be due to the inrush of oxygen into the crater.[3] As will be seen (§ 15), this bears a closer resemblance to the present rotations than any of the other types hitherto known.

§ 12. It seems most probable that the rotations here described find their origin in modifications in the composition of the globule of oxid at the anode. We will consider first the cause of the wandering of the positive base, and then the conditions necessary for the maintenance of a continuous rotation.

As has been stated, the anode globule on cooling is found to consist of magnetic iron oxid, $FeO.Fe_2O_3$. This oxid is known to possess a complex structure, and to undergo changes in its physical properties at certain critical temperatures.[4]

Walden[5] found Fe_2O_3 to be stable in air up to about 1350° C., at which temperature it dissociates into O and Fe_3O_4. Kohlmeyer,[6] on the other hand, assigns to the melting point of Fe_2O_3 the value 1565°, with transition points at 1300° and 1035°. Hilpert[7] calls attention to the influence of previous history and method of treatment on the dissociation temperature of Fe_2O_3, while Wüst[8] asserts that at 1050° the compound $FeO.Fe_2O_3$ is formed, at 1100° $2FeO.Fe_2O_3$, and at 1200° $3FeO.Fe_2O_3$. According to Hilpert, Kauffmann identified also $2FeO.3Fe_2O_3$. I know of no investigations on the reactions that take place at higher temperatures than these,

[1] Dufour, Jour. Phys., 5th Ser., 1, p. 109, 1911.

[2] Trotter, Electrician, 33, p. 298, 1894.

[3] Mrs. Ayrton, The Electric Arc, p. 300.

[4] *Cf.* Heaps, Phil. Mag., 24, p. 813, 1912. Somerville, PHYS. REV., 34, p. 311, 1912. Koenigsberger, Phys. Zeitschr., 13, p. 282. 1912.

[5] Walden, Jour. Amer. Chem. Soc., 30, p. 1350, 1908.

[6] Kohlmeyer, Metallurgie, 6, p. 323, 1909.

[7] Hilpert, Ber. Deutsch. Chem. Ges., 42, p. 4893, 1909.

[8] Wüst, Metallurgie, 5, p. 11, 1908.

but it seems not improbable that still others occur before the final reduction of the iron is accomplished. In addition, there is the possibility of the formation and dissociation of a nitride.

Apparently at any given gas pressure the temperature close to the positive base of the iron arc is determined solely by the current. At any rate, heating the rod to which the positive globule is attached does not perceptibly affect the rotations.

§ 13. *Temperature of the Anode Globule.*—A Pt : PtRh thermo-element was thrust into the molten globule after the arc had been started, and observations for temperature were made at various values of the arc current. Owing to the wandering of the arc and the turbulence of the molten oxids, the results were very irregular, but the mean temperature of the globule seemed to be in the neighborhood of 1600° C. for currents between 1.5 and 3 amp. Close to the positive base of the arc the platinum wire melted, and this occurred also when the thermo-element was thrust deeply into the globule to a point about one millimeter below the positive base, showing that here also the temperature is very high. Where the oxid touched the iron rod on which it rested, its temperature must of course have been below the melting point of iron, 1530°; half-way up the side of the globule the temperature was about 1450°, at a current of three amperes. The globule was about 4 mm. in diameter.

The relative brightness of different parts of the surface of the globule was observed by projecting an enlarged image of the globule onto the screen of a photometer, the other side of which was illuminated uniformly by an incandescent lamp. No estimate of the actual temperature by this method was attempted, because the emissivity of the oxids is not known. But it was evident that the surface temperature fell off considerably as the distance from the positive base increased, and as the current decreased, as was to be expected.

From these tests it is clear that in the neighborhood of the positive base the temperature is so high that it is impossible to conjecture what compounds may be present there. At the positive base itself the material may be reduced iron at all currents (except, of course, on the first stage). No conclusion as to the nature of the positive base can be drawn from an examination of the globule after it has cooled, for even in the absence of oxygen, as soon as the arc is put out, diffusion quickly removes all traces of the positive base. I tried quenching the globule suddenly with mercury on the instant of opening the switch in the arc circuit, but found that the globule flew to pieces on contact with the cold mercury.

§ 14. From the above considerations it is apparent that at any given current the compounds in the region immediately surrounding the positive base of the iron oxid arc are richer in oxygen than is the positive base itself. If the arc took place with the same ease from all these compounds, and from pure iron itself, there would be no tendency for the positive base to wander. In a preliminary communication,[1] the view was expressed that the positive base was more highly oxidized than the surrounding region, and that the cause of the rotations lay in a higher anode drop at this point. More recent experiments[2] have indicated, on the contrary, that the lower drop which seemed to be present when the anode was of metallic iron was due to the arc vapor rather than to the anode, and that in fact the arc takes place with greater ease from an oxidized anode. Hagenbach[3] has recently found the anode drop to be less from an oxidized anode than from the pure metal. Whether the tendency of the arc to burn from the oxids rather than from pure iron is due to a specific property of the oxids or to their lower boiling points cannot at present be determined. It is exceedingly difficult to obtain reliable values of the anode drop with an exploring electrode, owing to the small size and instability of the arc at the small currents in question.

It was found by Stark and Cassuto[3] that the anode drop in the arc increased with increasing temperature. If this is true of the iron oxid arc, it may furnish the reason why Hagenbach found the anode drop less from oxids.

The physical and chemical processes attending the progressive reduction and vaporization of the oxids may of themselves increase the ionization in the arc and thus lower the potential gradient.[4]

For these reasons, the following discussion is based on the hypothesis that the anode drop, owing to the reduction of the positive base, is somewhat higher than it would be if the arc could take place from the more oxidized surrounding region.

§ 15. It follows from the foregoing section that if the positive base chances to move slightly, the drop at its advancing edge is less than that over the rest of its surface, hence the motion continues along a more or less regular path.

The propelling force may be expressed thus:

$$F_1 = k_1(P - P'), \qquad (1)$$

where P is the value of the drop at the reduced positive base, P' that for the region immediately surrounding, and k_1 is a function of the current.

[1] Phys. Rev., 35, p. 77, 1912.
[2] Phys. Zeitschr., 14, p. 296, 1913.
[3] Hagenbach, Phys. Zeitschr., 12, p. 1019, 1911.
[4] Stark and Cassuto, Phys. Zeitschr., 5, p. 264, 1904.
[5] *Cf.* Child, Electric Arcs, New York, 1913, p. 181.

After the motion has become established, F_1 does not necessarily lie in the same direction as the velocity.

Herein lies the most reasonable explanation of the movement of the positive base. A similar view has been advanced by Wagner[1] to account for the irregular wandering at the cathode in the aluminum arc.

After the movement has once begun, the inrush of oxygen into the wake of the arc, combining with the reduced iron, may serve as an additional component of the propelling force.

§ 16. *The Production of Stable Rotations.*—The relations between the forces that control the rotations are shown in Fig. 5. In this figure O is the undisturbed position of the positive base, and Q its position at any time t. Then the movement of the base will be determined by the following forces: F_1 the propelling force, which makes an angle α with the radius vector produced; F_2 the central force (§ 17); and F_3 a resisting force which acts in a direction opposed to the element of path ds. F_3 arises partly from the resistance offered by the surrounding air to the motion of the column of vapor, partly from the fact that the advancing arc must raise the temperature of the positive base to vaporization. It must therefore increase as the velocity increases.

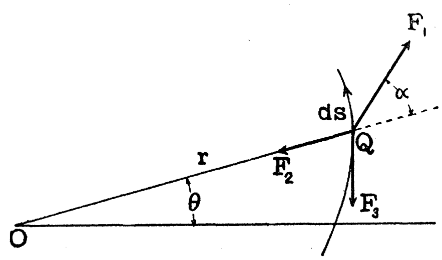

Fig. 5.

The equations of motion are as follows:

$$m\left[\frac{d^2r}{dt^2} - r\left(\frac{d\theta}{dt}\right)^2\right] = F_1 \cos\alpha - F_2 - F_3\frac{dr}{ds}, \tag{2}$$

$$m\left[\frac{1}{r}\frac{d}{dt}\left(r^2\frac{d\theta}{dt}\right)\right] = F_1 \sin\alpha - F_3\frac{rd\theta}{ds}. \tag{3}$$

From the nature of the phenomenon, it is impossible to express α as a simple function. Still it is certain that α tends to diminish as the distance $r = OQ$ decreases, for near the center the temperature is highest and the globule most reduced, hence that edge of the positive base that is farthest from the center will possess a lower anode drop than the nearer edge. This must tend to direct F_1 more strongly away from the center when r is small. The consequence of this will be to widen out the orbit into a circle. Thus if the positive base moves at all, *the motion must speedily resolve itself into a circular orbit with constant velocity.*

§ 17. In order to investigate the central force F_2, several series of

[1] Wagner, Der Lichtbogen als Wechselstromerzeuger, Leipzig, 1910, p. 90.

observations were made, in which the positive base of the arc was deflected by a magnetic field of known magnitude. Values of field intensity between 0.6 and 7 c.g.s. units were employed. The position of the negative base of the arc at the carbon cathode remained unchanged, the entire arc turning slightly around it as a center when the field was applied, keeping its form unaltered. In this way the stability of the arc against displacing forces could be studied, both when the rotations were present (in free air), and when they were absent (in absence of oxygen, see § 24). Since nearly the same magnetic deflections were obtained in each case, it seems fair to assume that in the rotations the positive base is subject to a restoring force, directed toward the center of the ring, obeying the same laws, at least qualitatively, as those derived from the magnetic experiments.

It is unnecessary to state the details of these experiments. As a result of them I found that for arc currents I between 2 and 4 amperes, and length l of arc from 3.5 to 9 mm., the restoring force F_2, expressed as a force in dynes acting on the positive base when the latter is displaced r cm. from its original position, is given approximately by the empirical equation

$$F_2 = \frac{Ilr}{(0.26l - 0.64) - (0.032l - 0.096)I}. \qquad (4)$$

For currents less than 2 amp., and also, curiously enough, for Type C, the value of F_2 is slightly larger than that derived from eq. (4). This equation is, moreover, not accurately applicable to the rotations, since in them only a part of the entire length of arc is affected, so that the effective value of l is not known. For the present paper it is enough to point out that F_2 varies directly as the radius, and hence as the diameter δ of the ring, and that it also increases as the current increases. For constant current and length, eq. (4) may be simplified thus:

$$F_2 = k_2\delta, \qquad (5)$$

in which k_2 is a constant.

§ 18. In what follows it will be assumed that the motion of the positive base has reached a steady state, the orbit being a circle of definite diameter and period, and the velocity being constant. The equations of motion (2) and (3), § 16, are now reduced to

$$-mr\left(\frac{d\theta}{dt}\right)^2 = F_1 \cos\alpha - F_2,$$

and

$$0 = F_1 \sin\alpha - F_3.$$

In the first of these equations we will put the normal acceleration a in place of $r(d\theta/dt)^2$, and then obtain with the aid of eq. (1), § 15:

$$a = \frac{F_2 - F_1 \cos\alpha}{m} = \frac{F_2 - k_1(P - P') \cos\alpha}{m}. \tag{6}$$

It has been shown that the retarding force F_3 increases with the velocity. If we write $F_3 = k_3 v$, we obtain from the second equation above:

$$v = \frac{F_1 \sin\alpha}{k_3} = \frac{k_1(P - P') \sin\alpha}{k_3}. \tag{7}$$

Since $F_1 \cos\alpha$ is finite, while F_2 is a central force varying directly as the distance, it is clear that the condition for stable circular motion is satisfied.

§ 19. The four types of rotation may now be studied in the light of equations (6) and (7). In Fig. 2 were shown the changes in frequency f and diameter δ of the rings with increasing current. From these, the curves in the lower part of Fig. 2 have been constructed, showing the linear velocity and normal acceleration. The values of v and a were derived from the equations

$$v = \pi\delta f$$

and

$$a = 2\pi^2 f^2 \delta.$$

The most striking conclusion to be drawn from the curves is, that the changes from ring to ring are due almost entirely to changes in normal acceleration. The linear velocity remains remarkably constant throughout.

For Types A, B and D, the observed decrease in a as the current increases may be ascribed to the increase in the mass m, though it must be remembered that F_2, k_1 and k_3 also are functions of the current.

Let us consider the transitions from one type of rotation to the next. On passing from Type A to Type B, a increases and δ decreases, hence F_2 decreases (eq. 5, § 17), and $F_1 \cos\alpha$ decreases *à fortiori* (eq. 6). Since at the same time v increases slightly (Fig. 2), it must be that α increases also (eq. 7). Thus in Type B the propelling force would seem to be less than in Type A, and to be directed more nearly parallel with the path. The decrease in F_1 must be due to an increase in P', the anode drop characteristic of the region surrounding the positive base. In other words, a modification in the composition of the oxid occurs here.

Between Types B and C, a decreases and δ increases, hence F_2 increases, as does also $F_1 \cos\alpha$. Unless the resisting force F_3 were greatly changed, this would be expected to make v increase. Instead, v is diminished, indicating a decrease in the value of α. In Type C, therefore, the propelling force F_1 seems to be very large and to have a pronounced radial component.

§ 20. Type C, while the most conspicuous when it appears, is also the most puzzling. It ceases altogether in an atmosphere of illuminating gas or of nitrogen, though the other types persist until the reduction of the oxid proceeds too far for their continuance. Free oxygen in the gas around the arc seems essential to the existence of Type C. Possibly at a certain critical temperature there is a sudden inrush of oxygen around the base of the arc, lowering the drop in the region close to the positive base and thus greatly increasing F_1 (cf. § 24). A further increase in current may bring about a more complete reduction of this surrounding region, so that the original condition is restored. This will have to remain mere conjecture until more is known of the oxids of iron at high temperatures. At any rate, the agitated appearance of the arc during Type C is favorable to such an hypothesis.

A careful examination of the spectrum of the arc before, during and after the appearance of Ring C failed to reveal any changes in the prominent lines of iron, oxygen, carbon, or nitrogen other than a gradual brightening as the current increased.

The cause of the changes in Ring C with increasing current seems to be essentially the same as for Ring A.

§ 21. Type D would appear to be a continuation of Type B if it were not for Type C. Indeed, it may be, as suggested above, that Type C is interjected in the midst of a single type of rotations to which both B and D belong. Type D seems governed by the same laws as Type B. The lack of agreement in the values of v in Fig. 2 results chiefly from the difficulty in determining the diameter. The rings are so minute that measurements on the photographic film were very difficult.

§ 22. *Lengthening the arc* from 3 to 6 mm. causes the frequency of Type C to decrease from 5 to 10 per cent., that of Type A to decrease at a somewhat greater rate. A dependence of the frequency of Types B and D upon the length has not been determined.

The change in frequency follows directly from the observed decrease in F_2 as the length increases (eq. 4, § 17). The fact that the dependence of frequency upon length is slighter than would be expected from eq. 4 is added evidence that only a part of the entire length of arc is affected by the oscillations.

Reference has been made (§ 7) to the cessation of the rotations at about five amperes. This takes place somewhat abruptly, the diameter of Ring D increasing not only up to 3 amp., as shown in Fig. 2, but beyond this: as long as the positive base continues in motion, the amplitude of its movement increases, although the form of the ring becomes indistinguishable between 3 and 4 amp. It may be that the positive base is surrounded with a zone of reduced iron which increases in width as the current increases. As long as the current is not too large, the positive base pushes across this zone on one side, and the movement is maintained. But at a certain critical current, in this case about 5 amp., the reduced zone attains such a width that the positive base fails to cross it any longer. The rotations then immediately cease, except for a few last convulsive movements that can generally be observed.

§ 23. *Conditions at the Cathode.*—When the cathode consists of a globule of iron oxid, no rotations are ever observed except when the arc is so short that the negative base is influenced directly by the rotations at the anode. One would suppose from Wehnelt's investigations that the cathode drop must be lowered at least as much as the anode drop by the presence of oxid. It may be, however, that even at small currents the cathode temperature is so high that a zone surrounding the negative base is reduced to the same degree as the negative base itself. The fact that the negative terminal of the iron arc always wastes away much faster than the positive is in agreement with this hypothesis.

There is also a quite different possibility that ought not to be disregarded, if it is true of iron oxid[1] as it is known to be true of certain other oxids in the molten state, that the substance conducts electrolytically. For in this case, as the current passes through the molten negative globule, there must be a transfer of oxygen ions to the negative base of the arc. The amount of oxygen liberated in this way by purely electrolytic conduction would amount, if two amperes flowed for five minutes, to 0.05 gram. Hence if the conduction is to any considerable degree electrolytic, there may well be a sufficient supply of oxygen near the negative base of the arc, to hold the cathode drop at a minimum value. No data are at present available for deciding between these two hypotheses.

At the anode, on the other hand, the contrary would take place if the oxid conducted electrolytically. The positive base would become depleted of its oxygen, thus increasing the reduction of the iron, and raising the anode drop.

Observations with Other Gases and Anode Metals.

§ 24. *Effect of Reducing the Amount of Oxygen in the Gas Around the Arc.*—The arc burned in air at atmospheric pressure, but the front of the

[1] Rasch, Phys. Zeitschr., 5, p. 375, 1904.

tube was closed by a glass window so that the oxygen gradually became exhausted, chiefly by combination with the carbon that served as cathode. The following changes took place:

All four types of rotation came at *larger* currents than usual. This was probably due in part at least to the fact that the globule was cooler and less plastic than in free air, and the positive base less concentrated, thus requiring a greater current to produce the conditions necessary for rotations. As the reduction proceeded, Type C was the first to cease, then Type A, while Types B and D seemed to merge together. Then for a time only Type D existed, continuing up to a current of about ten amperes; and after prolonged burning, the globule was so far reduced that no rotations whatever could be detected.

These facts all agree with the theory that the rotations are due to different oxids, and that Type D represents the oxid of lowest oxygen content.

Opposite effects were produced when a current of oxygen was allowed to play gently around the arc in air. The appearance of Type C came at a *smaller* current, for example, than under normal conditions.

Observations of magnetic deflections (§ 17) in air deficient in oxygen showed that the central force F_2 is of approximately the same magnitude when the oxygen is exhausted and no rotations are present, as in normal air.

§ 25. *Observations in Air at Reduced Pressure.*—The discharge tube was connected to a water aspirator, and observations made at various pressures between atmospheric and 420 mm. of mercury. In order to keep up the supply of oxygen, a slow current of air was allowed to be drawn through the tube, the rate of flow being so regulated as to hold the pressure at the desired value. In spite of this, the globule became somewhat reduced, so that the observed changes were in part due to lack of sufficient oxygen.

The changes observed with Types A, B and D were practically the same as at atmospheric pressure with deficient supply of oxygen, and the same reasoning is doubtless applicable to this case also. Type C on the other hand behaves quite differently. A decrease in pressure is followed instantly by a lowering of the pitch. A larger and larger current is required to introduce Type C, until at 420 mm. the current is 4.5 amp., frequency 385 (the lowest I have recorded), and diameter of ring is greatly increased. The normal acceleration is evidently greatly diminished at reduced pressure.

This is the more surprising, since there is evidence from magnetic observations at low pressure that the central force F_2 *increases* slightly as the pressure is lowered. It must be that the outwardly directed component of the propelling force increases greatly as the pressure decreases.

One would expect that a reduction of the gas pressure would lower the temperature of dissociation of the oxids, and thus cause the rotations to come at a smaller current. Thus Walden[1] finds that the dissociation temperature of Fe_3O_4 is about thirty degrees lower at 420 mm. than at atmospheric pressure. On the other hand, we must remember that at low pressure the globule is cooler, the positive base more diffuse, and that the positive drop is probably less than at atmospheric pressure.[2]

§ 26. *Tests with Other Metals.*—In conclusion, brief mention may be made of attempts to obtain the rotations with anodes of other materials than iron oxid. Only those substances were used that form fairly regular liquid globules. In most cases the cathode consisted of carbon. The anode was either in the form of a rod, or a pellet resting on a carbon holder.

Nickel.—After the anode had become oxidized, the positive base of the arc showed much agitation at currents between 2 and 5 amp. No ring could be seen, but the rotating mirror revealed irregular periodic movements of frequency ranging between 400 and 4,000. As in the case of Type D of the iron arc rotations, the frequency became less as the current increased.

In the neighborhood of 1.4 amp., the arc from a nickel oxide anode presents an extraordinary appearance. Two or three arcs seem to spring into being, all moving rapidly about, while in the telephone (§ 3) a strange medley of musical notes, covering a range of two octaves, is heard.

Cobalt.—Between 1.4 and 1.75 amp. the positive base is agitated and a soft shrill whistle can at times be heard. The rotating mirror shows irregular groups of waves of about the same size as those in Type C of the iron arc. The anode was always oxidized.

These facts all point to processes in the nickel and cobalt arcs similar to those in the iron arc, though the globule at the anode is evidently too little homogeneous, or conditions are otherwise too unfavorable, for the formation of steady rotations.

Copper.—No periodic movement of the positive base could be detected, though the arc often moved about irregularly, as is the case with any arc at small currents. When the copper oxid anode is in the form of a bead resting on a carbon holder, it often falls into a condition like the spheroidal state, owing to imperfect thermal contact with the carbon. At such

[1] Walden, Jour. Amer. Chem. Soc., 30, p. 1350, 1908.

[2] Cf. Child, this journal, 19, p. 129, 1904.

times a faint humming note is sometimes heard. Still, there is no evidence that at the anode of the copper oxid arc there are forces of the same nature as those in the case of iron.

Silver.—Though the silver does not oxidize, its behavior on a carbon holder is much like that of copper oxid. The positive base moves about continually, but its motion is comparatively slow, and there is absolutely no sign of such forces as produce the rotations.

Tin.—A white, fleecy oxid soon forms in air, but the arc prefers to burn from the molten metal rather than from this oxid, and there is no sign of any unusual movement.

Mercury.—The carbon cathode became red hot, even with a current as low as 0.5 ampere. The positive base seemed quite stationary, the arc burning from the metal, not from the oxid that formed; then after a few seconds it sprang suddenly to a new position on the surface of the mercury, and kept this process up at intervals as long as the arc burned. A high-pitched note was often heard. The arc formed a narrow column of vapor at right angles to the mercury surface, extending almost to the cathode, where it bent abruptly and continued for a short distance almost parallel to the surface of the cathode, finally ending at a bright spot on the carbon. This is mentioned because, whenever the note was heard, the vapor in the neighborhood of the *cathode* seemed agitated, as if the sound proceeded from it rather than from the anode.

From these experiments it seems clear that forces at the anode of the arc, tending to keep the positive base in a circular motion, are possible only when the anode consists of certain metallic oxids in a smooth and molten state.

My thanks are due to Messrs. A. C. Stevens, H. P. Frost and F. H. Frame, by whom many of the observations recorded above were obtained.

Summary.

The arc in air from an oxidized iron anode exhibits, under normal conditions, four types of rotation, which are called for convenience Types A, B, C and D. They occur in succession as the current is increased from about 1.5 to 2.5 amp., though Type D generally lasts up to about 5 amp. The characteristic features of each type, including its frequency, amplitude, and appearance, are described, and photographic records of the movements at the anode, together with the accompanying fluctuations in voltage and current, are shown.

Reasons are given for believing that these rotations owe their existence to a difference between the potential drop at the positive base of the arc and that characteristic of the surrounding region. At the positive base,

the oxid is more reduced and the potential drop is therefore greater; the high temperature probably enhances the effect still further.

In §§ 15 and 16 the conditions for the production of stable rotations are discussed, and in § 18 equations of motion of the positive base are derived. A comparison of these equations with the observed data throws some light on the nature of the forces acting on the arc. A more complete discussion of the dynamics of the rotations cannot be carried out, owing to the impossibility of securing sufficient data. The very high temperature of the arc makes it impossible to determine what oxids are at or near the positive base.

Observations with other metals and in other gases tend in the main to confirm the conclusions reached with iron oxid. Oxids of nickel and cobalt show some evidence of forces similar to those in the iron arc.

In conclusion, a word may be said concerning the proposal made at the recent conference of the International Union for Coöperation in Solar Research, that for the production of reference spectra of wave-length less than 4,000, the iron arc with a current of four amperes or less be used. As we have seen, at all currents less than five, rotations of some one of the four types generally occur when the iron arc burns in air. As the discharge passes from one type to the next, one would not expect the slight changes in the oxid at the anode to have any effect on the spectrum of the iron vapor. The writer, using a grating of medium resolving power, could not visually detect any characteristic change in the spectrum when the arc passed through Type C. Still, it would seem desirable, before adopting as standard the iron arc at small currents, to be quite sure on this point. Moreover, the fact that a part of the column of vapor is in motion during the rotations makes it somewhat difficult to use any restricted portion of the arc as source of light. This is especially true when the current lies between 2 and 2.5 amperes (Type C). By letting the arc burn in a gas that is sufficiently deficient in oxygen, however, the rotations can be entirely eliminated (§ 24).

Scott Physical Laboratory,
Wesleyan University.

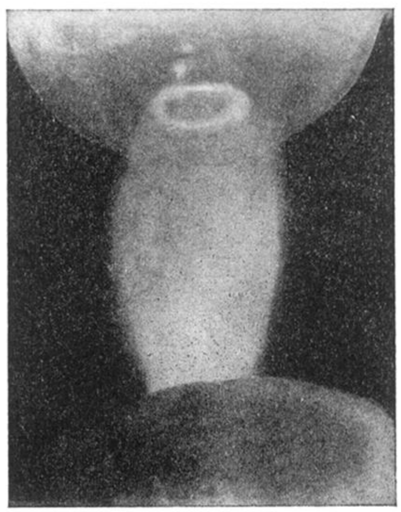

Fig. 4.

Iron arc rotations, Type C. Below: Carbon cathode. Above: Iron oxide anode. Current, 2.12 amp. Diameter of ring, 0.91 mm.