THE SILENT AND HISSING D.C. ELECTRIC ARC

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Summary

The d.c. electric arcs between graphite, iron, and copper electrodes exhibit a sudden discontinuity in their volt-ampere curves. The acoustic noise emitted on the high current side of the discontinuity is much louder than on the low current side, and the two modes of arc operation are called the "silent" and "hissing" forms.

The hissing of the arcs may be either an anode *or* cathode phenomenon. Hissing of the graphite arc is brought about by oxidation effects at the anode. Hissing of the metal arcs is caused by the boiling of one of the electrodes.

Noise and voltage oscillations across the arc are correlated and are intimately connected with the formation of vapour jets at the electrodes.

I. Introduction

As early as 1895, Mrs. Ayrton (1902) observed that the d.c. carbon arc had two distinct forms. She found the first or silent form occurred with low currents and in passing to the second form the arc emitted a hissing noise and there was a sudden drop in voltage across the arc.

The iron arc has been observed to behave in a similar fashion (Finkelnburg 1913; Baker 1954). They observed that the silent stage occurred with small currents and high voltages, while the hissing stage occurred with higher currents and lower voltages. The transition between the two forms was marked by a quite sudden change in the intensity of the noise emitted by the arc. Baker (1954) reported that the copper arc did not exhibit this dual nature.

Ayrton's (1902) explanation of the mechanism involved in the carbon arc is unsatisfactory, while no explanation has been advanced to explain the silent-hissing behaviour of the iron arc.

The present study extends the observations of Ayrton and Baker and introduces some new features of the phenomenon. The first part of the paper deals with the experimental observations; the second part considers a proposed explanation.

II. Experimental Observations

(*a*) *Experimental Methods*

The major part of the experimental work was carried out with a drawn d.c. arc between the various electrodes. The power was supplied by heavy-duty batteries (150 V), and a large inductance was included in the supply line. A battery charger could be run in series with the batteries, giving an available d.c. supply of 300 V.

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(b) *Volt-Ampere Curves*

(i) *Carbon.*—Figure 1 shows the discontinuity of about 10 V in the volt-ampere curve for graphite electrodes for an electrode separation of 5 mm.

(ii) *Iron.*—Figure 2 shows the volt-ampere curves for iron electrodes at various electrode separations. No hysteresis effect was observed, although the arc is somewhat unstable in the transition region, making accurate readings difficult to obtain.

As far as could be determined in the literature, carbon and iron are the only electrode materials for which the silent-hissing phenomenon has been observed. The possibility that the hissing of the iron arc may be due to the carbon content of the

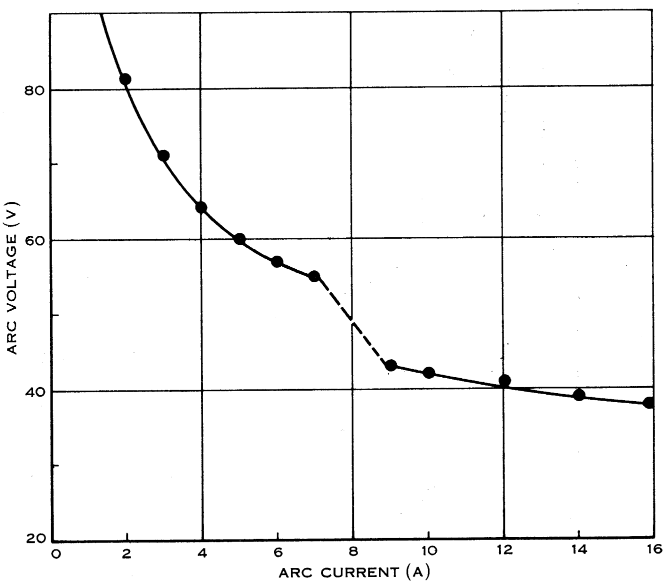

Fig. 1.—Volt-ampere curves for graphite electrodes with an electrode separation of 5 mm.

iron electrodes was investigated. The arc was run with electrodes of varying carbon content and also with spectrographically pure iron electrodes. No differences in the volt-ampere curves was detected, so the hissing of the iron arc is not associated with carbon content of the electrodes.

(iii) *Copper.*—The copper arc was examined in the current range 0.5–20 A and no discontinuity in the volt-ampere curve was observed. Generally speaking, the properties of iron and copper arcs in air are very similar, both being cold-cathode arcs. Thus there arose the puzzling question of why the iron arc should exhibit the silent-hissing phenomenon whereas the copper arc apparently did not. The audio noise emitted by the copper arc sounds very similar to that emitted by the iron arc in the hissing form, so it was suspected that if a silent form of the copper arc did exist, then it must be at lower currents. Below 0.5 A, however, the arc was unstable and would not maintain itself.

If the arc was protected from surrounding air currents by enclosing it by a quartz tube it was found the arc could be maintained down to 0.25 A. It was in this low current region that a silent form of the copper arc was observed. The volt-ampere curve for the enclosed arc is shown in Figure 3. This explains why Baker (1954) failed to observe a silent form of the copper arc, as his investigation only considered currents down to 0.7 A. The audio transition from the hissing to the silent form was quite marked, though not as pronounced as for the iron arc.

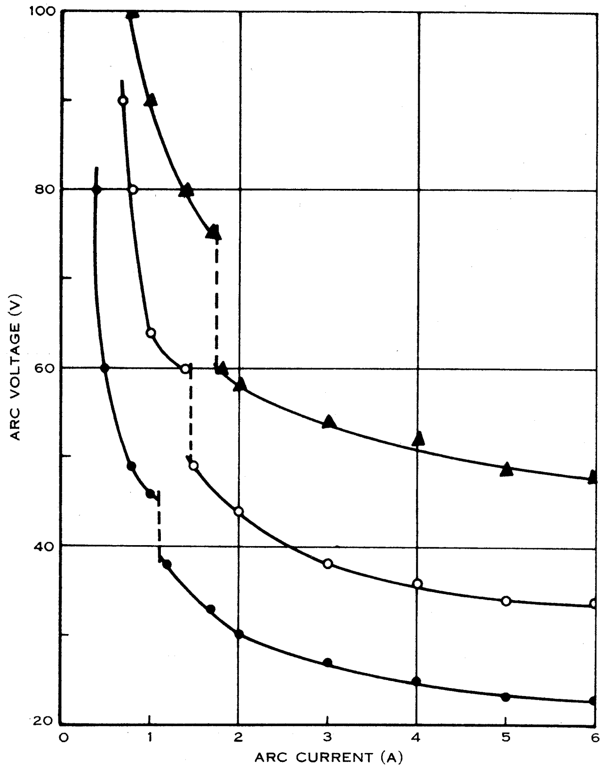

Fig. 2.—Volt-ampere curves for iron electrodes. ● Electrode separation 1 mm, ○ electrode separation 3 mm, ▲ electrode separation 6 mm.

(c) *Properties associated with the Discontinuity*

(i) *Critical Resistance.*—There is a critical resistance R_c, defined as the arc resistance V/I just before the transition from the silent to the hissing form. R_c was found to be independent of electrode separation and to have the values of 8 ohms for graphite, 47 ohms for iron, and 175 ohms for copper.

(ii) *Critical Current.*—If the current at the discontinuity is plotted against electrode separation, a linear relation is obtained. This is shown in Figure 4.

(iii) *Magnitude of the Voltage Discontinuity.*—Because the arc is unstable at the discontinuity, the exact magnitude of the voltage discontinuity is difficult to determine with any accuracy. Suffice to say it increases with increasing electrode separation, as can be seen from Figure 2.

(*d*) *Arcs in a Nitrogen Atmosphere*

The volt-ampere curves for the iron and copper arcs in a non-oxidizing (nitrogen) atmosphere still exhibit the discontinuity. That is, they still exhibit the silent

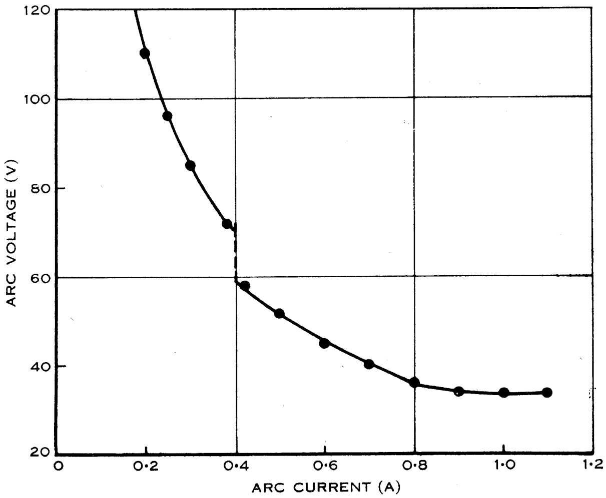

Fig. 3.—Volt-ampere curve for an enclosed copper arc with electrode separation approximately 1 mm.

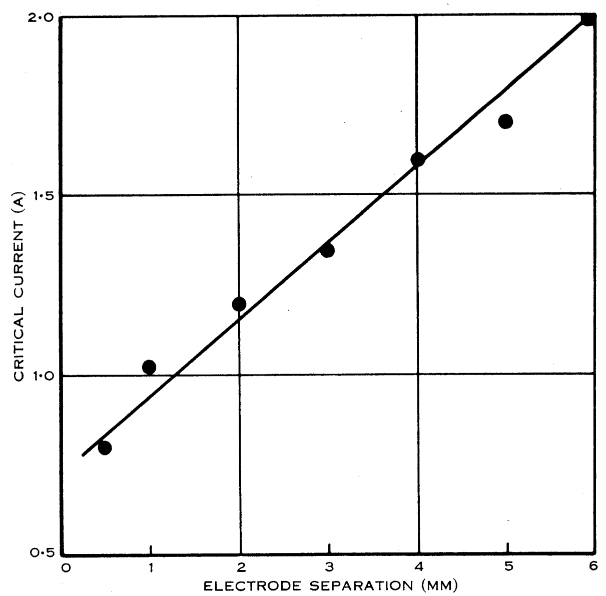

Fig. 4.—Critical current for the iron arc.

and hissing forms. The discontinuity is entirely absent from the graphite curve, however, and the graphite arc stays in the silent form for all currents.

Thus it seems reasonable to conclude that the mechanism involved in the hissing of the graphite and metal arcs is not the same; the hissing of the graphite arc is associated with some oxidation process while the hissing of the metal arcs is not dependent on oxidation effects.

(e) *Current Density at the Arc Electrodes*

Estimates of the current density at the cathode of cold-cathode arcs give densities of the order of 10^5 to 10^6 A/cm^2 (Cobine and Gallagher 1947; Somerville and Blevin 1949). Observations of the area of the electrode terminations suggest that the anode current densities may be an order of magnitude less than this. For the graphite arc in the silent form the cathode current density is about 450 A/cm^2 and the anode current density 60 A/cm^2.

(f) *Arc Temperatures*

At present there is a lack of agreement between published values of temperature for similar arc plasmas. The temperature of the plasma is of interest here because any difference in temperature between the silent and hissing forms of the metal arcs may be important in explaining the phenomenon.

Both theoretical and experimental considerations favour the measurement of the temperature of such plasmas from the intensity ratio of emitted lines. The theory is well known, so it will not be treated here. Line intensity ratios were measured by photographic photometry using the stepped sector technique for plate calibration. Standard methods for background correction were employed.

For the iron arc the lines 4147, 4325, and 4422 Å were used and the latest gf values quoted by Hefferlin (1959). The 5153 and 5700 Å copper lines were used. A number of temperature determinations was made and probable errors from all sources estimated. The following temperatures were thus determined:

$$T_{\mathrm{Fe}}\ (\text{silent}) = (4250 \pm 150)\ ^{\circ}\mathrm{K},\ \text{current} = 1\ \mathrm{A}$$

$$T_{\mathrm{Fe}}\ (\text{hissing}) = (4150 \pm 100)\ ^{\circ}\mathrm{K},\ \text{current} = 4\ \mathrm{A}$$

$$T_{\mathrm{Cu}}\ (\text{hissing}) = (5150 \pm 200)\ ^{\circ}\mathrm{K},\ \text{current} = 4\ \mathrm{A}.$$

(The silent copper arc could not be maintained long enough to obtain a usable plate with the fairly high dispersion of the spectrum required.)

Hence nothing definite can be said as to whether the silent and hissing iron arcs differ in temperature. The slightly lower value obtained for the hissing arc could be due to self-absorption. The shapes of the two forms of the arc are shown in Figure 5. The hissing arc is much wider, so there would be a greater diminution in the measured intensity because of self-absorption. Such absorption results in lines whose shape looks normal but in reality have a lower maximum value and a shape less peaked than they should have. Alternatively, the observed temperature difference could be a real difference and due to one of the electrodes boiling when the arc is in the hissing form (see Section III). The electrode vapour would be at a lower temperature than the plasma and would tend to cool the plasma.

(*g*) *Observations of the Electrodes*

(i) *Carbon*.—When the arc is silent, the discharge is between the hot-spots on the ends of the electrodes, these spots being less than the electrode diameter. As current is increased, the anode hot-spot increases in diameter until it covers the whole area of the electrode. If current is increased still further, the anode arc termination spreads around the sides of the anode and the arc changes to the hissing form. Associated with the transition is a contraction of the arc at the anode. The current density just before the transition is 60 A/cm^2.

(ii) *Iron*.—The only visible change in the appearance of the iron arc when hissing sets in is that the width of the plasma increases and the molten metal of the cathode hot-spot appears to become more liquid, suggesting that the cathode of the iron arc may start to boil at the silent-hissing transition. Hence the change in weight of

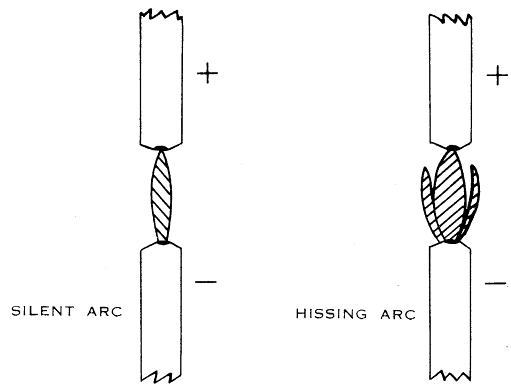

Fig. 5.—General shapes of the silent and hissing iron arcs.

electrodes in the silent and hissing forms was determined. The net rate of transfer in the silent form was 1.1×10^{-5} g/coulomb from the cathode to the anode. This rate increased to 2.3×10^{-5} g/coulomb in the hissing form. (Allowance was made for mass transfer from anode to cathode by positive ions.)

Plate 1 shows the anode and cathode of a hissing arc after it had been burning for some time, compared with the original. The smooth, hollowed-out surface of the cathode suggests that the cathode material boils off at an even rate, while the rough surface of the anode corresponds to the cathode vapour impinging on it.

This suggests that in the silent form of the arc, both anode and cathode hot-spot temperatures are below the boiling point of iron, and at the transition to the hissing form the cathode starts to boil.

(*h*) *Noise and Voltage Fluctuations in the Arc*

(i) *Iron*.—As far as could be determined, the only work done on the audio noise emitted by an arc is that of Baker (1954), who concluded that the noise emitted is closely related to the small oscillations in the arc voltage. These voltage oscillations are present in both the silent and hissing forms, even though the power is supplied by a steady d.c. battery source. At the transition from the silent to the hissing form there is an abrupt change in the mean magnitude of these voltage oscillations, as shown in Figure 6 for a 1-mm iron arc.

To examine the relationship between audio and voltage oscillations a microphone was placed near the arc and the hiss amplified and observed on one channel of a double-beam oscilloscope. The voltage across the arc was fed through a low-pass filter with the same frequency response as the combined microphone and audio amplifier and then examined on the other channel of the oscilloscope. Typical oscillograms are shown on Plate 2.

Before comparison of the oscillograms, allowance was made for a lag in the noise oscillogram due to the finite velocity of sound in air and the mechanical delay of the microphone. This resulted in the noise oscillograms in Plate 2 having to be moved forward with respect to the voltage oscillograms. The oscillograms were then

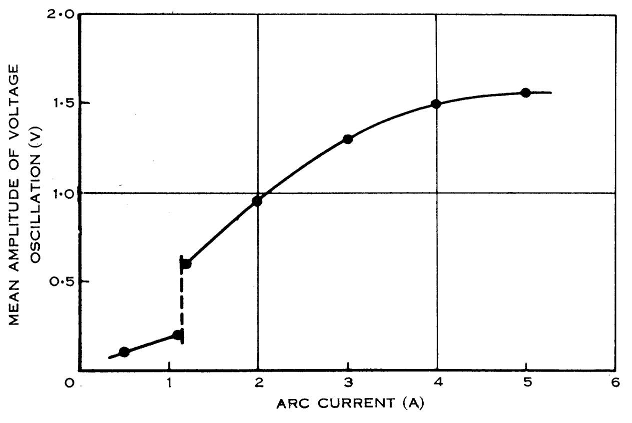

Fig. 6.—Mean amplitude of voltage oscillations across a 1-mm iron arc.

examined to see if peaks in the noise oscillogram corresponded to peaks in the voltage oscillogram. A statistical analysis of a number of such oscillograms revealed a strong correlation, indicating a close connection between electrical and noise phenomena. The correlation appeared to be slightly better when the arc was in the silent form. (Occasionally strong peaks were observed in the noise oscillogram with no corresponding peak in the voltage oscillogram. These are most likely caused by sputtering of the electrode material or by external sources.)

(ii) *Carbon*.—The silent form of the graphite arc is much "more silent" than the silent forms of the metal arcs, and no noise is detected by the microphone nor are voltage fluctuations associated with it. The hissing form shows somewhat similar noise and voltage oscillograms to those of the iron arc. There appears to be some correlation between the two oscillograms, though the correlation is by no means as good as with the iron arc.

(iii) *Frequency Spectra*.—Tape recordings were made of the noise emitted by the various arcs and these were subsequently analysed on a wave analyser, resulting in the frequency spectra shown in Figure 7. The response curve of the microphone and recorder was flat up to 12 kc/s.

The silent and hissing forms of the iron arc show the same frequency components, the only difference being in the amplitudes. The dominant frequency band is from 6 to 10 kc/s. The dominant frequency band of the hissing copper arc is about 8–12 kc/s. (The silent copper arc always had to be enclosed, so no frequency spectrum could be obtained.) The hissing graphite arc had a dominant band from 7 to 12 kc/s. (The graphite arc was recorded at a lower recording level than the metal arcs. Actual intensities are of no interest here, however, the spectral composition of the hiss being the point of interest.)

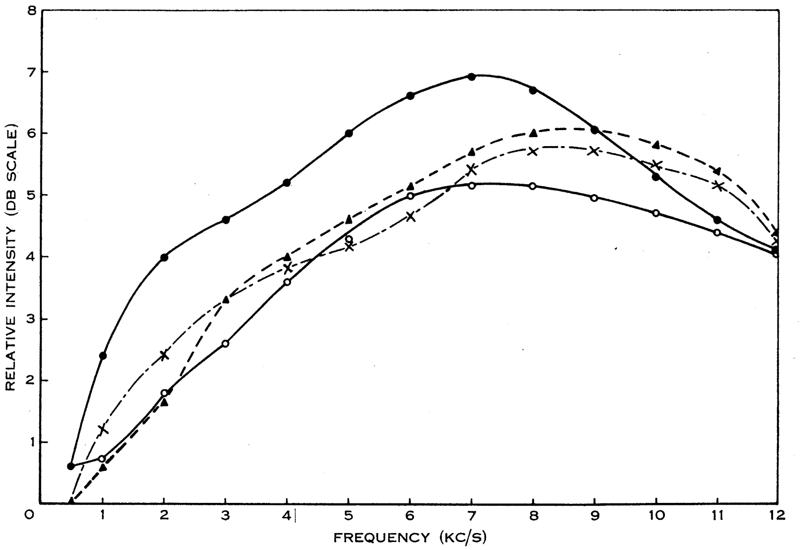

Fig. 7.—Frequency spectra.
○ Silent iron arc, ● hissing iron arc,
× hissing copper arc, ▲ hissing graphite arc.

III. A Proposed Explanation

(a) *The Carbon Arc*

Ayrton (1902) said that the hissing of the carbon arc was due to oxidation processes and that oxidation took place because of an increase in area of the anode termination, allowing oxygen to come into contact with the hot carbon. She said that the resultant chemical action caused a sudden decrease in the voltage and corresponding increase in the current (though no explanation is given as to why this should be so). This increase in current then drives the air away from the anode and these current fluctuations, causing alternate compressions and rarefactions of the air near the anode surface, produce sound waves resulting in the hiss of the arc.

Basically, Mrs. Ayrton's explanation is correct but the mechanisms have not been investigated. When the arc termination spreads to the electrode sides, oxygen reacts with the hot carbon, the reaction itself probably causing a good deal of noise at the temperatures involved. The reaction between carbon and oxygen to form carbon dioxide is exothermic, giving out 94 kcal/mole. This heat may cause vaporization of some of the electrode carbon, and sudden bursts of vapour given off in this way could conceivably contribute to the hissing noise.

It is thought that this sudden source of extra heat is responsible for the voltage drop of the volt-ampere curve. Bez and Höcker (1954) see the transition from the low current carbon arc with low anode current density (the silent form) to the contracted high current arc (the hissing form) as a transition from field to thermal ionization at the anode. (See Somerville (1959) for a treatment of field and thermal ionization.) Thermal ionization is associated with a *small* anode fall in potential over a long distance, while field ionization is associated with a *larger* anode fall in potential over a shorter distance. The present author suggests that the sudden source of heat from oxidation processes is sufficient to cause the transition from field to thermal ionization, resulting in the observed voltage drop of approximately 10 V.

Bez and Höcker (1954) suggest that thermal ionization takes place at the centre of the plasma while field ionization takes place at the cooler periphery. The consequent potential distribution will tend to drive electrons towards the axis and constrict the arc. This constriction is unstable and the anode termination oscillates between the micro-burning and macro-burning spot. Vaporization takes place at the micro-burning spot.

This vaporization undoubtedly takes place in the form of vapour jets — such jets have been observed at the anode of the carbon arc by Finkelnburg (1948). As would be expected there are no corresponding jets at the cathode. It is thought that it is the emission of these vapour jets that is mainly responsible for the hissing noise emitted by the carbon arc. Such jets would set up vortex effects at the anode. Vortex theory shows that the frequency of the expected noise is given by

$$f = Kv/D,$$

where f is the frequency, v the velocity of the jet, D the width of the constriction through which the jet is emitted, and K a constant.

Haynes (1948) found that initial jet velocities from metal electrodes have an initial velocity range of $\pm 12\%$. If this range is assumed for the carbon arc jets, then the observed range of frequencies recorded in the hiss (500–1200 c/s) can only be explained by a range in D, the diameter of the constriction of the plasma at the electrode. A range in the value of D by a factor of 25 is required to explain the observed frequency spectrum. Bez and Höcker have in fact observed micro-burning spots with diameters up to 1/35 of the normal diameter.

The electron motion causing the anode termination oscillation is thought to cause the current and voltage oscillations when the arc is in the hissing form. As this electron motion also results in the emission of vapour jets, which in turn result in the hissing noise, some correlation would be expected between noise and voltage oscillations. As mentioned previously, such correlation is observed, although it is not as pronounced as for the iron arc. Factors that could upset the correlation include noise caused by normal, "non-jet" evaporation, noise caused by spurting of the electrode material, and voltage oscillations caused by wandering of individual plasma streamers.

(b) *The Iron Arc*

The iron arc exhibits the silent-hissing phenomenon in a nitrogen atmosphere, so it is not associated with oxidation. Comparisons of oscillograms of noise and voltage fluctuations and of the frequency spectra suggest that the same processes are involved in each case, the silent-hissing transition being associated with a change in magnitude of the process(es). The definite correlation of noise and voltage oscillations of the arc in both the silent and hissing forms suggests that each fluctuation in the noise and voltage oscillograms is associated with some discrete process in the arc or at the arc electrodes.

The increase in the evaporation rate of the cathode at the silent-hissing transition suggests that the hissing is due to increased evaporation, while the argument of the previous paragraph results in the conclusion that the evaporation takes place by the vaporization of discrete amounts of electrode material.

It seems highly likely that this discrete vaporization takes place by *vapour jets* ejected from the electrode surface. Such vapour jets have been noted by other workers, especially in high-current-density arcs. They have been detected by high speed photography, by reaction pressure on electrodes, and by the pressure exerted on a light vane suspended in front of the electrodes. The main work on the subject is that of Haynes (1948) and Finkelnburg (1948). Somerville (1959) has summarized the main properties of these jets:

(i) Jets have been observed over a wide range of electrode materials, including carbon, copper, and iron.

(ii) They are directed normally to the electrode surface and are often in the form of sharply defined beams.

(iii) They occur with high current densities; jet velocity usually increasing with current density.

(iv) In arcs with metallic electrodes, jets usually appear at both anode and cathode, velocities being of the order of 10^5 cm/s, that of the anode jet often being the higher.

(v) In high current carbon arcs, there may or may not be electrode jets, depending on the current density. With wide electrodes no jets appear, but, if the area of the electrode spot is made small, jets appear whose velocities are of the order of 10^3 cm/s.

Finkelnburg (1948) and Haynes (1948) developed theories of jet formation, but these theories gave no satisfactory account of the sharpness with which the jets are often defined. Maecker (1955) seems to have solved the problem of their origin. He shows how they arise from compressive forces exerted on the arc by its own magnetic field. For a given total current, these forces give rise to a pressure that increases with current density. When a constriction exists at an electrode, the pressure will be greater at the place of high current density near the electrode than in the column. Consequently a pressure gradient exists normal to and directed away from the electrode surface and this drives the jets. Vaporization is not a necessary condition for jet formation. Maecker derived for the velocity of the jets

$$v^2_{\text{max.}} = 2I^2/\pi\bar{\rho}r^2,$$

where $v_{\max.}$ is the initial velocity of the jet near the electrode, I is the current, $\bar{\rho}$ the mean density of the gas or vapour between the electrode and the column, and r the radius of the electrode spot.

The continual emission of these high speed jets (velocities greater than sound) would result in the continual creation of shock waves in the plasma, resulting in the audible noise emitted by the arc in both the silent and hissing forms.

The measured loss in weight of the electrodes is consistent with the jets being emitted when the arc is in both the silent and hissing forms. At the transition the cathode boiling would facilitate the formation of the cathode jets. Probably the size of the jets emitted would increase. No doubt normal "non-jet" evaporation also increases.

These vapour jets would give rise to the observed voltage oscillations. The sudden injection of a jet of metallic vapour into the arc plasma would result in a momentary fall in the voltage across the arc. At the same time there would be a peak in the noise oscillogram.

The boiling of the cathode will greatly increase the concentration of metallic vapour in the arc. This metallic vapour is more readily ionizable than the gas atoms, so the voltage required to maintain the arc will fall, resulting in the observed discontinuity in the volt-ampere curves.

(c) *The Copper Arc*

The copper and iron arcs are both cold-cathode arcs. The ionization potentials of copper and iron are 7.7 eV and 7.9 eV respectively. Also, current densities are very similar in the two arcs. Hence, as might be expected, the behaviour of the two arcs is very similar and the theory of the last section for the iron arc applies equally to the copper arc.

The main difference between the electrode materials is that copper has a lower boiling point, specific heat, and latent heat of vaporization than iron. Hence one would expect that under similar conditions the cathode of the copper arc would boil at a lower arc current than for the iron arc. This is in fact the case as shown by the lower critical current for copper for silent-hissing transition (see Fig. 3).

IV. Anode or Cathode Phenomenon

Finkelnburg (1913) deduced that the hissing of the iron and carbon arcs was an *anode* phenomenon. He ran an arc with a carbon anode and iron cathode, and then with an iron anode and carbon cathode. In the former case the discontinuity corresponded to the critical current previously associated with the carbon arc, while in the latter case the discontinuity corresponded to the critical current previously associated with the iron arc. This experiment is misleading, however, and in fact the hissing may be an anode *or* cathode phenomenon.

Consider Finkelnburg's experiment in more detail:

(i) *Carbon Anode, Iron Cathode.*—As the current is increased, anode termination increases in area until it covers the whole electrode area. A further increase in current will cause the critical current density for carbon to be exceeded and hissing will set in. Thus hissing is an anode phenomenon in this case.

(ii) *Iron Anode, Carbon Cathode.*—The carbon cathode is a thermionic emitter. Thus the temperature of the cathode will not increase much as current increases as thermionic emission is an exponential function of temperature. But, as the current

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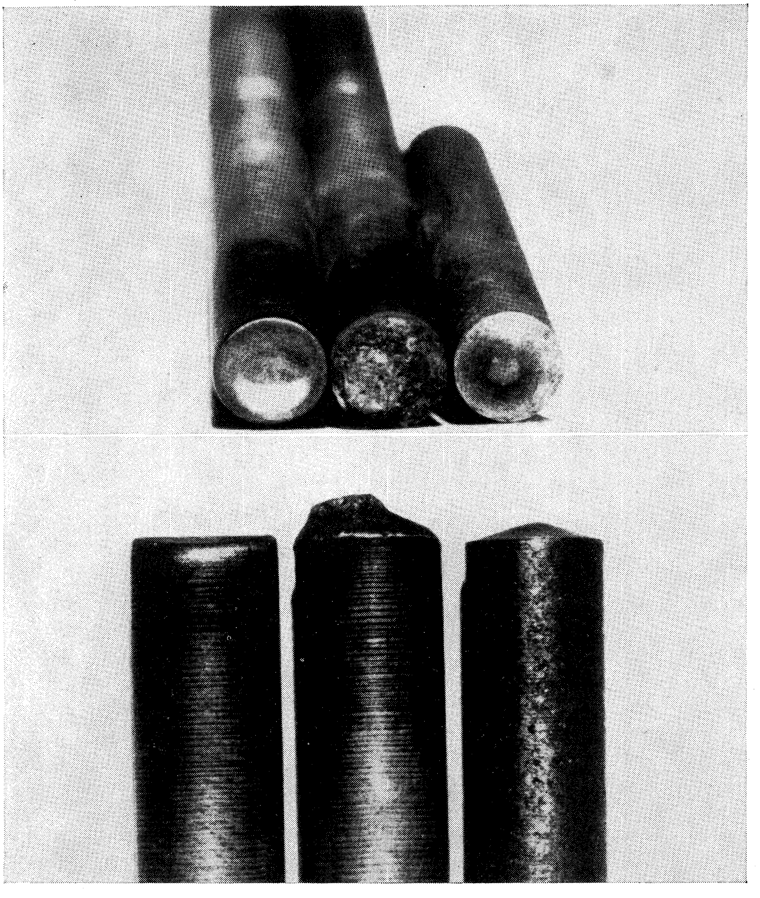

Iron electrodes after a hissing arc has been burning for 15 minutes; from left to right: cathode, anode, original.

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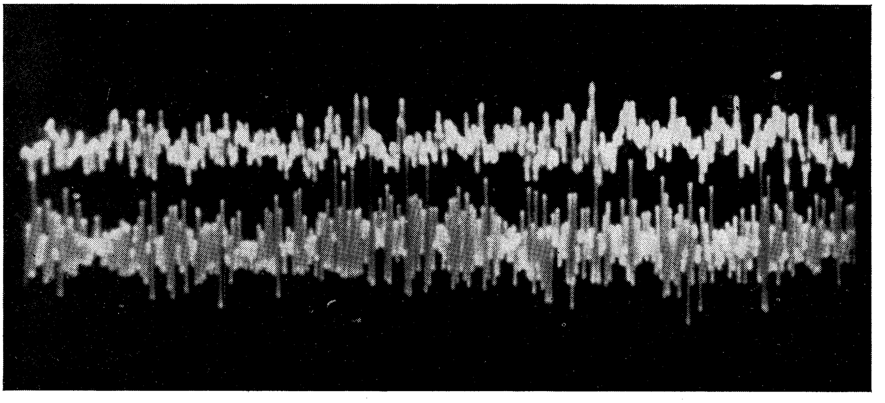

Fig. 1.—Frequencies less than 10 kc/s. Top: voltage; bottom: noise.

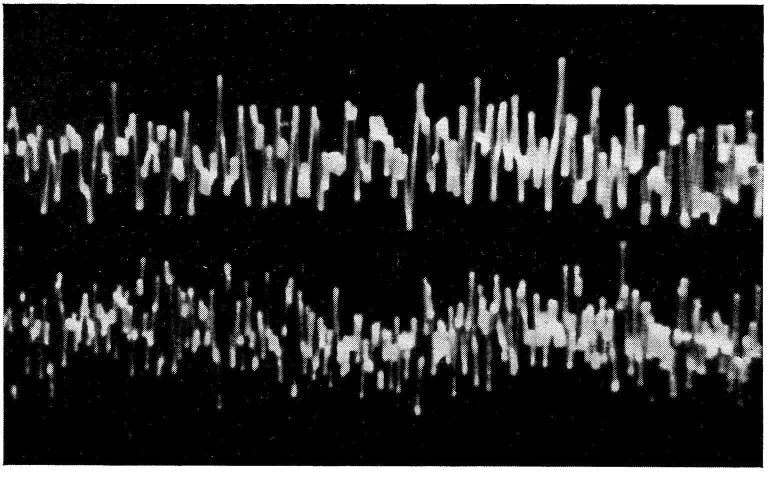

Fig. 2.—Frequencies less than 5 kc/s. Top: voltage; bottom: noise.

increases and the power dissipated in the arc increases, the temperature of the anode will rise until eventually it boils. The iron anode will boil then, so again the hissing is associated with the anode.

Now consider:

(iii) *Iron Anode and Cathode.*—As previously shown, the hissing is a *cathode* phenomenon.

Whether hissing is an anode or cathode phenomenon then depends on which electrode boils first, which in turn depends on the boiling points of the electrode materials, their specific heats, heats of fusion and evaporation, and the energy partition at the electrodes.

To verify this, arcs were run between various combinations of graphite, iron, and copper electrodes. As expected, whenever graphite was one of the electrodes, the hissing was associated with the anode. When one electrode is iron and the other is copper, however, the electrode that causes the hissing will be the electrode that boils first. Now the difference in boiling point between iron and copper (about 900 degK) is much greater than the estimates of temperature difference between anode and cathode of the metal arcs (about 200 degK, Cobine 1941). Hence the arc behaviour should be governed by the boiling of the copper electrode, whether it be cathode or anode. This was in fact the case, the hissing setting in at the low critical current previously associated with copper when copper was the cathode or the anode.

V. Arc spectra

The appearance of the second positive nitrogen bands near the anode of the silent arc (Baker 1954) but not with the hissing arc has been investigated. The determination of arc temperatures showed that this could not be due to temperature differences in the plasma. The formation of the bands has in fact been shown to be due to the vapour jets and the theory developed allows the determination of initial jet velocities from relatively simple experimental measurements. The spectral investigation has confirmed the part played by vapour jets in the metal arcs. This work will be published separately.

VI. Acknowledgments

The author wishes to thank Dr. S. C. Baker, who suggested this investigation, for many helpful discussions. Mr. K. Flisikowski helped with much of the photography.

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