Motion of Arc Cathode Spot in a Magnetic Field*

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The motion of the cathode spot of a mercury arc was observed under various transverse magnetic fields, arc currents, and inert gas pressures. With no inert gas, the retrograde velocity increased as the magnetic field strength increased. Addition of an inert gas at low pressures reduced the retrograde velocity and at higher pressures caused a forward (direction of magnetic force) motion.

The motion of the cathode spot in a magnetic field can be associated with electrostatic forces on positive ions produced by electron impact. A cathode spot assembly consisting of a group of electrons in the cathode, a positive ion sheath separated by a dark space from the cathode, and an electron cloud between the positive ion sheath and anode is postulated.

Electrons after acceleration through the cathode dark space would travel a curved path due to the magnetic field and produce new positive ions on the forward side of the cathode spot. These new positive ions would be attracted by the cathode spot assembly with a resultant force that would cause them to overshoot the positive ion sheath before being pulled into the cathode to start a new spot in the retrograde direction.

Addition of an inert gas reduces the mobility of positive ions to the order of that of the cathode electrons thus permitting forward motion of the cathode spot assembly to reduce the overshooting. Higher pressures would cause a forward spot motion.

INTRODUCTION

THE motion of the cathode spot of an electric arc in a transverse magnetic field has been previously investigated by Minorsky,[1] Smith,[2] Gallagher and Cobine,[3–5] Himler and Cohn,[6] and Miller.[7]

Minorsky[1] observed that under some conditions the cathode spot moves in a direction opposite to the force on the charges due to their motion in a magnetic field. This type of spot motion has been termed retrograde. Motion of the spot in the direction of the force due to the motion of the charges through a magnetic field will be called a forward motion.

With a special cathode Smith [reference 2e] found that the velocity of the arc spot in the retrograde direction increased with magnetic field strength, leveling off at about 120 m/sec and then suddenly rising at about 9000 oersteds to about 250 m/sec. Under special conditions the speed went to about 800 m/sec. Smith [reference 2(c)] also found that retrograde motion of the cathode spot occurred only for cold cathodes arcs.

Gallagher and Cobine[3–5] observed that with the addition of an inert gas to a mercury arc the retrograde velocity of the arc spot decreased. There was a certain pressure at which the arc stopped, and at pressures greater than this, the spot moved in the forward direction. They obtained an indication of a proportionality between the pressure needed to reverse the motion and the energy of the first excited state of the admixed gas.

APPARATUS

Figure 1 shows a cross section of the discharge tube mounted in the magnet. Not shown is an outlet to the vacuum system and inert gas supply. The tube elements are circular when viewed from above. The cathode is composed of a molybdenum stump standing in a pool of mercury. When the molybdenum has a very clean surface it is wet by the mercury which then rises around the stump. The arc spot is formed at the junction of the mercury and the molybdenum stump. Thus, the electric field and the path of the charged particles near the cathode are both horizontal. Since the magnetic field is vertical, the charged particles near the cathode have a horizontal force exerted on them because of their motion through the magnetic field. The force is in the same direction for both positively and negatively charged particles, since they travel in opposite directions. The cathode spot moves around the stump

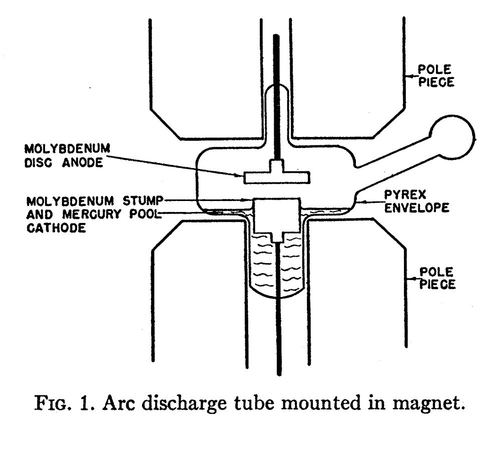

FIG. 1. Arc discharge tube mounted in magnet.

* Reported in large part at conference on Gaseous Electronics, Washington, D. C., October 24, 1953 [Phys. Rev. 93, 653 (1954)].
[1] N. Minorsky, J. de phys. et rad. (Paris) 9, 127 (1928).
[2] C. G. Smith, (a) Phys. Rev. 62, 48 (1942); (b) Phys. Rev. 69, 96 (1946); (c) Phys. Rev. 73, 543 (1948); (d) Phys. Rev. 83, 194 (1951); and (e) Phys. Rev. 84, 1075 (1951).
[3] C. J. Gallagher, Special publication of General Electric Company, and J. Appl. Phys. 21, 768 (1950).
[4] C. J. Gallagher and J. D. Cobine, Phys. Rev. 71, 481 (1947).
[5] J. D. Cobine and C. J. Gallagher, Elec. Eng. 68, 469 (1949).
[6] G. J. Himler and G. I. Cohn, Elec. Eng. 67, 1148 (1948).
[7] C. G. Miller, Report at Gaseous Electronics Conference October 24, 1953. [Phys. Rev. 93, 654 (1954)].

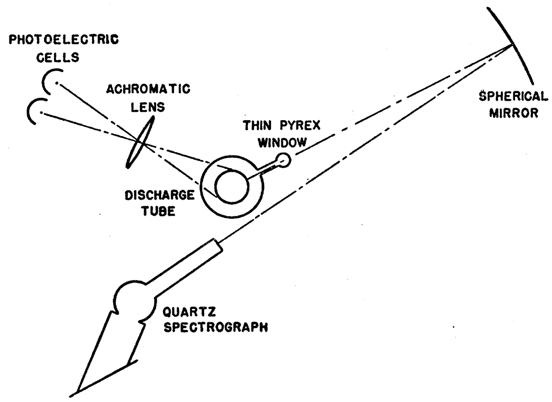

FIG. 2. Apparatus used in observing the arc.

at the junction between the mercury and the molybdenum stump.

Figure 2 is a top view of the apparatus used in observing the arc. Light from the arc is focused on two photoelectric cells close together. The output of these cells is fed into a cathode-ray oscilloscope along with the output of an audio oscillator to produce Lissajou figures. When the frequency of the audio oscillator is such as to give a single closed loop on the oscilloscope screen, the frequency of the cathode spot equals that of the audio oscillator. The spot velocity is determined from this frequency and the diameter of the stump. The use of two photoelectric cells permitted the determination of the direction of the spot motion and showed that there was but one spot. When the output of the photoelectric cells was fed into the vertical deflection channel of the oscilloscope with the horizontal sweep frequency set at the arc spot frequency, a stationary trace having two close peaks was obtained on the oscilloscope. Each peak could be associated with the cell whose output produced it by partially covering one of the cells and noting the peak whose height was reduced. This showed which cell received light first from the arc spot and thus showed the direction of motion of the arc spot.

The spectrum of the cathode spot region was obtained by focusing an image of the spot on the slit of a spectrograph as shown in Fig. 2.

RESULTS

The spot velocity as found by previous investigators and also in this work depends upon (a) magnetic field strength, (b) arc current, and (c) pressure of inert gas.

Figure 3 shows a plot of the spot velocity as a function of magnetic field strength for constant arc currents of 5.5 and 2.0 amperes and no inert gas in the tube. An increase in magnetic field strength is accompanied by an increase in retrograde velocity.

With the higher arc current (5.5 amperes) the spot velocity changes discontinuously to a value nearly twice as great at a certain magnetic field strength. The change was from about 112 m/sec to about 193 m/sec at a field strength about 10 500 oersteds. The magnetic field strength at which the break occurs changes with arc current as shown in Fig. 4. A decrease in arc current increases the field strength needed to produce the velocity discontinuity.

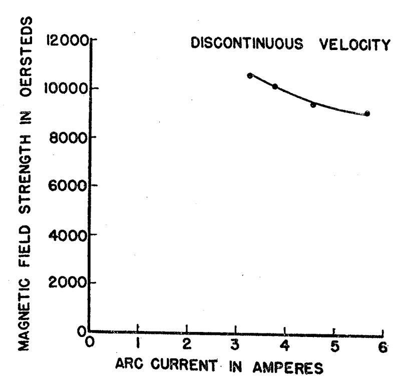

FIG. 4. Magnetic field strength *vs* arc current for the discontinuity in spot velocity. No inert gas.

Figure 5 shows the spot velocity plotted as a function of arc current for various constant magnetic field strengths and no inert gas present. The spot velocity increases in the retrograde direction as the arc current is increased.

With an inert gas (argon) in the tube at a pressure of 150 mm Hg the spot velocity depends on the magnetic field strength as shown in Fig. 6 for several values of the arc current. The shape of these curves is similar to those for no inert gas present (Fig. 3). However, the curves are shifted downward along the velocity axis toward the forward velocities, and the velocities are about one hundredth of the velocities with no inert gas.

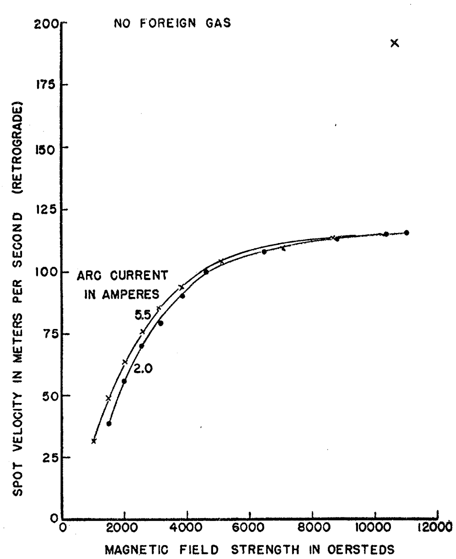

FIG. 3. Spot velocity *vs* magnetic field strength for constant arc currents. No inert gas.

For a given magnetic field strength, an increase in arc current increases the forward velocity, thus changing the velocity toward the forward direction. When there was no inert gas and the velocity was retrograde an increase in arc current increased the retrograde velocity (Fig. 3). With inert gas present there was no discontinuity in velocity at high magnetic field strengths.

Figure 7 shows a plot of the spot velocity as a function of argon pressure for two constant magnetic field strengths. With a low inert gas pressure the spot moves in the retrograde direction. Increasing the pressure causes the spot to slow down, stop, and then move in the forward direction.

The conditions required for a zero-spot velocity are shown in Fig. 8. The magnetic field strength to give

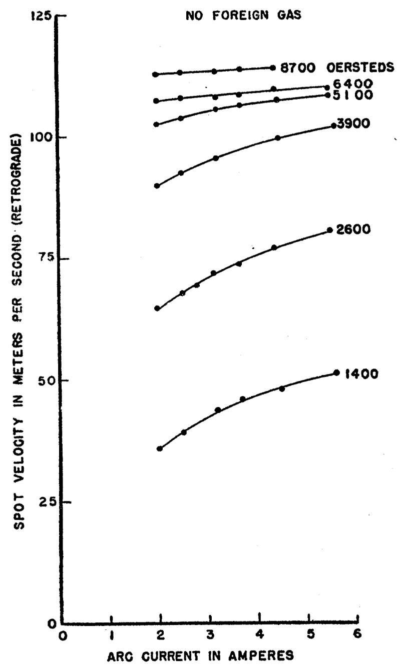

FIG. 5. Spot velocity *vs* arc current for constant magnetic field strengths. No inert gas.

zero-spot velocity is plotted as a function of arc current for constant gas pressures. In general, an increase in arc current requires an increase in magnetic field strength to hold the spot at rest. For a high gas pressure a small change in arc current requires a large change in magnetic field strength to compensate it, while for a low gas pressure the same change in arc current requires a small change in magnetic field strength to compensate it. If curves like these had been plotted for a constant retrograde velocity instead of zero velocity, the curve for zero gas pressure would have had a negative slope as may be seen from Fig. 3. and Fig. 5. For a constant retrograde velocity and no inert gas an increase in arc current requires a decrease in magnetic field strength to compensate it.

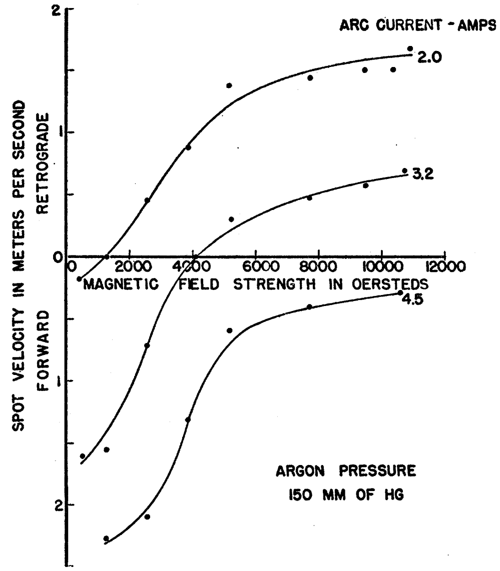

FIG. 6. Spot velocity *vs* magneitc field strength for constant arc currents. Argon pressure 150 mm Hg.

Figure 9 shows the inert gas (argon) pressure required to produce a zero-spot velocity at various arc currents for three constant magnetic field strengths. An increase in arc current requires a decrease in pressure to compensate it.

Spectra of Hg are shown in Fig. 10. Figure 10(a) shows the spectrum of the arc in a weak magnetic field. The central continuous spectrum is from the cathode spot while the lower part is due to the negative glow. (The part above the continuous spectrum is from

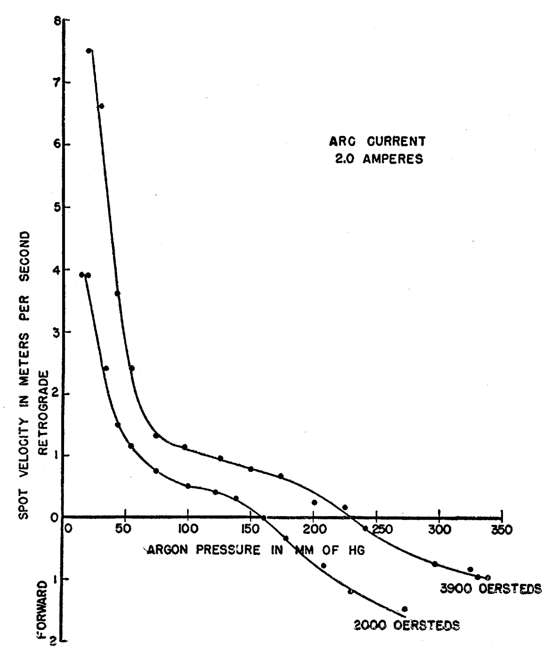

FIG. 7. Spot velocity *vs* argon pressure for constant magnetic field strengths.

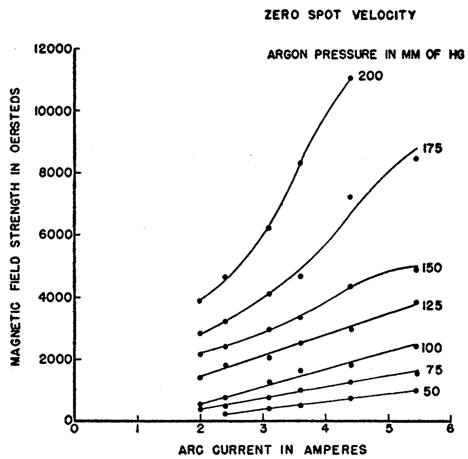

FIG. 8. Magnetic field strength *vs* arc current for constant argon pressures. Zero-spot velocity.

reflections of the cathode spot in the mercury pool.) The spectrum shown in Fig. 10(b) is of the arc in a magnetic field of about 12 000 oersteds. In the spectrum of the arc in a strong magnetic field several new lines appear and several others are greatly enhanced. These are Hg II lines. Smith [reference 2(d)] observed both Hg II and Hg III lines in the spectrum of the arc in a magnetic field of 10 000 oersteds.

The continuous spectra for the strong and weak magnetic fields are similar. That this continuous spectrum is not due to a high concentration of mercury molecules near the cathode is shown by comparing it with the continuous spectrum of mercury molecules shown in Fig. 10(c). (The center part of Fig. 10(c) shows the effect of heating the middle of the discharge tube. There is a weakening of one part of the Hg_2 spectrum and an enhancing of another part.[8])

SUMMARY

The results of these investigations and investigations by others may be summarized as follows: Let H = magnetic field strength, v = velocity of cathode spot of arc, I = arc current, and p = inert gas pressure.

Inert gas pressure zero: Increasing H increases v in retrograde direction; increasing I increases v in retrograde direction.

Inert gas pressure >50 mm Hg: Increasing H increases v in retrograde direction; increasing I increases v in forward direction; increasing p increases v in forward direction.

DISCUSSION

Several possible explanations of retrograde motion have been proposed. Longini[9] suggested that the magnetic field causes a shift in the forward direction for the electronic and positive ion space charges near the cathode spot with more shift for the electron space charge near the cathode surface than for the positive ion sheath above the cathode spot. This would neutralize part of the positive ion sheath in the forward direction and thus produce a maximum of electric field at a retrograde position for all but very strong magnetic fields. Longini assumed that the arc spot occurred at the position of highest electric field strength. Thus, the arc spot would move in the retrograde direction along with the maximum of the electric field strength. Longini recognized that according to this explanation the motion should change from retrograde to forward with very strong magnetic fields. Later observations show only an increase in retrograde velocity with increase in magnetic field strength.

Himler and Cohn[6] have suggested that if electrons are ejected from the cathode spot in all directions, those going in the forward direction might be returned to the cathode without producing any new positive ions, while those going in the retrograde direction although deflected upward by the magnetic field could produce new positive ions on the retrograde side of the cathode spot. These new positive ions then could form a new cathode spot at a position in the retrograde direction. It was pointed out by Gallagher[3] that this explanation required the ejection of more electrons in directions nearly tangent to the cathode surface then would be plausible.

Rothstein[10] has proposed that the current just outside the surface of the cathode might be carried in part by holes which move in the retrograde direction and start a new cathode spot when they strike the cathode. This proposal assumes that holes are more effective than positive ions in producing a cathode spot and assumes the existence of holes in a vapor. To obtain conduction by holes there must be many

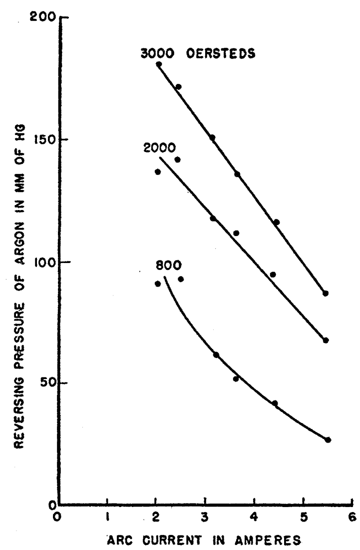

FIG. 9. Argon pressure *vs* arc current for constant magnetic field strengths. Zero-spot velocity.

[8] J. G. Winans, Phys. Rev. 42, 800 (1932).
[9] R. L. Longini, Phys. Rev. 71, 642 (1947); 72, 184 (1947).
[10] J. Rothstein, Phys. Rev. 78, 331 (1950).

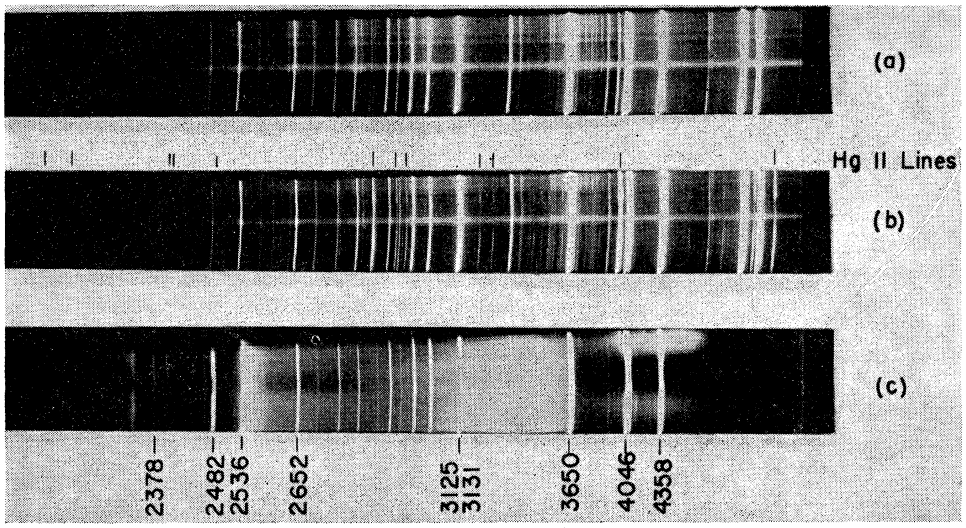

FIG. 10. Spectra of Hg. (a) Spectrum of the arc in a weak magnetic field, (b) Spectrum of the arc in a stong magnetic field and (c) Spectrum of Hg_2 molecules.

neutral particles which can supply electrons and thus becomes new holes. The vapor pressure of mercury near the cathode would not be expected to be high enough to permit this type of hole conduction.

Tanberg[11] proposed that rapid evaporation of partially ionized metal vapor from the cathode spot could provide a stream of positive ions moving away from the cathode. These positive ions could be deflected in the retrograde direction by the magnetic field and strike the cathode and form a new cathode spot on the retrograde side of the previous cathode spot. It is unlikely that a stream of atoms evaporated from the cathode spot would contain an appreciable number of positive ions since positive ions would be held near the cathode by the high electric field in the cathode dark space. This theory also would not account for the nearly doubling of the arc spot retrograde velocity at high magnetic field strengths.

A possible mechanism which is consistent with all observations of retrograde and forward motion so far made is illustrated in Fig. 11. The magnetic field is normal to the drawing. The potential difference across the cathode dark space from the spectral evidence shown in Fig. 10 must be about 20 or 30 volts while the total potential difference across the arc is about 12 or 15 volts. This potential distribution requires a positive ion sheath very near the cathode and an electron cloud between this sheath and the anode.

The proposed mechanism for the case in which no inert gas is present is as follows. Electrons emitted from the cathode spot are accelerated through the cathode dark space, and bent into a curved path by the force from their motion through the magnetic field. At the end of a free path for ionization they collide with atoms to produce new positive ions on the forward side of the cathode spot as shown in Fig. 11. These new positive ions are drawn toward the cathode spot region by the forces exerted on them by the electrons in the cathode, the positive ion sheath, the electron cloud above the sheath, and the electrons streaming toward the new positive ions (F_1, F_2, F_3, F_4, in Fig. 11). This gives the new positive ions a velocity which has a component in the retrograde direction. As these positive ions approach the cathode spot region they are shielded from the electrons in the cathode spot by the positive ion sheath and attracted toward the electron cloud. Their tangential velocity then carries them over the positive ion sheath after which they are pulled into the cathode and start a new cathode spot at a point in the retrograde direction from the previous cathode spot.

With no inert gas in the tube, the force of attraction between the new positive ions and the cathode spot assembly produces motion of the positive ions and practically no motion of the cathode spot assembly because the mobility of electrons in the cathode is much less than the mobility of the new positive ions. The mobility of Hg^+ ions in mercury vapor at a pressure of about 0.3 mm of mercury (tube temperature about 100°C) is about 10 000 (cm/sec) per (volt/cm) while the mobility of electrons in the cathode is near 40 or 50 (cm/sec) per (volt/cm). Also, it can be expected that the cathode spot assembly will not be greatly distorted by the forces exerted on it by the new positive ions.

An increase in magnetic field strength has several effects on the operation of the arc. The potential drop across the cathode dark space increases considerably, but only a slight increase results in the total potential difference between cathode and anode. This increases the charge in the electron cloud above the positive

[11] R. Tanberg, Nature 124, 371 (1929).

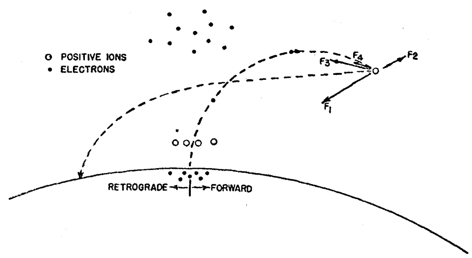

FIG. 11. The mechanism for a qualitative description of the cathode spot motion.

ion sheath and thus increases the total force on the new positive ions.

Also, an increase in magnetic field strength increases the bending of the electron path and new positive ions are produced closer to the cathode. The velocity of these new positive ions then has a larger component in the retrograde direction.

These effects cause the positive ions to overshoot the cathode spot to a greater distance in the retrograde direction when the magnetic field strength is increased. Thus, an increase in the retrograde velocity of the arc spot results from an increase in the magnetic field strength.

The approximate doubling in the retrograde spot velocity with an increase in magnetic field strength beyond 11 000 oersteds when no inert gas is present can be attributed to the production of Hg^{++} ions. The spectrum shows that excited Hg^{+} ions are produced. It is to be expected that Hg^{++} ions are also produced. The tangential force on Hg^{++} being twice that on Hg^{+}, the retrograde velocity should be nearly doubled when Hg^{++} ions are formed.

With an inert gas present high-energy electrons can be expected to ionize or excite gas atoms and not gain enough energy to produce doubly-charged ions like Hg^{++}. Thus, with an inert gas present, there should be no sudden increase in retrograde velocity with increase of magnetic field strength. This agrees with observations.

An increase in the arc current causes an increase in the total charge in the cathode spot assembly, and this in turn increases the force on each of the positive ions. With no inert gas present they overshoot further in the retrograde direction before starting a new cathode spot, and thus there results an increase in the retrograde velocity of the cathode spot.

The introduction of an inert gas into the discharge tube reduces the mobility of the positive ions very greatly since the mobility is inversely proportional to the gas pressure. Addition of argon to a pressure of 760 mm Hg reduces the positive-ion mobility from about 10 000 (cm/sec) per (volt/cm) to 1 or 2 (cm/sec) per (volt/cm). Thus, the mobility of the positive ions in the gas is reduced until it is of the order of that of the electrons in the cathode. The cathode spot assembly can then move in the forward direction during the time of motion of the positive ions. Also the tangential velocity acquired by the positive ions is rapidly dissipated by collisions with inert gas atoms, so that the positive ions will not be able to overshoot the cathode spot assembly as much as they did with no inert gas present. These effects produce a reduction in retrograde velocity and, if sufficiently large, cause a motion of the cathode spot in the forward direction. Under these circumstances an increase in arc current increases the charges in the cathode spot assembly and increases the number of new positive ions, thus increasing these effects. Experiment shows that the velocity increases in the forward direction with an increase in arc current when an inert gas is present.

CONCLUSIONS

The retrograde motion of the cathode spot of an electric arc in a transverse magnetic field when little or no inert gas is present can be described in terms of positive ions overshooting the cathode spot assembly.

A substantial amount of inert gas retards the movement of the positive ions to the extent that the movement of the cathode spot assembly in the forward direction is greater than the overshooting of the positive ions. This can account for the forward motion of the cathode spot with an inert gas present.

The writers wish to thank Dr. C. G. Smith for the use of a magnet and one of his arc tubes, and also for some pure molybdenum that was used in making electrodes of other tubes.

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Note added in proof.—A. E. Robson and A. von Engel [Phys. Rev. **93**, 1121 (March 1, 1954)] suggest that retrograde motion may result from a local reversal of magnetic field due to sharp bending of the electron current. While the process might give retrograde motion it would not account for the doubling of retrograde velocity at high magnetic fields. Also this mechanism requires that the retrograde velocity be nearly proportional to the square of the arc current while measurements (Fig. 5) show it to be less than proportional to the first power of arc current.

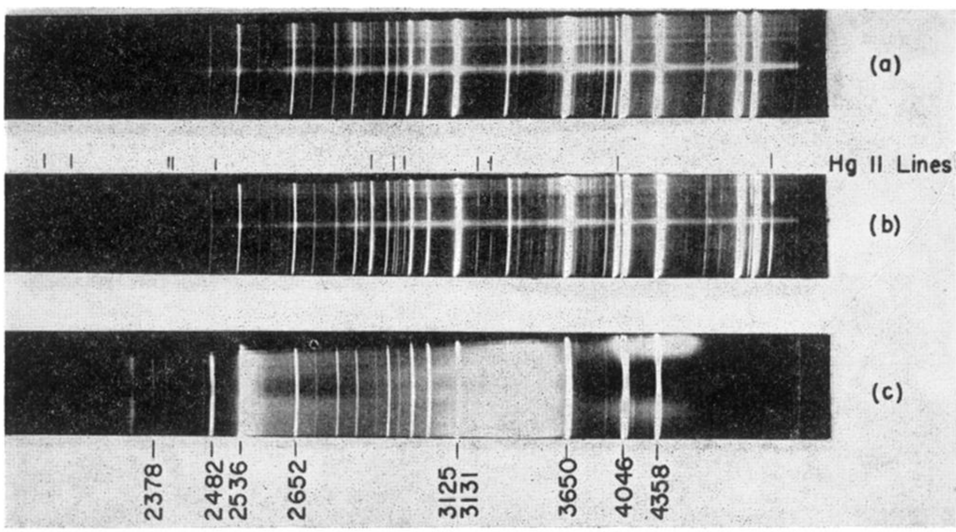

FIG. 10. Spectra of Hg. (a) Spectrum of the arc in a weak magnetic field, (b) Spectrum of the arc in a stong magnetic field and (c) Spectrum of Hg_2 molecules.