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REVERSAL OF DIRECTION OF ARC MOVEMENT IN A MAGNETIC FIELD UNDER REDUCED AIR PRESSURE

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It costs not less than $200, and usually more, per pound per year to carry equipment aboard aircraft. For this reason, space economy in electrical circuit - interrupting devices was attempted by use of modern permanent magnets for d-c arc blowout. It has been shown that a magnet of high coercivity and weighing only 1/10 of an ounce can be used in a switch to snuff a 10-ampere arc at ground level with long-lived reliability. Switches so equipped served well until planes began to fly higher than about 20,000 feet. Laboratory tests at simulated higher altitudes, however, revealed unexpected relations between ambient air pressure and the movement of arcs in transverse magnetic fields. Under certain relations of flux density and contact separation, it was observed that:

1. As air pressure decreases the arc moves less and less in the direction predicted by Ampere's law (the familiar left-hand, three-finger rule).
2. Over a range of critical pressure the arc is immobile and may destroy contacts.
3. At pressures below the critical range, the arc moves in the opposite direction to that predicted by Ampere's law.
4. Over a range of small contact separations, and within certain pressure ranges, there is discontinuity in switch-interrupting ability.
5. The higher the flux density the lower the altitude at which immobility occurs.
6. Variation in flux density over the length of the arc affects its movement.

The nature of arc structure and movement is most easily observed when contact separation is wide enough to interrupt the arc under the condition of immobility. For such observation, curved electrodes which can be moved from the closed to the open positions by electromagnetic means are mounted in a bell jar, as shown in figure 1.

Figure 2 shows the nature and position of the arc under specific conditions of flux and current values, at various pressures. Study of the action here seen makes it possible to explain the performance of a switch like that in figure 3 over a range of pressure changes and when adjusted for several contact separations, all of which are less than that which will interrupt the arc without blowout action of the magnet.

Where contacts are separated by 0.020 inch, there is a discontinuity in the arc-snuffing operation of the blowout magnet up to approximately 15,000 feet of altitude. With 0.035-inch contact separation discontinuity does not begin until approximately 10,000 feet of altitude, and continues to approximately 20,000 feet of altitude. The switch with contact separation of 0.070-inch was

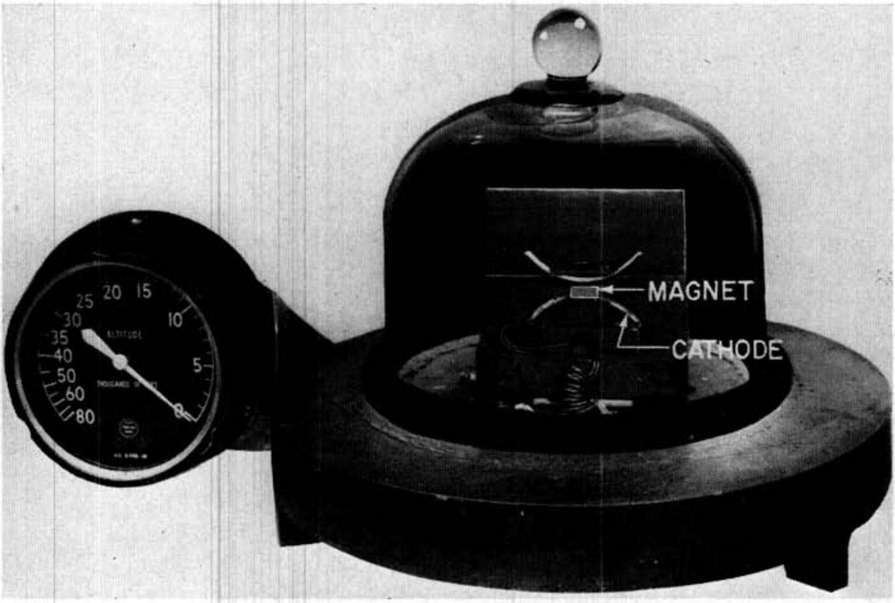


FIG. 1.—Silver arcing horns, solenoid driven for closing and opening contact. Permanent magnet provides a total of 550 lines of force. (Data supplied by Dallas.)

successfully used in many relatively low-flying aircraft. Here there is no discontinuity, but the switch failed to interrupt more than 1¾ amperes above about 20,000 feet of altitude.

From these data it might be reasoned that the difficulty of switching at altitude can be avoided by use of wide-contact separation. This is not always possible in the case of relays and sensitive switches, for operation force, motion, and switch size are limited by aircraft design.

When the unexpected effects of altitude were first observed in the Micro Switch laboratories in 1942, eminent authorities were consulted for explanation of the phenomena and for practical help in the design of switches which would avoid the problems. No one was found who was aware of the effect, and the only reference discovered in the literature is in Faraday's Diary,[1] and that barely hints at one phase. Following Micro's observation, a number of articles have been published in which there is agreement that the mechanism of the effect is to be sought in the cathode spot. The appearance of the arc shown in figure 2 bears out this reasoning, for the retrograde movement of the cathode end always leads the main column.

Dr. Charles G. Smith has reported the reverse motion of the cathode spot in mercury arcs, and suggested that it may be due to the negative Righi-Leduc effect.[2, 3] His work, however, appears to have been done entirely on mercury arcs at about 2-

[1] Michael Faraday's Diary, Jan. 13, 1862, vol. VII, 1820-1862.

[2] Heat is pushed at right angles to the magnetic field and at right angles to the temperature gradient.

[3] Smith, Charles G., The mercury arc cathode: Phys. Rev. 62: 48, July 1942.

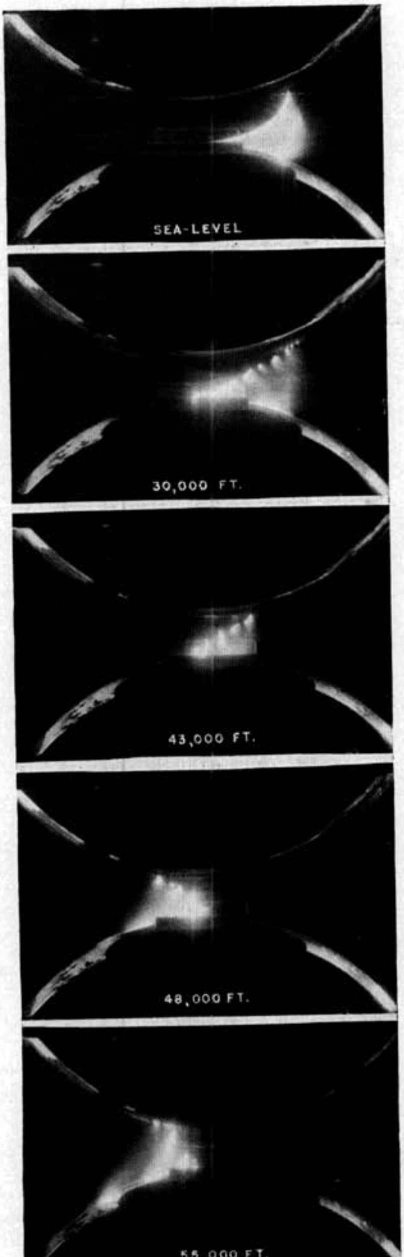


FIG. 2.—Position assumed by a 4.5 ampere 30 volt d-c arc between silver electrodes separated 0.200 inch at the center in the field of a permanent magnet providing a total of 550 lines, under varying simulated altitudes. The lower electrode was the cathode. The load circuit had an L/R time constant of approximately 0.035 second. (Data supplied by Dallas.)

millimeter pressure. Other workers have found retrograde movement between electrodes which produce both positive and negative Righi-Leduc effects (for example, Fe and Mg, Cu and Ag).[6] It seems improbable that changes of pressure could slowly reduce and then alter the sign of the Righi-Leduc effect. Yamamura points out that the conditions producing immobility, and its range, vary with electrode materials.[4-7] Various investigators of conditions in the cathode spot estimate that current density may be as great as 10,000 amperes per square centimeter, and that the positve column may reach 10,000°K. with still higher temperatures existing in gas molecules within the positive space charge cloud.

Uncertainty as to whether such conditions do exist, and the values which should be assigned, makes it difficult to construct mechanisms of performance with any assurance of their accuracy. Himler-Cohn,[5] Yamamura,[4] and others, however, agree in general that as the mean-free path is lengthened by reduced pressure, electrons, with energy corresponding to the cathode fall, diffuse outward

[4] Yamamura, Sakae, Immobility phenomena and reverse driving phenomena of the electric arc: Jour. Appl. Phys., March 1950.
[5] Himler, Gary J. and George I. Cohn, The reverse blowout effect: Elec. Eng., Dec. 1948.
[6] Smith, Charles G., Retrograde arc motion of supersonic speed: Phys. Rev. 84: 1075, 1951.
[7] Druyvesteyn, M. J. and F. M. Penning: Rev. Mod. Phys. 12: 87, 1940.

into the positive space charge cloud. It seems probable that the loci of these electrons are bent by the transverse magnetic field, as shown in figure 4. Those diffusing to the left are sufficiently accelerated by the electric field to ionize gas molecules with which they collide. Those moving to the right are decelerated by the electric field, since they are moving opposite to its direction. Thus there is more ionization at the left side than at the right, which causes the cathode spot to migrate to the left, opposite to the pondermotive direction in which the arc column is normally driven by a magnetic field. When the force of the leftward-migration effect balances that of the normal pondermotive force, immobility of the arc occurs. When the leftward-migration forces exceed those of the rightward forces, retrograde movement results.

The velocity with which the arc is driven in the normal Ampere's law direction decreases with decrease in air pressure until the point of immobility is reached. It seems reasonable to assume that this effect results from the expansion of the

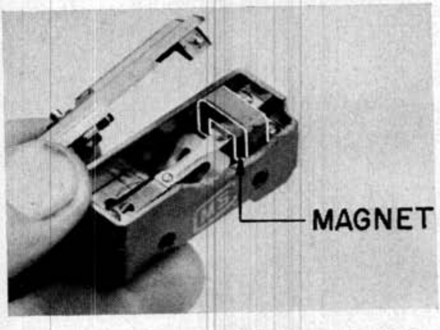


FIG. 3.—Commercial type of single-pole double-throw magnetic blowout switch rated at 10 amperes, 120 volts d-c at ground-level pressure. (Data supplied by Dallas.)

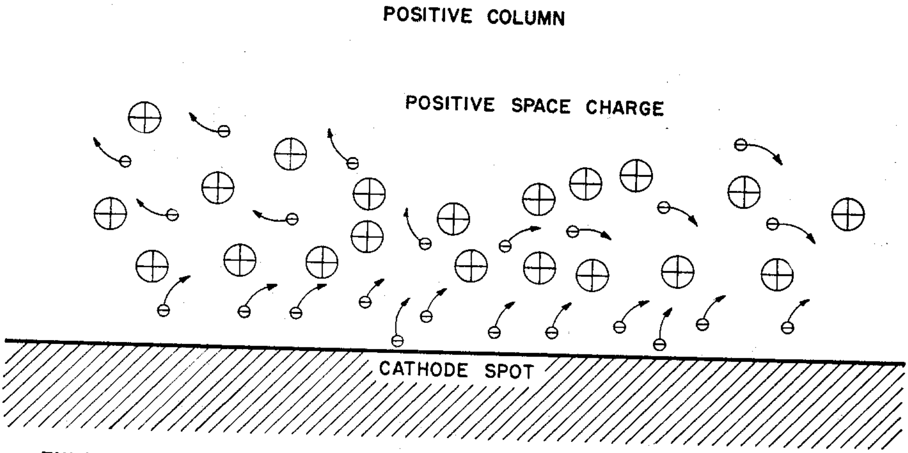
arc under lowered pressure, which produces a greater damping effect. After the point of immobility has been passed, however, the velocity with which the arc is driven increases with decreased air pressure. It can only be assumed that this increase is the result of increased forces in the retrograde direction which more than balances the damping effect of the continued increase in volume occupied by the arc. Smith[6] has reported mercury arcs driven in retrograde, circular paths in radial magnetic fields at four times sonic velocities for the pressures used.

Increase in density of the transverse magnetic field decreases the radii of curvature of electron paths, thus causing effective ionization, of the type shown in figure 4, under conditions of shorter mean-free paths. This theory is supported by the observation that increasing the strength of the blowout field lowers the altitude at which immobility occurs.

It is interesting to note that there is a period of momentary arc immobility immediately following contact separation. The time of persistence of such immobility increases as the conditions of permanent immobility with contacts fully separated is approached.

There is the further phenomenon that a very short arc cannot be moved by a magnetic field. Such permanent immobility exists for arcs of 0.4 millimeter length in a field of 50 gauss and at 0.2 millimeter length in a field of 400 gauss.[4]

Yamamura[4] comments that both the momentary and permanent immobility of short arcs may be ex-



ENLARGED PICTURE OF THE CATHODE SPOT. ⊕ POSITIVE IONS. ⊖ ELECTRONS. THE MAGNETIC FIELD IS DIRECTED PERPENDICULARLY FROM THE FRONT TO THE BACK OF THE PAPER.

FIG. 4.—(Data supplied by Dallas.)

plained by high temperatures in the cathode spot under such conditions. Other workers, such as Dallas, question whether such conditions may not be more readily explained by the small force acting in the normal direction when its length is short,[8] and that the momentary effect may to some measure result from the fact that as contacts begin to separate the arc necessarily starts out by being short.

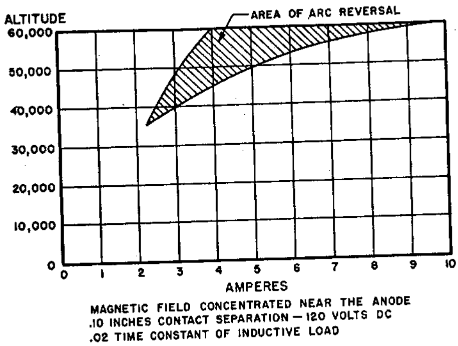
Regardless of the correctness of the theory behind these phenomena, they are of practical significance in that contact erosion produced by arcs which occur when contacts bounce, owing to the mechanical impact of closure, cannot be prevented by the use of blowout magnets, since such arcs, being both short in length and of short duration, are not moved by transverse magnetic flux.

Figure 5 shows that the area of arc reversal is at higher altitude when the magnetic field is asymmetrically shifted toward the cathode and vice versa. This observation bears out the theory that normal movement of the arc results from forces on the main column of the arc, and the retrograde leftward movement results from forces at the cathode end.

This effect can be demonstrated with the apparatus shown in figure 1, as the magnet is so located that flux density is greater at the lower electrode than at the upper. The arc moves as shown in figure 2 when the lower electrode in a denser field is the cathode. Reversal of the potential increases the altitude at which retrograde effect is seen.

Knowledge of this effect of non-uniform fields is of some practical value in building switches for use at altitude. Fortunately, however, many of the probelms of electrical switching at altitude are solved by hermetic sealing of switches under positive pressure of inert gas. This,

[8] The normal force moving an arc is proportional to the length of the arc times the current, times the mean flux density over its length.



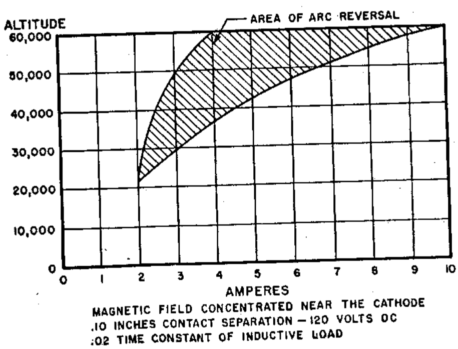


FIG. 5.—Effect of flux distribution over arc length. (Data supplied by Dallas.)

of course, completely avoids the puzzling problems of the immobile arc and some of the unknown effects at altitude of ozone, atmospheric composition, humidity, and ionization by cosmic rays. However, introducing mechanical actuation, free from variation under extremes of temperature and pressure, with certainty of permanent freedom from leak and the necessity of sealing enclosures without the use of either organic or ion-bearing solder flux, presents a series of challenging design, physical, chemical, and metallurgical problems which have not been completely solved. There has been sufficient progress, however, to enable many functions of high-flying aircraft to be carried out reliably by hermetically sealed, pressurized current-interrupting devices.

REFERENCES

BERRY, W. L., and J. P. DALLAS, Discussions, Am. Inst. Elect. Eng. Trans., vol. 63, 1944.

———, Higher voltage D-C aircraft electric systems: Am. Inst. Elect. Eng. Trans., vol. 63, 1944.

COBINE, J. D., and C. J. GALLAGHER, Current density of the arc cathode spot: Phys. Rev., vol. 74, Nov. 1948.

GALLAGHER, C. J., The retrograde motion of the arc cathode spot: Jour. Applied Physics, vol. 21, Aug. 1950.

GALLAGHER, C. J., and J. D. COBINE, Reverse blowout effect: Elect. Eng., May 1949, p. 469.

KOUWENHOVEN, W. B., Characteristics of arcs between moving electrodes: Am. Inst. Elect. Eng. Tech. Paper 49-129.

LONGINI, R. L., A note concerning the motion of arc cathode spots in magnetic fields: Phys. Rev., vol. 71, May 1947, p. 642.

———, Motion of low pressure arc spots in magnetic fields: Phys. Rev., vol. 72, July 1947, p. 184.

PHILLIPS, V. E. and W. P. MITCHEL, Peak voltages with D-C arc interruption for aircraft: Am. Inst. Elect. Eng. Tech. Paper 44-200.

QUILL, J. S., and L. T. RADER, D-C arc interruption for aircraft: Am. Inst. Elect. Eng. Trans., vol. 63, Dec. 1944.

SMITH, CHARLES G., Arc motion reversal in transverse magnetic field by heating cathode: Phys. Rev., vol. 73, March 1948, p. 543.