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ARC EXTINCTION PHENOMENA IN VACUUM.
II. Dependence upon Circuit Parameters

by

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SUMMARY Measurements of arc extinction currents for peak arc currents between 150 and 900 amp have been made for copper electrodes in vacuum. Current was limited by reactors of 0.83, 3.4, and 9.3 mH. The vacuum gap was also paralled by capacitors ranging from about 100 to 50 μF. Typically, a sequence of 75 arcing trials was used to obtain an average of the extinction current for a given circuit condition. Voltage transients produced by the extinctions were also measured. Generally, it is found that the average extinction current increases with capacitance paralleling the gap. The transient voltage produced by arc extinction, when the current is limited by any one of the reactors used, is a function of the capacitance paralleling the gap. This voltage reaches a maximum in the range 500 to 1000 pF, and is consistent with that calculated from a simple surge impedance view. Estimates from the charging rate of gap stray capacitances after low current arc extinction suggest that the gap can withstand voltage rise rates of at least 15 to 38 kV/μsec during the early recovery period.

KEY WORDS

vacuum arcs; current chopping

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ARC EXTINCTION PHENOMENA IN VACUUM.
II. Dependence upon Circuit Parameters

G.A. Farrall

I. INTRODUCTION

The spontaneous extinction of a vacuum arc at the end of an AC half-cycle is a phenomenon that has been studied in detail both analytically and experimentally. In most instances this work has been conducted from a vacuum interrupter applications point of view and has shown that the so-called chopping problem in connection with vacuum devices is not a severe one in most practical situations.[1, 2]

The present work is motivated from an interest in the arc itself. The very process of arc extinction represents a well-defined boundary between the conditions for existence of the arc and recovery of the gap, and so becomes of fundamental interest both from the arc stability viewpoint and that of dielectric recovery. To the author's knowledge there is not available in the open literature any comprehensive study of arc extinction for a contact metal under a wide variety of circuit conditions. We hope to at least partially fill this void and at the same time contribute to a more complete answer to the question, "Why does the arc spontaneously extinguish?"

II. EXPERIMENTAL

Current for this experiment was supplied from a 350 volt (peak) AC line capable of delivering 10, 000 amp half-cycles to an essentially short circuit load. The circuits used were of two general types given in Fig. 1. In Fig. 1(A), current is limited resistively whereas in (B) the current is limited by one of three air core reactors. In both circuits various values of capacitances are used to parallel the gap using leads which themselves have an inductance L' of about 4 μH. The capacitance represented by C_0 in Fig. 1 is that due to the power cables which were bound together to reduce inductance. The inductance, L, in 1(A) was located physically close to the gap so that the capacitance, C_0, was isolated from the gap. The resistance R in Fig. 1(B), however, was positioned close to the power source so that C_0 was effectively in parallel with the gap. Because of this effect, data are recorded for smaller values of capacitance in parallel with the gap for the inductive circuit than was possible with the resistive circuit.

The experimental tube is of a type used in many previous experiments.[3] The arc is drawn in a stainless steel arc chamber 5 inches in outer diameter between copper electrodes having a 2-inch diameter. With the tube mounted on an operating mechanism, the electrode gap opens at a speed of about 8 ft/sec. The fully open gap is 1/4 inch. The operation of the mechanism and application of voltage to the circuit are synchronized on each trial so that the contacts part within 3 msec of the beginning of a positive AC half-cycle. Using a Taktronix oscilloscope in a delaying sweep mode, the latter portion of each half-cycle arc was recorded on film typically at a sweep speed of 50 or 20 μsec/cm. A coaxial current shunt was used in series with the arc to record the current.

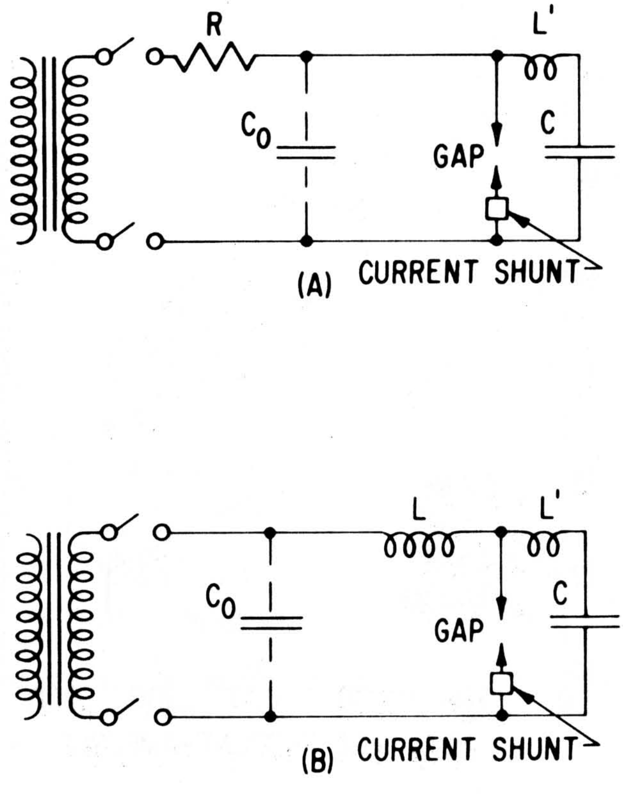

Fig. 1 Experimental circuits showing relative locations of power line capacitance, C_0, and capacitor lead inductance L'.

III. RESISTIVELY LIMITED CURRENT

In Fig. 2 are given measured values of extinction current as a function of peak arc current for four values of capacitance shunting the arc. These data were taken using the circuit of Fig. 1(A), each point shown in the average of between 75 and 100 trials. Despite this number the statistical scatter in the data is large. The points have been least-squares fitted to hyperbolic functions indicated by the drawn curves. The results show a marked decrease in extinction current with increasing peak current and also an increase in extinction current with increasing shunt capacitance.

This latter effect is more clearly illustrated in

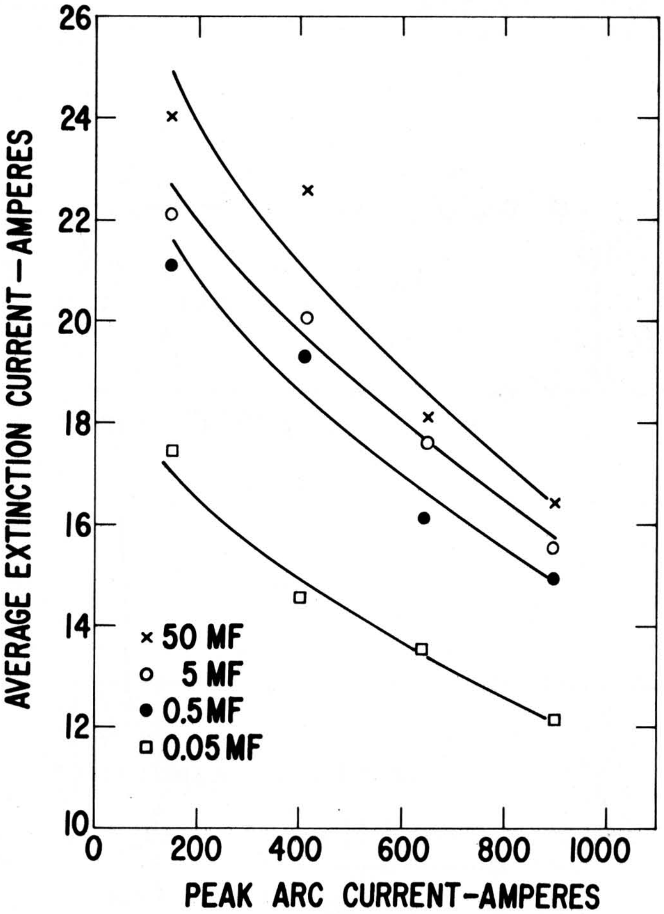

Fig. 2 Average extinction current as a function of peak arc current for various parallel capacitances.

Figs. 3 and 4 where a wider range of capacitances is considered. For each of the four magnitudes of peak arc currents, the increase in average extinction current is shown to occur at a diminishing rate for large values of capacitance. In a previous report[4] related to the present study, it was pointed out that this dependence of extinction current was associated with a particular level of current which is usually higher than the actual extinction current. At currents above this level instabilities in the arc current were few. Below this level, instabilities were observed and occurred more frequently at lower currents. It was concluded that the increase in extinction current with added capacitance is due to an impaired ability of the arc to be re-ignited from the voltage transient appearing across the arc; that is, the added capacitance does not act to introduce a greater number of instabilities into the arc, but rather exploits those which are already present possibly by reducing the rate of rise of the re-igniting voltage. The concept of the re-ignition of a faltering arc is certainly not new. This process was described by Lee, Greenwood, and Polinko[1] in 1959. The point we wish to emphasize in the present work is the existence of a particular level of current which distinguishes a period of a stably burning arc from a period of an unstably burning arc. This transition occurs, for the present work, at an instantaneous current of between 12 and 20 amp, depending upon the peak arc current or perhaps more properly the rate of change of current near zero and does not change when capacitance is added to the gap.

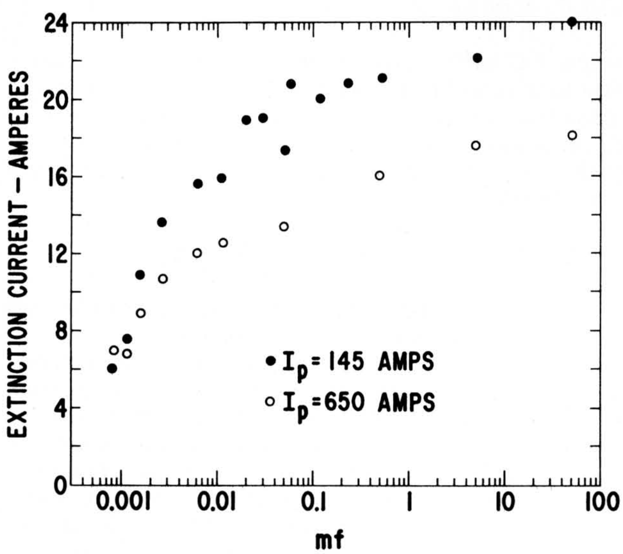

Fig. 3 Dependence of average extinction current upon parallel capacitance for peak arc currents of 145 and 650 amp (resistive circuit).

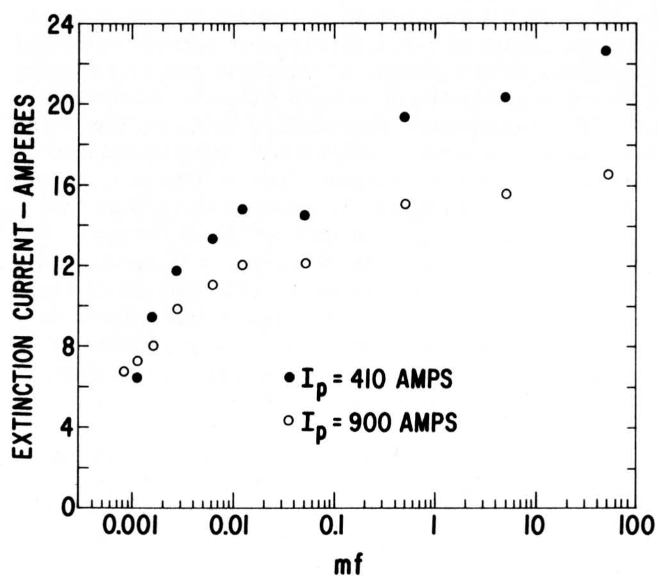

Fig. 4 Dependence of average extinction current upon parallel capacitance for peak arc currents of 410 and 900 amp (resistive circuit).

IV. INDUCTIVELY LIMITED CURRENT

Three different reactors were used to produce peak arc currents in the same range as that used for the resistive circuits. Figure 5 shows the average extinction current for these three cases for two values of shunting capacitance. Although three data points barely constitute a curve, the general behavior can easily be seen to be the same as for the resistive case. During these measurements the transient overvoltages produced by the extinction were also recorded. These results are given in Fig. 6 and lie within 10% to 20% of the voltages computed from the extinction currents based on the surge impedance concept.[5] The extinction of the arcs generally occurred in a time short compared with the natural frequency of the capacitance and the current limiting inductance.[4]

In Fig. 7 are given further measurements as a function of parallel capacitance. Figure 8 gives the corresponding measurements of transient voltages produced by the extinction. From these figures it is seen that despite the increasing level of extinction current with larger capacitance, this increase is not sufficient to keep pace with the decreasing surge impedance so that the above 1000 pF for each current, the voltage transient decreases with larger capacitance.

V. COMPARISON BETWEEN RESISTIVE AND INDUCTIVE CIRCUITS

We have already commented upon the similar

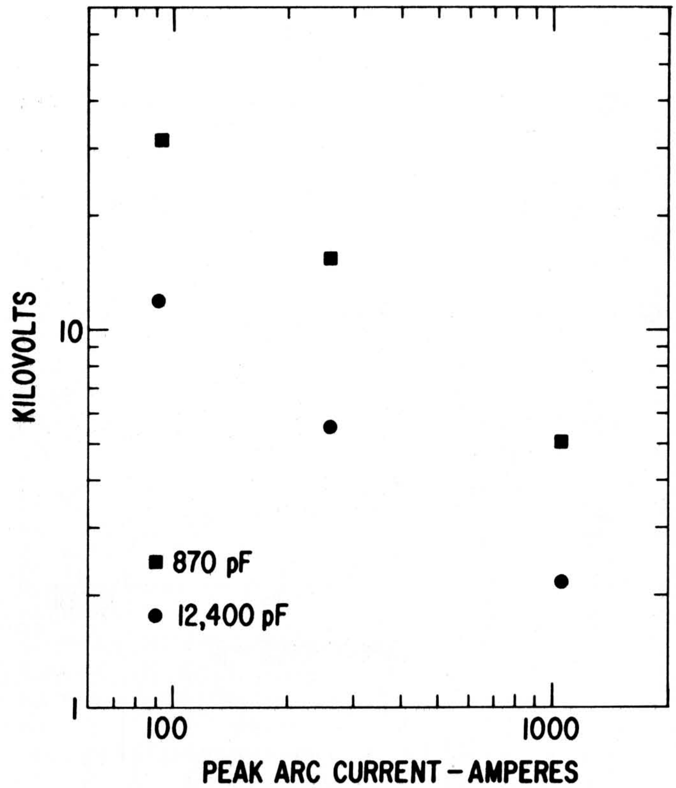

Fig. 6 Peak transient voltages produced by the arc extinction events of Fig. 5.

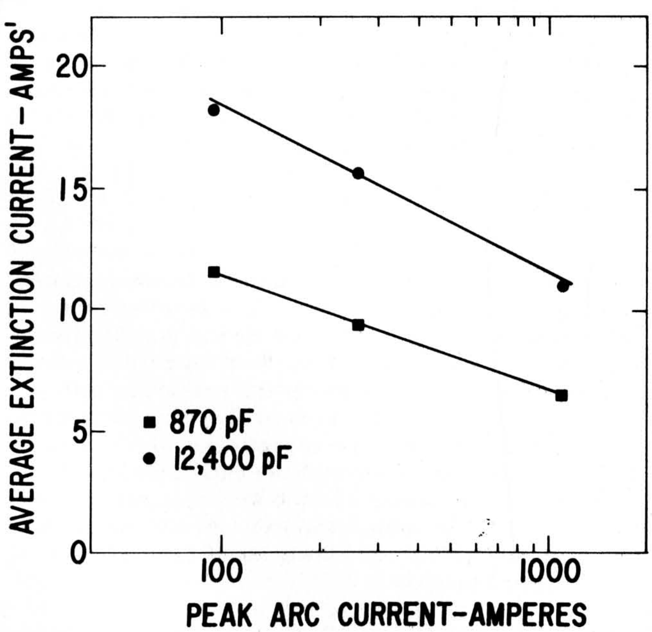

Fig. 5 Average extinction current for three values of peak arc current and two values of parallel capacitance (inductive circuit).

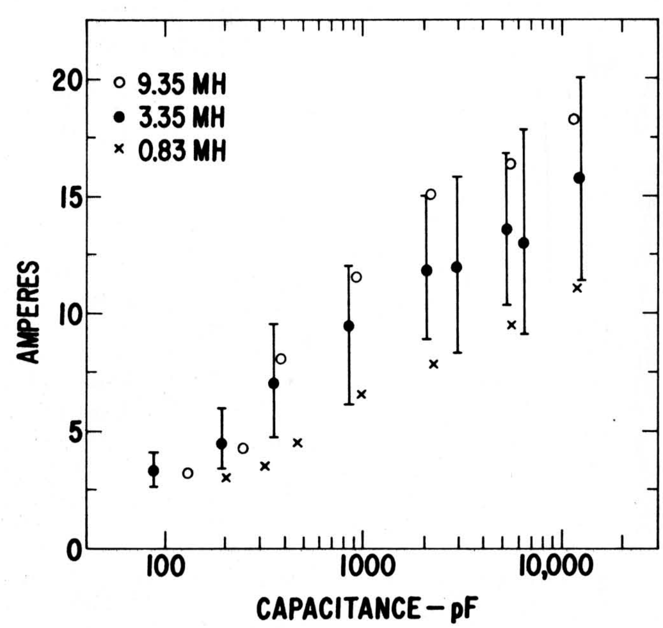

Fig. 7 Average extinction current as a function of parallel capacitance for three values of peak current limited inductively.

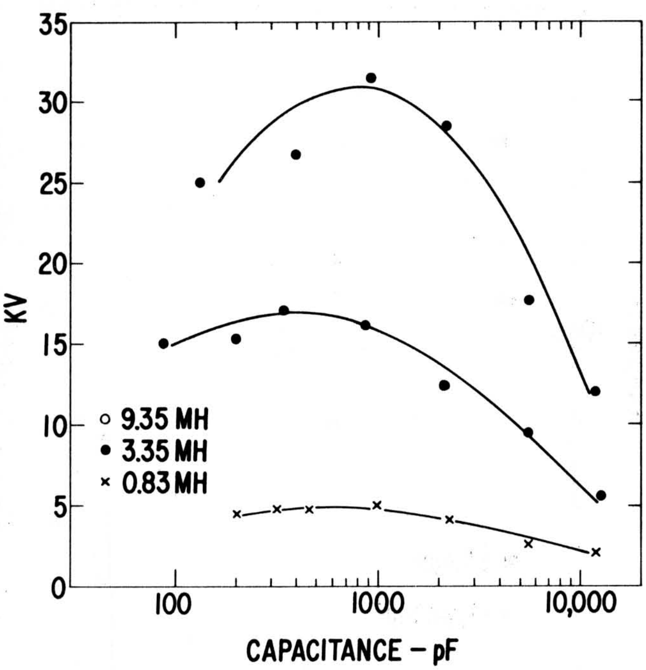

Fig. 8 Peak transient voltages produced by the arc extinction events described by Fig. 7.

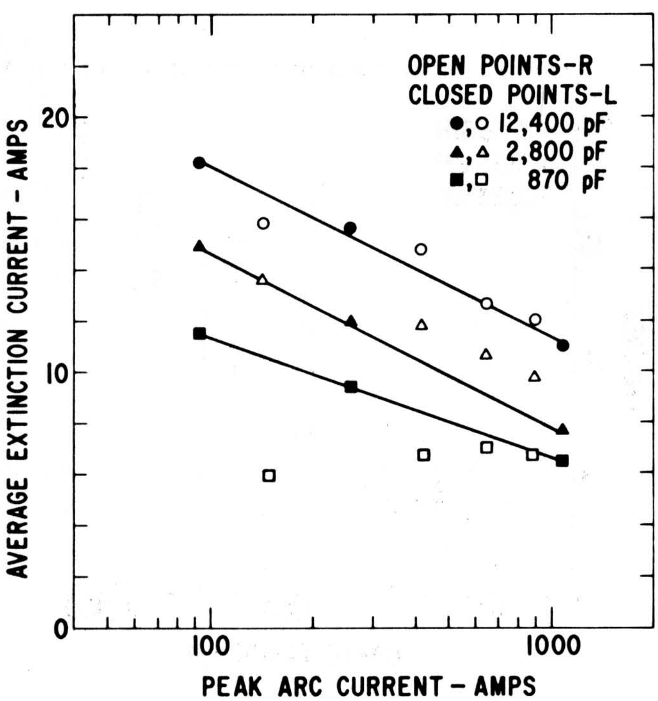

Fig. 9 Comparison of arc extinction data for resistively and inductively limited currents.

trends exhibited by the data for the inductive and resistive circuits. Figure 9 quantitatively compares the two. For both sets of data, comparable values of shunt capacitances were used. For the smallest capacitance, 870 pF, there is a strong divergence of the resistive and inductive data at low peak current with arcs being apparently more stable for the resistive circuit than for the inductive one. This effect is somewhat artificial, however, because with small peak current and small capacitance the extinction of the arc in the resistive circuit is very irregular.[4] The current waveform is highly distorted over a time period of several hundred microseconds preceding the actual extinction and the decay of current to zero is often very noisy, irregular, and indistinct. With larger capacitance, however, the extinction is much more uniform. These data suggest that there is no great difference between the stability of the arc in the resistive and in the inductive circuits. In fact, the data for the largest capacitance for both cases could be part of the same experimental curve.

It was anticipated prior to the experiment that the inductive circuit would produce more stable arcs and lower extinction currents than the resistive circuit for the same peak current. Young[6] has pointed out that the initial rate or rise of transient voltage following an arc extinction is given by

$$\frac{dV}{dt} = \frac{i_0}{C} \qquad (1)$$

provided that one neglects the current flow in the shunt capacitor just prior to extinction. It is possible that if the arc is surviving at the end of a half-cycle by repeated re-ignition in both the inductive and resistive cases, the extinction is dominated by dV/dt across the capacitor. The behavior thus should be similar in both cases.

VI. ARC EXTINCTION AND CONSEQUENT RECOVERY

At the instant of arc extinction, the interaction between the arc and the circuit has reached some critical condition for which the arc is just unable to survive. We have pointed out that the rate of rise of voltage immediately following the extinction of the arc is essentially determined by the magnitude of the extinction current and the capacitance which parallels the gap. If the arc exists at the end of a half-cycle by virtue of a repeated extinction - re-ignition process, the final extinction current and the gap capacitance should tell us something about the recovery processes of the gap.

For example, in Table I we consider the average extinction currents, I_c, measured for each of the three reactors of this experiment with no capacitance added to the gap. These currents, when divided by stray circuit capacitance, C_c, across the device, provide an estimate of the rate of rise in voltage

TABLE I

Estimates of Voltage Rise-Rates Across Capacitance, C_c, Following Extinction of Current I_c

L (mH)	I_c (amp)	C_c (pF)	I_c/C_c (kV/μsec)	t_{100} (sec)
9.35	3.3	130	25	4×10^{-9}
3.35	3.3	87	38	2.6×10^{-9}
0.83	3.0	200	15	6.6×10^{-9}

TABLE II

Recovery Strength of 1/2-Inch and 2-Inch-Diameter Silver Electrodes 0.2 μsec after a Chopped 250 Amp Arc

Gap	1/2 In. (kV)	2 In. (kV)
0.76	4.2	7
2.3	5.2	3
4.6	5.5	2.5

immediately after the extinction. Since the arc indeed did extinguish this rate of rise can, at least early in the recovery period, be withstood by the gap without further breakdown. The extinction current measurement thus also is a recovery strength measurement. We find average voltage rise rates lying between 15 and 39 kV/μsec. The significance that we attach to those numbers will depend upon the actual mode of extinction. If the arc, in its last several microseconds of existence, survived because of a succession of instability - extinction - re-ignition events, the above rise rates should reasonably reflect actual levels of voltage rise rates that can be withstood. If, however, the arc survives in the time period just before extinction without help from the external circuit by re-ignition, these numbers should be regarded as lower limits. That is, in the latter case the rise rate of voltage will be determined by I_c/C. The gap will at least withstand this rate since the arc fully extinguished at I_c. We have no way of knowing, however, whether or not the gap might have withstood a faster rise rate since the continuous sampling of gap strength during the declining current by re-ignition voltage, as in the first case, is assumed to be absent. In either case we should note that the indicated recovery rates are appropriate to an arc extinguished at about 3 amp. Had the arc extinction occurred at different levels we might expect different rates.

Also given in Table I is the time, t_{100}, required for the rising recovery voltage to reach an arbitrarily chosen level of 100 volts. The numbers shown are meant to illustrate the order of magnitude of time that might be involved in a re-ignition event. We find that the time required for the arc current to drop to zero once extinction is certain is of the order of 10^{-8} sec.(4)

All of the data described in this report were obtained with a gap length of 1/4 inch. There are some reasons, however, for suspecting that the observed results may not be strongly dependent upon gap length. Recovery strength measurements on silver electrodes in vacuum obtained with a chopped current of 250 amp are illustrative.(3) Table II summarizes the recovery strengths for contacts 1/2 inch and 2 inches in diameter for a delay of 0.2 μsec after arc extinction for three gap lengths. With the exception of the data for the 2-inch electrode at the shortest gap, the voltage to which the gap recovers in 0.2 μsec shows no strong dependence upon gap length. This result is given some support from measurements of post arc currents from these same silver electrodes.(7) A significant quantity of charge was found present in the gap shortly after arc extinction. The decay with time of this charge was quite likely dominated by slow-moving positive ions having essentially thermal velocities. Under this condition, when voltage is applied to the recovering gap, the net charge present in the gap is redistributed such that most of the voltage appears across a thin boundary layer at the electrode surface which is negative to the high voltage. Actual breakdown is thus expected to occur across this boundary, the properties of which are not strongly dependent upon the gap length.

Similar experiments on the recovery strength of copper electrodes as a function of gap length have not been made. Holmes, Broadhead, and Edels,(8) however, have made post arc current measurements for copper under similar conditions and have found results similar to those obtained for silver. There is little reason to suspect that silver and copper behave in any significantly different way when voltage is applied to the arc residue.

In the cases we have been discussing, the arc currents just prior to extinction have been a few hundred amperes, whereas the extinction currents given in Table I are a factor of 100 smaller than this. Despite the disparity in current magnitudes, we expect that qualitatively the same kind of nonuniform voltage distribution will occur for the low current extinctions as was inferred for the chopped high current. In the low current case, the decay of current, albeit small, is roughly a factor of 10 to 100 faster than the forced decay of the of the 250 amp arc. Further, the rise-time of recovery voltage after low current extinction is extremely rapid. These considerations, coupled with the fact that perhaps 10^{-8}sec just prior to the extinction itself, there existed a burning arc with its attendant charge distribution at the cathode surface, led the author to conclude that the voltage recovery rates in Table I are determined by the properties of a decaying cathode space charge layer rather than by the separation of the electrodes.

VII. CONCLUSION

The average extinction current for 2-inch copper electrodes has been found to decrease with increasing magnitude of half-cycle arc current and to increase with increasing values of shunting capacitance. There was found to be no major difference between extinction currents measured in circuits where the arc current limitation was resistive and extinction currents measured in inductively limited circuits with shunt capacitance in the range 1000 to 10, 000 pF. In resistive circuits, the extinction current increased with increased capacitance but at a rapidly declining rate above 0.1 μF.

From measured values of extinction current and stray capacitance of the gap, it is expected that immediately after arc extinction the gap will withstand voltage rise rates of at least 15 to 38 kV/μsec.

In this report we have considered experimental chopping currents as a function of peak arc current. We should point out that we consider the rate of change of current near a sinusoidal zero as the important independent variable rather than the peak current itself, at least for peak currents for which we would expect no appreciable anode melting. Thus from a more general view, the power frequency as well as circuit impedance considerations should be important. As a longer term goal we would hope eventually to be able to relate arc extinction phenomena under AC conditions to the limiting case of DC arc stability.

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