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RECOVERY CHARACTERISTICS OF VACUUM ARCS

by

J.D. Cobine and G.A. Farrall

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ABSTRACT

A study has been made of the breakdown and recovery strength characteristics of experimental vacuum interrupters incorporating a variety of contact materials. Our data show that much of the breakdown strength for these devices is gained in less than a 1/8-inch gap length. Experiments using a synthetic test system indicate that these experimental switches recover nearly all of their breakdown strength in 1 to 15 μsec after the cessation of peak arc current ranging from 400 to 3200 amperes.

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RECOVERY CHARACTERISTICS OF VACUUM ARCS*

J.D. Cobine and G.A. Farrall

INTRODUCTION

The development of reliable vacuum interrupters for power applications required an extensive study of both the factors that influence vacuum breakdown and of those that affect the recovery of electric strength subsequent to arcing.[1]

It has long been known[2] from studies of high-voltage accelerator tubes that a high-vacuum gap possessed an extremely high dielectric strength. This information is generally useful in designing the nonarcing surfaces such as electrode supports, shields, etc., that may be at high potentials within the vacuum structure. However, since previous vacuum breakdown studies were conducted using highly polished surfaces, they were of little use for surfaces that were rough from arcing. Obviously in designing for a given open-contact holdoff voltage in a circuit interrupter it must be assumed that the contact surfaces have been arced.

The vacuum switch is unique in that the conducting medium necessary to support the arc is supplied solely by the erosion of the contacts while arcing. When the arc is extinguished, the rate of dispersion and condensation of the metal vapor determines the recovery characteristics of the switch. Some research has been published on the recovery strength of vacuum arcs.[3] However, no study had been made of vacuum arc recovery strength for a wide variety of gas-free metals. Interruption tests with some vacuum circuit breakers[4] indicated the characteristics could be very good.

It is the purpose of this report to present a study of breakdown and recovery strength phenomena with simple experimental switches from which basic information was obtained.

VACUUM ARC CHARACTERISTICS

During the "burning" period the high-current vacuum arc is characterized by a multiplicity of highly mobile cathode spots of exceedingly high current density. These "emitting" zones are quite similar to those observed[5] on mercury-pool tubes and on cold metal electrodes in

*This report was prepared for presentation at the AIEE Winter General Meeting as Transaction Paper No. 62-139.

gases at high pressure where the current density is in the range 10^5 to 10^6 amp/cm^2. Previously reported spot analyses are equally applicable.(6, 7) These spots are the principal source of vapor in the vacuum arc(8) from which metallic vapor jets represent the removal of about one atom of cathode metal for every 1 to 13 electrons emitted.(9) The vapor density in these jets may be many times the Loschmidt number (2.7×10^{19} cm^{-3}) at the cathode spot, but when expanded to a distance of 1 cm the vapor is probably reduced to a density corresponding to a gas at standard temperature and a pressure of 10^{-3} to 10^{-2} Torr. Thus if a single electron were to traverse the distance from cathode to anode, it would experience conditions from high pressure where the mean free path is of the order of 10^{-5} cm to the lowest practical discharge pressure where the mean free path is of the order of centimeters. Most of the space between the electrodes is filled with a diffuse plasma. At high currents this plasma, representing ionized metal vapor, spreads through quite a large volume surrounding the electrodes. Under these conditions there are a multitude of cathode spots and many may move to remote points on the cathodes, or its supports, where they cannot "see" the anodes, but continue to feed current into the diffuse plasma. At current zero, the cathode spots extinguish(10, 11) in times of the order of 10^{-8} sec. Residual vaporization may be negligibly small from the cathode where the tracks often suggest loss by sublimation, with no evidence of melting. It is probable that vapor from the cathode spots has little effect on the electric strength of the gap in even a time as short as 1μ sec. At moderate currents the rate of recovery of electric strength should be very great. Furthermore, it has been estimated(12-14) that the atoms leaving the cathode spot have velocities of from 10^5 to 10^6 cm sec^{-1}. The expansion in vacuum with such high initial velocities probably means that the only cathode vapor existing in the gap at the instant of current zero is that produced by current flowing in only the last 100μ sec or less. Thus the evaporation at only a relatively low current need be considered.

Although the input power density is much higher at the active areas of the cathode than at the anode, the total power to the anode is higher than that to the cathode.(6) At low currents the anode may collect current from the plasma uniformly over its surface, such as occurs in a low-pressure arc tube, or by positive probe. At higher currents distinct anode spots appear. These are always formed on the anode face adjacent to the cathode and do not appear to wander as do the cathode spots. Thus, residual vaporization from the anode after current zero will be present where it can, at high currents, have a pronounced effect on the recovery strength. However, the density of this residual vapor is expected to be relatively low and probably does not exceed that which would be produced if the anode was at its melting point. The effusion of the residual vapor from the interelectrode region is certainly complex. The development of recovery strength after current zero can be expected to reflect the decrease of vapor and ion densities from the region between and surrounding the electrodes.

RESEARCH TUBE

The devices in which measurements were made were all of essentially the same construction as that indicated in Fig. 1. It should be noted that this is a research tube and differs appreciably in construction from a commercial interrupter, although the behavior of both devices is in many respects quite similar. To each vacuum envelope, which enclosed approximately 1 liter volume, was attached an ionization gage for monitoring pressure. All metal parts of the switch were carefully outgassed and the vessel evacuated to an operating pressure of 10^{-6} Torr or less. Most of the electrodes studied were of gas-free metal produced by a specially adapted zone refining process. Surrounding the electrodes is a cylindrical shield which prevented vapor and molten metal, evolved during arcing, from striking the glass. This precaution was necessary since metal vapor striking the glass wall would release gas and raise the pressure within the vessel. Furthermore, the breakdown strength of the switch would be considerably reduced if metal

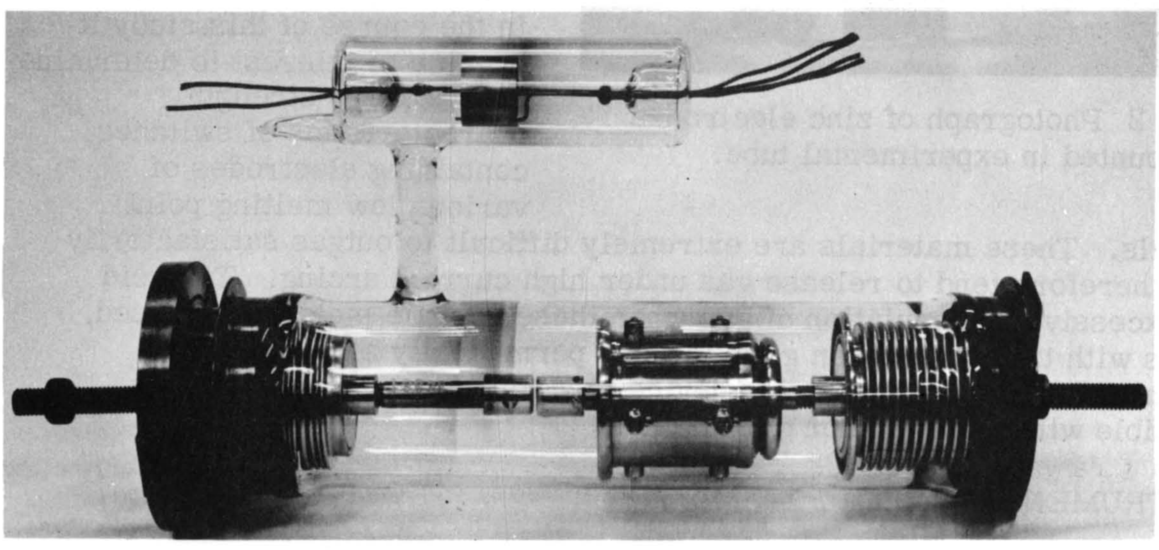

Fig. 1 Photograph of experimental vacuum interrupter.

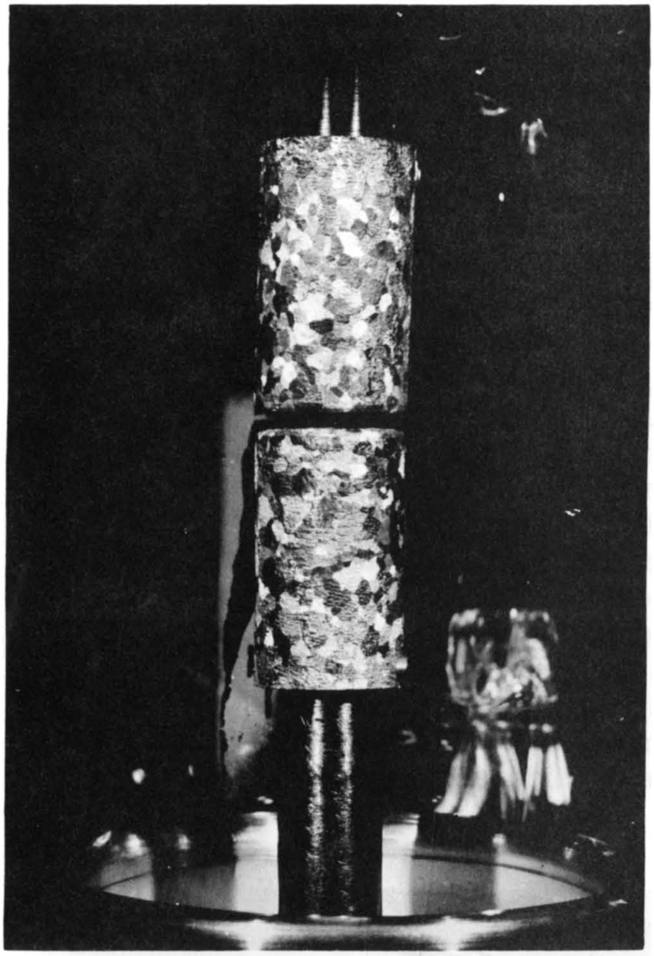

Fig. 2 Photograph of zinc electrodes mounted in experimental tube.

evolved during arcing were permitted to accumulate on the inside glass walls. The shield was mounted on quartz rollers and was movable by an external magnet so that the electrodes could be observed. Metal bellows on both ends permitted the two electrodes to be moved for alignment and operation. In Fig. 2 are shown a pair of zinc contacts, typical in size (3/4 inch diameter) and shape of most of the electrodes used in this study, mounted on supports within the sealed experimental tube. In the actual operation of the switch a mechanism was used which provided means for locking the two opposing electrodes in contact, then separating them by a solenoid. In the course of this study it became of interest to determine the recovery strength characteristics of switches containing electrodes of various low melting point metals. These materials are extremely difficult to outgas satisfactorily and therefore tend to release gas under high current arcing. To avoid an excessive accumulation of gas when these volatile metals were used, tubes with titanium ribbon getters were permanently attached. This permitted "pumping" a sealed device at a rate much faster than was possible with an ionization gage alone.

INSTRUMENTATION

The system used to measure arc recovery strength has been described elsewhere(15) and so will be discussed only briefly here with aid of Fig. 3. The system performs the following operations in the

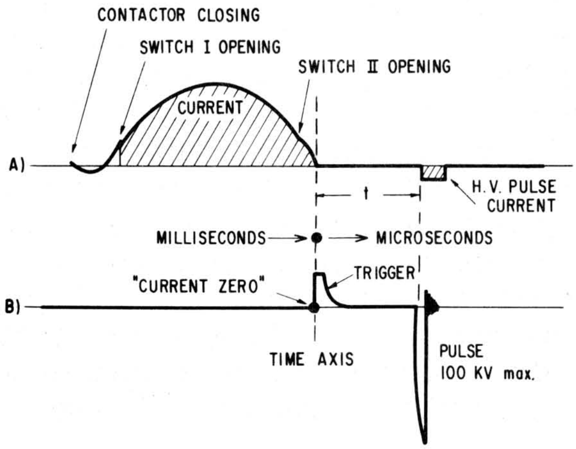

Fig. 3 Temporal relation of events in the recording of arc recovery strength.

sequence given: (1) one-half cycle of 60-cycle arcing is produced in the test switch; (2) the test switch is electrically isolated from the source of arc current; (3) the end of the half-cycle of arcing is noted and after a predetermined time delay, measured from this instant, a high-voltage pulse is applied to the test switch; and (4) the time delay and the voltage at which breakdown of the switch occurs are photographically recorded. This sequence of events is started by initially having the two switches in a closed position. A contactor from a 115 a-c current source is synchronously closed so that current flows in the two closed switches at the beginning of a 60-cycle half-cycle. Shortly after current is established the test switch (I) is opened, by means of a solenoid, drawing an arc. Later in this same half-cycle the backup switch (II) is opened. The two arcs "burn" for the duration of that half-cycle but extinguish when the current goes through a normal zero, due to the low voltage of the current source. At the instant of current zero a trigger signal is obtained from a peaking transformer from which all delay times are measured. This pulse serves to trigger a delay unit. The output of the delay unit triggers the high-voltage pulser which ultimately results in breakdown of the test switch. The maximum output voltage of the pulser is slightly in excess of 100 kv with a rise time of 0.2 μsec and a pulse duration of 2 μsec. A capacitance divider across the switch under test provides the input to a Tektronix type 517 oscilloscope (or type 545 modified for 12.5 kv accelerating potential) on which the breakdown voltage of the switch is recorded. Breakdown in the test switch results in an easily detected signal at the output of the coaxial shunt used to measure the current, which is observed on the Tektronix 535 oscilloscope. This instrument is triggered at current zero and therefore records the actual delay time between current zero and the applied high-voltage pulse. At short delay times this measurement is essential since, as the a-c arc current approaches zero, there are likely to be many arc instabilities which will cause a premature signal to appear at the output of the peaking transformer. One obvious risk in using this system is the possibility that breakdown will occur not in the test switch but in the backup switch. This latter switch must be selected, therefore, to have greater dielectric strength than the switch under test and must be opened later in the half-cycle of current so that less arcing occurs and a more rapid recovery is possible. Each operation of the total system as just described results in a single experimental data point. This method of determining arc recovery strength has wide application and has been used in experiments on ignitrons, thyratrons, gases at atmospheric pressure, [16] and vacuum switches.

VACUUM BREAKDOWN

In a discussion of arc recovery strength it should be pointed out that the ultimate voltage that a switch can withstand after arcing approaches as an upper limit, the breakdown voltage observed under static conditions with no arcing. The static breakdown characteristics of a switch are therefore an indication of the maximum recovery strength that can be expected.

The breakdown strength of a vacuum gap has been found historically to be far superior to that of atmospheric gases. [2] Typically the voltage that a gap can sustain decreases with reduced pressure (actually density) to a minimum and then begins to rise rapidly with further reduction of ambient gas density. This is illustrated in Fig. 4 which shows an idealized Paschen curve where breakdown voltage is plotted as a function of (pressure) x (gap length). When the pressure is reduced below the point where the mean free path is of the order of the tube dimensions, about a micron in many practical cases, the breakdown voltage ceases to be dependent upon the gas within the vessel and is influenced most strongly by the composition, condition, and arrangement of the electrode surfaces and the walls of the tube. This transitional range is shaded in Fig. 4. Below this transition the relative independence of breakdown on gas density is illustrated in Fig. 4 by plotting breakdown voltage vs gap length, d, instead of pd. Contrary to what is observed for the left branch of the normal Paschen curve, vacuum breakdown voltage decreases when the gap length is reduced. Vacuum breakdown initiation like the vacuum arc, must depend upon products evolved under the action of high fields from the electrodes and walls which are bombarded by field emitted electrons, rather than upon the medium in which the electrodes are immersed.

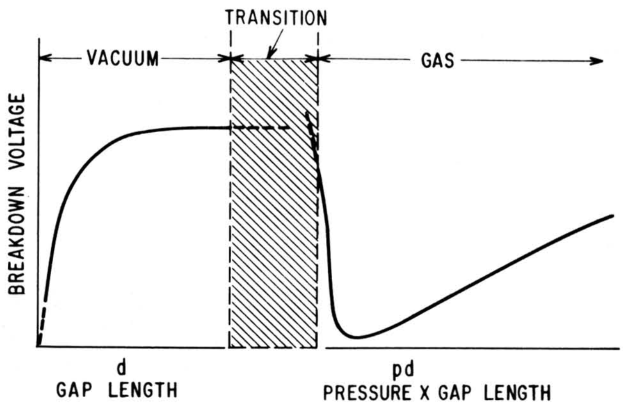

Fig. 4 Schematic Paschen curve and its relation to breakdown in vacuum as a function of gap length.

The actual value of breakdown voltage for a given gap depends quite strongly upon the condition of the electrode surfaces. Highly polished and thoroughly outgassed electrodes have shown particularly high breakdown voltages.(2) Contacts in a vacuum interrupter while having excellent voltage withstand ability cannot be expected to have properties identical with polished surfaces since the interrupter is required to hold off high voltage immediately after an arc has scoured and roughened the contacts. Measurements on Bi-Cu showed a decrease in breakdown strength after arcing to about 70 per cent of the non-arced measurement on rough contact surfaces. In general, improvement in breakdown strength after arcing can be obtained by applying successive high voltage impulse sparks. This does not alter the arc-roughened surfaces to any noticeable degree but probably does remove loosely adhering metal particles(17) from the electrodes deposited there by the vapor blast during arcing.

The breakdown strength of a series of experimental switches was determined by using the pulse generator of the recovery strength system in the absence of the arcing circuit. Figure 5 shows the average static breakdown voltage vs gap length for several rough surfaced electrode materials in a vacuum of the order of 10^{-6} Torr. Similar breakdown data for nitrogen are shown for comparison. The initial rapid rise in breakdown voltage for the vacuum case is to be noted. Most of the materials shown here gain much of their ultimate breakdown strength in less than a 1/8-inch gap for the particular geometry shown. Such a characteristic permits the use of short gaps in vacuum switches which results in simplifying the operating mechanism and in increasing the speed of operation over conventional switches in practical applications.(18) The curve for zinc beyond a gap length of 0.5 mm is not

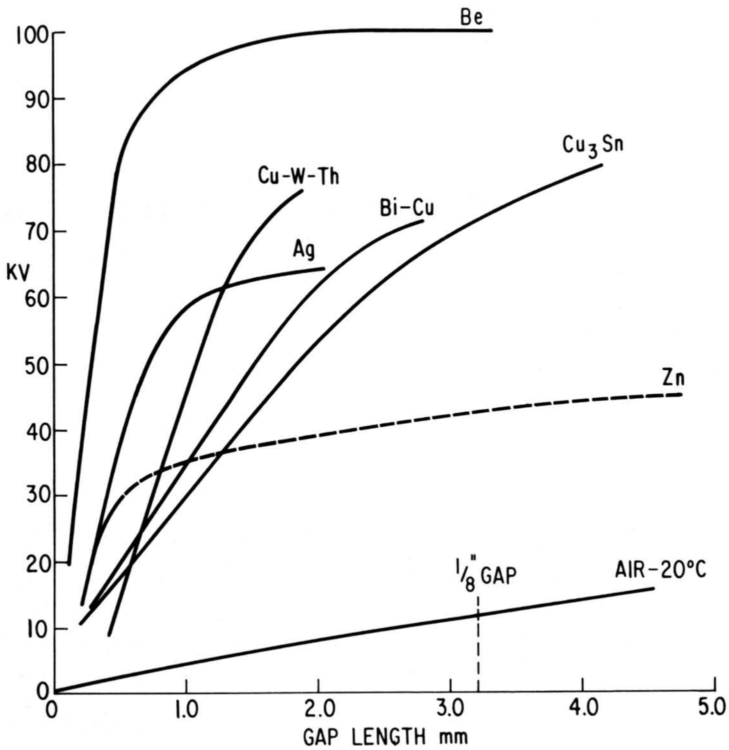

Fig. 5 Static breakdown characteristics for various electrode materials in vacuum.

characteristic of breakdown between the electrodes. Due to the rather high vapor pressure of this material, the inside surface of the glass envelope had, in certain areas, an opaque coating of metal deposited during a low temperature bakeout and limited arcing before the breakdown characteristic was determined. The fact that the dotted curve for zinc in Fig. 5 rapidly approaches a limiting breakdown voltage beyond the 0.5 mm gap length was largely determined by the increasing probability of a discharge to the coated walls rather than across the gap. This again emphasizes the need for adequate shielding of the insulating walls of a vacuum switch from the metal vapor eroded from the electrodes during arcing.

EXPERIMENTAL RECOVERY STRENGTH STUDY

To gain an initial perspective of the arc recovery strength characteristics in vacuum, measurements for electrodes of copper, which has been subjected to a zone refining process specially adapted to gas removal, in vacuum are compared with similar measurements for contacts in nitrogen at atmospheric pressure in Fig. 6. The electrodes in the latter case were of tungsten impregnated with zone refined copper. Both gaps were 1/4 (± 1/32) inch while the peak of the

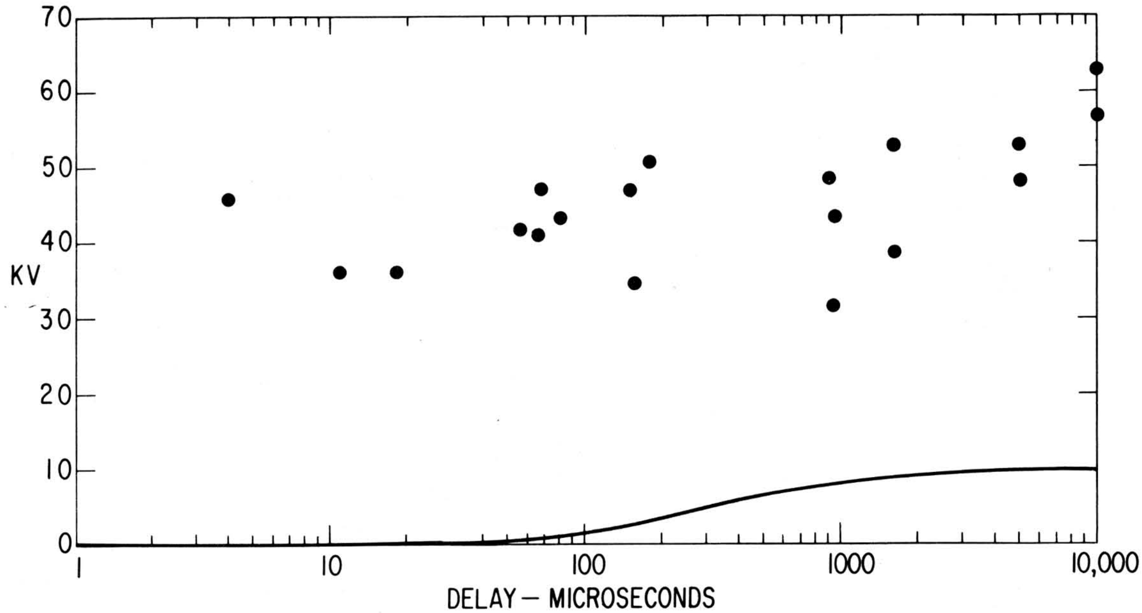

Fig. 6 The arc recovery strength of an experimental vacuum interrupter compared with that of a nitrogen filled device; ● solid curve for nitrogen points for vacuum at 1600 amps.

half-cycle of arc current was 1600 amperes. The nitrogen requires several milliseconds before it recovers a significant portion of its static breakdown strength. The rapid initial recovery of the vacuum characteristic is typical of most electrode materials in vacuum. Two significant advantages of the vacuum gap over an air gap are apparent in Fig. 6: (1) the high dielectric of the vacuum gap itself, and (2) the rapid recovery of this breakdown strength. It would therefore appear that if certain requirements are met in addition to voltage withstand ability, vacuum is an excellent medium for commerical interrupter use. In this study several electrode materials were examined for their recovery strength in the current range 400 to 3200 ampere peak. All gap lengths were adjusted to 7/32 inch.

Low reignition voltages after arcing might be expected for various reasons. It is obvious that rapid dispersal of metal vapor and arc plasma must be accomplished before the gap can be expected to withstand high voltages. Electrode metal must be free of gas. An excess of thermionically emitted electrons from localized "hot spots" on the "cold" anode surface may also alter the breakdown characteristics of the gap. Some of these problems are considered below.

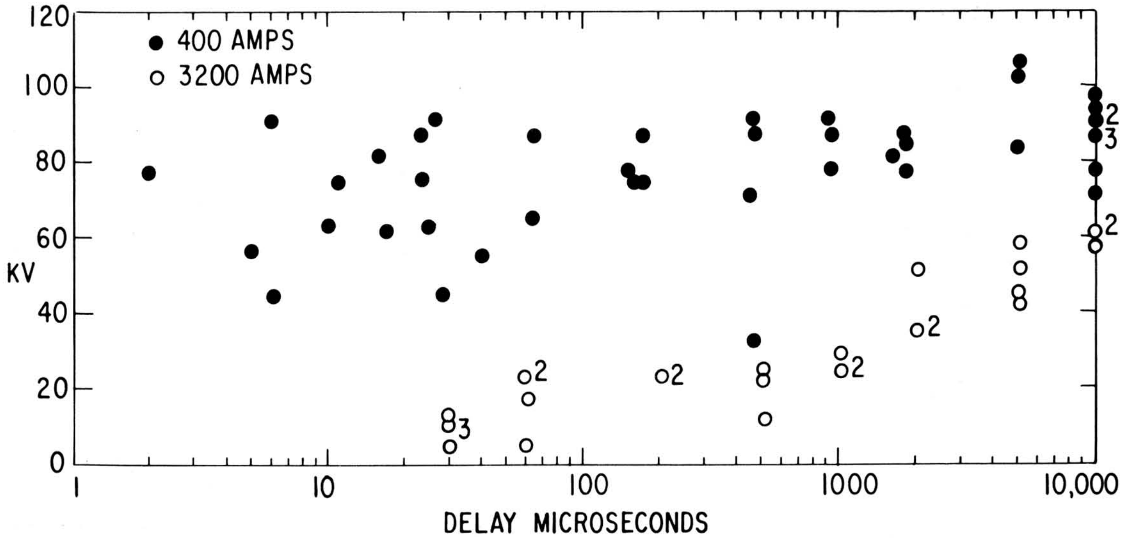

Fig. 7 Arc recovery strength characteristic for beryllium and its deterioration at high current.

Measurements for a switch using highly refined, but not entirely gas free beryllium, are shown in Fig. 7 as currents of 400 and 3200 amperes. Intervening tests at 1600 amperes show substantially the same characteristic as that of 400 amperes. Both of these curves show high reignition voltages even 1 μsec after current zero. The data points for 3200 amperes were taken in a sequence which began with the long delay times and progressed to the short delays. After conclusion of the recovery strength measurements at this current the static breakdown of the switch was found to be of the order of 30 kv and hardly better than the reignition values which appear at short delays in Fig. 7 at 3200 amperes. Furthermore, the low breakdown voltage could not be improved by further sparking. It therefore became clear that the gradual reduction in recovery strength shown in this figure was actually a deterioration of the vacuum within the vessel and did not reflect the recovery strength of a switch in usable condition. Although the experimental tube used in this study was equipped with an ionization gage, the pressure within the beryllium device after the high current tests could not be determined since its gage was damaged in previous testing. The condition of the switch therefore had to be assessed from the observed breakdown voltage. There is little doubt, however, that the deterioration of recovery strength for this switch on the high current curve was due to the release of excessive quantities of gas from the beryllium as a result of severe arcing. This type of failure plagued[1] earlier experimenters in the vacuum switch program who lacked gas-free non-refractory metals for contacts.

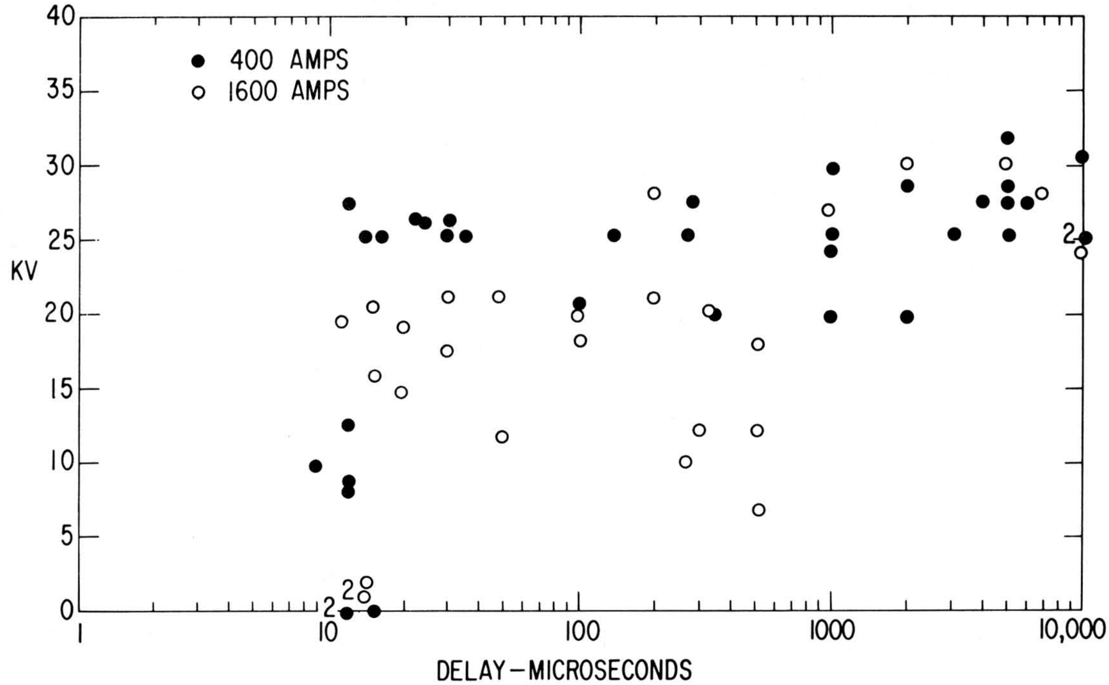

Fig. 8 Arc recovery strength characteristics for zinc contacts.

It was mentioned earlier that one of the requirements for rapid recovery was that the interelectrode region be cleared of erosion products from the action of the arc on the electrodes. Zinc, which has high vapor pressure, provides a good illustration of the low reignition voltage that can occur at short recovery times, as a result of an excessive metal vapor density. Data on a switch using recast specially zone-refined zinc for contacts at 400 and 1600 amperes are shown in Fig. 8. The low points at 10 μsec are to be noted. It is further seen that relatively low reignition voltages were measured at 1600 amperes even as long as several hundred microseconds after current zero. These are both due to the excessive vapor present at current zero. It may be recalled from the earlier discussion of the static breakdown characteristic for this switch that there was an appreciable coating of zinc on the inside of the glass envelope. The ultimate recovery strength for this switch like the static breakdown probably represents failure to the walls of the tube rather than across the gap.

A contact material having somewhat greater recovery strength is the intermetallic compound Cu_3Sn as seen in Fig. 9. The peak

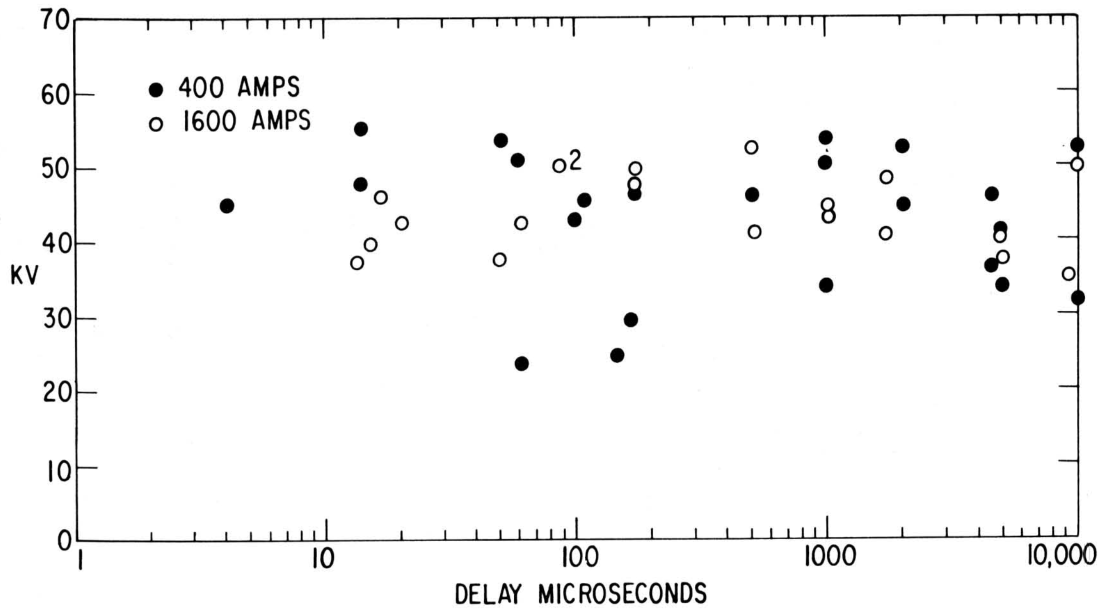

Fig. 9 Arc recovery strength characteristics for Cu_3Sn contacts.

currents used here were 400 and 1600 amperes with the data for the latter current again shown by circles. It is to be noted that the recovery strength at both currents is approximately the same and does not vary greatly for delay times longer than 15 μsec after arc extinction. This behavior was observed on most of the switches for which we have data. That is, the vacuum switch recovers most of its electric strength in less than 15 μsec. In the literature on vacuum breakdown, refractory materials have been shown to have the higher breakdown voltage for polished electrodes, than the less refractory metals.[19] There are, however, reasons mentioned elsewhere[20, 21] for preferring the less refractory metals in certain applications.

Experiments on a switch incorporating thorium bearing contacts illustrate the possible effect of thermionic emission on recovery strength. The electrodes were of tungsten to which 7 per cent thorium had been added. This was sintered and the matrix impregnated with copper. The static breakdown of these contacts was found to be rather high (see Fig. 5) so that the long time delay recovery strength is also expected to be high. The data for peak currents of 400 and 1600 amperes are shown in Fig. 10. At the lower current it is seen that the reignition voltages are relatively high except for the two points at 1 and 3 μsec. At 1600 amperes, however, a drastic reduction in the recovery characteristic takes place as is outlined

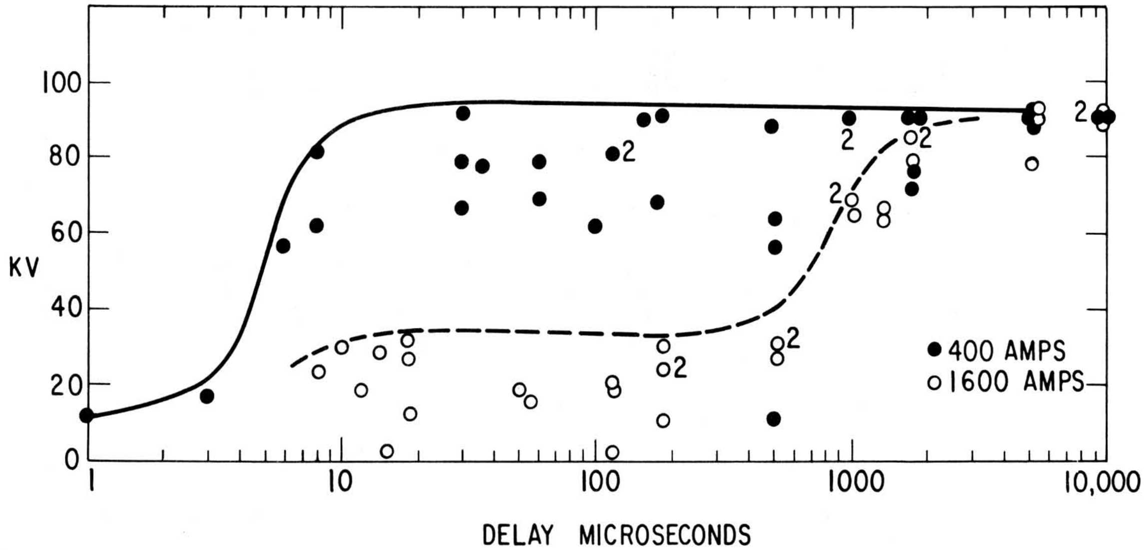

Fig. 10 Arc recovery strength characteristics for Cu-W-Th contacts.

by the dashed curve in Fig. 10. This long delay is undoubtedly due to residual thermionic emission from the former anode contacts still cooling from the localized high temperatures produced by the half-cycle of arcing.

The recovery characteristics for silver contacts at currents of 400, 1600, and 3200 amperes are given in Fig. 11. The rapid initial recovery strength of the vacuum switch at all three currents is illustrated here. It is also seen that the recovery strength at all three currents is substantially the same. Experiments on this silver switch, Fig. 11, gave results which do not differ from those of other contact materials tested, such as an alloy of Cu-In, the intermetallic compound Cu_3Sn, and pure copper.

In Fig. 12 is shown the recovery data obtained for Bi-Cu at 400 and 1600 amperes. An unexpected result of these data and that for other switches is that recovery strength in the range 400 to 3200 peak amperes seems to be higher at higher currents. It is possible that at higher currents the cathode spots move rapidly away from the center and over the outer electrode surface, producing less evaporated metal vapor in the interelectrode region.

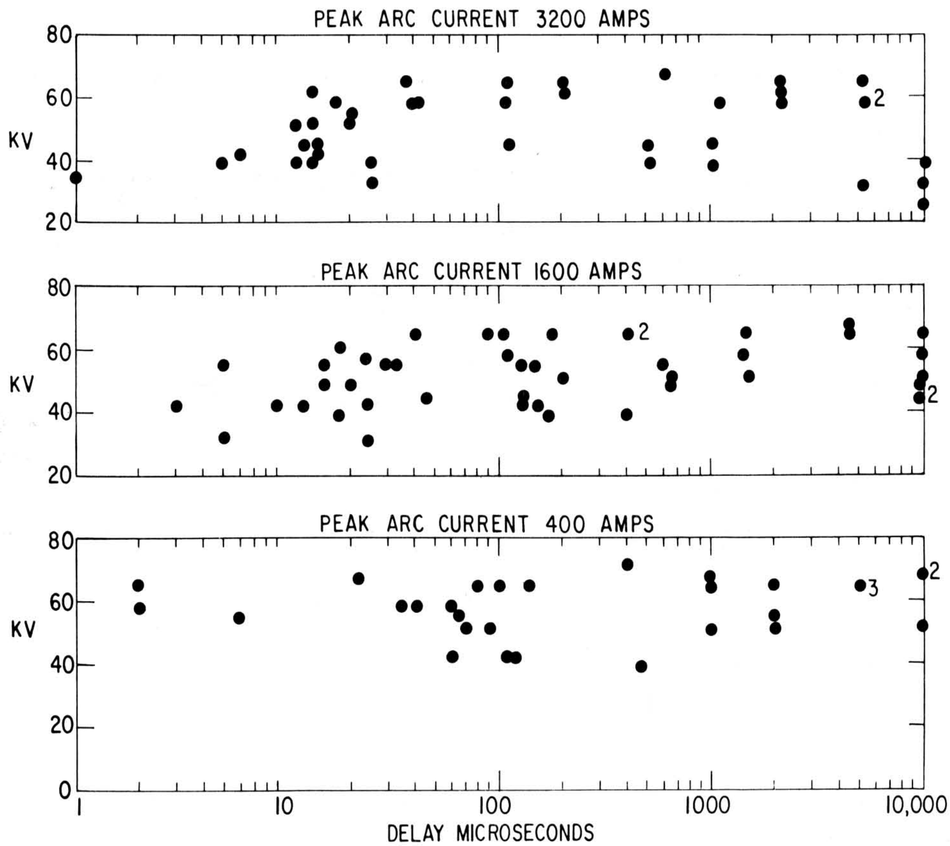

Fig. 11 Arc recovery strength characteristics for silver contacts.

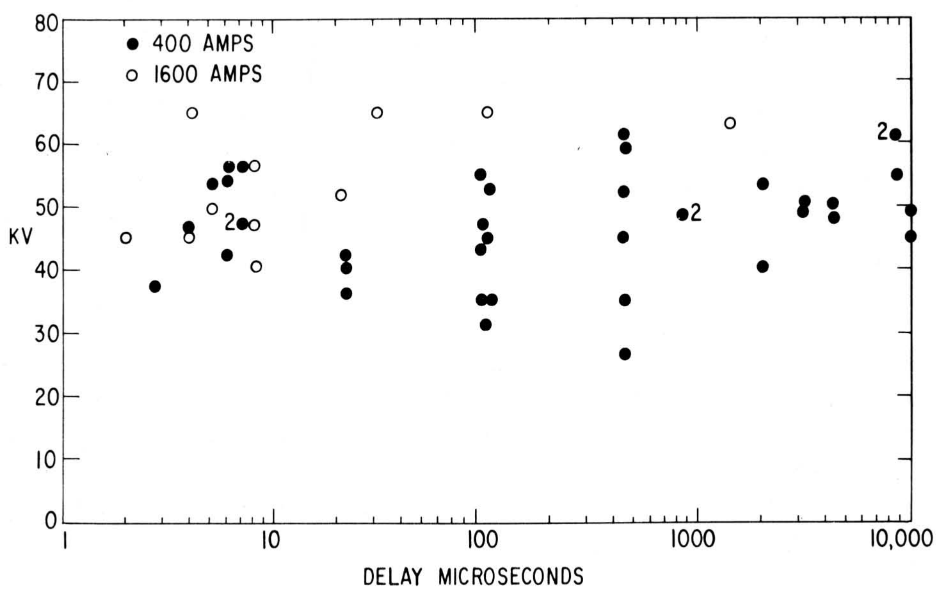

Fig. 12 Arc recovery strength characteristics for bismuth copper contacts.

DISCUSSION

We have already mentioned that the ultimate recovery strength of a switch can be no better than the static vacuum breakdown voltages of the contact material. In 1956, Rozanova and Granovskii[19] performed experiments on vacuum breakdown, the results of which indicated that the static breakdown voltage is related to the mechanical strength of the electrode material. They suggested that the Cranberg clump theory for the initiation of vacuum breakdown might be applicable, if modified to include the concept of metallic particles being torn from an electrode surface in the presence of high electric fields. This combination of ideas is given qualitative support from the recovery strength data on the switches discussed. Zinc might be expected to be low because of low mechanical strength and an abundance of loose metal particles on the electrodes after arcing. Copper-tin, while still mechanically quite brittle, would not be expected to produce the abundance of free particles as would the zinc.

Nothing has been said thus far of the scatter in the recovery strength curves presented. In our experiment a high-voltage pulse of constant rate of rise (100 kv max) is applied to a gap and is expected to cause breakdown in the gap. The voltage at which breakdown occurs is measured oscillographically. Variations in breakdown voltages for the vacuum gap with polished electrodes have been found in the past; it therefore is not unexpected that a similar scatter of breakdown voltages should occur to a higher degree when the contact surfaces have been roughened by arcing. An experiment can of course be performed in which reignition voltages for a given delay time by definition has a unique value. That is, if the value of reignition voltage is defined as that peak pulse voltage which produces breakdown at a given delay time N out of No trials, the observed value becomes unique. The statistical distribution of values in this case however is contained in the collection of N_0 applied pulses, some of which produced breakdown, some which did not. Our method of presenting actual breakdown values also differs from conventional criterion for testing switching devices wherein the question of interest is most commonly that of whether or not an interrupter can clear a rated current at a given system voltage and natural frequency--that is, a "yes" or "no" answer is required. When the performance of an experimental switch was studied both on an a-c system and by the impulse system, the impulse recovery strength was somewhat lower than the a-c reignition voltage. A knowledge of the voltage at which a vacuum gap fails, however, can provide a sound basis for evaluating the power handling ability of a given device.

CONCLUSION

In the light of the data presented, perhaps the most important part in the construction of a vacuum switch is the selection of contact material. This point is given further emphasis when application requirements other than recovery strength are considered. The rapid recovery strength in the vacuum switch after current zero is demonstrated in all of the data discussed. The vacuum switch is unique in its ability to withstand high voltage after extinction of high-current arcs, and is therefore well adapted to high-current, high-voltage commercial applications.

ACKNOWLEDGMENTS

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SECTION: Physical Studies

DEPARTMENT: General Physics Research