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RECOVERY OF VACUUM GAPS AFTER ARCING

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ABSTRACT

This paper reviews the recovery of vacuum gaps: i.e., the return of the voltage holdoff capability of a vacuum gap after it has ceased to sustain a vacuum arc. After a brief description of vacuum arcs, the paper discusses cathode and anode arc phenomena as they affect recovery. Finally, various experimental results pertinent to recovery are presented and discussed.

During conduction a vacuum gap contains electrons, ions, neutral atoms (vapor), and macroparticles of electrode material. At current zero the production of electrons, ions, and macroparticles ceases immediately. If an anode spot is present it will take tens of microseconds to milliseconds for significant production of neutral vapor to cease; the time depending upon the rate at which the anode spot cools, which in turn depends upon the anode material and upon the size and depth of the anode spot at current zero. Early recovery is controlled by ions, later recovery by neutral atoms. The ultimate recovery voltage is a function of electrode surface properties. Magnetic fields may be used to promote recovery by helping to clear the vacuum gap of ions and electrons and by preventing the formation of anode spots or moving them before current zero.

The most important requirement in obtaining the fastest recovery times is to design the vacuum gap to avoid the formation of anode spots, thus insuring that only cathode recovery phenomena are significant.

An earlier version of this paper was prepared as a section of the chapter, Vacuum Spark Gaps, in a book, Gas Discharge Closing Switches, editor, G. Schaefer, to be published by Plenum Press.

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INTRODUCTION

Operation of vacuum gaps often involves the occurrence of an arc between the electrodes of the gap. This arc is traditionally referred to as a vacuum arc, although a metal vapor arc is a more precise definition since the carriers of the arc current come from one, or both, electrodes. The magnitude of the arc current can be the normal operating current of the external circuit, as in motor switching or pulsed power applications, or it can greatly exceed the normal current, as in the occurrence of faults on electric power systems. The proper performance of a vacuum gap often depends upon its ability to successfully interrupt such currents and to subsequently withstand an appreciable voltage across the gap without breaking down. It is this subject, the recovery of vacuum gaps, i.e., the return of the voltage holdoff capability of a vacuum gap after it has ceased to sustain a vacuum arc, which is the subject of this paper.

Vacuum gaps may be divided into three main types, as shown in Figure 1 and described in Table 1. Vacuum interrupters (VI) usually have two metal electrodes, which are normally in contact when carrying a continuous current and are separated when interrupting a current. The electrodes usually are operated mechanically, being closed to start operation and opened to initiate an arc, which is then interrupted. The VI has the advantage of metal-to-metal contact during normal operation, thus offering minimal power losses and longer operating life. This advantage is perhaps more important in utility power system applications than in pulsed power applications.

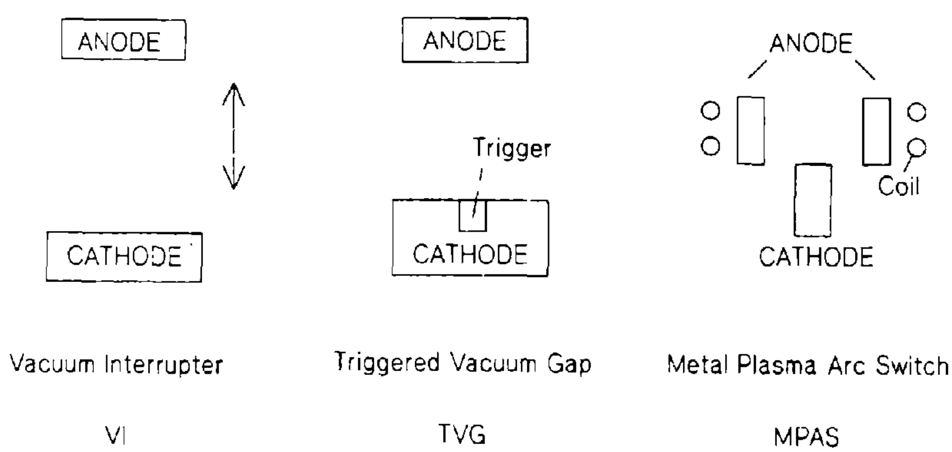

Figure 1. Types of Vacuum Gap Devices

Table 1. Characteristics of Types of Vacuum Gaps

Type	Characteristic Metallic Conduction	Arc Voltage	Triggerable?	Turn off Possible?
Vacuum Interrupter (VI)	Yes	Low	Yes*	Requires Current Zero or External Circuitry
Triggered Vacuum Gap (TVG)	No	Low	Yes	Same
Metal Plasma Arc Switch (MPAS)	No	Moderate	Yes	Yes

*Possible with laser or a separate trigger.

Triggered Vacuum Gaps (TVGs) also have two metal electrodes but, in addition, contain a trigger which may be built into either electrode or which may be a separate third component. TVGs are frequently used as closing switches because their operation, initiated electrically instead of mechanically, can be much faster than with VIs. However, the lack of direct contact between the electrodes in the TVGs means that they are much less suitable than VIs to carry continuous currents. In power system applications, TVGs may have triggers in both electrodes or a trigger separate from either electrode. This could include an external laser trigger. For direct current (dc) or unipolarity applications, a built-in trigger is normally installed in the cathode. Designs combining the attributes of both a VI and a TVG are also used, such as a TVG with provision for bringing the electrodes into contact, or a VI which can be triggered.

Metal Plasma Arc Switches (MPAS) usually have a coaxial arrangement with an annular anode. The initiation of a current in a MPAS is usually done with a trigger. The application of an external magnetic field is used to extinguish the arc in a MPAS. The great advantage of a MPAS is this ability to turn off the arc when desired, without requiring additional external circuitry or having to wait for a natural current zero. However MPASs possess the disadvantage of having arc voltages of hundreds of volts when operating in their conducting mode, so they suffer from severe power losses when handling high currents.

This paper will focus mainly on the recovery of VIs, and also TVGs, which exhibit similar recovery behavior. The recovery of MPAS will be included when discussing the effect of magnetic fields on the recovery of vacuum gaps.

All current carriers in a vacuum arc must have their origin at an electrode, because there is no significant ambient source. Particular carriers may be produced in the gap, but their neutral precursors come from an electrode. During the conduction of current through a vacuum gap there exists an equilibrium between the production and loss of current carriers. The loss of current carriers from the gap includes the flow of current carriers to the electrodes (which must equal the current through the external circuit) and the flow through the sides of the gap to the surroundings. The production of current carriers is predominantly at the electrodes, although some ionization may occur in the gap under the proper conditions.

When the current through the gap is extinguished, production of carriers at the electrodes ceases and the population of carriers in the gap dissipates. Then, after a finite time no current carriers are present; the gap can sustain its full voltage and may be said to have fully recovered. However, a sufficiently high voltage applied to the gap while current carriers are still present will cause the production of carriers to restart and the population of carriers in the gap to increase until the gap is carrying a current limited only by the external circuit. In this case, the vacuum gap has failed to recover. The recovery of a vacuum gap requires that the population of carriers in the gap and the production of carriers or precursors at the electrodes be less than the quantity necessary to sustain an appreciable current, and that they remain below this limit when a recovery voltage is applied to the gap.

Before discussing the details of recovery in vacuum gaps, a brief description of a vacuum arc will be presented for background purposes. A good general reference on vacuum arcs is Lafferty [1]. (Note that the list of references is not complete. Recent papers, especially review papers, are emphasized; thus, the references are not necessarily to the original works on a particular subject.)

A vacuum arc may be divided into three regions: cathode, column, and anode. The column in a vacuum arc consists only of material produced in the cathode or anode regions. Thus unlike other types of arcs, where the column can be the dominant feature of the arc, the column in a vacuum arc is a secondary effect. Its relative importance, or even presence, depends upon the length of the gap. The vacuum arc, therefore, will be described primarily in terms of the anode and cathode regions, which can strongly influence each other under the proper conditions.

CATHODE REGION

The cathode region is a source of electrons, ions, neutral vapor, and macroparticles [2]. (The term macroparticle is used to denote a clump of neutral atoms, which can range in size from micron-sized clusters to droplets.) The current at the cathode consists primarily of electrons emitted from the cathode, with a significant contribution from ions incident upon the cathode. The emission of electrons from the cathode is caused by the combined effects of intense local electric fields and high local temperatures. This emission is described by the equations of Thermal-Field emission [3]. The ions are produced in a region of high density plasma just above the area where the electrons are emitted. This area where the electrons and ions are produced is usually referred to as the cathode spot. The ions are produced with energies corresponding to potentials well above the cathode drop, in fact to potentials significantly greater than the overall arc voltage [4,5,6,7,8]. Unlike gas arcs, in vacuum arcs a significant fraction of the current consists of ions traveling from cathode to anode. The ion flux leaving the cathode region amounts to about 7% to 10% of the overall arc current [9,10].

Macroparticles of cathode material are also emitted from the cathode. Most of these macroparticles are emitted in directions near the plane of the cathode. The relative amount of macroparticles depends strongly on the particular electrode material.

A small quantity of neutral vapor is emitted from the cathode, most probably not directly from the cathode spot region, but rather from a part of the cathode surface where the cathode spot had been [11]. Significant quantities of neutral vapor can be present in the gap, but this neutral vapor is produced mainly by evaporation from the macroparticles emitted from the cathode [12,13,14].

Good reviews of cathode phenomena are those of Lyubimov and Rakhovskii [15] and Hantzsche [16].

ANODE REGION

The anode region can also be a source of ions, electrons, vapor, and macroparticles. Unlike the cathode, which must be an active site of phenomena for there to be a vacuum arc at all, the anode is not necessarily an active electrode. In fact, the anode region in a vacuum arc can operate in five different modes depending upon conditions (electrode material and geometry, arc current waveform, etc.) [17]. In one low current mode the anode is completely passive, acting only as a collector of flux emitted from the cathode. A second low current mode can occur if the anode material is readily sputtered, then a small flux of sputtered anode material is present. In both of these low current modes, the behavior of the vacuum arc is primarily determined by the cathode. A third mode can appear at intermediate currents. In this mode the anode begins to take an active part in the vacuum arc, but the overall arc behavior is still dominated by the cathode. The remaining two modes are high current modes where an anode spot (or spots) appears. An anode spot usually covers a significant part of the anode surface, has a temperature near the atmospheric boiling point of the electrode material, and is a copious source of vapor and ions. Anode phenomena have been reviewed by Miller [18].

RECOVERY MECHANISMS

As mentioned previously, the recovery of a vacuum gap requires: (1) that the population of current carriers (charged particles) in the gap and the production of such carriers or precursors at the electrodes be less than the quantity necessary to sustain an appreciable current; and (2) that the density of current carriers remains below this appreciable current limit when a recovery voltage is applied to the gap.

Recovery is defined thus because of the two ways by which a vacuum gap can fail to sustain a recovery voltage. If the gap ceases to conduct current, but a sufficiently large recovery voltage is applied, then electrical breakdown occurs across the gap and the gap again conducts a current. This type of recovery failure is called "dielectric" breakdown. Dielectric breakdown occurs because of either the geometry and material of the vacuum gap (an interelectrode vacuum breakdown) or the density of neutral vapor in the gap (a low pressure breakdown). A preceding arc affects dielectric breakdown by the changes it may have caused to the electrodes, specially the surfaces, and also by the neutral vapor it generated.

The second type of recovery failure occurs if a significant amount of residual charge is still present in the vacuum gap when the recovery voltage is applied. The application of recovery voltage in this case will cause a movement of the residual charge (i.e., a residual current). The combination of residual current and recovery voltage may supply enough power to the gap so that the current increases rather than decreases. The current can then increase to the point where it is limited by the external circuit, effectively causing the gap to fail. This type of failure is called "thermal" breakdown because of its similarity to breakdowns in gas gaps, where the primary failure mode is heating of the gas. In a vacuum gap, however, a thermal failure usually implies excess power input to the electrodes. Both types of failures described can occur in any switch, the relative importance depending strongly upon the particular type of switch (oil, gas, solid-state, vacuum, etc.), and upon the current and voltage waveforms.

Since the voltage of vacuum arcs is relatively low, recovery of a vacuum gap normally requires that the current go to zero at some point. This current zero is inherent when interrupting alternating currents. However, vacuum gaps can interrupt direct currents with the aid of external circuitry [19,20,21]. Recovery of vacuum gaps can also be produced or aided by external magnetic fields [22,23,24,25]. General discussions of vacuum arc recovery phenomena have been presented by others [26,27,28,29,30].

Recovery in low current vacuum gaps is controlled by cathode phenomena, since the cathode is always an active electrode. Anode phenomena become important only when considering recovery of high current vacuum gaps. Recovery mechanisms for cathode and anode phenomena will be discussed, first separately, and then together.

CATHODE PHENOMENA RECOVERY

Cathode spots turn off very quickly, so at current zero usually there is effectively no further emission from the cathode. The recovery, therefore, depends upon the material present in the gap at the time of current zero (electrons, ions, neutral atoms, and macroparticles) and the applied recovery voltage waveform.

However, Smeets has shown that under certain conditions [high di/dt from either forced current zeros (reverse current injection) or arc instabilities (as current chopping)], a conducting shield (if present) can serve as a temporary auxiliary anode. In this case, current can flow from the cathode to the shield even after the current to the anode has ceased. This permits the continuing existence of cathode spots on the cathode, so that "...current zero in the cathode current is reached several hundreds of ns after current zero of the anode current."[31]

Estimates can be made of the influence of vapor in the gap at the time of current interruption on the subsequent ability of the gap to hold off the recovery voltage. Typically such estimates assume that the gap has recovered when the density of neutral vapor in the gap has decreased to the point at which the mean free path for electrons in the vapor is longer than the gap. Rich and Farrall obtained reasonable predictions for the recovery of 250-A vacuum arcs on silver electrodes using such considerations [32].

The decay of neutral vapor density in the gap milliseconds after current zero is much slower than would be expected from calculations of the time necessary for the initial neutral vapor present in the gap at current zero to dissipate [12,33]. This slower decay at later times is probably caused by the presence of a significant source of neutral atoms in the gap for a time after current zero. Theoretical calculations based on the assumption that these neutral atoms are produced by evaporation from cooling macroparticles in the gap are in good agreement with the experimental data [12,34].

Ions are also present in the gap after current zero. Using experimental values for the energy of the ions produced by the cathode spots during the vacuum arc, one can predict the rate at which the ions should leave the gap. As expected, removal of the ions is faster for gaps with small spacing and large electrodes. The initial decay of ion density in the gap agrees well with the decay predicted using the steady-state ion energies, however, later decay becomes appreciably slower than predicted. Bauer and Holmes found that this slower decay could be explained by assuming that a burst of low energy ions appeared at the time of arc extinction [35,36]. Dullni, Schade, and Gellert found that significant quantities of very low energy ions ($E < 1$ eV) were present in their vacuum gap immediately after current zero [37]. They concluded that the initial recovery of the gap was controlled by the density of charge carriers in the gap. Similar conclusions were reached by Smeets [31].

With no electric field present, the decay of the ion-electron plasma is controlled by the rate at which the ions leave the gap. If an electric field is present (e.g., from a recovery voltage), the ions and electrons will tend to separate and form voltage sheaths at the electrodes. If voltage is applied immediately after current zero, these sheaths can result in electric fields on the order of 10^7 V/m [28,38,39].

The macroparticles present in the vacuum gap at current zero have little effect upon immediate recovery, except for their action as a source of neutral atoms after current zero. It has been suggested by Rylskaya and Pertsev that such macroparticles may contribute to breakdowns of the gap occurring long after recovery would normally be considered to be complete (such late breakdowns are often called "delayed" breakdowns, since they occur tens or hundreds of milliseconds after current zero) [40]. Macroparticles present on a electrode surface and subsequently detached may also contribute to such delayed breakdowns. When power frequency alternating voltages are present, a macroparticle inducing a breakdown may make several passages across the gap before the breakdown occurs.

At currents from a few amperes to a few hundred amperes, the density of material in the gap is low enough that ion-ion and ion-neutral collisions may be neglected. This is a free-fall, or ballistic regime, where ion motions may be modeled as individual trajectories. Because the production of ions and neutrals at the cathode is proportional to the arc current, as the current increases so does the density of ions, neutrals, and macroparticles in the gap. Eventually ion-ion and ion-neutral collisions become important and, finally dominate. The interelectrode motion of material may then be modeled as a collision-dominated fluid flow [41]. In such a higher density regime, recovery would be expected to be slower than in the ballistic regime for two reasons: there is more material in the gap, and the collisions retard its decay.

ANODE PHENOMENA RECOVERY

While the anode can be active in low and intermediate current modes, it normally dominates recovery only in the two high current modes, that is, when an anode spot is present. If the electrodes are composed of readily sputterable material, then even at relatively low currents a flux of atoms will leave the anode. Some of these sputtered atoms may be ionized by the flux of electrons, thus contributing to the population of ions in the gap. At low currents, however, the flux of anode atoms and ions is always less than the cathode ion flux. Only when an anode spot is present does the flux of material from the anode exceed that from the cathode. This anode flux consists primarily of neutral vapor.

Macroparticles are also produced by anode spots; and, while a significant fraction of the neutral vapor can be ionized by the electron current to the anode, the intense flux of neutral vapor from the anode spot normally dominates the recovery. Because this vapor has a temperature of the boiling point of the electrode material, it moves slowly. Since anode spots are much larger than cathode spots they cool much more slowly. While a cathode spot can cool and effectively disappear in times less than a microsecond, a well-established anode spot can require a millisecond or longer to cool.

When anode phenomena are significant, the recovery of a vacuum gap is normally dominated by the decay of neutral vapor in the gap, which in turn depends upon the cooling of the anode spot. Unlike the cathode region, where the production of ions, neutrals, and macroparticles normally ceases at current zero and the only continuing source is evaporation of neutral atoms from the cooling macroparticles in the gap, the evaporation of neutral vapor from the anode spot region can persist in significant quantities for milliseconds after current zero.

When both the anode and cathode regions are active, the interelectrode gap is usually filled with a collision-dominated plasma. (Exceptions can occur for long gaps and small electrodes, i.e., the gap being larger than the electrode diameter, especially with direct currents. Under such conditions an anode spot can form at currents of a few hundred amperes. Here the plasma in the gap may be treated as individual ions in free flow.) At currents just above those at which an anode spot forms, the main source of ions is still the cathode; but at higher currents and with well-developed anode spots, the ion fluxes from cathode and anode are comparable. The main source of neutral vapor is the anode spot, except that at relatively short gaps (and high currents) an "intense arc" mode can occur, characterized by the presence of severe erosion at both anode and cathode. Gellert, Schade, and Dullni investigated intense arcs, finding that appreciable quantities of material were emitted from both electrodes (Cu) for some time after current zero [42]. Liquid droplets (diameter generally less than 200 μm, velocity of a few m/s) were emitted by the cathode up to 600 μs after current zero. Larger (mm diameter) droplets were emitted by the anode as late as 8 ms after arcing, with solidification of the anode surface occurring even later!

When an anode spot appears, recovery time can increase significantly. Designating recovery time as fast or slow, and observing that fast recovery is mainly controlled by cathode phenomena while slow recovery is mainly dependent upon anode phenomena, a sketch of the occurrence regions for fast and slow recovery for a vacuum gap is presented in Figure 2. The sketch is qualitative, because the exact location of the boundaries between the regions depends strongly upon the electrode material, the electrode and gap geometry, and the arc current waveform.

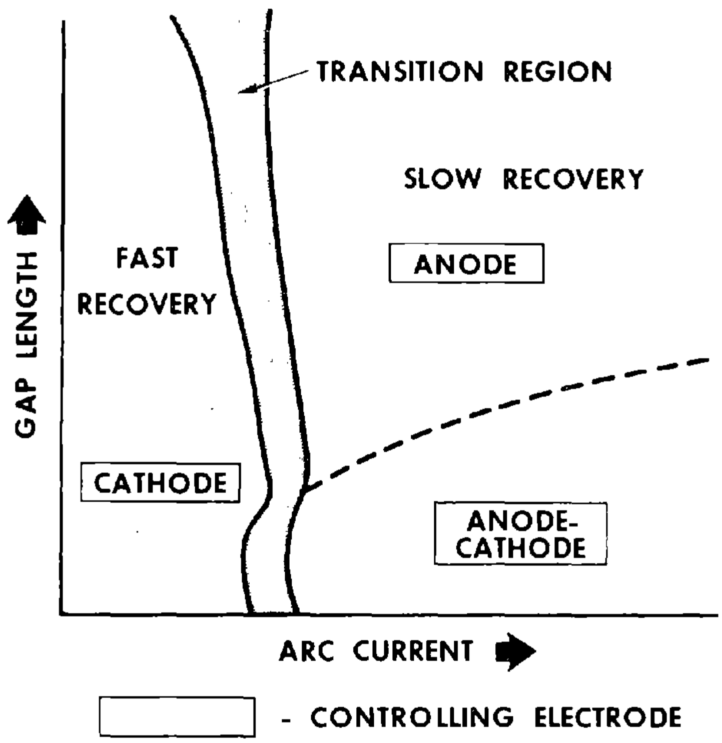

Figure 2. Fast and Slow Recovery as a Function of Arc Current and Gap Length

Immediately (ns) after current zero, most of the carriers required to carry the current flowing just before current zero are still present in the gap, while conditions at (or near) the site of the last cathode spot are favorable for reestablishment of a cathode spot. Thus, application of a relatively modest recovery voltage at this time can cause a vacuum arc to reoccur. Conditions on the cathode change quickly, however, soon the generation of a cathode spot effectively requires its ignition at a new site. The ion density in the gap becomes negligibly small, in times on the order of microseconds. Neutral vapor can persist in the gap for milliseconds, but unless an anode spot was present, the vapor density quickly becomes too small to affect recovery. At longer times, the ignition of a vacuum arc requires the occurrence of a vacuum breakdown, and thus is controlled by conditions at the electrode surfaces.

The recovery capability of a vacuum gap, therefore, is limited by the lowest voltage holdoff capability among the three mechanisms: ions, neutrals, and electrodes. A qualitative sketch of the relationships of these mechanisms for a representative gap is shown in Figure 3. The exact shape and location of these curves for an actual vacuum gap depends upon the gap geometry and material, the arc current waveform, and the recovery voltage waveform.

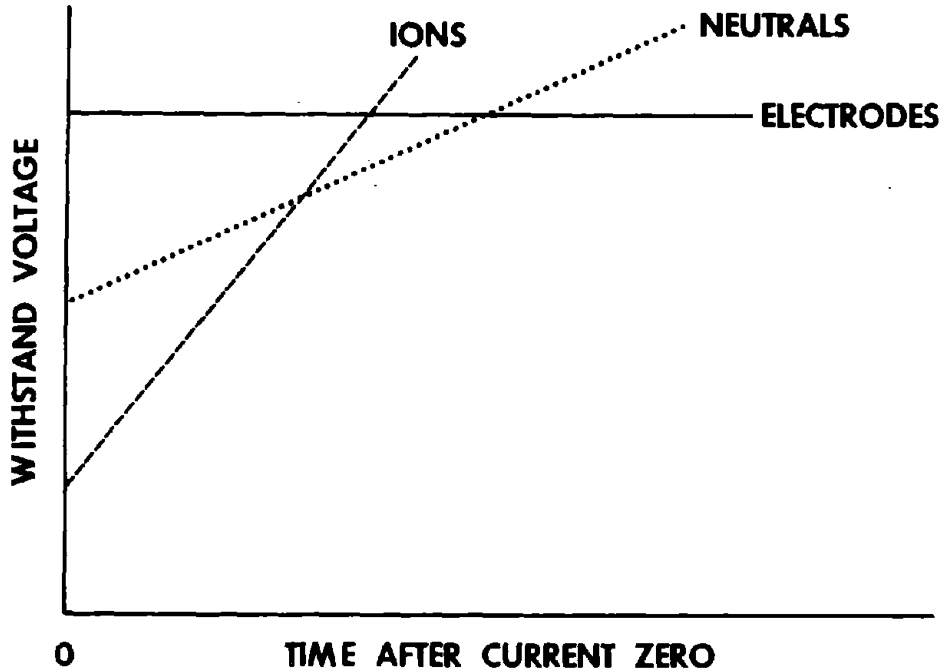

Figure 3. Influence of Breakdown Mechanisms on Recovery Capability of a Vacuum Gap

It should be mentioned that recovery on power systems (50/60 Hz) differs from repetitive shot recovery, in that the recovery voltage for power systems is normally reversed from the arcing voltage. That is, the arc anode becomes the recovery cathode and vice versa. This is an important reason why refractory metals are not used for electrodes in vacuum interrupters. For example, a tungsten anode can carry higher currents than a copper anode without forming an anode spot. But in the process, the tungsten anode can become very hot, sufficiently hot in fact that, during recovery, the new cathode can still be so hot that it thermionically emits enough electrons to cause recovery failure. For this and other reasons, refractory metals may be used in low current vacuum switches and contactors, but not where recovery after interrupting appreciable currents is important.

EXPERIMENTAL RESULTS

Many recovery measurements have been made using power frequency alternating currents (50,60 Hz). Because of the short time constants of most cathode phenomena, if these currents are allowed to extinguish at the natural current zero of the circuit, then the cathode phenomena are dominated by the influence of the last few microseconds of arcing before current zero. To obtain data pertinent to higher currents, the techniques of using high frequency currents or synthetically-induced current zeros have been employed. A useful method of obtaining a synthetic current zero is to inject a counter current through the vacuum gap, with the counter current having a magnitude equal to or slightly greater than the original arc current. This counter current technique has been used also as a method of interrupting dc arcs.

Most recovery measurements have been made using sinusoidal type waveforms (power frequency, higher frequency, or unipolar pulses) because of their practical implications and ease of generation. Some work has been done using rectangular (more precisely, trapezoidal) waveforms because waveforms in which the current is uniform over an interval before the arc is extinguished offer advantages in obtaining and interpreting data.

Farrall made considerable use of the counter current technique when investigating recovery phenomena in vacuum arcs [26,27,28]. Some of his results are shown in Figure 4. The recovery voltages were obtained by applying pulsed voltages to the vacuum gap at varying times after forced current zeroes and by measuring the voltages at which the gap broke down.

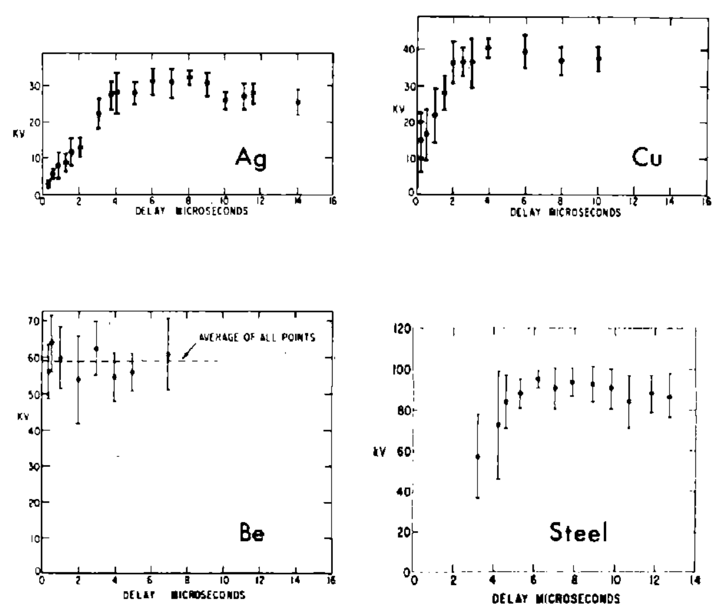

Figure 4. Recovery of Dielectric Strength After Vacuum Arc [27,28]

The results for silver electrodes are typical. The voltage strength of the gap is near zero right at the time of current zero, but recovers in a roughly linear manner for several μs until full recovery occurs. The results for steel are similar. Note that recovery voltage for copper appears to start out at about 10 kV. This is an effect of the finite time (in this case, about half a microsecond) required for the arc current to be forced to zero. The finite value of recovery voltage at current zero for copper reflects the operation of the various recovery mechanisms in the gap while the current was being forced to zero. A stronger example of this is shown by the beryllium results, where apparently the gap completely recovered during the forced arc extinction process. Note that the electrode material also has a strong effect on the maximum recovery voltage.

The geometry of the vacuum gap has a very strong effect on the recovery process. This is shown in Table 2. Increasing the electrode diameter (D) for a given gap length (g), or decreasing the gap length for a given electrode diameter, can significantly reduce the recovery time. This presumably reflects the loss of ions and vapor from the gap by either escape through the sides or collection by the electrodes. Similar results were obtained by Zalucki, Seidel, and Kutzner [43]. This effect becomes much smaller for relatively long gaps (low D/g ratios). Kimblin observed that, for his conditions (copper: D = 25 mm, I = 930 A), increasing the gap from 6 to 13 mm did not greatly change the rate of recovery, but did increase the recovery voltage at a given time [44].

Table 2. Effects of Changing Gap Geometry on Measured Recovery Times, Silver Electrodes in Vacuum (250-A Arcs With Forced Current Zeros [28])

Electrode Diameter (mm)	Gap Length (mm)	Recovery Time (μs)
50.8	0.76	1
50.8	2.3	4
50.8	4.6	12
12.7	0.76	7
12.7	2.3	12
12.7	4.6	20-30

Increasing the electrode diameter offers additional advantages at higher currents. For small diameter electrodes, increasing the anode diameter (with other conditions held constant) significantly raises the critical current for anode spot formation [45]. The effect is strongest when the electrode area is less than the area of an unconstrained anode spot, but is still present for larger electrodes. In this instance, the improvement in recovery is caused by the moving anode spot spending less time in a given location and thus producing less deeply heated electrodes. When the electrode diameter has increased to the point where the moving anode spot does not cross its previous track (on that arcing cycle), there is no further effect. Many workers have observed this effect of electrode size on maximum interruptable current. A recent reference is Behrens and Erk [22].

The magnitude of the interrupted current can have a strong effect on the recovery times, as shown in Table 3. This is probably a result of both the effect of increased numbers of current carriers in the gap and changes at the electrodes (the cathode for the given experimental conditions). The electrode material can strongly affect the influence of the current magnitude [46].

Table 3. Effects of Changing Arc Current on Measured Recovery Times, Silver Electrodes in Vacuum*

Arc Current (A)	Recovery Time (μs)
40	2
80	1
170	4
250	4
510	10
1080	13

*Electrode: D = 50.8 mm, g = 2.3 mm. Arc Current Forced to Zero in About 0.5 μs [27,28].

Frind et al., investigated recovery at higher currents, where anode phenomena become significant [47]. They used a rectangular current pulse because of the advantages it offered in analyzing their results. They performed a set of recovery measurements where the arcing time was kept fixed at 4.5 ms, but the magnitude of the arcing current was varied over a wide range, from 250 A to 12 kA. These results are shown in Figure 5. At the lowest currents, recovery was quite rapid, taking 7 μs for a 250-A arc. They found that recovery times increased smoothly with increasing current, up to currents of 4000 A, where the recovery time had increased to 40 μs. At this point a sharp increase in the recovery time occurred, with the recovery time reaching a value of 630 μs at an arc current of 12 kA. They attributed the change in slope of the curve to anode recovery mechanisms becoming important. The long recovery times at higher currents then would indicate the dominance of anode phenomena.

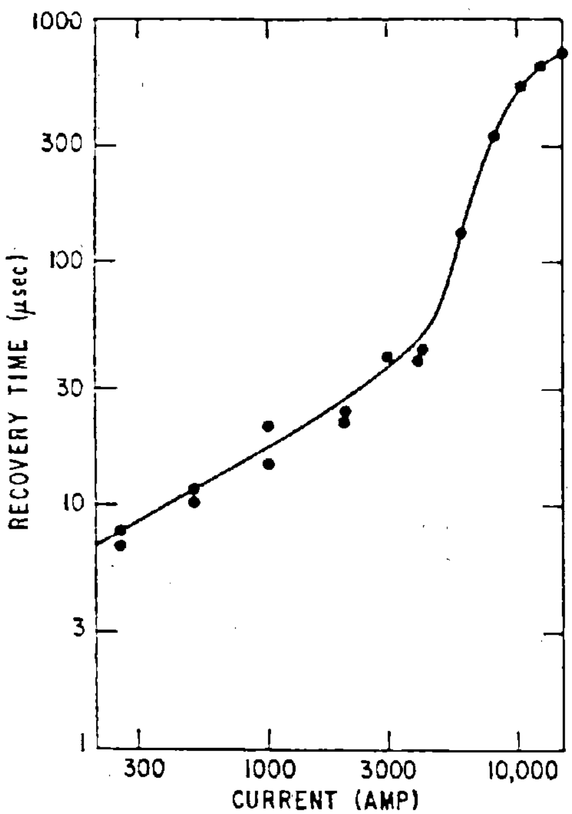

Figure 5. Recovery Time Versus Current Amplitude, Copper-Based Electrodes (D = 25.4 mm, g = 9.5 mm; Trapezoidal Current Pulse, Duration = 4.5 ms [47])

Li and Wang investigated recovery for 50-Hz arcs with peak currents of 3 to 8 kA [48]. They found shorter recovery times than did Frind et al., but the apparent differences in results may be attributed mainly to Li and Wang's use of 50-Hz waveforms instead of Frind's trapezoidal waveform (for example, 400 μs before the natural current zero of a 8 kA peak, 50-Hz arc; the instantaneous current is 1 kA) [47].

Frind et al., also found a strong influence of the arcing time before arc extinction on the recovery time, as shown in Figure 6 [47]. Anode phenomena presumably dominated the recovery process for these experiments, which explains why the recovery times are fairly long even for the relatively short current pulses.

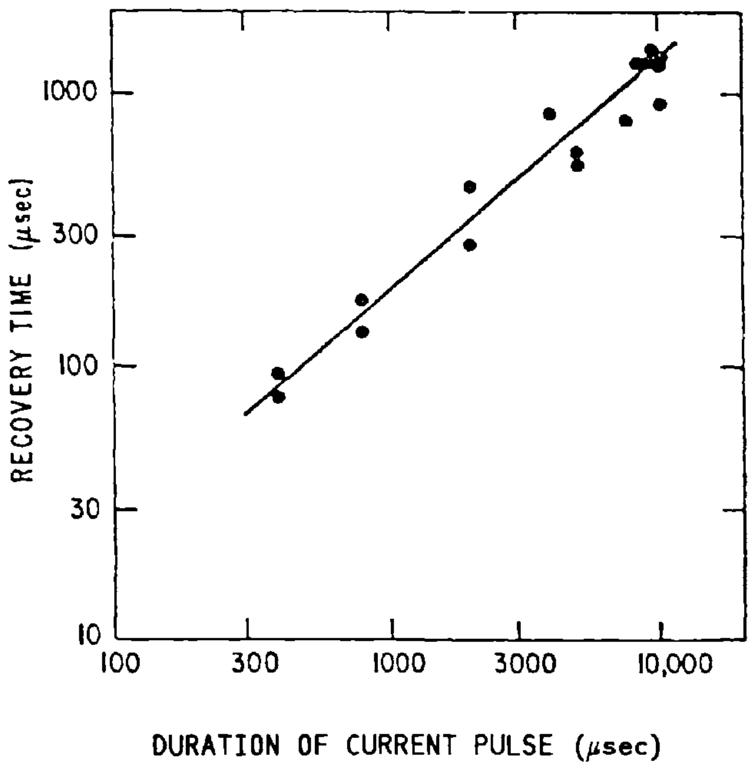

Figure 6. Recovery Time Versus Current Wave Duration (Heating Time), Copper-Based Electrodes (D = 25.4 mm, g = 9.5 mm; Trapezoidal Current Pulse, I = 12 kA) [47]

One of the few papers to report on recovery after a brief arc is that of McDonald et al. [49]. After a 1.8-kA, 250-ns pulse, it took 20 to 30 μs for their gap (molybdenum, D = 80 mm, g = 3 mm) to recover (using holdoff probabilities of 90% to 99%).

Recovery in vacuum gaps has been usually investigated for times of μs to a few ms after current zero. Breakdown at longer delays was investigated using chromium-composition electrodes (D = 80 mm, g = 15 mm; drawn arc, with 50 Hz waveforms [40]). It was discovered that the probability of breakdown peaked 10 to 30 ms after current zero, then decayed exponentially with a time constant of 0.1 s. These delayed breakdowns were explained as being caused by free macroparticles in the interelectrode gap.

Several investigators have measured both the current from the gap during recovery and the recovery voltage. Yanabu et al.,found that the peak value of the post-arc current (I_p) increased in a linear manner with increasing arc current [50,51]. At a certain value of arc current (I_{pc}), which depended on electrode material, a sudden increase in the slope of the I_p versus arc current curve occurred. Similar results were obtained by Dullni et al. [37]. Both groups interpreted this change in slope as being caused by arc concentration and the formation of an anode spot. Yanabu et al., further observed that, at values of arc current somewhat above I_{pc}, the gap began to fail to recover [50,51]. These results are shown in Table 4.

Table 4. Currents at Which the Peak Value of Post-Arc Current Shows a Sharp Increase (I_{pc}), or Above Which Failures to Interrupt Occur (I_f)

Material*	I_{pc} (kA rms)	I_f
Cu	26	>35
Cu-Bi	22	23
Cu-W	16	32
Ag-W	12	21

*Axial Magnetic Field Electrodes; D = 90 mm, Contact Diameter = 45 mm, g = 30 mm. Magnetic Flux Density at Center of Electrodes = 2 mT/kA; di/dt = 16 A/μs, dV/dt = 8 kV/μs [50,51].

Childs, Greenwood, and Sullivan measured the post-arc current, residual post-arc charge, and recovery of diffuse vacuum arcs at moderate currents (1 to 5 kA) [19]. They concluded that, at currents of 1 to 3 kA, the limit on recovery seemed to be the rate of rise of the recovery voltage (or an associated factor); while for currents of 3 to 5 kA, the residual charge in the gap (Q) appeared to be the determining factor.

An interesting observation on the effect of the rate of decrease of the arc current before current zero on recovery was made by Böhme and Fink [52]. They observed recovery for a VI finding that, for di/dt less than 75 A/μs, any recovery failure always occurred as a dielectric breakdown. With di/dt greater than 170 A/μs, failures were always thermal. For intermediate values of di/dt, both kinds of breakdowns occurred.

DISCUSSION

The recovery time and voltage of a vacuum gap depend upon the electrode material, the geometry of the gap, the waveform (magnitude, shape, duration) of the arc current, and the waveform of the recovery voltage. A listing of the material parameters which can affect recovery are given in Table 5. There are strong correlations between many of the listed parameters, so usually only a few parameters are used in choosing electrode materials.

Table 5. Parameters Influencing Recovery in Vacuum Gaps

	Gap Parameters	
	E_i	- Energy of ions in gap
	N_a	- Density of atoms in gap
	N_e	- Density of electrons in gap
	N_i	- Density of ions in gap
	N_{mp}	- Density of macroparticles in gap
	R_{mp}	- Rate of evaporation from macroparticles in gap
	T_{mp}	- Temperature of macroparticles in gap
	Electrode parameters	
Thermal:	C	- Specific Heat (solid)
	C_l	- Specific Heat (liquid)
	Q_e	- Vaporization (condensation) energy
	Q_m	- Fusion (melting) energy
	R_{ev}	- Rate of evaporation
	T_o	- Electrode temperature
	T_b	- Boiling temperature
	T_m	- Melting temperature
	α	- Diffusivity
	λ	- Thermal Conductivity
Physical:	M	- Atomic mass
	W_d	- Strength to break Ultrahigh Vacuum contact welds
	Y	- Young's Modulus
	ρ	- Mass density
	ϕ	- Work function
	σ	- Electrical Conductivity
Surface:	R	- Roughness of surface
	S_r	- Sputtering coefficient
	W_{kk}	- Mass ejected from electrode in droplet form
	δ_e	- Secondary electron emission coefficient for electrons
	δ_i	- Secondary electron emission coefficient for ions

Exactly how recovery time is defined is important and can strongly affect the ratings of different materials. For example, consider the results shown in Figure 4 [27,28]. If recovery time is defined as the time for the gap to recover to 80% or 100% of its ultimate recovery voltage, then the materials fall into the order: Be, Cu, Ag, steel. But if we consider the recovery time to a given voltage or the recovery voltage at a given time, then the sequence changes. For example, at 3 μs the materials recovered as follows: Be - 59 kV, Cu - 35 kV, Ag - 22 kV, and steel - 55 kV; which are 100%, 88%, 73%, and 61%, respectively, of their final recovery voltages. Now the sequence becomes Be, steel, Cu, Ag.

The electrode material exerts a strong influence on the recovery time. Zalucki and Kutzner considered their previous work, together with work of others, to obtain a sequence of recovery times for different electrode materials (arc currents less than 1 kA, thus cathode-controlled recovery) [53]. Their sequence of material, arranged in increasing order of recovery time, is: Be, Al, W, Ta, steel, Cu, Ag, Cd.

Recovery time appears to correlate somewhat with atomic mass, in that the light elements Be and Al have the fastest recovery, and Ag and Cd the slowest; but this idea breaks down when considering the refractory metals. Zalucki and Kutzner pointed out that if one arranged the metals in order of increasing sputtering coefficient, then they fell in much the same sequence as their recovery sequence [53].

A well-established effect on recovery is the relative gap size, i.e., the ratio of electrôde diameter (D) to gap length (g). A large relative gap (high D/g ratio) would mean that the material in the gap at current zero would not have to travel far to strike an electrode and be removed; therefore, gaps with high D/g ratios should recover faster than gaps with low ratios. This effect is clearly shown in Table 2. An increase in gap ratio presumably acts in the same manner as a decrease in sputtering coefficient, both effects serving to clear the gap of material faster, thus promoting recovery.

The observation of Childs et al., that recovery was limited by dV/dt for arcs of 1 to 3 kA, might be seen as indicating that the recovery voltage was acting on individual ions, thus supporting a ballistic model as appropriate for lower current vacuum arcs [19]. At currents above 3 kA they found recovery to depend upon Q, the residual charge in the gap at current zero. This could be understood as indicating that now collisions are important, and a fluid-flow model is preferable. The importance of Q in controlling recovery is supported by the experimental results of Yanabu et al., [50,51] and Dullni et al. [37], and by the theoretical work of Zalucki and Kutzner [53].

Once an anode spot forms, recovery times increase greatly; so if rapid recovery is desired, then the gap geometry, material, etc., should be designed to avoid the formation of anode spots.

MAGNETIC FIELD EFFECTS

Magnetic fields can be used directly or indirectly to aid the recovery of a vacuum gap. Application of a kilogauss-pulsed magnetic field at the time of current zero helped clear the gap, thus augmenting natural recovery processes [54]. Magnetic fields can be used to indirectly aid recovery by forcing the current to zero instead of waiting for the natural current zero. For this application, the magnetic field is usually applied transversely to the current [55]. However, Gilmour and Lockwood described a MPAS which was turned off by applying an axial magnetic field [56]. Since the occurrence of an anode spot significantly increases recovery time, magnetic fields may be applied during arcing to prevent the formation of an anode spot [23,25,57]. Such magnetic fields are usually applied axially (parallel to the current), and are frequently self-generated by appropriate geometry of the electrodes and current paths [24]. A good example of preventing anode spot formation by designing the electrode geometry to produce self-generated magnetic fields which keep the arc diffuse is the rod-array design of Rich et al. [58,59]. In a TVG, this rod-array design interrupted 63 kA with 97 kV recovery voltage (at about 60 Hz). Similarly, axial magnetic field electrode interrupters (with design emphasis on voltage or current respectively) have interrupted 32 kA at 145 kV or 200 kA at 12 kV [60].

When anode spots are allowed to form, a transverse (azimuthal) magnetic field can be applied to move the anode spot rapidly over the surface of the anode, thus decreasing the heating at any given point. This can significantly increase the current which the gap can interrupt [22,57,60].

SUMMARY AND CONCLUSIONS

During conduction, a vacuum gap contains electrons, ions, neutral atoms (vapor), and macroparticles of electrode material. At low currents, all electrons, ions, and macroparticles are emitted from the cathode. Some neutral vapor comes from the cathode, but most is produced by evaporation from macroparticles in the gap. The ions have potentials of tens of volts and flow freely to the anode. This ion flux is 7% to 10% of the total current. At moderately high currents, collisions in the gap become important, resulting in some ionization; but the majority of ions still come from the cathode. At still higher currents, anode spots form. Anode spots emit copious quantities of ions and neutral vapor. In this instance, the ion production at both electrodes is comparable, but the neutral vapor in the gap comes mostly from the anode. An exception can occur at relatively short gaps, where an "intense arc" mode may be present; in this case, the cathode also emits copious amounts of neutral vapor.

At current zero, the cathode production of electrons, ions, and macroparticles ceases immediately, but neutral atoms continue to be evaporated from macroparticles in the gap for microseconds. Production (if present) of anode ions and sputtered anode atoms also ceases at current zero. The ions in the gap at current zero leave quickly, although a group of low energy cathode ions which appears at current zero dissipates more slowly than the more energetic ions. The electron density decreases along with the ion density. If a voltage is applied to the gap immediately after current zero, then the electrons and ions will clear the gap faster, separating to form voltage sheaths at the electrodes. The macroparticles leave the gap more slowly, probably in hundreds of microseconds, but do not cause recovery failures except in rare cases. Neutral vapor density decreases at first by dispersion of the vapor present at current zero, but after some microseconds the contribution of evaporation from macroparticles becomes significant. If an anode spot is present, it will take tens of microseconds to milliseconds for significant production of neutral vapor to cease; the time depending upon the rate at which the anode spot cools, which in turn depends upon the anode material and upon the size and depth of the anode spot at current zero.

Early recovery is controlled by the ions (with an upper limit set by neutral atom density) and later recovery is controlled by neutral vapor. The ultimate recovery voltage is a function of the electrode surface properties and the geometry of the gap. Recovery failures tend to be thermal at first, and become predominantly dielectric at later times. Minimum recovery times occur with high D/g ratios (i.e., relatively short gaps), but greater final recovery voltages are obtained with longer gaps. Materials of low atomic weight and low sputtering coefficients tend to have the fastest recovery times. Magnetic fields may be used to promote recovery by helping to clear the gap of ions and electrons and by preventing the formation of anode spots or moving them before current zero.

The most important requirement in obtaining the fastest recovery time is to design the vacuum gap to avoid the formation of anode spots, thus insuring that only cathode recovery phenomena are significant.

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