Vacuum Arcs

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I. General Description of the Vacuum Arc
II. Detailed Characteristics of the Vacuum Arc
III. Applications of the Vacuum Arc

GLOSSARY

Anode spot Molten area on the positive electrode surface of an arc that releases metal vapor because of heat generated by concentrated electron bombardment.

Arc Self-sustained, low-voltage, high-current electrical discharge.

Cathode spot Highly mobile, minute luminous area on the negative electrode surface of an arc that emits electrons, jets of plasma, and metallic vapor.

Cathode-spot track Erosion marks left on the negative electrode of an arc by the passage of a cathode spot.

Chopping current Magnitude of the arc current just prior to arc extinction.

Current chopping Sudden cessation of arc current at the time of arc extinction.

Current zero Zero of an alternating sinusoidal current.

Electron temperature Average translational kinetic energy of the electrons in a plasma.

Field emission Liberation of electrons from unheated metal surfaces produced by sufficiently strong electric fields.

Plasma Region in an electrical discharge that contains very nearly equal numbers of positive ions and electrons and may contain neutral particles as well.

Sheath Space-charge region at the boundary of a plasma with an excess of either positive or negative charges.

Thermionic emission Evaporation of electrons from a metal surface produced by heating the metal.

AN ARC may be defined as a discharge of electricity, between eletrodes in a gas or vapor, that has a voltage drop at the cathode of the order of the minimum ionizing or minimum exciting potential of the gas or vapor. The arc is a self-sustained discharge capable of supporting large currents by providing its own mechanism for electron emission from cathode spots on the negative electrod. However, the term *vacuum arc* is a misnomer. What is really meant is a "metal vapor arc in a vacuum environment." But since vacuum arc is in common usage and has been accepted in the literature, it is retained here. A vacuum arc, then, burns in an enclosed volume that, at ignition, is a high vacuum. A characteristic feature of such an arc is that after ignition it produces its own vapor from the electrodes that is needed to achieve the current transport between the electrodes. In such a vacuum arc, one can clearly distinguish phenomena that occur at the cathode and the anode and in the plasma occupying the space between the electrodes. Because these phenomena are exceedingly complex and interrelated, there are no general theories that completely describe the vacuum arc or predict its behavior.

The electrical discharge in a mercury-arc rectifier tube is an important example of a vacuum arc. Here the metal vapor is mercury supplies mainly by the cathode spots on a mercury pool. An anode, usually made of carbon, collects electrons from the plasma. Evidence of vacuum arcs has been found on the walls of various fusion devices. Here one observes cathode spots and cathode-spot tracks. Such arcs are believed to be of the homopolar type. The discharge in a thyratron is also characterized by a low voltage and high current, but is not a true arc because of the absence of cathode spots. The energy to heat the thermionic emitting cathode is supplied by an external source, not by the discharge itself. The discharges found in vacuum circuit breakers and triggered vacuum gaps are true vacuum arcs. These are described at the end of this article.

I. GENERAL DESCRIPTION OF THE VACUUM ARC

The vacuum arc is shown in idealized form in Fig. 1. A slow-motion color movie of such an arc is a beautiful sight to behold. One sees a cold cathode surface covered with isolated, small, brilliant spots. These cathode spots move erratically over the cathode surface, sometimes dividing into two or more fragments or extinquishing and reforming elsewhere on the cathode. Associated with the cathode spots are luminous jets that shoot off into space and constantly change direction. Between the electrodes one sees a diffuse glow whose color is characteristic of the electronically excited metal vapor of the electrodes. If the arc has been burning for some time, one is also likely to see on the anode a bright stationary spot of molten metal. This anode spot will be completely surrounded by an intense glow. As one looks away from the central region of the arc, the glow becomes more diffuse, eventually disappearing. Let us now examine these phenomena in more detail.

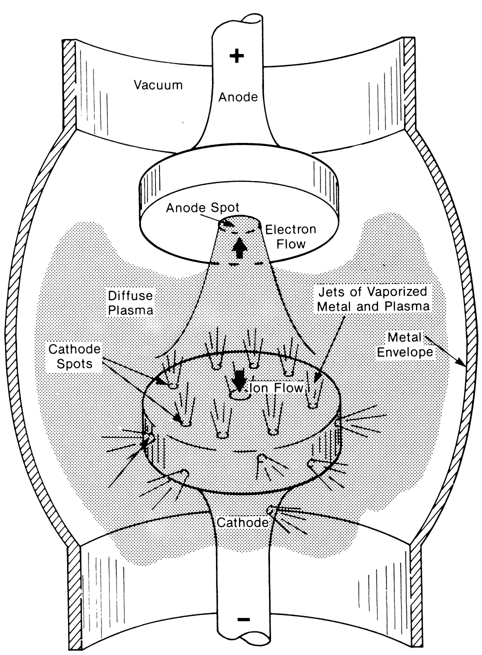

FIGURE 1 Structure of the vacuum arc.

The high-current vacuum arc forms in the metal vapor evaporated from the electrodes. Electron current is fed into the arc by a multiplicity of highly mobile cathode spots that move about on the negative electrode. The current density in these small spots is exceedingly high and is often of the order of a million amperes per square centimeter or more. Jets of plasma and metallic vapor, with velocities of up to 1000 m/sec, also have their origin at the cathode spots. In the formation of these jets, which are the principal source of plasma and vapor in the vacuum arc, one atom of metal may be removed from the cathode for every 10 electrons emitted. The moving cathode spots leave pitted tracks on the cathode surface that show little evidence of cathode melting, although these cathode-spot tracks often suggest loss of metal by sublimation. The exact mechanism responsible for the emission of electrons and the ejection of metal vapor and plasma from the cathode spots is not fully understood and has been a source of wonder and controversy since the phenomena were first investigated. However, thermionic emission and field emission undoubtedly play an important role, since positive ion bombardment and space-charge effects produce extreme local heating and intense electric fields, respectively, at the cathode surface.

Upon arc ignition (Section II.A), the space between the electrodes quickly fills with a diffuse plasma consisting of partially ionized metal vapor. At high currents this plasma expands into the volume surrounding the electrodes and their supports. At low currents the positive electrode collects electron current from the plasma uniformly over its surface. The metal shield or vacuum envelope that surrounds the arc also collects charges from the plasma and metal vapor. At high currents one or more distinct anode spots may appear. These spots always form on the end of the anode, which faces the cathode, in contrast with the cathode spots, which some-times wander off the end of the cathode and move about on the sides of the electrode. The anode spot also tends to remain in one position, in contrast with the mobility of its counterparts on the cathode.

At the anode, electrons striking the electrode carry essentially all of the arc current, whereas at the cathode, the ions striking the surface account for only about 10% of the current, with emitted elections supplying the remainder. Consequently, there is a difference in the power dissipated at the two electrode surfaces. The cathode is bombarded by ions with a relatively low total energy, but

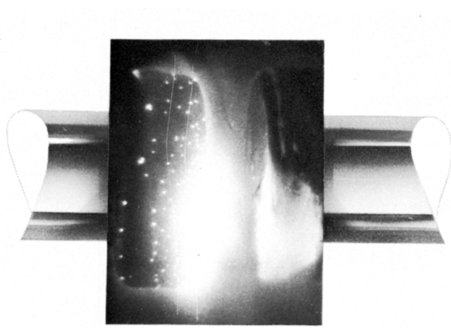

FIGURE 2 Photograph of a vacuum arc showing anode spot and cathode spots with plasma jets. (Photograph courtesy of Dr. Gerhard Frind, Corporate Research and Development, General Electric Company.)

since most of these are landing in the small areas of the cathode spots, the power density is high. At the anode, on the other hand, a large stream of high-energy electrons is bombarding the relatively large anode spot, subjecting the anode to a much higher total power input. This bombardment inevitably causes the anode surface to melt and vaporize at high currents. The magnetic pinch effect also contributes to a concentration of energy input to the anode spot. This concentration of power will eventually destroy the anode unless the arc is extinguished. Figure 2 shows a photograph of the typical vacuum arc with an anode spot.

II. DETAILED CHARACTERISTICS OF THE VACUUM ARC

A. Arc Ignition

The essential requirement of establishing an arc between metal electrodes in a vacuum is to initiate an electrical discharge that will lead to the development of a cathode spot. This development requires the presence of a plasma, that is, both electrons and ions, in the gap. The process usually begins by inducing cold-cathode electron emission, which builds up to the point where the heat generated vaporizes a minuscule portion of either or both electrodes. The metal vapor thus produced is partially ionized by the electrons. Positive ions and radiation then strike the cathode and enhance the electron emission. With the release of more vapor, these effects become cumulative. The discharge then develops into a metal-vapor arc, with intense ion bombardment of the cathode leading to the formation of a cathode spot. Additional cathode spots may then develop, depending on the magnitude of the arc current, which is determined almost entirely by the external circuit. It is essential that the power supply connected to the electrodes be capable of supplying a sufficiently large current to maintain a stable arc. The value of this current will depend on the electrode material but will range from a few tens of amperes to several hundreds, as discussed in Section II.E. The open-circuit voltage required to initiate the arc will depend on the triggering method. A simple method of starting the arc by increasing the applied voltage will now be discussed in some detail.

As the voltage across a vacuum gap is increased, electrical breakdown will eventually occur. At a certain level of voltage, in the range of many kilovolts, the negative electrode will begin to emit electrons. This room-temperature emission occurs as tiny jets form small regions on the surface, and the emission's magnitude increases sharply with further increases in voltage, leading ultimately to breakdown. This field emission is dependent on the work function and magnitude of the electric field at the cathode surface. The latter may be enhanced by surface roughness or protrusions on the cathode. The total emission current will generally be much less than an ampere; but since the areas of emission are small, the current densities reach extremely high values. As current densities in the 10^8 A/cm^2 range are reached, for a particular area, breakdown will generally occur. At these current densities joule heating occurs and the small emitter area is vaporized. The metallic vapor produced is partially ionized by the emitted electrons. The positive ions are accelerated by the electric field between the electrodes toward the cathode surface, which is bombarded with considerable energy. When this bombardment eventually causes the formation of a cathode spot, the vacuum arc is established. Additional cathode spots may then develop, depending on the magnitude of the arc current, which is determined by the external circuit.

Obviously, absorbed gas, dust, and especially insulating particles on the cathode will effect the breakdown voltage. In long gaps the positive electrode may also affect the breakdown process. In this case, high-energy electrons bombard the anode and produce metal vapor, which is then ionized. The ions thus produced strike the cathode and produce a more abundant electron emission. Under some circumstance, loose metallic particles may become charged and then accelerated across the gap by the electric field. On impact these particles may vaporize or produce vaporization of the electrode material. The presence of loose particles can reduce the breakdown voltage of a vacuum gap to a level as much as 50% below that of the particle-free case. There is also evidence that for a given electrode geometry and gap spacing, the breakdown voltage increases with the hardness and mechanical strength of the electrode material.

A vacuum arc may also be initiated with less than 100 V across the gap by first bringing the electrodes in contact and then separating them with current flowing. As the electrodes are parted, the area in contact diminishes until only a small metal constriction bridges the two electrodes. This bridge is heated to the melting point by resistive heating, and vaporization follows at an explosive rate. The high temperature and electric field at the negative electrode cause a field-enhanced thermionic electron emission to flow. This emission ionizes the metal vapor, thus producing a plasma capable of carrying an arc current within the space formerly occupied by the bridge. Intense ion bombardment of the cathode leads to the formation of a cathode spot and the arc is fully established as the electrodes are further separated. A similar type of breakdown can be obtained by placing a wire between the separated electrodes and melting it with a high-current discharge.

In the presence of a high-electric-field coldcathode, electron emission may be initiated by injecting a plasma into a vacuum gap from an external source or by bombarding either electrode with high-energy electrons, ions, or radiation from, for example, a laser beam. Any of these processes will lead to breakdown and the formation of a vacuum arc.

B. Cathode Spots

The cathode spot, which is essential for the very existence of a vacuum arc, is the least understood of all vacuum-arc phenomena. Clearly, it is the source of electron emission for the arc, but it also provides plasma and metal vapor. The cathode spot is a highly efficient electron emitter. The current carried by a single spot depends on the cathode material and may vary from several amperes to a few hundred for most metals. When the arc current exceeds the current that a single spot normally carries, additional spots will form, sometimes by the enlargement or division of the original spot and also by the formation of new spots. Cathode spots do not respond instantly to a demand for an increase in current when the voltage applied across the arc is increased. It would appear that the spots normally operate at maximum current for the available heated emitting area and require a thermal response time of several microseconds to meet a demand for increased current.

Sometimes what appears to the eye as a single cathode spot is actually, on closer examination, numerous, small, active areas. This cellular substructure is found more frequently on mercury cathodes and may consist of a cluster of 4–12 cells.

Because cathode spots have a finite lifetime, they often extinguish and reform elsewhere on the cathode while the arc is burning. These spots are seldom stationary and move about on the cathode surface in a random, erratic way, sometimes reaching speeds of 30 m/sec on copper. It would appear that they tend to repel one another and also move in reverse to the direction expected for a conductor carrying current when a magnetic field is applied parallel to the cathode surface.

When the arc current is reduced, by decreasing the applied voltage or inserting resistance in the external circuit, the number of cathode spots will diminish. As the current is further reduced, a point is reached where only one cathode spot remains. The remaining spot has a statistical lifetime that is quite short at low currents and it will suddenly vanish during a period of less than a microsecond. When this occurs the arc is extinguished. The arc current flowing just prior to arc extinction is called the chopping current.

The current density in a cathode spot is phenomenally high. Estimates have ranged from 10^3 to 10^8 A/cm^2. This wide range of uncertainty is associated with the problem of accurately determining the active emitting area of a cathode spot that may range in size from 10 μm to several hundred. Regardles of the uncertainty, the electron emission current density is enormous compared to conventional electron emitters. The mechanism that provides such high emission densities is not well understood but is believed to be some form of field-enhanced thermionic emission.

In addition to the electron emission, the cathode spots also provide a copious supply of ions for the vacuum arc. Experimental analysis has shown that this stream of ions consists of singly and multiply charged high-energy positive ions of cathode metal. A majority of the ions have energies greater than the arc voltage and, consequently, would have no difficulty in reaching the anode. The cathode spot ions are rich in multiply ionized particles that frequently exceed the singly ionized ones, especially for refractory metal cathodes. The total ion current has been estimated at about 8% of the arc current.

Cathode spots are also a source of evaporated neutral metal vapor, and they eject tiny liquid droplets along trajectories nearly parallel to the cathode surface. Unlike the ions, the energies of most of the neutral atoms ejected are quite low, corresponding to the temperatures of the portions of the cathode surface from which they are evaporated. It is believed that most of the neutral vapor found in the vacuum arc does not come directly from the cathode spots themselves, but is evaporated from inactive former sites of the moving spots and from the micrometer-size liquid droplets ejected by the cathode spots during their flight to the electrodes and walls surrounding the arc.

The moving cathode spots leave behind on the cathode surface a trail of irregular pits, craters, and depressed valleys called cathode-spot tracks. Although these tracks usually show little evidence of gross melting, microscopic examination shows melting, evaporation, and possibly loss of metal by sublimation. The tracks are not always continuous and sometimes show areas that appear almost undisturbed. Some areas of the tracks show evidence of splashing of liquid metal, leaving behind a trail of solidified waves and spherical droplets. The amount of erosion from these cathode tracks is usually expressed as micrograms of mass eroded per coulomb of charge passing through the arc. It is found to vary significantly with experimental conditions such as arcing time, arc current, and cathode size. For copper cathodes the evaporation loss is between 35 to 40 μg/C. However, there is a much larger loss of metal, nearly seven times, associated with the ejection of liquid droplets.

C. Anode Spots

The main function of the anode in a vacuum arc is to collect sufficient electrons from the ambient plasma to sustain the external circuit current. However, it is probable that some high-energy positive ions from the cathode spots also reach the anode. In addition, the anode receives neutral atoms of metal vapor that may condense on its surface and radiant energy from both the cathode and the plasma. All these quantities tend to heat the anode surface, but electron bombardment is by far the largest contributor. As a result, the anode will melt if the arc is allowed to persist for any appreciable time and may even occur within a few milliseconds at current levels of several thousand amperes. Continued heating of the anode leads to an arc instability that can be described as follows.

At low currents when the vacuum arc is first initiated, the anode collects electron current uniformly over its surface from the plasma. Normally, the anode is not a positive ion source and the small electric field in the plasma tends to drive the positive ions away from the anode. The absence of positive ions causes the buildup of an electron space-charge sheath around the anode with an accompanying anode drop of potential through which the electrons are accelerated as they stream to the anode. These electrons bombard the anode with energies that not only correspond to the anode fall of potential, but to the average electron temperature energy and the electron heat of condensation as well. At a sufficiently high current density, some local area of the anode—usually an edge (Fig. 2) or a rough spot where the heat conductance is poor—will be heated enough to release metal vapor. The vapor is immediately ionized by the high-energy electron stream. The positive ions neutralize the negative space charge in the volume adjacent to the anode area emitting the metal vapor and produce a sharp reduction in the anode fall of potential. The lower voltage drop causes more current to flow into the anode in this area. This increase in current flow is also aided by an increase in the random electron current density in the plasma resulting from the increased metal vapor density. The local increase in current flow to the anode heats it even more, causing additional metal vapor to be emitted and ionized. This condition leads to a runaway effect, causing a constriction of the arc at the anode with the production of an anode spot. At this point, the total arc voltage will decrease. The intense local heating produced at the anode spot may cause destructive melting of the anode unless means are provided to disperse, or force rapid motion of, the anode spot. Unlike cathode spots, anode spots readily respond to the force of a magnetic field applied parallel to the anode surface and move in the direction expected.

The temperature of the anode spot for copper electrodes has been estimated to be between 2500 and 3000 K. Temperatures are lower for the more volatile metals and higher for the more refractory ones. Unlike cathode spots, the anode spots are quite diffuse with areas up to a square centimeter depending on the arc current. Current densities of 10,000 A/cm^2 are typical in an anode spot. Since the formation of an anode spot is heat induced, it is clear that points, irregularities, sharp edges, and loosely attached particles can cause variations in the spot initiation. It is not uncommon for more than one spot to form simultaneously on an anode, but these usually draw together and collapse into a single anode spot. Luminous areas have been seen on the anode in vacuum arcs that are not true anode spots, especially in low-current arcs and arcs of short duration. Instead, these may be anode spots in the early stages of development or other inhomogeneities in the arc or on the anode surface. When a true anode spot fully develops, an anode jet is clearly visible and there is a copious supply of vapor to the discharge. The arc then constricts and there is a substantial drop in arc voltage. The arc becomes more stable and takes on the characteristics of a high-pressure arc, which indeed it may well be since the metal vapor density is approaching that of atmospheric pressure.

D. Interelectrode Phenomena

The processes that occur in the space between the cathode and anode of a vacuum arc are rather uneventful compared to those at the electrodes, but nonetheless they are very complicated and not easily subject to analysis. The interelectrode volume is filled with a diffuse plasma whose main function is to provide a conductive medium for the arc current transport between the electrodes. In the absence of an anode spot, the vapor and most of this plasma is provided by the spray from the high-velocity jets that have their origin in the cathode spots.

The voltage distribution in a vacuum arc has been idealized in Fig. 3. At the cathode, one must distinguish between the potential distribution in the region of the cathode spot and the areas away from the spot. The solid line

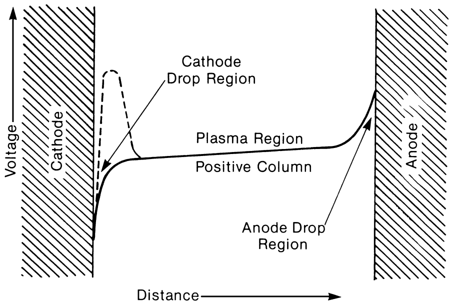

FIGURE 3 Schematic representation of the potential distribution in a vacuum arc.

showing the potential varying montonically between the cathode and anode is the classical distribution that one would expect in an area remote from a cathode spot. This solid line shows a region close to the cathode with a potential drop roughly equal to the ionization potential of the electrode metal, normally about 8V. The dotted line shows the potential distribution that may exist in a cathode spot region. This voltage hump has not been verified experimentally but is predicted on the basis of experimental observations that singly and multiply charged ions with energies in excess of the arc voltage exist in the interelectrode plasma. The details of this voltage distribution are unknown, and it may not even exist since the presence of the high-energy ions has also been explained to be the result of magnetic compression and heat expansion processes in the cathode spot.

Beyond the cathode fall region lies the positive column. In this region there exists a highly ionized diffuse plasma at a temperature approximating 10,000 K. The potential gradient is quite small because the ions and electrons are present in essentially equal numbers and because the conductivity of the plasma is very high, approaching that of a metal. The potential drop across the positive column will depend on the arc current and the column length, which is usually quite short for vacuum arcs and is only a few volts for arc currents of several hundred amperes or less.

The plasma and metal vapor in the positive column extend out to the shield or container walls encompassing the arc. The metal vapor and metal droplets from the jets will collect on the relatively cool walls. In addition, if the shield is not electrically connected to the arc circuit, it will assume a floating potential that is slightly negative with respect to the plasma and collect ions and electrons at the same rate. If the shield is connected to the cathode, a positive ion sheath is formed over its inner surface adjacent to the plasma. This is in contrast to the flaming sheath that surrounds a high-pressure arc operating in open air.

Before the formation of an anode spot, the metal vapor and plasma density in the positive column are so low that the mean free path of the electrons is comparable to the dimensions of the arc. Thus, thermal ionization and space-charge neutralization must be minimal. However, in the region of the cathode spots the metal vapor density is very high and ionization can readily occur.

The voltage drop at the anode is a result of negative space charge produced by the flow of electrons from the plasma to the anode in the absence of positive ions. Normally, the anode is not a source of positive ions and the potential gradient in the positive column tends to drive the positive ions away from the anode. The magnitude of the anode fall of potential will depend on the arc current. Once the anode is heated to its vaporization point, positive ions will form in this space and the potential drops drastically.

E. Arc Stability

All arcs tend to be unstable, particularly at low currents, because the cathode spots on which the arc is dependent for its existence are inherently unstable. Without knowing the intricate details of all the phenomena that occur in cathode spots, one can make some general observations about their behavior. Obviously, the cathode spot requires a feedback mechanism for its existence. The cathode-spot surface emits electrons and neutral vapor. These must interact to produce positive ions, which, in turn, bombard the cathode surface to produce the required temperature and field for additional emission of electrons and vapor. If this feedback becomes less than unity, the cathode spot will cease to exist. By observation of the fanatical motion of cathode spots over all faces of the cathode surface, with complete disregard to the position of the main discharge, one can only conclude that the cathode spot feedback mechanism is only slightly greater than unity and the spot is continually seeking a favorable environment on the cathode surface for its survival. Further evidence of cathode-spot instability is given by their short average statistical lifetime. For a copper cathode spot, the lifetime may average on the order of only a few tens of microseconds when the arc current is limited by the external circuit to a few amperes. The life increases markedly with current, and for a 10-fold increase in current, the lifetime increases 10,000 times.

If an adequate power supply voltage, well above the arc voltage, is assumed, high-current vacuum arcs of 1000 A or more will burn indefinitely. The burning time is limited only by the ability of the electrodes to dissipate the heat. Even though the lives of the individual cathode spots may be quite short, there are always enough of them in existence at any one time in a high current to keep it burning.

At arc currents in the 100 A range when only a few cathode spots may be present, the probability of them all vanishing at the same instant is quite high, and when this occurs the arc is extinguished.

Vacuum arc lifetimes not only increase strongly with increasing arc current, but are also dependent on the properties of the electrode material. Average lifetimes tend to increase with increasing atomic weight and vapor pressure and to decrease with increasing thermal conductivity. Figure 4 shows the average lifetime of arcs drawn between electrodes of various metals in vacuum as a function of arc current.

Increasing the circuit voltage above the arc voltage has only a modest effect on increasing the arc lifetime. The same is true for increasing the series inductance of the circuit. On the other hand, increasing the parallel capacitance across the arc will shorten the life of a vacuum arc. There is evidence that low-current arcs may survive by a succession of extinction–re-ignition events during which transient re-ignition voltages are developed by the series inductance of the circuit and the rapid decrease in current by the abrupt extinction of the arc. Excessive capacitance in parallel with the arc will limit the rate of rise of this voltage, thereby reducing the probability of arc re-ignition.

Unlike many gas discharge devices, vacuum arcs have a positive resistance characteristic; that is, the arc voltage

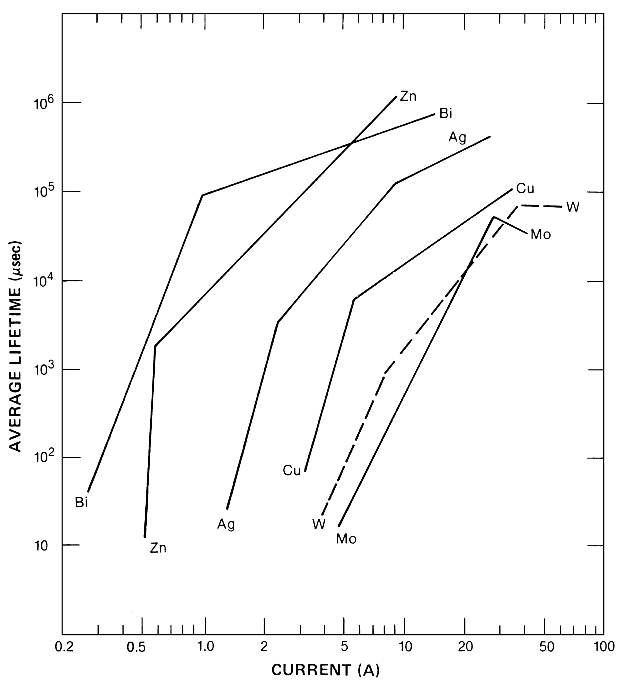

FIGURE 4 The average lifetime of low-current vacuum arcs for various electrode metals. [Reproduced with permission from Farrall, G. A., Lafferty, J. M., and Cobine, J. D. (1963). *IEEE Trans Commun. Electron.* **CE-66,** 253. © 1963 IEEE.]

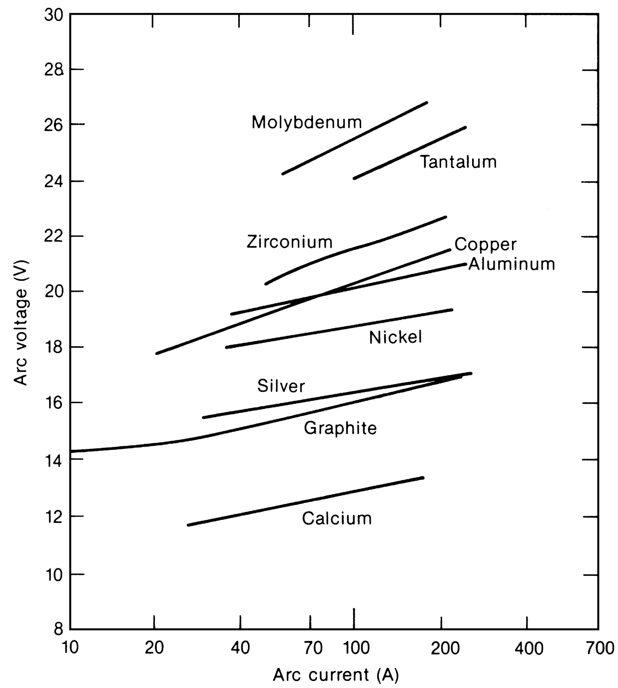

FIGURE 5 The volt–ampere characteristics of vacuum arcs for various electrode metals. [Reproduced with permission from Davis, W. D., and Miller, H. C. (1969). *J. Appl. Phys.* **40,** 2212.]

increases with arc current. Because of this characteristic, two or more vacuum arcs will operate stably in parallel without the need for series ballast impedances. Figure 5 shows the volt–ampere characteristics of low-current vacuum arcs for a number of electrode materials. The electrodes are approximately 1.27 cm in diameter separated by 0.5 cm.

Even at low-arc currents where only one cathode spot exists, the arc still exhibits a positive resistance characteristic. One can thus assume that a single cathode spot also has a positive resistance characteristic, as indeed must be the case since multiple cathode spots exist in parallel in high-current vacuum arcs. Probe measurements indicate that most of the increase in arc voltage with increasing current occurs at the electron space-charge sheath at the anode.

Even though vacuum arcs are stable at high currents, they, like most gas discharges, are quite noisy. Studies of copper vapor arcs have shown that there is a noise voltage superimposed on the dc arc voltage. The frequency spectrum of the noise power density is flat to at least 15 MHz and is detectable at frequencies higher than 8 GHz. Oscillographic voltage traces of this noise show a large number of narrow, *positive* voltage pulses. As the arc current is decreased from 50 to 10 A, the dc arc voltage drops about 3 V. However, the noise amplitude increased dramatically from 4 or 5 V to over 25 V and occasionally pulses exceeding 60 V or more are seen. It is believed that these positive voltage pulses are produced by sudden decreases in arc current brought about when a cathode spot or perhaps one of its constituent cells decays. The absence of negative voltage pulses in the noise spectrum shows that even though the cathode-spot currents can decrease very quickly from their normal values, they are slow to increase and appear limited by a thermal response time rather than by the arc circuit response time.

As previously discussed, the vacuum arc never dies quietly when the arc current is decreased. With decreasing current a point is reached where only one cathode spot remains. A further decrease in arc current makes this spot very unstable, and while it is carrying a finite current, it suddenly disappears in a time of the order of 10^{-8} sec. This rapid decrease in the current through the circuit inductance will generate a positive voltage surge that may cause the arc to momentarily restrike one or possibly more times before finally extinguishing. This phenomenon is called current chopping and the magnitude of the arc current just prior to arc extinction is called the chopping current. Chopping current is dependent not only on the physical properties of the electrode material and the external circuit, as previously discussed, but also on the rate at which the arc current is decreasing prior to extinction.

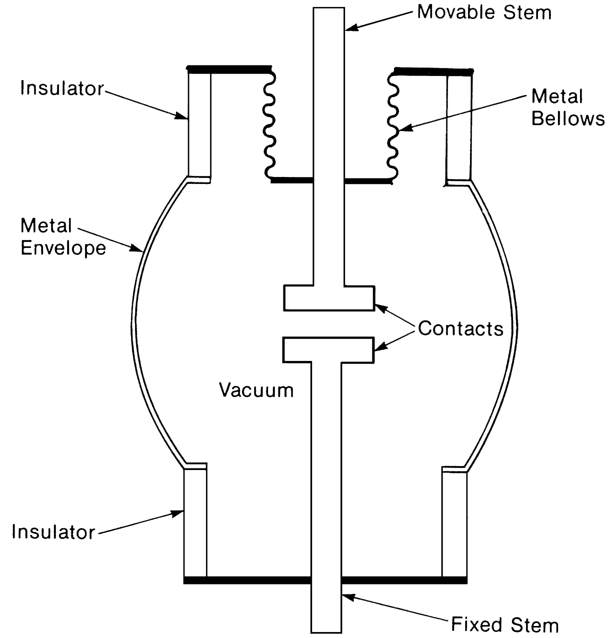

FIGURE 6 The basic elements of a vacuum switch.

III. APPLICATIONS OF THE VACUUM ARC

A. High-Power Vacuum Interrupter

Notwithstanding its complexity and elusiveness to quantitative analysis, the vacuum arc has been harnessed to serve a number of useful purposes. A modern example is the high-power vacuum circuit breaker.

The simplicity and elegance of reliably interrupting large alternating currents in high-voltage circuits by separating two metal contacts enclosed in a vacuum (Fig. 6) had long fascinated scientists and engineers, but early attempts to do so were doomed to failure because of the lack of supporting technologies in vacuum and metallurgical processing. In the early 1920s at the California Institute of Technology, R. A. Millikan, in his research on the field emission of electrons from metals, observed that vacuum gaps had a very high dielectric strength and that many tens of kilovolts would not break down a vacuum gap of only a few millimeters in length. R. W. Sorensen of the same institution applied this phenomenon in his invention of the first vacuum switch. The early work of Professor Sorensen and the General Electric Company showed great promise, but it soon became evident that the sealed vacuum switch of the early 1930s could not offer the high reliability demanded by the electric utilities, for the reasons already mentioned. Twenty years later, after substantial progress had been made in vacuum and metallurgical processing, the General Electric Company took a fresh look at this old problem and successfully developed a high-power vacuum interrupter. The potential advantages of current interruption in a vacuum can be more easily understood by a brief review of the operation of a vacuum switch in a high-voltage, ac circuit.

When the simplified vacuum switch shown in Fig. 6 is closed with the two electrodes in contact and normal current flowing, some heat is developed. Since there are no convection losses in a vacuum and since radiation losses are negligible, the heat generated at the contacts must be carried out by conduction along the leads. Therefore, contact resistance must be low to avoid excessive temperature rise.

When a fault current develops, for example, from a short circuit, an actuating mechanism quickly separates the contacts and a vacuum arc forms between the contacts. Normally, the separation of the contacts does not exceed 0.5 in., and were it not for the fact that alternating current is involved, the high-current arc would continue indefinitely. However, as the first zero is approached on the ac wave, the arc becomes unstable and extinguishes in times of the order of 10^{-8} sec. As discussed in Section II.E, an important characteristic of the vacuum arc is that it does not extinguish at the normal current zero, but at a finite current before current zero, as shown in Fig. 7. The current at which this occurs is called the chopping current. For a short vacuum arc, this current is dependent on the

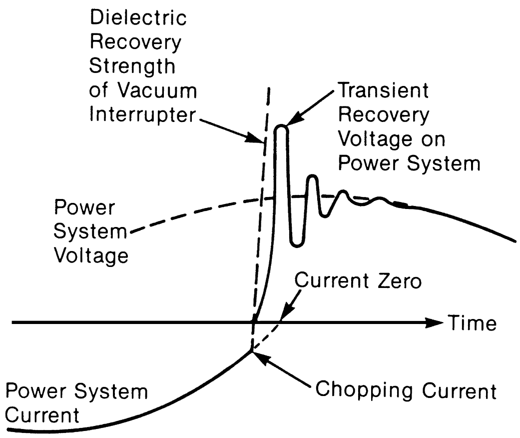

FIGURE 7 Interruption of a fault current by a vacuum circuit breaker and the subsequent transient recovery voltage.

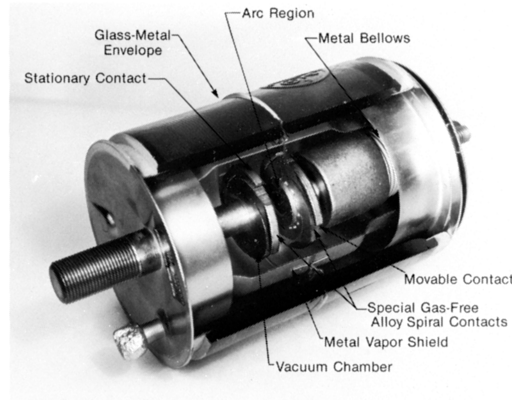

FIGURE 8 A modern 500-MVA vacuum interrupter.

physical characteristics of the contact material (Section II.E). This abrupt cessation of arc current can be a source of difficulty in inductive circuits because of the insulation damage produced by the high-voltage surges. The vacuum switch is particularly susceptible to this difficulty, because the recovery of the electric strength across the gap is so rapid as to permit the development of high overvoltages in the apparatus unless the chopping current is limited to a sufficiently low level.

After current zero, the voltage across the switch is reversed in polarity and—depending on transient circuit conditions—may build up at the rate of 5 to 10 kV/μsec or more. If the rate of dielectric recovery strength of the vacuum switch gap exceeds the rate of rise of the impressed voltage, as shown in Fig. 7, the arc will not restrike and the circuit will have been interrupted. 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 rapid rate of dispersion and condensation of the metal vapor in the gap determines in part the fast recovery characteristics of the switch. After extinction of the arc, the residual evaporation from the cathode will be negligibly small. At the anode, on the other hand, where melting at the anode spot may have occurred at high current, the residual evaporation may be considerable and have a pronounced effect on the recovery strength. It is clear that anode spots should be avoided if possible.

The advantages to be gained by using vacuum switches for current interruption are many. Because the high breakdown strength makes possible a vacuum gap less that 0.5 in. in length, the actuating mechanism for opening the switch can be relatively simple and fast acting. In the vacuum switch, current interruption occurs at the first current zero after opening; thus the arcing time is usually less than one-half cycle and the energy dissipated in the switch is comparatively small. The fast recovery of the vacuum gap eliminates the necessity for an interrupting medium, such as oil or gas, with its attendant maintenance problems. With a completely sealed switch, there is no fire or explosion hazard.

Figure 8 shows a modern vacuum interrupter capable of interrupting a fault current of over 30,000 A at 15.5 kV. Although rather simple in appearance, the vacuum interrupter contains a considerable amount of sophisticated technology. The device is contained in an evacuated glass-metal envelope. One electrical contact is fixed in position and the other is attached to the vacuum envelope through a flexible metal belows so that it can be moved to open and close the switch. The contacts are surrounded by a metal shield to prevent the metal vapor from the arc from condensing on the glass envelope and spoiling its insulating properties.

The electrical contacts are the most important element in the vacuum switch and are worthy of a detailed description. The ideal material for vacuum switch contacts must satisfy several requirements simultaneously. Foremost, the material must be gas free. If the contacts contain gas it will be released on arcing and accumulate in the switch on successive operations, thus destroying the vacuum and causing the switch to break down at low voltages when the contacts are open. The switch must have a rapid recovery of electric strength immediately after arcing and a high ultimate breakdown strength. The contacts must not weld while carrying high momentary currents or when closing in on a short circuit. This antiwelding characteristic requires that the electrical resistance of the contacts be low, which will also minimize heating during the flow of normal continuous current. Finally, the arc drawn between the contacts must be stable at low currents to prevent the generation of overvoltages by current chopping.

Since each of these characteristics requires, in general, the exploitation of different physical properties of the contact material, these demands are not easily satisfied simultaneously and, in some instances, may even be contradictory. For example, zinc, which has a very high vapor pressure, has a chopping current of only 0.5 A. However, the recovery strength is very poor because of the high rate at which metal vapor continues to pour off the anode after current zero. Medium-vapor-pressure metals such as copper, which has a good electrical conductivity, are generally soft and tend to stick or weld easily in a vacuum. They are also incapable of maintaining their shape under the high mechanical stresses of rapid opening and reclosing normally encountered in an interrupter. Low-vapor-pressure refractory metals such as tungsten are hard and do not weld, but have a severe chopping problem. It is apparent then that since no ideal contact material can be found if one is limited to pure metals, composite materials must be considered.

The ideal composite material, then, should be hard and have a relatively high melting point, but also be good electrical conductor and contain at least one component with a high vapor pressure. The vacuum interrupter shown in Fig. 8 has contacts made of a two-phase binary alloy of cooper with a few percent of bismuth. In the liquid phase the bismuth is soluble in copper, but on solidification it precipitates out in the grain boundaries and on the surface of the copper. Since the bismuth is virtually insoluble in the copper, the high electrical and thermal conductivity of the copper is retained. The bismuth precipitate in the copper grain boundaries hardens the alloy and produces a weak, brittle weld interface that is easily broken on impact by the vacuum interrupter opening mechanism. Finally, the presence of the high-vapor-pressure bismuth during arcing reduces current chopping. The copper and bismuth are made remarkably free of gas by zone refining, a technique developed by the semiconductor industry for purifying silicon.

As previously mentioned (Section II.C), molten anode spots tend to form on the positive electrode during high-current arcing. Their formation should be avoided in a vacuum switch because of the adverse effect on the recovery strength of the vacuum gap immediately after current zero when the voltage is building up rapidly in the reverse direction. A hot anode spot will not only continue to evaporate metal vapor into the vacuum gap and reduce its recovery strength, but will also favor the formation of cathode spots as it becomes the new cathode. The formation of anode spots has been minimized in the interrupter shown in Fig. 8 by the introduction of spirals in the outer section of the disk contacts. Current flowing in the spiral portions of the contacts produces a magnetic field that exerts a force on the arc column and keeps it moving, thus distributing the arc energy over a large portion of the positive contact.

B. Triggered Vacuum Gap

The triggered vacuum gap (TVG) is basically a vacuum switch with permanently separated contacts and a third electrode to which an impulse voltage may be applied to rapidly initiate a vacuum arc between the main contacts. The advantages of such a device are the high current-carrying capacity and short breakdown time. Triggered voltage gaps can be designed to break down in less than 100 nsec and carry currents of at least 10^6 A. They have found applications as high-speed protective devices to short out components in danger of damage by overvoltage or overcurrent. They are also used in commutating circuits and as “make switches” in fusion devices.

The design and vacuum processing of a TVG is similar to that of a vacuum switch. The selection of a proper gas-free electrode material for a given gap will depend on the application requirements. However, one need not be concerned about contact welding and resistance to mechanical deformation since the electrodes are permanently separated and do not move. Relaxation of these requirements gives more freedom in the selection of electrode geometries to carry high currents and of electrode materials for rapid breakdown, fast recovery, and high ultimate breakdown strength if any of these features is required.

As discussed in Section II.A, the presence of both electrons and ions is required in a high-voltage vacuum gap to initiate breakdown and establish a vacuum arc. These can be conveniently injected into the vacuum gap in the form of a plasma to give rapid breakdown with a minimum of jitter. One such arrangement for plasma injection is shown in Fig. 9. A ceramic cylinder is coated with titanium hydride only a few millimeters thick. A V-notched groove is then cut through the metallic hydride into the ceramic, forming a ceramic gap. A shield cap is placed on one end of the ceramic cylinder, and a lead wire is attached to the cap. This assembly is inserted into a conical recess in the cathode electrode of the main vacuum gap as shown.

To operate the trigger, a positive voltage pulse is applied to the trigger lead. The ceramic gap breaks down and an arc is established between the titanium hydride electrodes, thus releasing hydrogen and titanium vapor, which are ionized and sustain the discharge. Expansion and magnetic forces produced by the discharge current loop drive the plasma out of the conical recess into the main gap. As the plasma spreads out into the main gap, a high-current glow discharge is first established between the main electrodes. This glow is rapidly transformed into a high-current vacuum arc. It would appear that the main gap discharge uses the cathode spots already established on the trigger electrode in the initial stages of buildup. Measurements indicate that, with peak current pulses of 10 A through the trigger electrode, the main gap will break

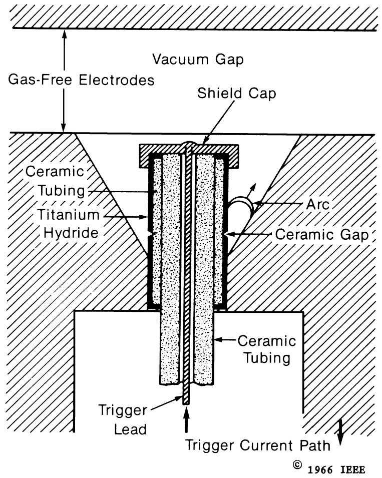

FIGURE 9 Cross-sectional view of an arrangement for triggering a vacuum gap. [Reproduced with permission from Lafferty, J. M. (1966). *Proc. IEEE* **54,** 23. © 1966 IEEE.]

down in less than 0.1 μsec with jitter times of about 30 nsec when 30 kV is applied to the main gap with an electrode separation of $\frac{1}{8}$ in. The trigger energy required is less than 0.01 J. The main gap may be broken down with trigger pulses as low as 50 V; however, longer delay times result.

The quantity of hydrogen released on firing the trigger is extremely minute and there is no accumulative pressure rise due to hydrogen. The presence of the hydride is by no means essential to the operation of the trigger. Breakdown of the gap can be produced by ionization of metal vapor eroded from the trigger electrodes. The energy required to produce breakdown of the gap with an unloaded trigger is about 10 times that required when hydrided.

Reversal of the trigger pulse polarity or placement of the trigger in the anode electrode of the main gap requires more energy for triggering. The principal reason for this is that the cathode spots for the trigger discharge are no longer on the cathode of the main gap and cannot share in the development of the main discharge.

Other trigger electrode configurations are possible for injecting plasma into the main vacuum gap. For example, a coaxial plasma gun may be used that can be well shielded from the main gap discharge. However, such devices all require more trigger energy than the device shown in Fig. 9.

A number of triggered vacuum gaps have been developed over a wide range of currents and voltages for various applications. Some fast TVGs can carry only capacitor discharge current for a few microseconds, while others can carry 60-Hz power line currents of tens of thousands of amperes for one-half cycle. The operating voltages may range from a few hundred volts to 100 kV. Figure 10 shows a TVG with a rating of 73 kV and 125,000 A that is used to protect the series-compensating capacitors on the

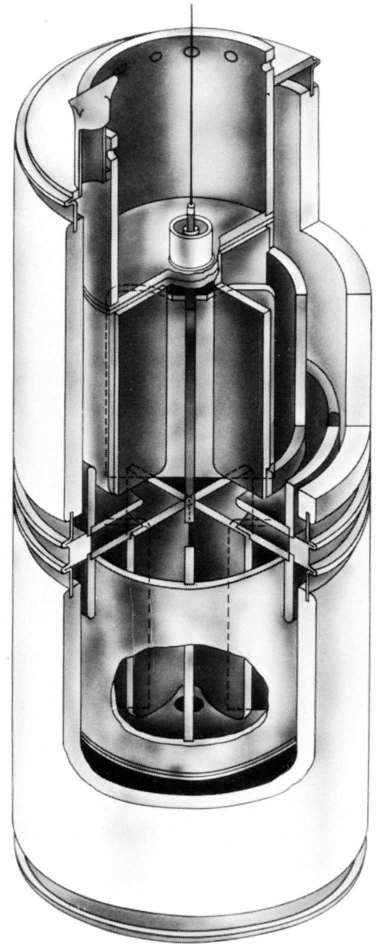

FIGURE 10 Sketch of a 9000-MVA triggered vacuum gap used to protect the series-compensating capacitors on the 500-kV. Pacific intertie ac transmission line. Two communicating gaps in series with an interdigital paddle-wheel geometry were used to disperse the vacuum arc and avoid anode-spot formation.

500-kV Pacific intertie ac transmission line that runs from the Columbia River to Los Angeles in the United States.

Triggered vacuum gaps have also been designed with a movable contact so that they can be made to conduct quickly with the contacts open and then closed to protect the gap if a large current is to flow for an appreciable time. This can also be accomplished by placing a TVG and vacuum switch in parallel.

C. Vacuum Fuse

The vacuum fuse is another example of the use of high-current vacuum arcs for current interruption and the protection of power circuits. Its design is similar to that of a triggered vacuum gap with the fixed arcing electrodes bridged by a fuse element that conducts current under normal conditions. On the incident of a fault or other abnormal condition that produces a large current flow, the fuse element melts and opens the circuit between the electrodes. This initiates a vacuum arc in the same way that it is established when the contacts of a vacuum switch are separated while carrying current, as described in Section II.A. Once the vacuum arc is established, the device functions like a vacuum interrupter with its contacts in the open position.

hThe relatively short length of the fuse element allows the heat generated in it by the normal load current to be conducted out through the heavy leads supporting the arcing electrodes. The arcing electrodes also act as a heat sink to conduct heat away from the fuse element under temporary overload conditions. Under fault conditions the heat cannot escape quickly enough, and the fuse melts at a necked down portion in the center of the bridging element and creates a vacuum arc. The arc quickly melts and vaporizes the remainder of the fuse element, creating conditions essentially identical to those in an open vacuum interrupter. Obviously the fuse bridge element must be made from gas-free material or the fuse will not function properly in a high-voltage ac circuit.

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