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Technology of Fast Spark Gaps

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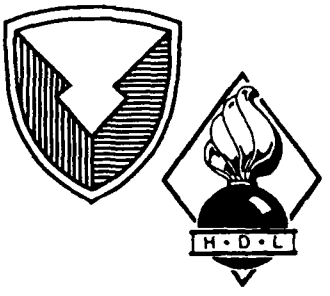

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To protect electronic systems from the effects of electromagnetic pulse (EMP) from nuclear weapons and high-power microwave (HPM) weapons, it is desirable to have fast-responding protection components. The gas-filled spark gap appears to be an attractive protection component, except that it can be slow to conduct under certain conditions. This report reviews the literature and presents ideas for construction of a spark gap that will conduct in less than one nanosecond. The key concept to making a fast-responding spark gap is to produce a large number of free electrons quickly. Seven different mechanisms for production of free electrons are reviewed, and several that are relevant to miniature spark gaps for protective applications are discussed in detail. These mechanisms include: inclusion of radioactive materials, photoelectric effect, secondary electrode emission from the anode, and field emission from the cathode. There are four principal ways to use field emission: carbon electrodes, the Malter effect, use of dielectrics with large relative permittivity, and inclusion of varistor material inside the spark gap. Approximately 50 references are cited to the archival literature, conference papers, and patents.

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Foreword

The electromagnetic field from a high-altitude detonation of a nuclear weapon (high-altitude electromagnetic pulse (HEMP)) has a rise time of the order of a few nanoseconds, and the field from high-power microwave (HPM) weapons has an even shorter rise time. It is important that protection methods be fast responding so that the voltage seen by vulnerable electronic circuits is clamped to a safe value before the threat waveform is able to damage vulnerable electronic systems. The spark gap is one of the most valuable protection components because it is small and rugged, has small capacitance, and is able to carry transient currents on the order of kiloamperes. However, spark gaps can be slow to conduct in some situations. As a result of this concern, J. Kreck of the U.S. Army Harry Diamond Laboratories (HDL) suggested that the author investigate ways to make spark gaps switch in less than a nanosecond.

Drafts of this report have benefitted from review by Bruno Kalab, Alford Ward, and Robert Garver, all of HDL. This work began on indefinite delivery contract DACA88-86-D0005, delivery order 8, between the U.S. Army Construction Engineering Research Laboratory and The Pennsylvania State University. Because of the large amount of literature on this subject, the work was continued during contract DAAL03-87-K-0078 between the U.S. Army Research Office and The Pennsylvania State University.

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1. Introduction

Electrical discharges in gases have been studied by many physicists and electrical engineers since the late 1800's. In addition to fundamental knowledge about the behavior of atoms and subatomic particles, there have been many useful applications of electrical discharges in gases.

A pair of electrodes with gas in between is particularly useful as a switch. Normally the switch is nearly an ideal open circuit. When a sufficiently large voltage is placed across the electrodes, a spark occurs in the gas between the electrodes. If a sufficiently large current is available, the spark channel becomes an arc. The arc is approximately a short circuit: the voltage between the electrodes is only about 20 ± 10 V, even for currents on the order of a few kiloamperes. This effect has been used for many years to protect telephone equipment from damage by lightning. More recently this effect has been used for protection of electronic equipment from damage by the electromagnetic pulse (EMP) from nuclear weapons.

The switching action of a spark gap has also been applied in pulsed laser apparatus. The development of pulsed lasers has recently received much attention in nuclear fusion and physical chemistry research. Additional work on spark-gap switches has been supported by development of directed-energy weapons and simulation of effects of nuclear detonations.

There are several advantages of using spark gaps in protective circuits:

1. Gas tubes are the principal component for shunting large transients away from vulnerable circuits. Typical miniature spark gaps in a ceramic case can conduct transient current pulses of 5 to 20 kA for 10 μs without damage to the spark gap, except for mild erosion of the electrodes.

2. Gas tubes have the smallest capacitance of all presently known nonlinear transient protection devices. The shunt capacitance of a typical spark gap is between 0.5 and 2 pF. Thus spark gaps are one of a few nonlinear devices that can be used to protect circuits in which the signal frequency is greater than 10 MHz.

3. A spark gap is inherently insensitive to polarity of the voltage across the electrodes. Thus a single spark gap can provide protection against either polarity of transient overvoltages.

The operation and construction of spark gaps have been described by Kawiecki [1971, 1974],* Cohen, Eppes, and Fisher [1972], and Bazarian [1980]. The application of spark gaps in transient circuits and their advantages and disadvantages compared to other protection components was discussed by Standler [1984].

One problem with the use of spark gaps for overvoltage protection is that there is a time delay between the application of the overvoltage and the establishment of the arc discharge between the electrodes. This time delay can range from slightly less than 10^{-9} s to more than 10^{-5} s, depending on the construction of the spark gap and the time rate of change of voltage across the gap, dV/dt. The electromagnetic field from a high-altitude detonation of a nuclear weapon (high-altitude electromagnetic pulse—HEMP) has a rise time on the order of a few nanoseconds. It is important that protection methods be fast responding so that the voltage seen by vulnerable electronic circuits is clamped to a safe value before the EMP waveform reaches its peak. As a result of this concern, this review of ways to make spark gaps switch in less than a nanosecond was undertaken.

Miniature spark gaps used to protect electronic circuits and systems from transient overvoltages are low-cost components. Other applications of spark gaps, such as fusion power, particle accelerators, and pulsed-light sources, involve more complicated and expensive spark gaps. Because this investigation is concerned only with techniques to make better protective devices, ideas were considered only if they were applicable to spark gaps that met all the following criteria:

1. small volume (less than 1 cm^3);

2. no external apparatus (e.g., no external trigger circuit, no photo-ionization from a laser or ultraviolet emitting lamp, no electron beam, no cryogenic liquids); and

3. multiple-shot lifetime (e.g., no explosive effects, no rapidly consumable electrode materials).

An additional criterion, that of low cost, was also considered. However, it was decided not to use cost of materials or techniques as a criterion for this study. Future research and development could be used to reduce the cost of new materials or techniques that appear promising but are presently too expensive.

*References are listed at the end of the report.

The breakdown process, how gases make the transition between insulator and conductor, is reviewed first. Processes for liberating electrons from material, a key event in the breakdown process, are then reviewed. Finally, practical suggestions are presented for constructing spark gaps with quicker breakdown.

2. Gas Breakdown

We now consider the macroscopic phenomena that are observed in the operation of spark gaps. The numerical examples of current in the following definitions are for typical miniature spark gaps with dc firing voltages between about 90 and 150 V. We consider what happens when the source voltage, V_{in}, is slowly increased (e.g., $|dV_{in}/dt| < 10^2$ V•s^{-1}). The absolute value of the voltage between the electrodes immediately before the conduction of the spark gap is called the "dc firing voltage" or "self-breakdown voltage."

A glow is a stable electrical discharge with a current that is usually less than 10 mA. The luminous region covers part or all of the cathode. The spectrum shows lines and bands due to the gas between the electrode.

An arc is a stable, large current discharge. The voltage between the electrodes is relatively small (usually between about 10 and 30 V). An arc is a high-temperature phenomenon and the electrodes are consumed, as in arc welding applications. The spectrum of the arc shows lines due to vaporized electrode material. A minimum current between about 50 and 500 mA is required to maintain an arc. If the current in the gap is reduced below this minimum current, the spark gap returns to either the glow or nonconducting state.

3. Overview of the Response Time of Spark Gaps

We now consider the transient operation of a gas tube. For rapidly changing waveforms (e.g., 1 kV/μs or more), the actual firing voltage is observed to be several times greater than the dc firing voltage [Trybus et al, 1979]. The dc firing voltage alone is sufficient to produce an electric field between the electrodes that is necessary to get ions and electrons to energies that will produce ionization by collision, such as in a glow discharge. So why does the tube require larger voltages to conduct? The conduction processes are not instantaneous: a definite time is required for a conducting channel to form in the gas.

One theory is that a filamentary wave of ionization, which is called a "streamer," propagates from the cathode toward the anode. Streamers emit

light and have been observed. Once a streamer has traveled between the two electrodes, a conducting channel between the two electrodes is available. A delay occurs between the time of application of a voltage across the spark gap and the time that an arc occurs inside the spark gap.

The time delay comes from two effects: (1) an electron that is capable of initiating the breakdown must be released in the gas, and (2) an additional time is required for the electron to form a glow or arc discharge that results in the collapse of the voltage across the gap. These effects are called the "statistical" and "formative" times, respectively. An excellent review of this topic has been given by Kunhardt [1980]. The initial electrons are commonly provided by cosmic rays, or radioactive material inside the spark gap. An alternate source of initial electrons is field emission from the cathode in the large magnitude of electric field inside the gap before breakdown. Especially if the initial electrons are provided by cosmic rays, the time required to obtain these electrons will be a random variable, hence the name "statistical time lag." However, there is also a random variation in the "formative time lag" [Levinson and Kunhardt, 1982].

There is no consensus on how to measure the delay times of a spark gap. Lindberg, Gripshover, and Rice [1980] gave the following operational definitions of the two time lags. The statistical time lag is obtained by measurements of the voltage across the gap. It is the time interval between the application of the voltage pulse and the beginning of the decrease in voltage across the gap. (This assumes that the pulse width of the applied voltage is greater than the statistical time lag.) The formative time is determined from measurements of the current in the spark gap. The interval between the beginning of the current and the constant arc current is the formative time lag. The formative time occurs while the voltage across the gap is decreasing from the peak impulse breakdown voltage to the arc voltage. Lindberg, Gripshover, and Rice [1980] noted that at large values of dV/dt, the statistical time lag was less than the rise time of their voltage generator, and the spark gap often has an anomalously "early" breakdown.

Kunhardt [1980] avoided using the words "statistical" and "formative" time lag in connection with laboratory measurements of breakdown. Instead he used "switch delay" to indicate the time interval between the application of the overvoltage and when the current in the gap became 10 percent of the peak current. He also used the time interval between the 10- and 90-percent points of the current in the spark gap as the "current rise time." Kunhardt [1983] suggested that the time required for breakdown may not be the sum of the statistical and formative times. This subject appears confusing, partly owing

to different definitions of statistical and formative times by different researchers and partly owing to incomplete understanding of the physical phenomena. The response time for spark gaps is commonly measured with a voltage source that has a constant rate of rise, dV/dt, before conduction of the spark gap. For rates of rise larger than about 1 kV/μs, the firing voltage of the spark gap is appreciably greater than the dc firing voltage. The response time, Δt, is given by

$$\Delta t = V_f/(dV/dt) \ ,$$

where V_f is the peak impulse voltage across the spark gap. A plot of V_f as a function of Δt is shown in figure 1 for a modern, but not state-of-the-art, spark gap. Lines of constant dV/dt are also shown in figure 1.

The ratio of V_f to the dc firing voltage is called the "impulse ratio." Spark gaps having impulse ratio values less than 3 would be greatly desirable for protecting vulnerable equipment against overvoltages with short rise times.

The response time approaches an asymptotic limit as dV/dt is increased above about 100 kV/μs. This limit may be caused by a delay time that is not inversely proportional to the electric field strength.

Singletary and Hasdal [1971] found minimum response times between about 1.8 and 3.0 ns at rates of rise of about 1 MV/μs for a dozen different spark gaps with dc firing voltages between 90 and 800 V. There was little correlation

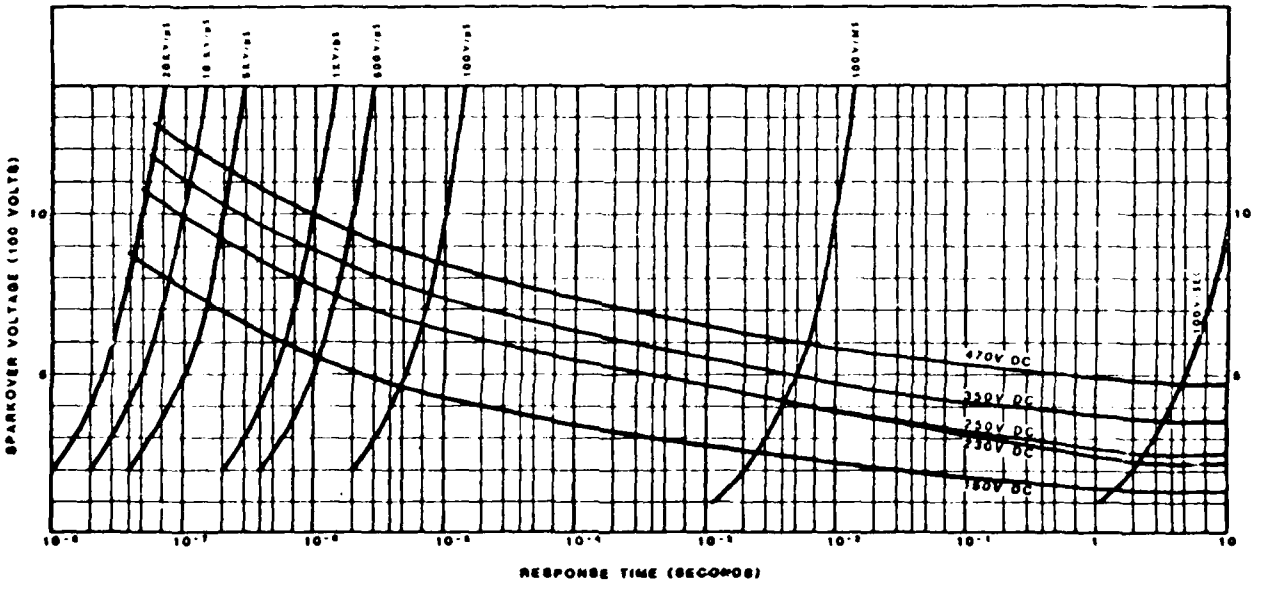


Figure 1. Values of Δt and V_f for a modern, but not state-of-the-art, spark gap. (Courtesy of Joslyn Electronic Systems.)

between dc firing voltage and the response time. Most of these spark gaps were conventional types that were designed for protection from lightning and not fast gaps that were designed for protection against EMP. They noted that these times are approximately the transit times of positive ions between the electrodes. This agreement may be accidental.

The standard determination of response time of a spark gap measures the time for the voltage across the gap to reach a maximum when dV/dt is a constant. This determines the time required for an unspecified type of gas discharge to develop. This is not necessarily the best measure of response time for protection applications. It might be more appropriate to measure the time required for a highly conducting arc to develop. This end condition could be determined by specifying that the voltage across the gap must be less than, for example, 30 V for a current of at least 100 A. Cary and Mazzie [1979] measured the resistance of a spark gap with a resolution of 0.05 ns; this is an alternative way of specifying the time for a highly conducting arc to develop.

4. Theoretical Lower Limit to Response Time of a Spark Gap

It is of great interest to calculate a lower limit to the response time of a spark gap. A typical spark gap is composed of two parallel plate electrodes. If we knew the distance between the electrodes and the maximum speed of the charged particles that traverse the gap during prebreakdown phenomena, we could estimate the minimum time required for breakdown. This is a complicated calculation, and the details of the physics of breakdown are not yet understood. However, one can make the crude estimates in the following paragraphs. These are not estimates of statistical or formative times, but only simple calculations of travel times.

Practical spark gaps for transient protection applications will have an electrode spacing of about 0.15 mm or more. If the electrode spacing is less than 0.15 mm, it is easy for metal particles from the arc to bridge the gap between the electrodes and form a short circuit. There are also production difficulties associated with manufacturing spark gaps with small gap spacings.

Kunhardt [1983] mentions that runaway electrons ahead of a streamer might have speeds on the order of 10^8 cm/s. Murooka and Kayama [1979] found maximum speeds of streamers of about 3×10^8 cm/s. If we use these values for speed, the minimum response time of a spark gap is between 0.05 and 0.15 ns when the electrode spacing is 0.15 mm. However, Kunhardt [1983] states

that "the breakdown time may be less or equal to an electron transit time across the gap."

An absolute lower limit to the time required for breakdown is given by the distance across the gap divided by the speed of light in vacuo. For a 0.15-mm gap spacing, this limit is 0.5 ps. There is no doubt that the actual breakdown process time will be longer than this estimate.

An additional lower limit to the time required for the development of a highly conducting arc comes from the inductance of the discharge channel and the impedance of the transmission line that is connected to the spark gap. Levinson et al [1979] performed experiments in which the discharge channel was simulated by very thin wire (0.25 mm diam), and coaxial cable with a characteristic impedance of 50 Ω was used. They found that the 10- to 90-percent rise time of the current was 0.35 ns for a gap spacing of 10 mm. Presumably, a gap spacing of 0.15 mm would have a rise time of about 5 ps due to the inductance of the gap when used in a 50-Ω system. The time delay due to the inductance of such a small spark gap is probably much less than the time lag due to breakdown processes in the gap. Note that this calculation does not consider the inductance due to the spark gap package and wire leads. When this additional parasitic inductance is considered, the response time will be increased.

5. Production of Electrons

The key feature to creating an arc discharge is to make a large number of electrons available for current between the electrodes. There are a surprisingly large number of ways to produce a free electron from an atom. The different production mechanisms are listed below. We then discuss each mechanism in the context of its application in miniature spark gaps for protection.

1. *Photoelectric effect.* An incident photon (usually ultraviolet light, x rays, or low-energy gamma rays) is absorbed by an atom and an electron is liberated. This effect can occur in gases or at the surface of conductors and insulators.

2. *Compton effect.* An incident photon can be elastically scattered by an electron in an atom, with the release of a photon of lesser energy and a recoil electron.

3. *Pair production.* An incident photon with sufficiently high energy can interact with an atom and create an electron-positron pair.

4. *Beta decay.* An electron, which is also called a "beta particle," is emitted during decay of certain radioactive isotopes.

5. *Ionization by collision.* Ionization by collision requires incident particles with sufficiently large kinetic energy. These incident particles can be produced in several ways:

(a) alpha particle or an electron with kinetic energy greater than about 30 eV,
(b) any charged particle in an intense electric field, or
(c) neutral particles at high temperatures (e.g., in flames or arcs).

6. *Field emission.* Electrons can be "pulled out" of a solid surface by an electric field on the order of 10^8 $V \cdot m^{-1}$.

7. *Thermionic emission.* At relatively high temperatures, electrons are "boiled off" from metal surfaces. (This effect was used to supply electrons in vacuum tubes; the filament or heater circuit supplied the thermal energy for thermionic emission.)

We now discuss the relevance of each of the processes listed above to the initiation of an arc inside a spark gap.

Spark gaps used as switches in a laboratory environment may use a pulsed laser to initiate the electrical discharge by the photoelectric effect. This method provides a potent source of initial ions and eliminates the statistical time lag [Kunhardt, 1980]. Such an arrangement is impractical for spark gaps used as protective devices. Without an initial source of light, the photoelectric effect cannot initiate the discharge. However, photoionization may be an important secondary process in breakdown. It is possible that the light from prebreakdown streamers might produce photoionization. Collisions between charged particles and electrode material may also produce photons that are useful for photoionization.

The Compton effect is important only for incident photons with relatively large energies (e.g., on the order of 30 keV or more). Pair production is impossible unless the incident photon has an energy of at least 1.02 MeV. These high-energy photons have a relatively long range between interactions, compared to the lower energy photons that are important in the interactions

involving the photoelectric effect. Since processes are desired that can produce large numbers of electrons in a small volume, the Compton effect and pair production are unimportant for miniature gas-filled spark gap applications.

Beta decay, which is an important process to be used to produce initial electrons that can begin streamer formation, is discussed in detail in section 7.

Ionization by collision is a very important process in spark gaps. An incident particle collides with an atom and produces a free electron and a positive ion. For this to happen, the kinetic energy must be greater than the energy required to liberate an electron from the atom. In most cases, the incident particle will be charged (e.g., a free electron) and its kinetic energy will come from traversing an electric field inside the spark gap. However, it is possible for the kinetic energy to come from random motion at high temperatures—for example, when the arc channel is well developed. During the initial breakdown processes the temperature will be too low for random thermal motion to produce electron-ion pairs.

Particles with sufficient kinetic energy may have ionizing collisions with atoms of gas or by impact at the electrode surface. An impact of a single electron at the anode can liberate several secondary electrons in a process which is described in detail later. A positive ion with sufficient kinetic energy is able to liberate electrons from atoms at the cathode surface. Ionization by collision is the dominant mechanism for sustaining a glow discharge.

Electrons that are accelerated in the intense electric fields inside the gap immediately before breakdown collide with the anode and produce ultraviolet light and soft x rays. This radiation may then liberate additional electrons by the photoelectric effect.

It is important to recognize that ionization by collision cannot be responsible for producing the *initial* electron that starts the avalanche process. However, once an initial electron is available in an intense electric field, ionization by collision can be an efficient mechanism for exponential growth of the number of free electrons.

Field emission, which is an important process to be used in the development of fast spark gaps, is discussed in detail in section 9. Because the rate of emission of electrons is greater in intense fields, field emission is a more effective mechanism for use in spark gaps than a mechanism whose rate of production is independent of electric field, such as radioactive decay.

The thermionic effect in bulk material cannot be important in the initial part of the gas discharge because the gas and electrodes are too cold. The thermionic effect may be a substantial source of electrons during prolonged operation in arc discharge.

We now treat the relevant processes for the production of electrons in greater detail.

6. Photoelectric Effect

Alkali metals (lithium, sodium, potassium, rubidium, cesium) have the smallest work function and thus can liberate electrons with relatively low-energy photons. Kawiecki [1971, 1974] put CsCl or KCl in a concave cavity at each electrode in order to exploit the photoelectric effect.

The alkali metals have a low melting point. Except for lithium, they could be a liquid at normal operating temperatures of electronic equipment (up to 100°C). They also have a low boiling point (685 to 1330°C at one atmosphere of pressure) and will be vaporized by high temperatures in an arc discharge. The temperature problems with alkali metals can be avoided by forming a salt, a halide. However, halides are insulators and cannot be coated over the entire electrode surface.

The probability of releasing an electron by the photoelectric effect is not necessarily large for photons greater than the work function of the material. Each material will have a complicated spectral response that needs to be matched to the emission spectra of the gas in order to maximize the emission of electrons by the photoelectric effect.

7. Beta Decay — Radioactive Prompting

Beta decay is an attractive way to produce a steady-state population of free electrons inside a spark gap. Such free electrons could start the avalanche process and eliminate the statistical time delay. Suitable isotopes should have no gamma radiation, be easy to produce, and have a value of half-life between about 10 and 10^5 years. Gamma radiation is undesirable because it has a long range (low probability of interaction) and might present a hazard to personnel. A long half-life is desirable because the spark gaps need not be replaced often and the shelf life is long. Isotopes with a very long half-life (e.g., greater than

10^5 years) would require a relatively large mass of radioactive material in order to obtain an appreciable initial activity.

Suitable choices of beta-emitting isotopes include tritium gas (^3H) or electrodes that contain ^{63}Ni. (^{147}Pm has a half-life of only 2.6 years, but is an otherwise suitable beta-emitter.) ^{85}Kr is also suitable, except that the maximum initial energy of the beta particles is 670 keV, which is rather large. Particles with a larger energy have a smaller probability of interaction: high-energy particles may traverse the gas inside the spark gap and make few, if any, ion pairs. The high-energy particles will make ion pairs within solid materials inside the spark gap, but these ion pairs will be ineffective in stimulating conduction in the gas.

A typical initial rate of decay to stabilize the dc breakdown voltage in a spark gap is about 0.1 μCi [Clarke, 1972; Bazarian, 1980]. The unit of activity is the curie (Ci); one curie is equivalent to 3.7×10^{10} disintegrations per second. Although one beta particle (electron) is emitted, on the average, every 0.3 ms from a 0.1-μCi source, the secondary electron-ion pairs produced by the collision of the beta particle with atoms of the gas will persist for a much longer time. Thus the beta-emitting isotope provides, indirectly, a source of ions that is continually present.

Bazarian [1980] stated that 10 to 100 μCi of radioactive material was required to eliminate the statistical time lag for values of dV/dt between 0.1 and 10 kV/μs.

Clarke [1972] has described the safety of prompting of spark gaps with tritium. The principal danger to human health would be the inhalation of a *large* amount of tritium gas (e.g., 10 mCi). Such an accident is improbable because each spark gap contains much less tritium than the amount that would be dangerous, and the gaps are hermetically sealed.

The maximum collision cross section for electrons in inert gases occurs for electrons with energies between about 50 and 150 eV. A beta emitter with a low maximum energy, such as tritium, is particularly suitable.

Use of radioactive isotopes that emit alpha particles would be more effective than beta emitters, because alpha particles have a greater collision cross section (greater probability of interaction, more ions per unit distance of travel). Most alpha-emitting isotopes also emit gamma rays, or the isotopes decay to daughter products that produce gamma radiation. Because it is highly penetrating, gamma radiation may be hazardous to people near the

spark gap. One alpha-emitting isotope that does not produce gamma radiation is ^{210}Po, but it has a half-life of about 0.4 years, which is too short to be useful.

8. Secondary Electron Emission

When electrons bombard an anode, secondary electrons are released from the anode material. The yield of secondary electrons is δ, where δ is the number of secondary electrons divided by the number of incident electrons. Observations with many different metals show that δ reaches a maximum value of less than 2 for incident electrons with an energy between about 200 and 800 eV [McKay, 1948, pp 67-68]. Tungsten has a relatively large maximum value of δ, about 1.4, and is suitable for spark-gap electrodes owing to its low vapor pressure at high temperatures. Secondary emission is a fast process: the time delay between the arrival of the incident electron and the release of the secondary electron is less than 0.1 ns [McKay, 1948, p 81].

When electrons bombard insulators, the yield can be much greater than for metals. Alkali halides have maximum values of δ between about 5.5 and 7.5; glasses have maximum values of δ between about 2.0 and 3.0; oxides of alkaline earths (e.g., MgO, BaO, SrO) have maximum values of δ between about 2 and 12 [McKay, 1948, p 98]. A spark gap with a coating of MgO on the electrodes to give a "particularly high field electron emissivity" was patented by Bahr and Peche [1972].

Secondary emission may be useful in making spark gaps fast responding. However, to maximize the yield, the incident electron must have an energy of a few hundred electron volts. If the electron obtains this energy by traveling from the cathode to the anode without colliding with an atom of gas, then a time delay will occur. Part of this time delay is due to the travel time of the electron, and part to the rate of rise of voltage between the electrodes. For example, if dV/dt is 1 MV/μs, it will take 0.2 ns to obtain 200 V between the electrodes.

9. Field Emission

Field emission of electrons from a metal cathode has been shown to be important in the transition from positive streamers to spark breakdown [Nasser, 1966]. There are two basic ways to exploit field emission: (1) use geometries that provide enhanced electric fields and (2) use materials with

small values of the work function. The standard way to obtain enhanced electric fields is to use a small radius of curvature, as on the tip of a needle. This is difficult inside the geometry of a spark gap, particularly when it is considered that the electrodes must be able to conduct a large current density during operation in the arc regime. Materials with small values of work function are more active at both photoelectric emission and field emission, so both processes may be exploited with this one feature.

It is well established that electrodes are pitted after operation in the arc regime. Sharp protrusions are often found on the edges of these pits [Sinha et al 1981; van Oostrom and Augustus, 1982; Mesyats, 1983]. The electric field near the tip of these protrusions will be enhanced, and the tip is a likely site for field emission. These pits in the electrode surface will be created by routine testing of each spark gap by the manufacturer, as well as during use as a protective component.

Four possibilities for producing field emission are discussed in detail below: (a) carbon electrodes, (b) the Malter effect, (c) "dielectric stimulated arcing" phenomenon, and (d) use of metal-oxide varistor material to emit electrons in intense electric fields. All four phenomena can be a source of electrons in an intense electric field.

9.1 Carbon Electrodes

Levinson and Kunhardt [1981] investigated the time required for breakdown with aluminum, brass, and graphite electrodes in a 10-mm gap filled with nitrogen at a pressure of 73 kPa (550 mm Hg). The graphite electrodes had both a smaller time lag and much less statistical variation in time to breakdown than the other two electrodes, as shown in figure 2. The time lag in these plots is determined empirically and is an unspecified combination of the statistical and formative times, RC times, and the rise time of the external voltage generator.

Prolonged operation in the arc regime will produce a considerable amount of free carbon particles between the electrodes. The carbon dust is an erratic conductor. For many years, spark gaps with carbon electrodes and a gap spacing of about 0.1 mm were used to protect telephone systems. The carbon dust produced appreciable noise that interfered with the normal operation of the telephone system.

Brainard and Anderson [1980] crushed carbon-composition resistors and clamped particles with a diameter of about 0.5 mm between the electrodes of

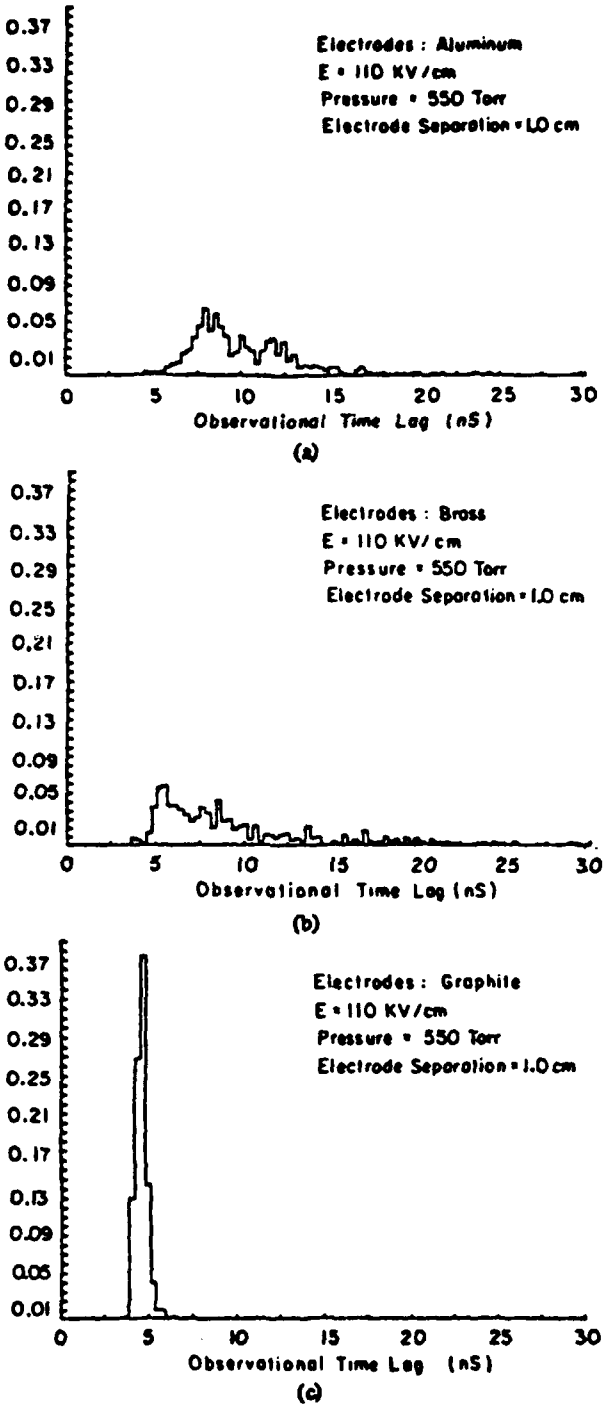


Figure 2. Observational time lag for three different electrode materials as determined by Levinson and Kunhardt [1982].

a spark gap in air. The presence of the carbon-composition material reduced the breakdown voltage when a pulse with a 50-kV/μs rate of rise was applied. Material with a higher conductivity (110 versus 750 Ω mm) had a lower breakdown voltage. The emission of light from the material was detected about 20 ns before breakdown, when the material appeared to have an

increased conductivity. Photographs of the discharge indicated a flashover at the surface of the carbon-composition material.

Carbon-composition resistors are formed of carbon mixed with a clay binder to control the conductivity. Could the clay binder influence the breakdown process? Tests with rutile particles between the electrodes showed a much greater breakdown voltage than with carbon-composition particles. The carbon is apparently an "active" ingredient. However, the breakdown voltage with rutile particles was consistently less than the breakdown voltage of a plain air gap.

Brainard and Anderson [1980] concluded that field emission might have been responsible for part of the reduced breakdown voltages observed with the carbon, and all of the reduced breakdown observed with the rutile particles. They suggested that thermionic emission or bulk breakdown of the conductive materials was responsible for the particularly low breakdown voltage observed with conductive material in the gap. Invoking thermionic emission is perhaps surprising. Very large currents per unit area can flow in microscopic protrusions, and the local temperature may be large. However, large temperatures will probably take a time on the order of microseconds, owing to the heat capacity of the material and its thermal conductivity. Work on field emission from conductive particles needs to be extended to a nanosecond time scale.

Huang, Hsu, and Kwok [1984] described a fast, low-voltage spark gap that they used as a source of ultraviolet light. They broke a carbon-composition resistor in half. The resistor material formed the anode. A needle tip was used as the cathode, as shown in figure 3(a). The tip of the needle touched the carbon-composition material and formed a resistance between 8 and 18 times greater than the original resistor value, as shown in figure 3(b). When an overvoltage was applied, an arc with a length of about 0.1 mm formed between the needle tip and the bulk resistor material. A time delay of about 5 ns was achieved with a value of dV/dt on the order of 100 kV/μs. The minimum dc breakdown voltage for this device was measured to be just 28 V. This is near the minimum possible breakdown voltage for a gas-discharge process. The presence of resistor R2 in series with the gap and the unipolar nature of the device make this device unsuitable for applications where a circuit must be protected from an overvoltage. However, this is an interesting experiment that indicates that field emission from carbon can produce short breakdown times. (Note: Paschen's law gives a minimum dc breakdown voltage for an air gap as about 300 V. The example cited above clearly contradicts Paschen's law. The failure of Paschen's law for very small electrode distances was explained by Boyle and Kisliuk [1955].)

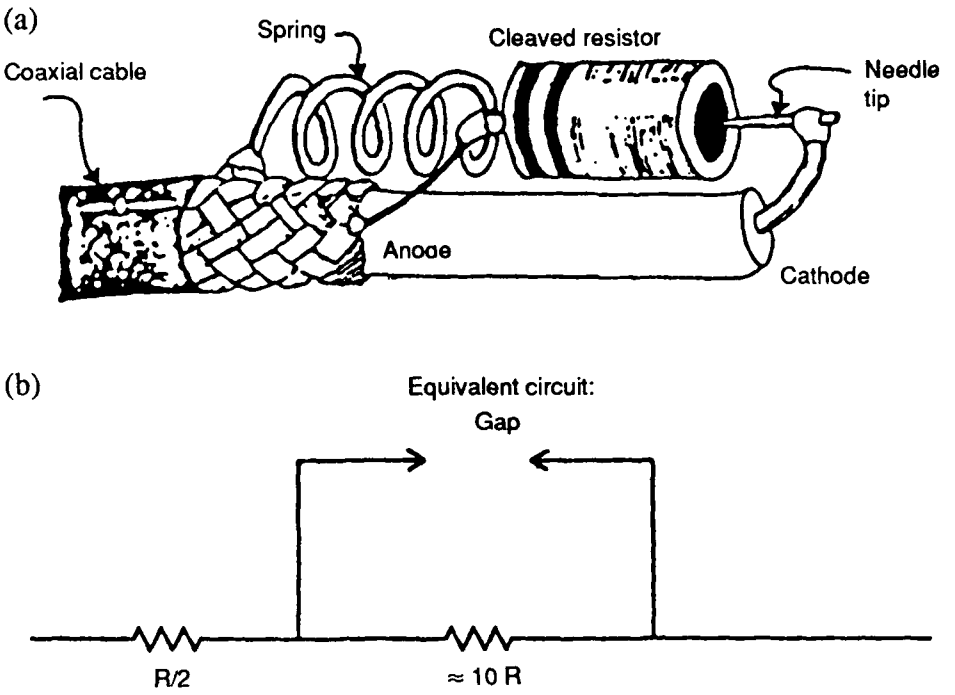


Figure 3. Low-voltage spark gap developed by Huang, Hsu, and Kwok [1984].

9.2 Malter Effect

Malter [1936] discovered that an oxidized aluminum electrode was a very effective source of electrons. Apparently, thin layers of insulating material on the cathode acquire a positive charge from positive ion bombardment or from the photoelectric effect. This produces an intense electric field between the positive charge on the insulator and the negative charge on the surface of the conducting cathode. Field emission of electrons then occurs from the cathode. Most of the electrons have a relatively large initial velocity and penetrate the insulating material without neutralizing the positive charge [Nasser, 1971, p 235]. Several types of oxides have been found to be particularly effective: MgO, Al_2O_3, and SiO_2.

An additional mechanism makes the Malter effect possible at the anode. If an incident electron strikes an insulating surface and more than one secondary electron is released, then the insulating surface acquires a net positive charge. Although the charge on the surfaces of the insulator and the anode has the same polarity, an intense electric field can still be created.

That SiO_2 exhibits the Malter effect is particularly interesting. SiO_2 has the largest electron mobility of any insulator, about 20 $cm^2\ V^{-1} \cdot s^{-1}$ in electric fields of about 5 $MV \cdot m^{-1}$ or less [Hughes, 1978]. At greater magnitudes of the

electric field, the electron velocity saturates at about 2×10^7 cm•s^{-1}. It is apparently unknown whether there is a connection between the large velocity of electrons and the Malter effect.

One difficulty with using the Malter effect in fast spark gaps is that there is a time lag inherent in the Malter effect. The insulating material must acquire surface charge before the Malter effect can begin to produce electrons. Once the Malter effect begins to produce electrons, production may continue for hours after the primary charging process ceases [McKay, 1948, p 117; Dobischek et al 1953].

It would be interesting to see whether alkali metal halides would be useful for the Malter effect. These halides also could emit electrons by the photoelectric effect, which would be an additional mechanism for acquiring positive charge on the insulating halide.

9.3 Dielectric-Stimulated Arcing

When certain crystalline dielectric materials are placed in an intense electric field, electrons are emitted from the surface of the dielectric. When this is used to initiate an arc in a gas that surrounds the dielectric, the phenomenon is called "dielectric-stimulated arcing." This subject appears to be poorly understood; it *may* be a variant of the Malter effect. The distinction made here is that dielectric-stimulated arcing involves large insulators, while the Malter effect involves microscopic insulators. In dielectric-stimulated arcing, electrons are apparently released from the dielectric in the intense electric field where the dielectric and electrode touch.

Cooper and Allen [1973] used dielectric-stimulated arcing to decrease the response time of spark gaps. The spread of dc firing voltages that were obtained in a batch of spark gaps was also reduced. Insulators with larger values of relative permittivity, which is also called "dielectric constant," produced smaller time lags [Kofoid, 1960; Cooper and Allen, 1973]. This result is probably caused by the larger electric field at the electrode-dielectric interface due to increased polarization of the dielectric materials with a larger relative permittivity.

Alumina (Al_2O_3) has a thermal coefficient of expansion that is a good match for electrodes fabricated from Kovar®, and so alumina is a common choice for the body of a spark gap. Rutile (TiO_2) has a relative permittivity that is 10 times greater than that of alumina, and Cooper and Allen suggested that rutile was "the most appropriate material...for a dielectric-stimulated arcing

application." Barium titanate ($BaTiO_3$) has a relative permeability that is 500 times greater than that of alumina, but barium titanate was difficult to use.

Cooper and Allen [1973] showed that use of dielectric-stimulated arcing with rutile made the breakdown voltage essentially independent of the rate of rise of the voltage across the gap for rates as large as 50 kV/μs. This work needs to be extended to larger rates of rise, e.g., 1 MV/μs.

Cooper and Allen [1973] recognized that the use of materials with large values of relative permeability between the electrodes of spark gaps would increase the parasitic capacitance of the spark gap. This would be a serious disadvantage in applications where high-frequency signals are normally present. The capacitance could be reduced by avoiding the coaxial dielectric sleeve in their application and returning to a standard spark gap geometry, as described in the next paragraph.

Kawiecki [1971] drew two narrow lines of graphite (about 0.6 mm wide), parallel to the axis of the spark gap, on the interior wall of the ceramic case of a spark gap. One line of graphite was connected to each electrode. He claimed that the enhanced electric field at the end of the graphite line was responsible for "stabilizing the operating characteristics" and providing a much faster response. At a 10-kV/μs rate of rise, a gap with a dc breakdown voltage of 250 V conducted at 500 V with the graphite and 3000 V without the graphite. Dielectric-stimulated arcing from the alumina ceramic wall might be responsible for the performance of these strips. Alternately, field emission from the graphite may be responsible. Once the electrical discharge is established, the majority of the current is conducted in a discharge in the gas and does not pass through the graphite. This is due to the relatively low conductivity of the graphite lines compared to the ionized gas.

Bazarian [1980] placed a layer of ceramic with a relative permeability of more than 10^3 between two electrodes of a spark gap, as shown in figure 4. The resulting spark gap had a capacitance of 20 pF for an electrode spacing that had a dc breakdown of 550 V. Models that had a larger dc breakdown voltage, and hence a greater electrode spacing, had less capacitance. This arrangement apparently avoided the difficulties that Cooper and Allen [1973] had with barium titanate. Berkey [1940] described a similar spark gap and showed how to use the insulator and electrode geometries to form an intense electric field at the junction of the insulator and the electrode.

Mitsubishi Mining and Cement developed a novel spark gap [Ando et al 1985]. A ceramic cylinder was coated with an SnO_2 conductive film, and lead

wires were fitted to each end of the cylinder, as shown in figure 5. The conducting film was removed from one or more rings, each of which had a width of about 20 μm. The device was mounted in a glass tube that was filled with 95 percent Ar and 5 percent Ne. The ceramic in the microgap is claimed to supply electrons by field emission. After the electrical discharge was initiated, the discharge was supposedly between the metal end caps and not across the microgap. The end caps were separated by about 3 mm, a relatively large spacing for electrodes in a gap with a dc breakdown voltage of about 200 V. Tests with a 2-MV/μs rate of rise show a time delay of about 3.5 ns for devices with a 180-V dc breakdown rating [Gray, 1983]. These devices clamped at more than 60 V, rather than the 20 ± 10 V that is typical of a spark gap in the arc regime. Perhaps this large clamping voltage is due to the long discharge path inside the gap.

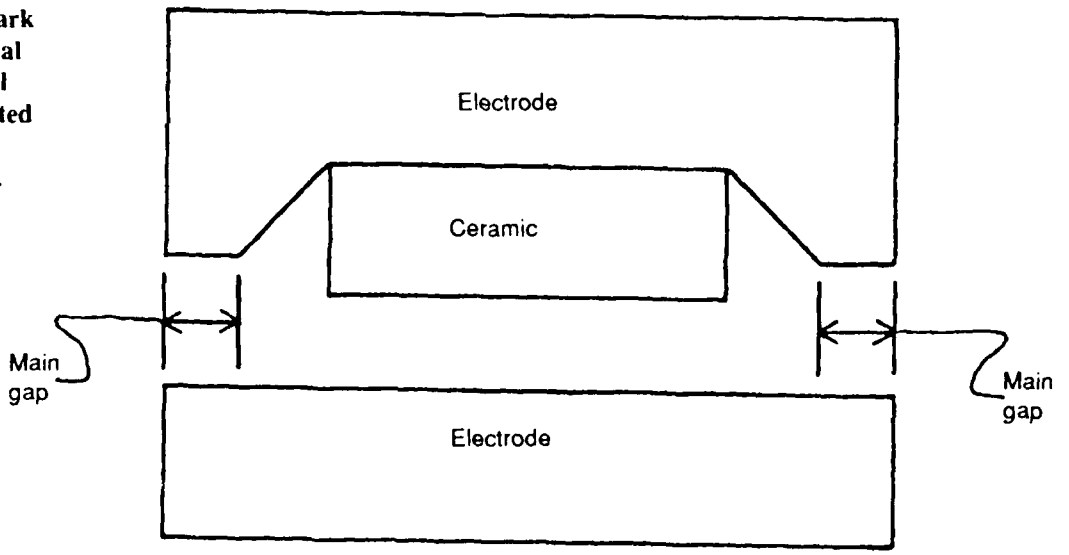


Figure 4. Fast spark gap (cross-sectional view of cylindrical dielectric-stimulated arcing spark gap [Bazarian, 1980]).

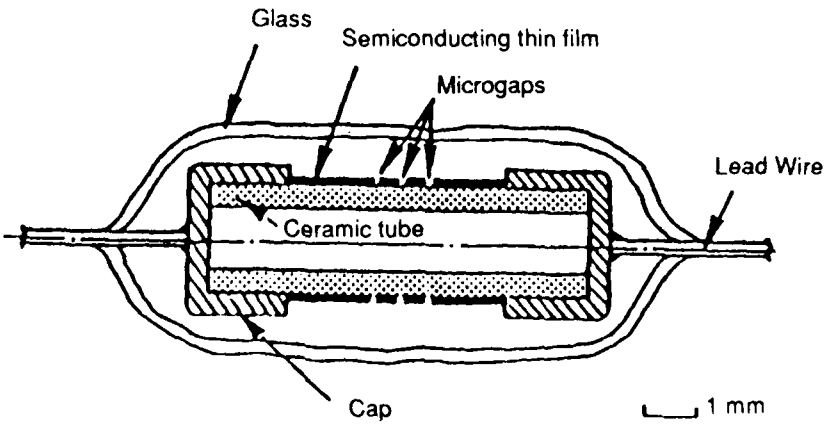


Figure 5. Microgap discharge developed by Ando et al [1985].

9.4 Use of Varistor Material Inside a Gap

Brainard, Andrews, and Anderson [1981] used pellets of zinc oxide varistor material with a diameter of about 0.2 mm between two spark gap electrodes, as shown in figure 6. At low voltages the zinc oxide varistor functioned in the usual nonlinear manner. At higher voltages, an arc in air was initiated by an electrical discharge at the point of contact between one electrode and a varistor pellet. The arc was claimed to protect the varistor from damage by excessive current.

This is a particularly important suggestion because the inclusion of the varistor material will attenuate transient overvoltages before the spark gap conducts. The speed of response of the metal oxide-varistor material has not been determined, but is known to be less than 0.5 ns [Philipp and Levinson, 1981]. Hence, it is less important to have a fast-responding spark gap when a varistor is connected in parallel.

If the varistor material clamps the voltage across the spark gap at too small a value, then the spark gap will not conduct. In order for the spark gap to be able to shunt current away from the varistor, the clamping voltage of the varistor at expected surge currents should be several times greater than the dc breakdown voltage of the spark gap. However, the substantial parasitic capacitance of the metal-oxide varistor material may cause unacceptable circuit loading in applications that operate at frequencies that are greater than about 100 kHz.

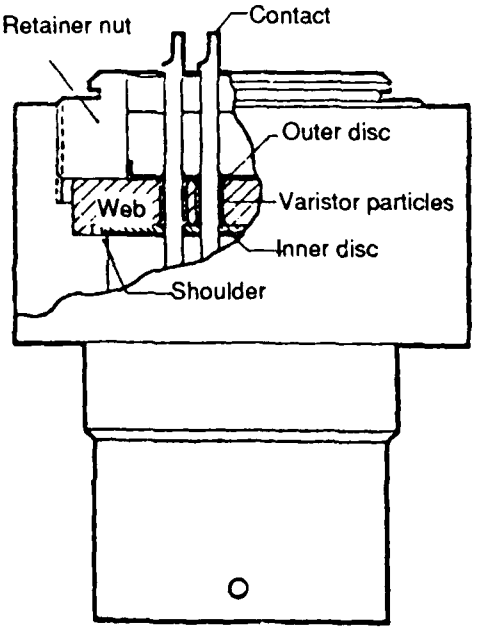


Figure 6. Varistor particles 0.15 to 0.20 mm in diameter between electrodes of spark gap developed by Brainard, Andrews, and Anderson [1981].

10. Effect of Gas Type and Pressure

It is uncertain what gas composition is best to use for fast-switching spark gaps. The exact composition and pressure of gas inside spark gaps is usually considered proprietary information. Some information has been disclosed in patents and is discussed below, together with information from a few archival papers.

Inert (noble) gases are commonly used in spark gaps. For example, Lange et al [1984] used 97% nitrogen and 3% hydrogen at a pressure of about 1.5 MPa inside a spark gap. Toda [1985] used a mixture of 49% helium, 49% argon, and 2% hydrogen with a gap spacing between 0.02 and 0.3 mm to obtain fast response time owing to unspecified mechanisms. Bazarian and Kineyko [1974] used a mixture of 80% argon and 20% hydrogen. Siemens literature claims argon and neon are "predominantly used" in 1980.

Cary and Mazzie [1979] used pressures of 3.4, 170, and 340 kPa to show that spark gaps with greater pressures developed a highly conducting arc more quickly. Gaps filled with pure argon appeared to be faster than gaps filled with H_2, N_2, or a mixture of 5% H_2 and 95% Ar.

Felsenthal and Proud [1965] compared measurements and theoretical predictions for the formative time lag in various gases. A minimum formative time of about 0.5 ns was found for air; this occurred for pressures between about 1 and 10 kPa. The smallest formative time observed in their study, 0.3 ns, occurred with an insulating gas, Freon 12. It is not known whether this result contradicts that of Cary and Mazzie [1979], which was described in the preceding paragraph, or whether the times required for different processes have different dependences on pressure so that some processes are faster and others slower when pressure is increased.

Rapp and Englander-Golden [1965] showed that krypton has a relatively large cross section for ionizing collisions with electrons. Krypton may be an appropriate choice for fast spark gaps in order to maximize ionization by collision. The gas pressure can be adjusted so that electrons acquire sufficient energy to make an ion by traveling one mean free path in the intense electric field before breakdown.

Electronegative gases, such as O_2, NO_2, and halogens, bind free electrons and form negative ions. Because negative ions have much less mobility than free electrons, the presence of electronegative gases is undesirable in spark gaps.

The Penning effect is commonly used to produce a spark gap with a small dc breakdown voltage between about 70 and 100 V. To obtain the Penning effect, two different kinds of gases are mixed together, e.g., 0.1% argon in 99.9% neon. Photons released from metastable atoms of the more common species can produce photoionization of the less common species. However, the release of photons from the excited metastable atoms is a slow process that can take tens of milliseconds. Therefore, spark gaps that use the Penning effect will *not* be fast responding. It has been shown that at values of dV/dt of 5 MV/μs, a spark gap with a dc breakdown voltage of 230 V is faster responding than a gap with a dc breakdown voltage of 90 V [Singer, 1987]. It appears that spark gaps with subnanosecond response time at a 1-MV/μs rate of rise will have a nominal dc breakdown voltage of at least 150 to 250 V.

11. Preionization of Spark Gaps

One very effective way to make spark gaps faster responding is to continuously operate them in the glow regime. This is a very old idea which can be traced back to Wynn-Williams [1926]. The continuous current maintains a large population of electrons and positive ions. Smith et al [1986] showed that with a 0.1-mA keep-alive current, the time to breakdown could be made as small as 0.2 ns. It is possible that the actual time to breakdown was even smaller because this time was near the limit of the oscilloscope. To obtain the same rate of charge separation as this current with radioactive additives, several hundred curies of tritium would be required, which is a dangerously large amount.

The use of an external power supply for the keep-alive current violates the conditions for a practical protective device that were given in the introduction of this report. However, Parks [1983] and de Souza and Eggendorfer [1985] showed how to use a spark gap and a delay circuit to permit the overvoltage itself to preionize the spark gap. The fundamental circuit of de Souza and Eggendorfer is shown in figure 7. This technique requires no external components, since the delay circuit can be built into the spark gap, as will be discussed later.

The trigger terminal may be a conducting band around the outside of the insulating case of the spark gap, located between the two electrodes, as shown in figure 8(a). There is no conducting path inside the spark gap between the trigger terminal and the remainder of the spark gap. In this way, the trigger terminal forms one electrode of the capacitor in the delay circuit. The

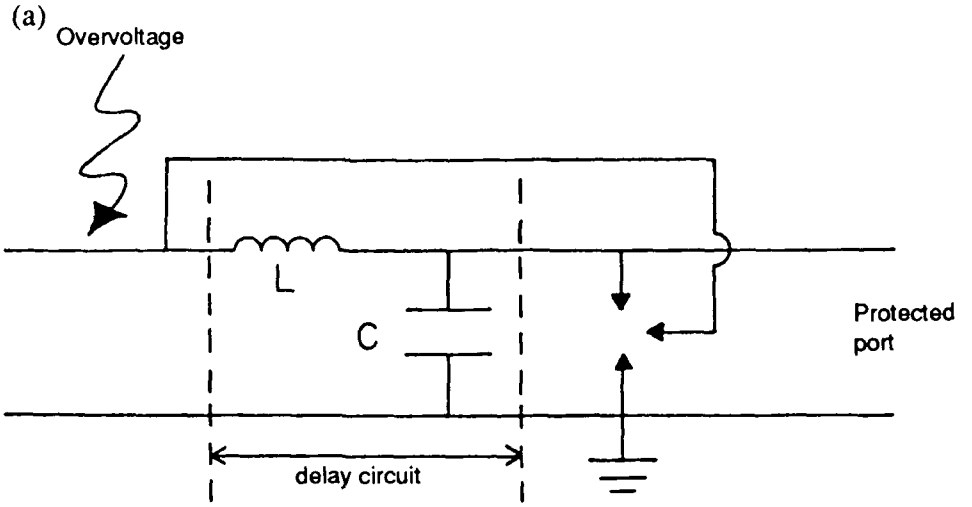


Figure 7. Self-triggering spark gap [de Souza and Eggendorfer, 1985].

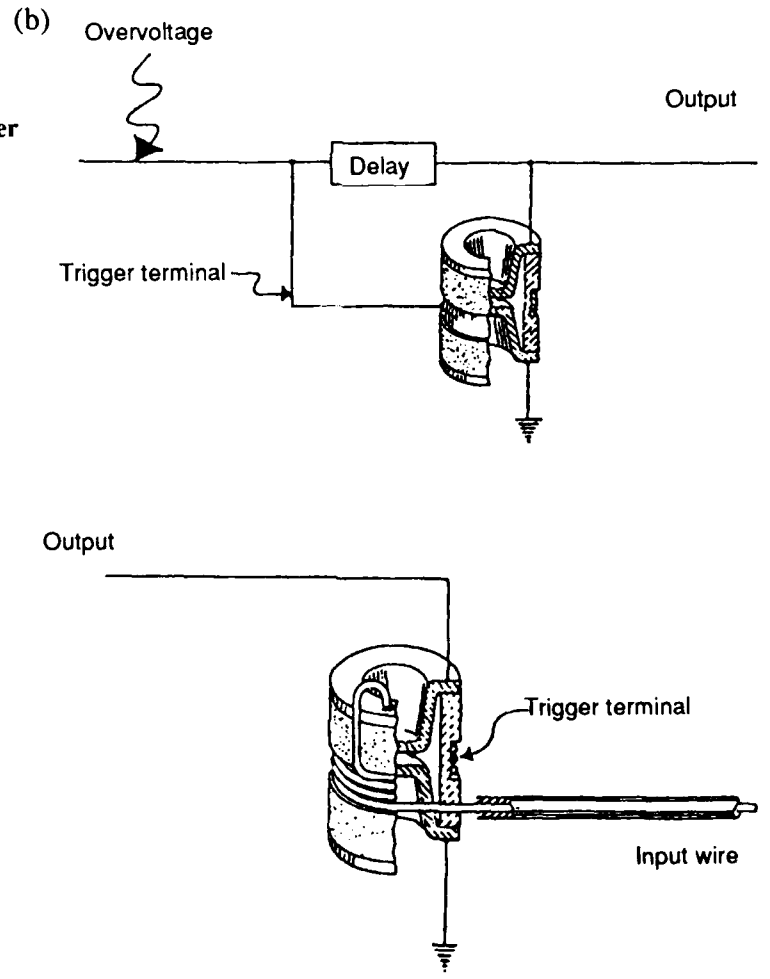


Figure 8. Practical implementation of self-triggering spark gap by de Souza and Eggendorfer [1985].

triggering is accomplished by electrons produced by field emission inside the spark gap.

The inductor in the delay circuit may be wound on the side of the ceramic case of the spark gap, as shown in figure 8(b). If space permits, an inexpensive ferrite bead can be used to produce inductance for the delay circuit [de Souza and Eggendorfer, 1985]. This would require a three-terminal spark gap.

Typical delay times might be on the order of a few nanoseconds (e.g., $C = 3$ pF, $L = 3$ μH), although longer delay times would be preferable. The use of this concept is restricted to systems with a maximum signal frequency less than about 50 MHz, due to attenuation in the delay circuit.

12. Multiple Gaps in Parallel

Levinson et al [1979] performed experiments to study the inductance of a spark gap. They simulated the discharge channel by very thin wire(s). They found that when two wires were used, the rise time was about 60 percent of the value when a single wire was used, for a gap spacing of 38 mm. They concluded:

> If minimization of current risetime is to be achieved, reduction in the electromagnetic discontinuities must be considered. One way to accomplish this is by multi-channelling. From our results, the most desirable condition, for this case, is the simultaneous creation of either two or four channels at the outer edges of the spark gap.

When spark gaps are used in fixed laboratory situations, complex external triggering apparatus, such as a pulsed laser, may be used to initiate nearly simultaneous discharges. However, creating simultaneous discharges in spark gaps for transient protection applications is more difficult because of constraints on cost and volume.

Taylor and Leopold [1983] also advocate using multichannel spark gaps to obtain low jitter in switching time. However, Kushner et al [1985] showed that individual arc channels that were closely spaced (about 1 mm apart) were not independent. The coupling of the magnetic field of the currents in the two channels made the inductive voltage drop independent of the number of channels. Furthermore, because there is less current in each channel when there are multiple channels, each channel is cooler and therefore has a greater resistance. Kushner et al [1985] concluded that there is no advantage in having multiple closely spaced channels.

Therefore, multiple channels would appear to be beneficial only in large spark gaps and not in miniature spark gaps used for protection of terminals from overvoltages.

13. State-of-the-Art Fast Spark Gaps

It is well known that spark gaps conduct more quickly when $|dV/dt|$ is increased, up to about 100 kV/μs. Older literature cites dynamic or impulse breakdown voltages for a rate of rise between about 1 and 10 kV/μs. Literature from manufacturers of state-of-the-art "fast" spark gaps gives the maximum breakdown voltage at a rate of rise of about 1 MV/μs, a factor of 10^2 or 10^3 greater than that used to specify the old "slow" spark gaps. While there is no doubt that the new "fast" gaps conduct more quickly, one should recognize that the old "slow" gaps would be faster responding if they were tested with the new steeper waveform. It is suggested that complete specifications for a spark gap should, among other parameters, specify the maximum breakdown voltage, V_f, at three different rates of rise: 1 kV/μs, 10 kV/μs, and 1 MV/μs. This would allow users to compare performance of devices from various manufacturers.

Several state-of-the-art products are discussed below, concluding with some comparative specifications for each of these products.

General Instrument Corporation (Signalite Division, later C.G. Clare Division) has marketed a UniImp® series of fast spark gaps since about 1962. These devices were described by Bazarian [1980]; dielectric-stimulated arcing (as shown in fig. 4) is used to reduce response time.

The English Electric Valve Company, Ltd., developed the model GXS spark gap in 1980. A typical breakdown time of 0.6 ns at a 1.5-MV/μs rate of rise is claimed by the manufacturer. This is a large device with a volume of about 8 cm^3. The manufacturer states that two processes make this device fast responding: (1) the spark gap contains tritium and (2) the Malter effect is used. The manufacturer's data sheet states that the total activity of the tritium is "less than 150 μCi." This is a relatively large amount of tritium, although it poses no significant hazard to human health when sealed inside a spark gap.

Some specifications of fast spark gaps are listed in table 1. The parameter η is the ratio of the impulse breakdown voltage, V_f, to the nominal dc breakdown voltage, at the specified rate of rise. The "≤" symbol means that the manufacturer specifies a maximum value; other values are average or typical.

Table 1. Fast Spark Gap Specifications

Manufacturer and model	DC breakdown voltage	η at 10 kV/μs	η at 1 MV/μs
Clare UBD-550	550	≤ 1.2	—
EEV GXS2.5	250	—	≤ 4.0
MOV 65/200	200 ± 50	—	≤ 5.0
MOV 65/550	600 ± 100	—	≤ 2.2
Joslyn F5033-20	200 ± 30	3.2	5.0
Joslyn F5033-35	350 ± 50	2.3	3.1
Joslyn F5033-50	500 ± 75	1.9	2.6

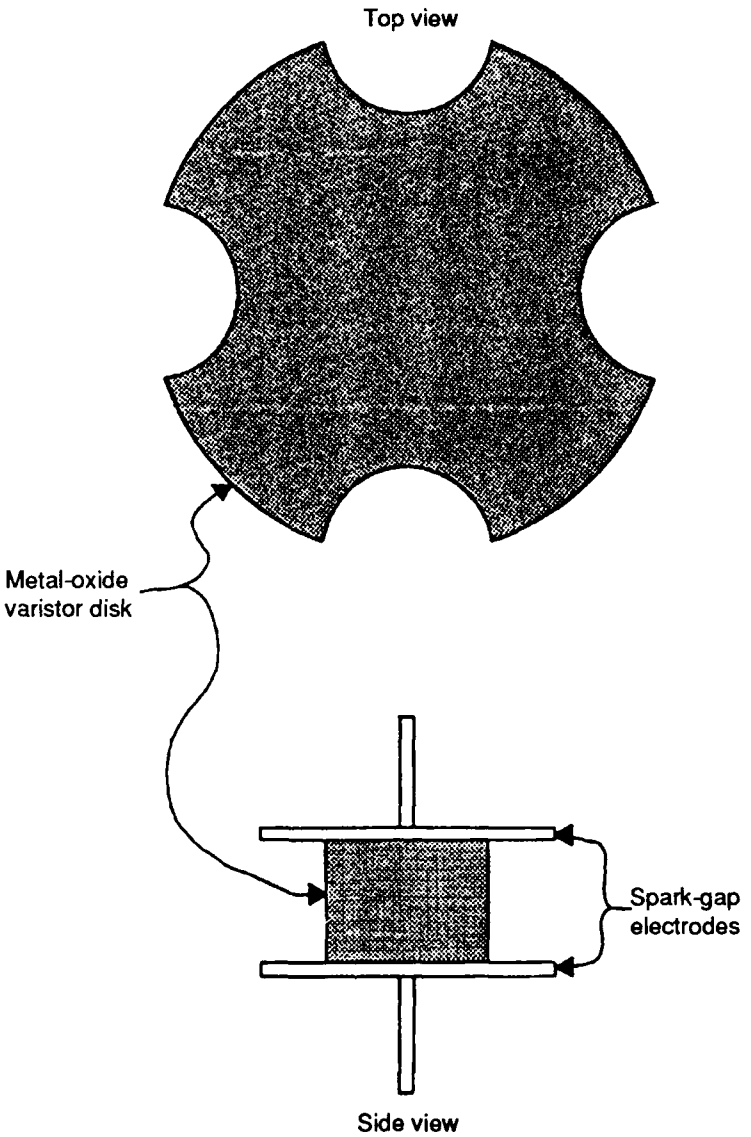
14. Conclusion: Suggestions for Developing Faster Spark Gaps

It is recommended that fast-responding spark gaps have both a relatively large amount of radioactive prompting (e.g., 100 μCi of ^3H) and application of multiple kinds of field emission, such as carbon or varistor material between electrodes, Malter effect, or graphite strip inside ceramic case. The following idea is proposed to combine a varistor between the electrodes and to provide multiple discharge channels inside one device.

As noted above, in the section on multiple gaps in parallel, it may be desirable to have several gas discharges in parallel to avoid some of the variations in breakdown times (jitter). It is difficult to initiate nearly simultaneous multiple discharges in a spark gap without complex external triggering apparatus. One way may be to connect a large number of gaps in parallel. These gaps may share a common chamber of gas, but a poorly conducting material should be used for internal baffling in order to make the gaps independent during prebreakdown. This suggestion can be combined with the dielectric stimulated arcing idea of Brainard et al [1981] by using metal-oxide varistor material for the baffling.

During a prolonged overstress, the gas temperature in the conducting channel will be very high. If the baffling confines this high-temperature gas, the gas pressure may cause the baffling to explode. For this reason, the gaps should be wedges or semicircles cut into the perimeter of a varistor disk, as shown in figure 9. The space between the varistor disk and the ceramic case of the spark gap would form a large chamber of gas, which would act as a shock absorber.

Figure 9. Novel idea for spark gap.



As noted above, carbon electrodes release copious amounts of electrons by field emission. This effect can be exploited by using a new material, reticulated vitreous carbon, that consists of an open-cell, rigid carbon "foam." This material was developed in the mid-1970's as a filter for fluids and as a scaffold for work at high temperatures or with corrosive agents. A relatively fine mesh of vitreous carbon, perhaps about four pores per linear millimeter, should be placed between the electrodes of a spark gap. If field emission from the sharp edges of the carbon does not adequately stimulate development of the arc, chemical vapor deposition methods could be used to deposit alkali metal halides inside the pores of the carbon. These halides are excellent emitters of photoelectrons.

About 90 percent of the volume of reticulated vitreous carbon is void. Thus an electrical discharge should develop inside the carbon material. The material is opaque so that multiple, optically independent discharge channels may be established inside and around the periphery of the carbon material. Multiple discharge paths would be desirable to decrease some of the statistical delay in the development of an arc channel.

In addition to development of faster spark gaps, research needs to be done on the following topics:

1. Investigating the physics of breakdown process at values of dV/dt of the order of 1 MV/μs.

2. Determining the optimum gas mixture and pressure for fast-breakdown spark gaps. Then determining the optimum photoelectric material in order to obtain the maximum number of electrons given light emitted from excited atoms of gas.

3. Investigating field emission phenomena, including the Malter effect, dielectric-stimulated arcing, and conducting material (e.g., carbon, silicon carbide, zinc-oxide varistor) between electrodes. This research needs to have subnanosecond time resolution.

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