

ELECTRODE EROSION IN A HIGH ENERGY SPARK GAP*

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Abstract

The erosion rates for hemispherical electrodes, 2.5 cm in diameter, made of graphite, copper-graphite, brass, two types of copper-tungsten, and three types of stainless steel have been examined in a spark gap filled with air or nitrogen at one atmosphere. The electrodes were subjected to 50,000 unipolar pulses (25 μ s, 4-25 kA, 5-30 kV, 0.1-0.6 Coul/shot) at repetition rates ranging from 0.5 to 5 pulses per second (pps). Severe surface conditioning occurred, resulting in the formation of several spectacular surface patterns (craters up to 0.6 cm in diameter and nipples and dendrites up to 0.2 cm in height). Surface damage was limited to approximately 80 μ m in depth and was considerably less in nitrogen gas than in air. Anode erosion rates varied from a slight gain for several materials in nitrogen to 5 μ cm³/Coul for graphite in air. Cathode erosion rates of 0.4 μ cm³/Coul for copper-tungsten in nitrogen to 25 μ cm³/Coul for graphite in air were also measured.

Introduction

High energy spark gaps with lifetimes of 10⁸ shots are seen as one of the critical components in pulsed power systems used for particle beam systems, lasers, nuclear isotope separation, electromagnetic pulse simulation, and thermonuclear fusion reactors. The performance of a pressurized spark gap as a high energy, rep-rated switching device is typically characterized by its hold-off voltage, recovery time, delay time, and jitter, [1]. The switch lifetime is determined by the electrode erosion, gas decomposition and disassociation, and insulator damage that occur as energy is dissipated in the switch [2].

The purpose of this study was to measure the erosion rate of different electrode materials as a function of current in order to generate a data base from which theoretical models describing the complex erosion process could be developed and verified. In addition, the electrode surfaces were examined in an effort to define the erosion characteristics and to reduce the material parameter space used in further studies.

Experimental Apparatus

Spark Gap

The spark gap shown in Fig. 1 was designed to facilitate frequent electrode and insulator replacement and to allow for accurate control over electrode alignment and gap spacing. The electrodes are composed of three parts: the brass support (which also serves as a channel for gas flow), the brass adapter, and the electrode tip. The hemispherically shaped electrode tips are 2.5 cm in diameter and are made from the various materials studied. The Lucite inserts provide protection for the main gap housing and also provide a surface which gives a permanent history of the discharge debris which is deposited on the walls.

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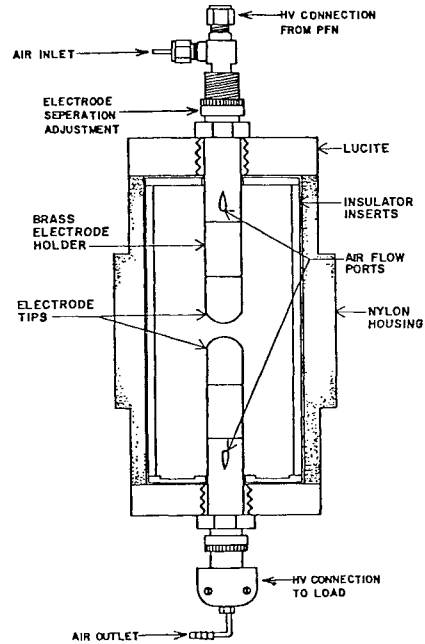


Fig. 1. Spark Gap for Erosion Studies.

Test Circuit and Conditions

Numerous experimentors have measured erosion rates for high current (10-800 kA), oscillatory discharges [3-7]. A few have studied erosion rates in high current (> 10 kA), unipolar discharges using brass and copper electrodes only [8,9]. A test circuit capable of delivering a unipolar pulse was chosen for this study, both to simplify separate investigations of the erosion processes at the anode and the cathode and to simulate more closely certain applications. Figure 2 shows the test circuit, the current waveform and the test conditions. The circuit, consists of a six-section Rayleigh pulse forming network (PFN) which is resistively charged to the self-breakdown voltage of the spark gap by a 30 kV, 1 A, constant voltage power supply. When the gap breaks down, the PFN is discharged into a matched, 0.6 Ω , high power load. Further details of the test circuit and load design are discussed elsewhere [10].

Materials Tested

The electrode materials tested were: brass (SAE 660), stainless steel (304, 20Cb-3, 440-C) [11], copper-tungsten (K-33 [12], 3W3 [13]), graphite (ACF-10Q), and copper-graphite (DFP-1C) [14]. This combination of materials allowed for:

- 1) a comparison with existing data for brass and stainless steel [3,4,8,15].
- 2) utilization of materials which empirically have given good spark gap performance [3, 6, 16].

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| 14. ABSTRACT The erosion rates for hemispherical electrodes, 2.5 cm in diameter, made of graphite, copper-graphit e , brass, two types of copper-tungsten, and three types of stainless steel have been examined in a spark gap filled with air or nitrogen at one atmosphere. The electrodes were subjected to 50,000 unipolar pulses (25 Bs, 4-25 kA, 5-30 kV, 0.I-0.6 Coul/shot) at repetition rates ranging from 0.5 to 5 pulses per second (pps). Severe surface conditioning occurred, resulting in the formation of several spectacular surface patterns (craters up to 0.6 cm in diameter and nipples and dendrites up to 0.2 cm in height). Surface damage was limited to approximately 80 hm in depth and was considerably less in nitrogen gas than in air. Anode erosion rates varied from a slight gain for several materials in nitrogen to 5 Bcm3/Coul for graphite in air. | | | |
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3) the testing of several new materials, namely copper-graphite, and the stainless steels 20Cb-3 (previously used in highly corrosive environments in MHD generators) and 440-C (a high strength stainless steel).

The thermophysical properties of these materials are given in Ref. 10.

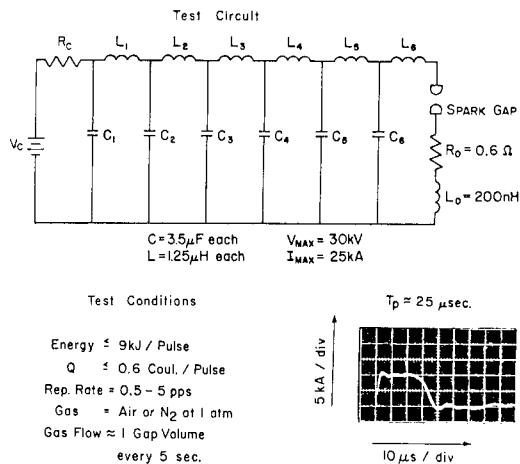


Fig. 2. Test Circuit and Experimental Conditions.

Experimental Results

Erosion Characteristics

The change in mass of the spark gap electrodes after 50,000 shots was measured with an analytical balance with a precision of ± 5 mg. The results for the cathodes are shown in Fig. 3. Although many authors report erosion rates in $\mu\text{g}/\text{Coul}$, the actual factor determining lifetime is the volume eroded, hence the units $\mu\text{cm}^3/\text{Coul}$. The results for brass are discussed later because of the failure of the electrodes due to gross material extraction.

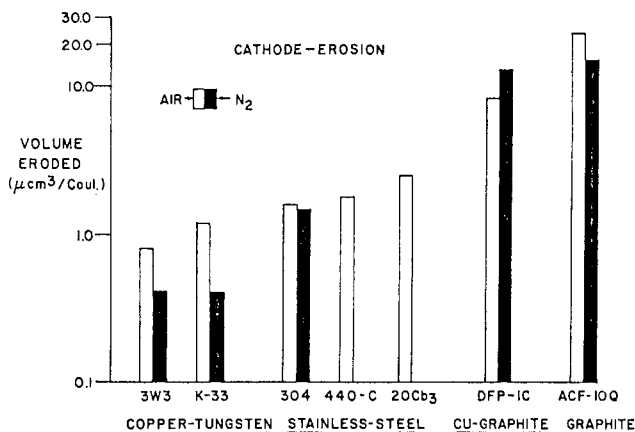


Fig. 3. Cathode Erosion Rates for Different Materials in Air and Nitrogen.

Material: A ranking of the volume erosion rate for each material investigated, from smallest to largest, is:

- Cathode: CT-3W3(N₂), CT-K-33(N₂), CT-3W3(Air), CT-K-33(Air), SS-304(N₂), SS-304(Air), SS-440-C(Air), SS-20Cb-3(Air), CG(Air), CG(N₂), G(N₂), G(Air)
 - Anode: CT-3W3(Air), CT-K-33(Air), SS-440-C(Air), CG(N₂), SS-304(Air), SS-20Cb-3(Air), G(Air).
- (The rest of the anodes showed no net erosion).

As expected, the copper-tungsten composites gave the lowest volume erosion rate. Somewhat surprising, however, was the excellent performance of the stainless steels (304 and 440-C) and the poor performances of the graphite materials as cathodes. From the results obtained for stainless steel in a pulsed discharge it is seen that the high erosion rate reported by Gruber and Suess [3] for an oscillatory discharge was possibly a result of using a stainless steel which was a poor anode material. Previous studies which indicated that graphite was highly resistant to erosion were done at a much slower repetition rate (0.03 pps) and thus, gave a significantly lower erosion rate ($< 1 \mu\text{cm}^3/\text{Coul}$). More recent results by Bickford [15] at 1000 pps gave an erosion rate of $41 \mu\text{cm}^3/\text{Coul}$, which is reasonably close to the value of $25 \mu\text{cm}^3/\text{Coul}$ measured in this experiment. A summary of the erosion rates found by other investigators is given in Ref. 10. If one takes into account the lower values of current used in this study, then the results obtained in this experiment are in generally good agreement with the measurements of other investigators.

Polarity: Unlike previous experiments, where oscillatory current conditions masked any polarity effect, a distinct difference in the cathode and anode erosion rate and most likely the erosion mechanisms themselves were observed for a unipolar pulse. The ratio of cathode to anode erosion varied from 1.5 in stainless steel (304) to 16 in copper-graphite for those materials which had significant anode erosion. Carder [8] reported ratios of 2.5 to 5 for brass under similar conditions. Previous experiments which gave cathode to anode erosion ratios less than one were done at much higher pulse repetition rates (10-1000 pps) [15-18]. In addition, the results obtained by Petr [18] were done with smaller anode diameters and gap spacings (both ≤ 2.5 mm).

The cathode erosion rates are shown in Fig. 4.

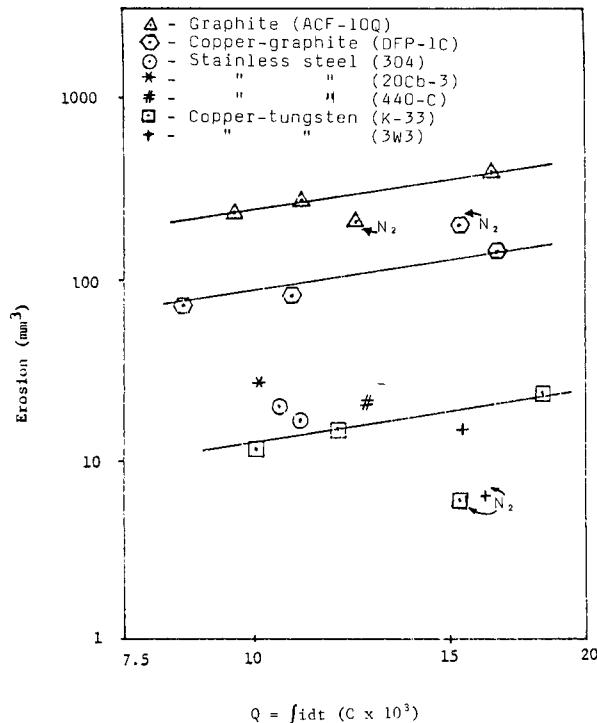


Fig. 4. Cathode Erosion as a Function of Total Charge Transferred in 50,000 Shots.

The cathode erosion has a linear dependence upon the quantity $Q = \int i dt$ over the entire range of currents. Since the energy in the arc is equal to $\int v_{arc} i dt$, this indicates that the main source of energy producing molten material and subsequent vaporization and droplet ejection is in the cathode fall region of the arc and not in localized i^2R losses in the material.

In general, anode erosion rates were somewhat scattered; however, some agreement with an erosion rate approximately proportional to $Q^{1.5}$ was observed for graphite. A similar dependence has been found experimentally and derived theoretically by numerous other investigators [19-21].

Some anodes actually gained mass, which indicated that material was being transferred from the cathode to the anode and/or chemical reactions were forming compounds on the anode. The material transfer was demonstrated experimentally when a stainless steel cathode was found to deposit molten material on a graphite anode. Gray and Pharney [22] proposed a reasonable model for this effect at low currents, which is based upon the reduction of the ion bombardment force on the molten cathode material during the fall of the current pulse.

Gas: The erosion rate for copper-graphite, in nitrogen, increased slightly whereas the rates for most of the other materials were smaller, by a factor of 2-3. In addition, the cross sections of the stainless steel electrodes shown in Fig. 5 show a significant reduction in the depth and amount of damage when the gas is nitrogen rather than air. The gas may affect the erosion in one or more of the following ways:

- 1) by forming chemical compounds on the electrode surface which alter:
 - a) the thermal stability [23]
 - b) the current density at individual attachment sites in the arc [24], and
 - c) the lifetime of each attachment [24]
- 2) by producing accelerated chemical reactions at the electrode surface [25], particularly at impurity sites or at the grain boundaries in stainless steel [26].

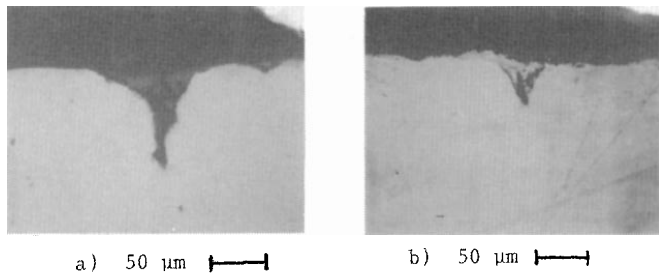


Fig. 5. Cross Section of Stainless Steel (304) Cathode in a) Air and b) Nitrogen.

Surface Conditions

The surface of the electrode tips were examined after 50,000 shots. The analysis techniques utilized were Auger electron spectroscopy (AES), scanning electron microscopy (SEM), and optical photography.

Brass: The surface of the brass cathode is shown in Fig. 6. Large scale melting is evident, with dendrites or metallic protrusions up to 0.2 cm long existing on the surface. The self-breakdown voltage for these electrodes dropped from 20 kV to 3 kV in approximately 2000 shots as a result of macroscopic field enhancements. In addition, the voltage self breakdown distribution was characterized by a series of "jumps" thought to be due to large particles being "blown" off the ends of the protrusions. Originally it was thought that the material being "pulled out" of the bulk electrode was lead, but the results of the AES analysis indicate the surface consists primarily of carbon, copper, and oxygen, with a notable absence

of zinc and lead. From these results and those found by Marchesi and Maschio [6] it is obvious that brass has only limited use in repetitive operation at higher levels of charge transfer.

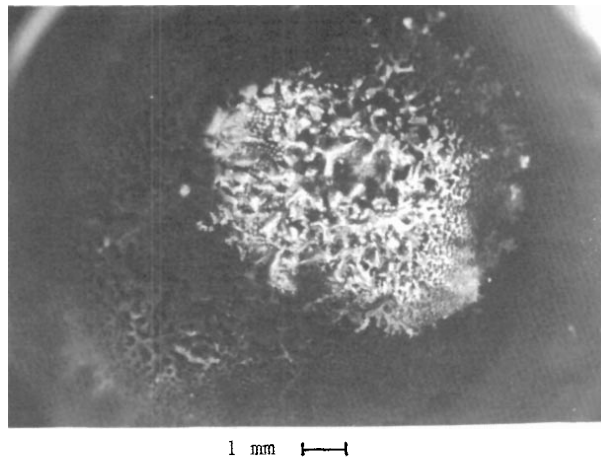


Fig. 6. Surface of Brass Cathode in Air.

Although the mechanism for the material extraction is not completely understood, Belkin [27] showed that the electromagnetic force resulting from the discharge can play an important role at large currents. In addition, Fitch and McCormick [28] observed gross material extraction from stainless steel electrodes as a result of asymmetrical current connections.

Cathode: The cathodes for most of the remaining materials are shown in Fig. 7. Considerable erosion has taken place, especially on the graphite materials, and the stainless steel and copper-tungsten cathodes show evidence of severe melting. Although it is not easy to see in the photographs, all cathodes showed a distinct tendency to form a large scale crater whose diameter increases with increasing gap spacing and current. Similar macroscopic cratering was observed by Watson [29] who explained the results with the use of a hydromagnetic flow model. An SEM examination of the surface of a stainless steel cathode showed a remarkable similarity between the electrode surface features existing at the edge of the macroscopic crater and particles found on the insulator inserts. In addition, all insulators were covered with solid particles, 10-100 μm in size, distributed within a narrow band adjacent to the electrode surfaces. These results indicate that a considerable portion of the solid or molten electrode material is ejected parallel to the electrode surface.

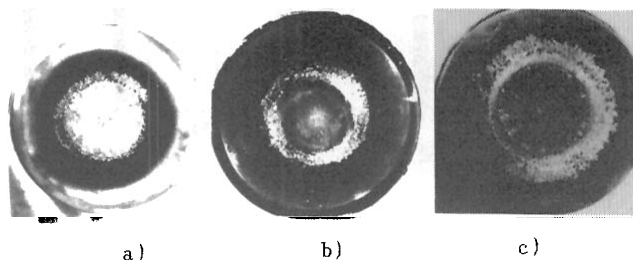


Fig. 7. Cathode Surface of a) Copper-Tungsten (K-33), b) Stainless Steel (304), and c) Copper-Graphite (DFP-1C) in Air.

Anode: The anodes corresponding to the cathodes shown in Fig. 7 are shown in Fig. 8. The graphite and copper-graphite anode erosion occurs primarily in a band, 0.8 cm wide, with the inner radius located 0.3 cm from the center of the electrode. This pattern is consistent with the results of Johnson and Pfender

[30] which showed that an annular-shaped attachment region of high current density can exist at the anode. The copper-tungsten and stainless steel anodes indicate that melting and vaporization have taken place over the entire surface. Like the pattern at the cathode, the diameter of the anode erosion region increases with increasing current.

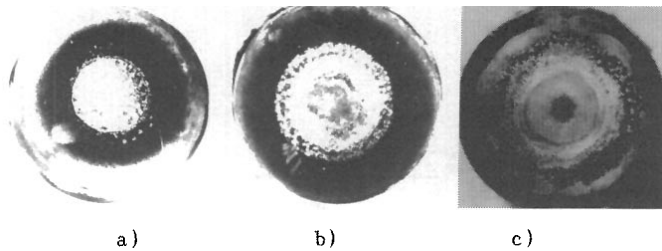


Fig. 8. Anode Surface of a) Copper-Tungsten (K-33), b) Stainless Steel (304), and c) Copper-Graphite (DFP-1C) in Air.

Conclusion

The erosion rate and surface damage of the electrodes were determined for several materials utilized in a high energy spark gap. The results from these preliminary studies have led to the following conclusions:

- 1) The electrode erosion rates and mechanisms are highly polarity dependent and thus, results for oscillatory and unipolar discharges can be considerably different.
- 2) A large amount of the erosion is in the form of solid and molten material removed parallel to the electrode surface and apparently from the edge of the macroscopic craters found on the cathode.
- 3) Cathode erosion rates are proportional to the total amount of charge transferred for a fixed repetition rate and pulse width.
- 4) Stainless steel (304) may be an economical replacement for copper-tungsten composites as a cathode material for the conditions studied.

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