alternate measures could be used to remove the trends shown in Fig. 6, they did not significantly reduce the statistical fluctuations and to avoid confusion, were not presented. Actually, for long times, the threshold field implied by the breakdown probability curves of Fig. 7 is more useful.

Similar speculations concerning the area dependence can be made. The data of Table I show a law of form $A^{1/10}$ brings the data for 3 cm$^2$ and 81 cm$^2$ into close agreement. Proceeding another way, one may use the data to solve for the area dependence. This results in an area dependence exponent of 0.108. Miller [6], and VanDevender [2], who worked with larger surfaces, recommend an area exponent 0.06.

ACKNOWLEDGMENT

The authors gratefully acknowledge the skill and care of L. W. Hardesty and K. Chilton who constructed the apparatus and assisted in the testing.

REFERENCES


Abstract—Flat aluminum foil fuses were exploded electrically by discharging a capacitor bank into a series combination inductance (~600 nH) and fuse. The 2.54 × 2.54 × 0.0023-cm foils were exploded in a sealed chamber. The time-to-burst (TTB) and fuse voltage characteristics were investigated as a function of the fuse environment. Results are given for foils exploded in various gases and liquids.

I. INTRODUCTION

ELECTRICALLY exploded conductors are useful in a wide variety of pulsed power applications. Fast foil current breakers have been used to sharpen current pulses from capacitor banks [1]–[3] and from explosive magnetic flux compression generator-transformer systems [4]–[7]. In addition, fuses have been used as the high speed elements for multiple stage switching in inductive energy storage systems [8]–[9]. Finally, we mention that exploding wires have been used in a number of novel schemes for the purpose of launching hypervelocity projectiles [10]–[12].

Despite a wide variety of experimental work, there remains much that is not understood about the electrical explosion of conductors. Edge effects which lead to breakdown, for example, are not well understood. It seems reasonable that breakdown at the edges of the foil is due to corona discharge and explosions due to irregularities which are introduced when the foil is cut. There is some evidence, however, that there may be mechanisms other than corona discharges which lead to edge breakdowns [13]. The effect of volume changes is also not well understood. Although electrical conductivity is known to be relatively sensitive to volume changes, a constant volume approximation is generally used in order to avoid difficult hydrodynamic calculations [14]. Finally, we mention the effects of the surrounding medium on fuse characteristics. It is not clear, for example, what the characteristics of the surrounding medium should be in order to best inhibit electrical breakdown. On the one hand, it is suggested that the surrounding medium should confine the metal vapor in order to inhibit collisionally induced ionization and subsequent breakdown [1]. On the other hand, it has been suggested that heat transfer and chemical reactions with the surrounding medium can inhibit electrical breakdown [15].

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Effects of Surrounding Medium on Electrically Exploded Aluminum Foil Fuses

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Manuscript received February 4, 1980.
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The purpose of this work is to attempt to gain a better understanding of the effects of the fuse environment on fuse performance. In this paper we report the results of measurements of the time-to-burst (TTB) and peak hold-off voltage for aluminum foils exploded in various media. TTB was measured for foils exploded in air, water, and aluminum oxide. Peak hold-off voltage was measured for foils exploded in various gases and liquids.

II. EXPERIMENTAL DETAILS

The foils were exploded by discharging a capacitor bank into an inductance in series with the aluminum foil.

The capacitor bank is a low inductance bank with ignitron switches. The nominal charging voltage is 20 kV, the capacitance is 98 µF, and the inductance is 80 nH. The maximum bank current is about 600 kA.

A 540-nH (measured from the ringing frequency) inductance was placed in the discharge circuit for inductive energy storage purposes as well as to isolate the bank from the high voltage generated across the exploding foil. This inductance consists of a parallel plate transmission line and 15 coaxial cables between the bank and the line.

The foils were connected between the plates of the transmission line and were enclosed in a Nylon cylinder capped on one end by an aluminum plate and on the other end by the bottom plate of the transmission line. Electrical contact with the foil was made by pinching each end of the foil in a massive aluminum electrode. Inter electrode distance was set at 2.54 cm by means of lucite posts positioned around electrode edges. Flat aluminum foils 2.54 cm × 2.54 cm × 0.023 mm were used in all experiments.

Fuse current was measured with a low inductance current viewing resistor. Fuse voltage was measured with a resistive divider.

III. EXPERIMENTAL RESULTS AND DISCUSSION

Fig. 1 is a typical example of current and voltage waveforms obtained in this work. Fig. 1 shows that there are a number of well-defined stages in the discharge of the capacitor bank through the foil. For approximately the first 6 µs of the discharge, the fuse voltage changes very little. The foil resistance also changes very little and the current is not far from what is obtained in the case of zero resistance. At t ≈ 6 µs, there is an abrupt change in the slope of the voltage curve. At this time, a solid to liquid phase transition is in progress and fuse resistance is rapidly increasing. After about 200 ns, however, the fuse resistance begins to decrease very rapidly presumably due to ionization and breakdown of the metallic vapor.

Fig. 2 is a plot of the TTB as a function of capacitor bank voltage for foils exploded in air. TTB is defined as the time to peak voltage measured from the point where the current departs from its initial value of zero. The solid line in Fig. 2 was plotted according to the theory of Maisonnier et al. [1]. According to this theory, the Joule heat energy is equal to the change of the internal energy of the foil. This leads to the equation

\[ \frac{\sqrt{2} \omega C^2 V_0^2}{\pi s^2} \left( \frac{1}{4} \sin 2\omega t + \frac{\omega t}{2} \right) = k_1 a \]  

where

\[ a = \frac{\sqrt{2}}{\pi} \gamma \int_{T_0}^{T_V} \rho^{-1} de \]  

and

\[ C_1 \]  bank capacitance
\[ V_0 \]  initial bank voltage
\[ S \]  cross-sectional area of the foil
\[ \omega \]  angular frequency of sinusoidal current
\[ \gamma \]  mass density of foil
\[ \rho \]  resistivity of foil
\[ e \]  internal energy per unit mass

Fig. 1. Current and voltage waveforms for foil exploded in 50 percent O₂, 50 percent N₂ at 200 psig. Upper trace: Fuse voltage; 2 kV/div. Middle trace: Fuse current; 20 kA/div. Lower trace: 1-µs time marks.

Fig. 2. TTB versus bank voltage for foils exploded in air. Dots are experimental points and the curve is drawn according to the theory of [1].
$T_0$ initial foil temperature

$T_v$ foil temperature at vaporization.

The quantity $a$ can be calculated from handbook tables and has the value $a = 2.2 \times 10^{16}$ for aluminum [1]. The value of $a$ corresponds to slow adiabatic heating at atmospheric pressure.

The numerical factor $k_1$ takes into account the rapid heating encountered in exploding foils. Maisonnier et al. [1] suggest $1 < k_1 < 3$. Using the measured value of $\omega$ and other known values of physical parameters, (1) was solved numerically. The solid line shown in Fig. 2 was obtained with $k_1 = 2.2$. The fit is seen to be quite good.

TTB as a function of capacitor bank voltage was also measured for foils exploded in distilled water and in aluminum oxide greater (-3 percent), Due foils that tance our Burstev various measurements. Ahead done done while indeed Conte for cal reaction [15], changing the relative resistance of the foil by a factor of 20 requires 4.5 kJ/g in water and 3.2 kJ/g in air. The TTB is 3.2 $\mu$s in air and 3.7 $\mu$s in water. We have not observed this effect possibly because the natural frequency of our system is smaller by a factor ~2. Our results, however, do agree with those of Salge et al. [9].

We now consider the maximum standoff electric field measurements. These measurements were made for foils exploded in various gases at pressures ranging from 0–200 psig and in various liquids over the density range 0.9–3.1 g/cm$^3$. This was done in order to test the assumption of two models: the vaporization wave model [17] and the heat transfer-chemical reaction model [15].

According to the vaporization wave hypothesis, a vaporization wave propagates inward from the conductor surface. Ahead of the wave, the material remains in the conducting state while behind the wave, the material is in a vaporized insulating state. If the vapor cloud is free to expand, mean free path effects should eventually lead to ionization and breakdown in the vapor. This has been observed [13]. Breakdown should be inhibited by increasing the density of the surrounding medium.

Fig. 3 is a plot of the maximum standoff electric field as a function of density for foils exploded in a 50 percent N$_2$ 50 percent O$_2$ gas mixture. This plot shows that the electric field does indeed increase with density in accordance with the vaporization wave theory. The same effect was observed for the other two gases used as shown in Table I. The peak electric field was very nearly the same in all the liquids except for transformer oil.

We now consider the heat transfer-chemical reaction model. Conte et al. [15] have used this model to explain their results for aluminum foils exploded in water. An exothermic chemical reaction between the foil and water is thought to occur. The extra heat drives the fuse toward higher resistance and more rapid explosion. Foils exploded in H$_2$O$_2$ exhibited higher hold-off voltage than foils exploded in H$_2$O presumably because H$_2$O$_2$ is more chemically active than H$_2$O.

In this investigation we have searched for chemical reactions in gases and liquids. According to Table I, the maximum electric field for the gases tends to decrease with increasing oxygen concentration. The peak electric field was the same for H$_2$O as for the more chemically active H$_2$O$_2$. Thus the results of this work provide no support for the chemical reaction model. We do not reject this model, however, because we have not investigated other factors which may be important such as TTB, foil dimension, and rate of energy transfer.
It is interesting that at the same density, the peak electric field is greater for helium than for the other gases. This effect may be due to vapor cloud cooling since helium has a relatively high thermal conductivity.

IV. CONCLUSIONS

In conclusion, this work indicates that TTB is largely independent of the surrounding medium. We have also found no evidence that chemical reactions affect fuse performance. We have found some indication that heat transfer to the surrounding medium may inhibit breakdown. Finally, we have found that the hold-off voltage increases with gas density in the pressure range 0–200 psi, but there is a weak dependence on gas species.

REFERENCES


High-Pressure Surface-Discharge Plasma Switches

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Abstract—Surface-discharge plasma switches operating at high gas pressures with gas discharge laser and resistive loads have been the subject of empirical investigations in recent years. The particular interest has been in the low-inductance uniform multichanneling evident in these switches, in conjunction with high hold-off voltages that have been observed at multiatmosphere operating gas pressures. This paper will review the progress to date and present a theoretical model of the surface-discharge plasma switch that explains the observed data.

INTRODUCTION

The surface-discharge plasma switch or surface-discharge spark gap (SSG) has been a subject of empirical investigations in recent years. The first record of surface discharges as a light source was reported by Toepfer [1]. This interest was aroused by the experimental fact that surface or sliding sparks could readily be fixed to a predetermined spatial position on the surface making them a highly reproducible source of high-brightness illumination. These initial studies were begun using glass plates with the return current conductor on the rear side. Far more reproducible discharges were later obtained through semiconducting substrates, and these have been used for many years for acoustic shock wave diagnostics. The most popular semiconducting substrate for demonstration purposes was moistened chalk, and a vast range of experimental data are available from the studies of Toepfer [1]. The low-inductance sliding spark light source subsequently developed has been in use for many years, providing ultraviolet (UV) radiation down to the Li III series [2]. Electron densities of $10^{18}$ cm$^{-3}$, and temperatures up to 20 eV, have been observed in low-inductance geometries, with a minimum light emission wavelength of 20 Å measured. For many years, indeed up to the present time, the use of the sliding discharge as a light source has been a well-established technique.

In 1974 Martin recognized the importance of the surface discharge as a source of low-energy electrons for the preionization of carbon dioxide lasers and executed a rather detailed study of the surface-discharge dependence upon the applied voltage and initial state conditions [3]. In the course of this work he observed that the initial surface charge state of the substrate was crucial to the production of uniform channels or streamers at low electric fields applied (some kilo-