

A METHOD FOR ENHANCING EXPLODING ALUMINUM FOIL FUSES FOR INDUCTIVE STORAGE SWITCHING

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ABSTRACT

The success of inductive storage systems is dependent on the development of fast, low loss opening switches. An approach to this problem is to stage several successively faster switches, such as circuit breakers and fuses, in a manner so as to minimize overall losses while achieving an effective fast opening time. In this paper, we discuss the properties of an aluminum foil fuse immersed in water or hydrogen peroxide for use as one of the final fast acting elements. Although it has been shown that the time to explosion is dependent on the fuse material, peak current amplitude, and risetime, we speculate that the opening characteristics are also influenced by chemical reactions and heat transfer with the surrounding medium. Data is presented showing that the final resistivity can be optimized by proper foil dimensions and further increased by the use of a chemically more active surrounding medium such as hydrogen peroxide.

I. Introduction

One of the major problems which must be solved in developing practical inductive storage systems for pulsed power applications is the design of a fast, efficient opening switch. There presently exists no single opening switch which possesses high current capabilities, high voltage hold-off, low losses during conducting periods, and μ sec opening times. An approach to this problem is to stage several successively faster switches, such as circuit breakers and fuses^{1,2}, in a manner so as to obtain a desired voltage level while limiting the time during which the lossy switches conduct. Metal foil fuses, although not viable as switches for long duration conduction due to their inherent high resistive losses, are applicable as the final fast current interrupting element. Maisonier et al³ have shown that the dimensions of the foil fuse depend on the fuse material, peak current, time to peak current, and energy available. Additionally the voltage desired and the maximum stress before restrike affect the dimensions. The experiments reported here show that the opening of the fuse may also be influenced by chemical reactions and heat transfer with the surrounding medium. Specifically we describe an aluminum foil fuse immersed in water or hydrogen peroxide. We speculate that the aluminum foil reacts chemically with the water or peroxide in an exothermic reaction to produce aluminum oxide, resulting in an increased final resistivity of the exploded fuse. This is supported by the fact that resistivities with water were up to four times higher than values found in the literature and that using H_2O_2 produced final resistivities twice as great as those with water. Data is

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presented which illustrates that the ignition of the chemical process is dependent on the rate of transfer of energy from the foil to the water bath. Traces are also given showing the enhancing effect of H_2O_2 .

II. Operation Of A Foil Fuse With Chemical Effects

The basic physics involved in the operation of a fuse has been understood for many years. Briefly, the fuse is an initially low resistance conductor which absorbs energy from the current passing through it by ohmic heating. If the gain in energy is greater than losses via cooling processes, the resistance increases, resulting in an even higher rate of energy absorption. This self heating of the fuse continues causing it to pass from the solid state to the liquid state and finally into the vapor state. During this last phase change the resistance increases the most rapidly and causes the desired current interruption. We believe that the internal energy of the foil is also influenced by chemical reactions and heat losses as qualitatively illustrated in Fig. 1. Although overly simplified, the figure shows the energy gained by the foil due to self heating by the exothermic chemical reaction (proportional to T^5), and energy lost to the surrounding medium via cooling (proportional to T). The dotted line represents the net energy gain or loss. Since the ignition temperature for an aluminum-water reaction is approximately $700^\circ C$, the low temperature operation of the foil is affected only by cooling. Between the temperatures T_1 and T_2 the chemical reaction dominates and the foil internal energy increases faster than losses by cooling. Above T_2 cooling again dominates. Thus operation in the temperature range of T_1 to T_2 forces the resistance to change the most rapidly. The shape and amplitude of the chemical reaction curve depends on both the fuse material and surrounding medium (chemical reactivity) and the geometry (i.e. reaction rate proportional to surface area). The slope of the heat loss curve depends on the geometry (surface area exposed to the surrounding medium). Based on these arguments, it is expected that for a constant cross sectional area the voltage generated across the fuse should pass through a maximum as the surface area is varied; i.e. thin foils with large surface area would have poor operation due to rapid heat transfer to the water, while thick foils with small surface areas would have poor operation because the limited aluminum-water contact area reduces the chemical reaction rate.

The performance of the fuse has been accurately simulated by the use of a computer program. The resistivity up to vaporization was simulated using the handbook calculated curve of conductivity vs. internal energy provided by Masioner et al³. For the vaporized resistivity, values obtained empirically were used. Between the liquid phase and the final exploded state the foil was assumed to vaporize in "sheets" at the surface, forming two parallel resistances, one high (vapor) and one low (liquid). The code is presently being expanded to attempt to simulate cooling effects.

III. Experimental Apparatus

The aluminum foils were driven by a capacitor bank and appropriate inductor as illustrated schematically in Fig. 2. Two facilities were available for testing. Their parameters are summarized in Table I.

The first facility was limited to testing fuses no longer than 18 in. in length and only under open circuit conditions. The second facility could accommodate fuses up to 1 m in length and had provisions for driving resistive and capacitive loads. Electrical diagnostics include two Rogowski coils placed so as to measure the current leaving the capacitor bank and current through the fuse. In the cases where a load is employed the load current can be inferred by the difference of these two coils. The fuse voltage is measured by a copper sulfate-carbon resistor voltage divider. Additional diagnostics include open shutter photographic observation of foils exploded in water and chemical analysis of the tamping medium by the use of chelating techniques. The latter, which measure the amount of aluminum in solution, requires the addition of the organic chemical ethylenediaminetetraacetic acid (EDTA) to the water or peroxide. The concentration of EDTA is low enough that the shunt resistance is high with respect to the exploded resistance of the foils. Its only anticipated effect is that it may slightly enhance any chemical reaction because it tends to strip the surface oxide layer from the aluminum thus exposing pure aluminum to the water for reaction.

The foils were stretched using two methods. For water tamping without chemical analysis, the ends of the foils were clamped to two circular brass plates and then immersed in a cylindrical stainless steel tank 5 ft in diameter and 5 ft high. One plate was attached to the bottom of the tank with banana plugs. The foil was stretched by pulling the other plate up with a nylon rod and clamping the rod. This top plate was attached to the storage inductor, which was also immersed in the tank, by a short length of RG-8 inner conductor (with insulation). For shots with H_2O_2 or the chelating agent, the foil was placed in a 3/4 in. long, 1.5 in. i.d. G-10 fiberglass laminate tube with brass endplates constrained by tie-rods. The tube was then immersed in the large tank and connected to the storage inductor.

IV. Experimental Results

Initial experiments were performed using the 300 μ F, 6.6 kV bank to determine the effect of the fuse material on the fuse performance. Mg, Cu, Ag, Au, and Ta were tested in addition to aluminum. Using a quality factor based on the interruption time and the final resistance, the fuses were rated from best to worst as Al, Mg, Cu, Ag, and Au with aluminum significantly better than the other materials⁴. This is exactly the same order as the relative chemical activity of these elements.

The exception performance of aluminum lead to a limited parameter variation study during which the foil thickness was varied from .2 mils to 1.2 mils and the foil length was varied from 7 in. to 18 in. From this data the effect of surface area for a constant cross sectional area was observed. Fig. 3 shows traces which indicate that as the surface area increases the voltage passes through a maximum. As discussed above, we attributed this to the combination of chemical and thermal processes. Note that exploding the foils in the large tank or in the G-10 tube with water produced similar waveforms, indicating that the additional tamping provided by the tube had no effect.

The replacement of the water with H_2O_2 showed an increase in the

final resistivity of the foil and consequently an increase in the voltage generated. Fig. 4 compares the performance of an 8 in. long, .7 mil thick, .8 in. wide exploded in water and H_2O_2 solutions with 30 %, 50 %, and 70 % concentrations. The 70 % solution produced an output voltage of 42 kV which is twice that of the water case.

Shots using the 144 μF bank charged to 15 kV have produced voltages of up to 270 kV for a .3 mil thick, 4.2 cm wide, 85 cm long foil in water and 230 kV for a .5 mil thick, 2.54 cm wide, 85 cm long foil in water. A 50 % solution of H_2O_2 has been used to increase the voltage output of the .5 mil thick foil to 295 kV. No restriking of the fuse has been observed in any of these three shots. These voltage values correspond to maximum voltage stresses of approximately 3.1 kV/cm in water and 3.5 kV/cm in H_2O_2 . Voltage risetimes (10 % to 90 %) ranged from 6 to 8 μsec in all cases. The peak resistivity calculated from the water shots is approximately 21 $\mu\Omega\text{-m}$ and 32 $\mu\Omega\text{-m}$ for 50 % H_2O_2 shots.

Data from shots with EDTA have not been completely analyzed as of this writing. Preliminary tests, such as pH changes, indicate some reaction has occurred. EDTA solutions up to .1 molar in concentration have shown no increase in the voltage output over pure water shots. The scatter for these shots, however, appears to be less, possibly indicating that the reducing action of EDTA conditions the foil surface in an advantageous manner.

Open shutter photographs of foils exploding in water show two salient features. Light emission from the foil ends is extremely high indicating that these regions may be exploding earlier than the remainder of the foil. This is probably caused by higher energy absorption at these locations due to the added contact resistance. Light is also brighter at the edges of the foil. This is probably a geometry effect. If so, tubular foils or insulating rods with aluminum deposited on their surfaces may function better.

V. Conclusions

The data presented here illustrates that the opening characteristics of aluminum foils immersed in water can be optimized by a choice of dimensions which appear to influence chemical and thermal processes. The current interruption can be further enhanced by using H_2O_2 as the surrounding medium, giving further support to the chemical reaction argument. These factors minimize the lengths of foils necessary to achieve a given voltage and hence minimize both the energy required to explode the total foil and the inductance associated with the fuse. These results are especially important when considering fuses in systems applications.

VI. References

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VII. Figures and Tables

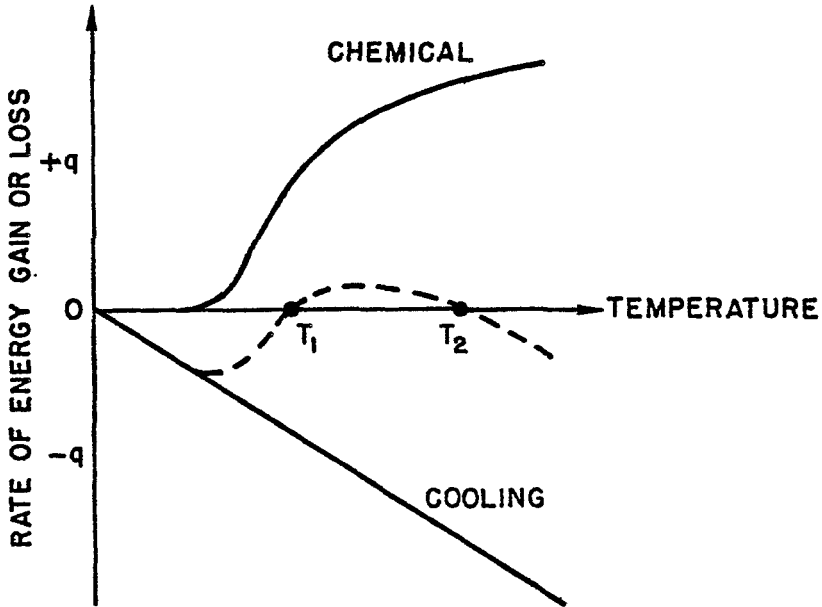


Fig. 1. Qualitative illustration of chemical and cooling effects. The dotted line represents the net rate of energy loss or gain.

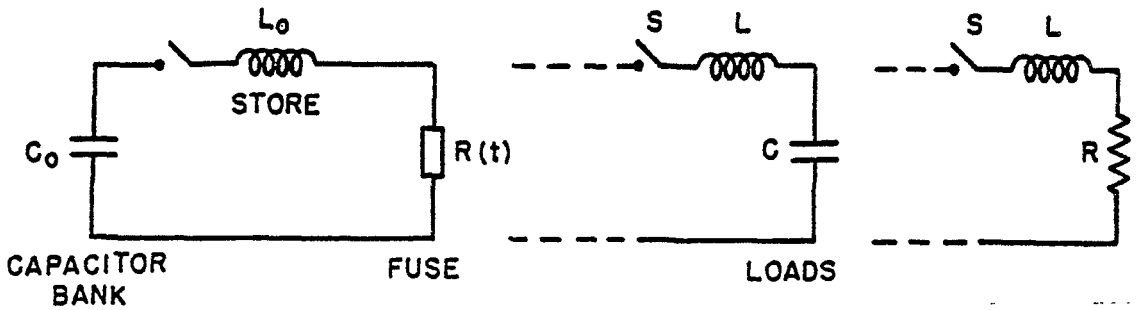


Fig. 2. Schematic diagram of fuse testing facility.

Facility	C	L	V _{max}	T _{peak}	I _{peak}
1	300 μF	400 μH	6.6 kV	545 μsec	5.7 kA
1	300	250	6.6	430	7.2
1	300	12	6.6	95	165.
2	144	225	20.	280	16.

Table I. Summary of fuse testing facility parameters.

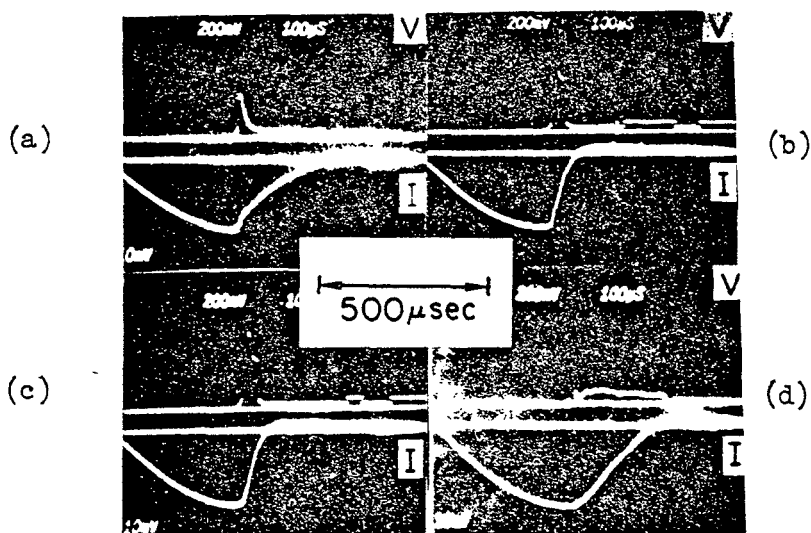


Fig. 3. Aluminum fuse voltage as a function of surface area for a constant cross sectional area. Surrounding medium is water.

- (a) $l = 37$ cm, $w = 0.4$ cm, $t = 9.4 \times 10^{-3}$ cm.
- (b) $l = 37$ cm, $w = 1.5$ cm, $t = 2.5 \times 10^{-3}$ cm.
- (c) $l = 37$ cm, $w = 2.1$ cm, $t = 1.8 \times 10^{-3}$ cm.
- (d) $l = 37$ cm, $w = 7.8$ cm, $t = 0.5 \times 10^{-3}$ cm.

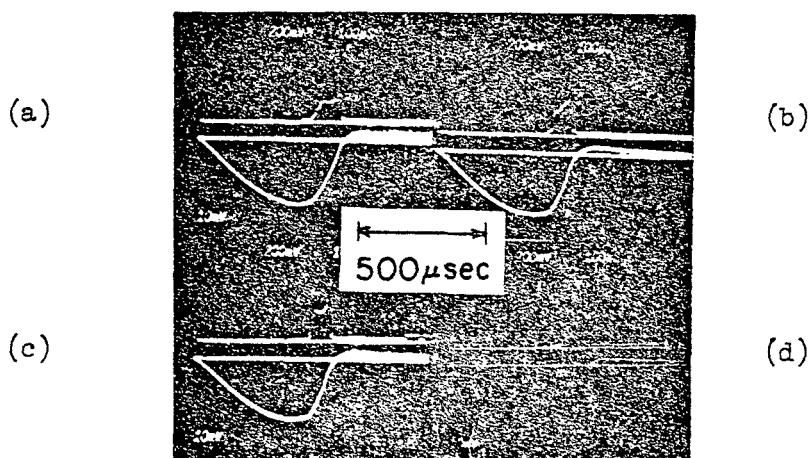


Fig. 4. Aluminum fuse voltage as a function of surrounding medium. The foil dimensions are: $l = 8$ in., $w = .8$ in., and $t = .7$ mil.

- (a) Pure water. $V_{\text{peak}} = 21$ kV.
- (b) 30 % H_2O_2 .
- (c) 50 % H_2O_2 .
- (d) 70 % H_2O_2 . $V_{\text{peak}} = 42$ kV.