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RECOVERY CHARACTERISTICS OF EXPLODING WIRE FUSES IN AIR AND VAC--ETC(U)

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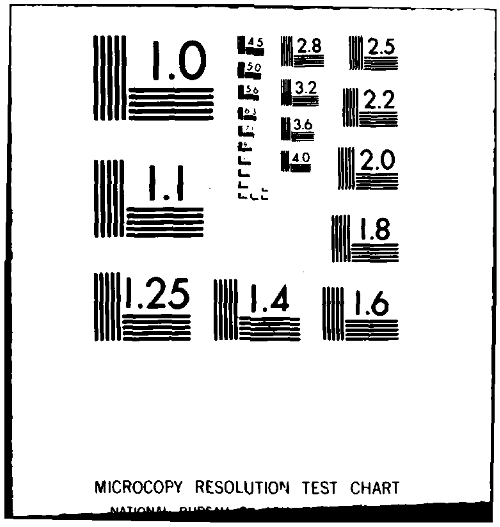
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The dielectric strength of exploded wire fuses during the vaporization and after recovery period and the resistivity of the opening fuses are functions of time and depend on the medium surrounding the fuse channel. These parameters determine the efficiency of power flow from the storage system to the load. Specifically, design of experiments using loads with variable impedance, such as imploding plasmas, require detailed information on the fuse characteristics during the time when the load impedance is changing. To provide data that determines the interaction between

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20. Abstract (Continued)

fuses and variable impedance loads, inductive and recovery electric fields and fuse resistance in air and vacuum were studied. The results show the inductive field amplitude follows the dependence on vaporization time similar to that established for other media and for longer vaporization times. The characteristics of recovery rate of fuses in air and vacuum differ drastically due to the early onset of ionization in fuse channels in vacuum.

CONTENTS

RECOVERY CHARACTERISTICS OF EXPLODING WIRE FUSES IN AIR AND VACUUM

I. INTRODUCTION

Metal fuses have recently gained wider application for current interruption in inductive storage systems, being rather simple devices with a capability to perform demanding functions. They are employed in megajoule level systems,[1,2,3] where they provide opening times of about a microsecond, as well as in smaller pulser systems where fast (~ 100 nsec) output voltage risetime has been obtained.[4,5] To extend their usefulness, staging of fuses has been employed to provide higher power multiplication.[2,6] Because the staging requires that the voltage generated by the succeeding switches appear across fuses that have previously exploded,[2] the rate at which the dielectric strength is restored must be known. Borisov et. al.[7] measured the dielectric strength of the products of the exploded copper fuses in air and in quartz sand as a function of the delay between the initial current interruption (i.e. fuse vaporization) and the reapplication of the voltage. In their experiments (using currents with risetime of about 25 μsec), the delay time, Δt, ranged from 10^{-5} sec to minutes, with the restoration of the dielectric strength proceeding most rapidly in 10^{-4} to 10^{-2} sec range. Conte et.al.[2] have studied the same phenomena for aluminum fuses (foils) in water using similar current and current risetime (30 kA and 50 μsec, respectively). The results are reproduced in Fig. 1 from Reference 2. The initial recovery to a level of ≥ 20 kV/cm strength is associated with the cooling of fuse products. The subsequent drop may be due to chemical heating and the resulting increase of the ionization[8].

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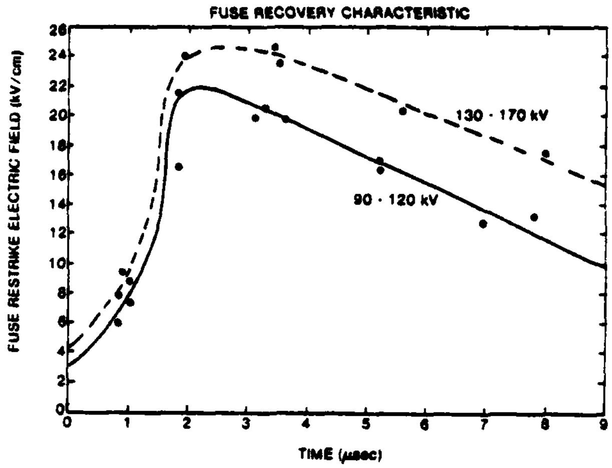

Fig. 1. Dependence of the dielectric strength of Al foil fuses on Δt. Higher strength is obtained when more energy is deposited in the foil fuse, resulting in higher inductive voltage.

The energy associated with vaporization of fuses represents not only a decrease of pulser system efficiency, but also leads to strong shocks that are difficult to contain. For this reason, a choice between good tamping material (quartz sand) and a medium (e.g. water) that optimizes fuse characteristics, such as inductively generated electric field, often is not satisfactory. To provide additional options for design of experiments, as well as to further the understanding of the interruption mechanisms in the microsecond regime we have examined, for the first time, the rate of recovery of fuses exploded in vacuum and have extended the data on the recovery of fuses exploded in air to a time regime of $\leq$ 10 μsec. In this study, current risetimes are of the same order as those of References 2 and 7. (Copper was chosen as fuse material, since most of the published data relevant to this work has used copper wires). The use of vacuum and (to lesser extent) of air as the medium in contact with the fuse, essentially eliminates the problem of mechanical shocks. We have found that for fast-rising currents (~ 1 μsec), the electric field generated by the interruption of the current by Cu fuse in vacuum is nearly (~ 50%) as high as that associated with fuses operating in other media. These results, thus, open up the possibilities of using conveniently such switches in close vicinity (i.e. by reducing substantially the mechanical shocks) to loads, such as imploding plasmas.

II. FUSES IN ATMOSPHERIC AND LOW PRESSURE AIR

Study of fuse behavior in vacuum and in low pressure gases has been limited in the past, largely, to applications such as plasma, light, and x-ray source development.[9] The most thorough studies of electrical properties and the mechanisms responsible for them have been performed in Sweden.[10,11,12] The value of inductively generated electric field was found to be about 5 kV/cm at ambient gas pressure of 10^{-5} Torr.[12] It is suggested[12] that the induced field is limited by a restrike caused by neutral vapor layers or thermionically emitted electrons, depending on the boiling point of the material. We find that the restrike field, E_r, for Cu fuse decreases also with current pulse duration (referred to as "charging time" and denoted as t_e), before the explosion (vaporization) of the fuse, in a manner similar to that for wires exploded in the atmospheric gases and liquids,[13] i.e., $E_r \propto t_e^{-\alpha}$ where $\sim 0.3 < \alpha < 1.0$ covers all cases. No studies of the dielectric strength recovery rate have been performed for fuses in low pressure environment.

Fig. 2 shows the dependence of E_r on t_e for 0.12 mm diameter Cu fuse in vacuum. For comparison, the same dependence of the restrike field of fuses exploded in air, as obtained by Braunsberger et.al.[13] and in our study (at long and short charging times, respectively) is shown. The values of E_r in vacuum and in air (for $t_e \leq 100\ \mu sec$) have been obtained using the circuit shown in a simplified form in Fig. 3. A low voltage capacitor is discharged through fuse 1, with time to peak current of 15 μsec. By selecting different fuse 1 diameters, t_e was varied (together

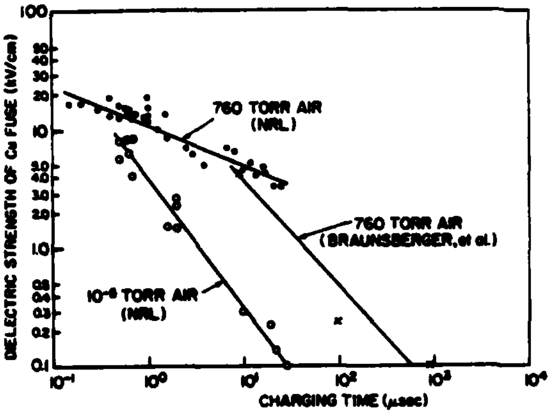

Fig. 2. Inductively generated electric field, E_r, at restrike, shown as a function of t_e for fuses exploded in vacuum and at atmospheric pressure.

with the current in the fuse at t_e), to provide some of the data in Fig. 2. Other data in Fig. 2 was obtained by using fuse 1 as current steepening switch. Commutation of the current to fuse 2 provided up to 10 kA, with a rise of 1.5 μsec, into the low pressure chamber. The variation of the fuse 2 diameter provided the data points for $0.1 < t_e < 3$ μsec.

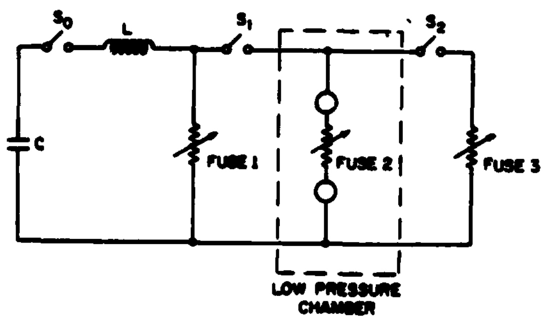

Fig. 3. Inductive circuit for determining the restrike voltage of fuses in vacuum. Capacitor C(60 μF) charges up to 10 kV. The inductance L is approximately 3.5 μH. No lead and fuse inductances are shown.

Although E_r of up to 10 kV/cm can be generated by fuses in vacuum, this field does not exceed that obtainable with fuses when their expansion is partly confined by atmospheric pressure air. Fig. 4 shows how E_r of Cu fuses varies with pressure of the surrounding air. The confining function of the surrounding medium is negligible for $P \leq 50$ Torr. Furthermore, the restrike field is always less than the electrode gap breakdown field, E_b,

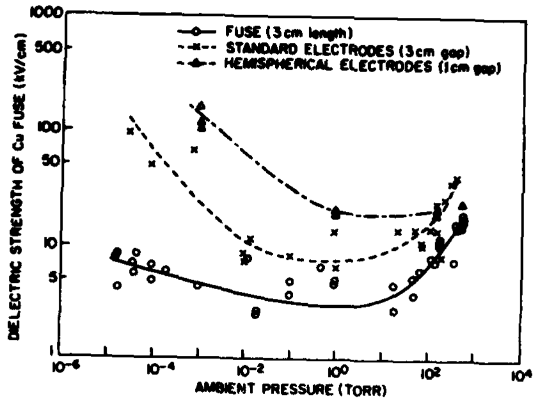

Fig. 4. Pressure dependence of E_r generated by opening of the fuse is compared with the electrode gap breakdown field, E_b. E_b was obtained for flat electrodes (standard) used in mounting of fuses. Also higher breakdown strength was obtained for rounded electrodes with lower field enhancement

in the pressure range of 10^{-2} to 50 Torr, $E_r \simeq E_b$, with E_r rising to about 8 kV/cm at low pressure. This suggests that breakdown around the fuse, rather than fuse expansion may be responsible for the low values of E_r in the Paschen regime ($10^{-3} \leq P \leq 10^{1}$ Torr). Fuse data shown in Fig. 4 was obtained by exploding fuses in the low pressure chamber (with no fuse 3 in the circuit). Fuse 3 was used, in turn, to measure E_b of the two types of gap electrodes. The half-width of the voltage pulse generated by either fuse 2 or fuse 3 was about 200 nsec. Current and t_e, associated with fuse 2 are 5 to 10 kA and 1.5 μsec, respectively. By measuring electrode gap breakdown it was determined that with the exception of the low breakdown region where data scatter is quite large, these electrodes do not effect the observed value of restrike field. Hemispherical electrodes with low field enhancement were also tested to establish maximum practical fields that can be supported if better fuse performance were obtained.

Fig. 4 shows that the induced fields are about 9 and 20 kV/cm for fuses operating in vacuum and air respectively. Fig. 5 shows that, in the cases where restrikes occur, the current interruption (at 3.5 kA and 2.1 kA in air and vacuum) and induced voltage waveforms have similar histories. The recovery of the fuse in vacuum, however, was found to be substantially different from that in air or in water[2]. The difference appears to be due to the early onset of ionization, normally absent when media other than vacuum are used. Fuses in both air and vacuum were studied in the range $0.6 \leq \Delta t \leq 10\ \mu sec$.

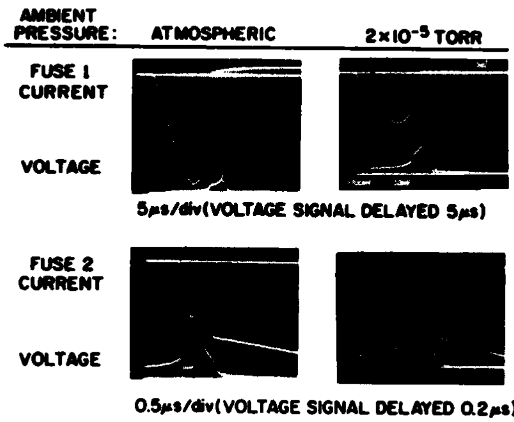

Fig. 5. Oscilloscope traces of the voltage across, and current through, fuses 1 and 2. Fuse 2 operated at atmospheric and low pressure (left and right traces, respectively) at sufficiently high induced fields to produce restrikes, evident by the current increase after the initial interruption. Peak voltage is 50 kV (left) and 30 kV (right).

The mechanism that determines the recovery field, E_r, of the fuse exploded in air involves the pressure and temperature distribution of the expanding fuse and of the heated air that surrounds the fuse[7]. Therefore, E_r is expected to depend on the delay between the vaporization (that leads to current interruption and subsequent commutation to fuse 3, shown in Fig. 3) and the reapplication of the voltage generated by fuse 3. This dependence is shown in Fig. 6. For small Δt, the recovery field $E_r(t + \Delta t)$ is approximately equal to the restrike field $E_r(t)$. At large Δt (11 µsec), the recovery field is much smaller, due to substantial expansion of the fuse channel. In fact, the dependence of E_r on Δt matches with the 1-2 kV/cm measured by Borisov et.al.[7] at Δt of about 60 µsec, for Cu fuses in air with somewhat different history of charging current.

The recovery characteristics of fuses exploded in vacuum are more complex, because from the time of on-set of vaporization there appears, in contrast to wires exploded in air, strong ionization of the channel. Such ionization would result from the thermionic emission of electrons and ions (and their acceleration in the Ohmic potential drop across the fuse) during

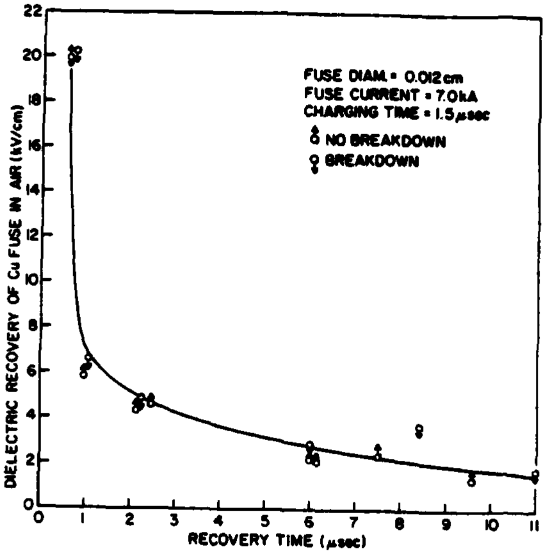

Fig. 6. Recovery field, E_r, of fuses exploded in air. The field is determined by converging the breakdown and no-breakdown data (by adjustment of fuse length) to a minimum difference.

the heating and vaporization phase as suggested in References 11 and 12. The resistance of the vapor is lowered by ionization, relative to fuses in air, as can be deduced from the traces in Fig. 5. The on-set of ionization was indicated in References 10 and 12. This is also supported by resistivity measurements, during and after vaporization, which are consistent with presence of free electrons. The resistance is of Spitzer type[15], i.e., the resistivity (for T_e in ^oK), valid for $n_e/n_o \geqslant 10^{-2}$, is

$$\eta = 3.8\ 10^3 \frac{Z \ell n \Lambda}{T^{\frac{3}{2}}} \text{ (Ohm-cm)} \qquad (1)$$

and does not depend significantly on the electron density, n_e. The resistance per unit length, $r = \eta/A$, scales inversely with the cross section area, A, of the expanding channel. At vaporization time (for charging time of 3.5 μsec) Bennet[14] shows that typical fuse channel diameter (in air) is 0.2 cm at the time of current cut-off, so that for T_e of 1 to 2 eV and effective $Z \approx 1$ (with $\ell n\Lambda \simeq 0.9$-3.3 as established by Burtsev et.al.[16]) $r \simeq 0.2$ Ohm/cm. Observed values of r were in the same range. Such behavior of the fuse in vacuum makes it difficult to achieve total current interruption in the fuse. As the current commutation is attempted, residual current continues through fuse 2. The voltage developed across fuse 3 was used to indicate the behavior of fuse 2 resistance, which appeared to drop slowly with increasing Δt. This drop can be explained by the scaling $r = \eta/A$, with A increasing with radial velocity of about[17] 5×10^5 cm/s for current driven channels.

To obtain the condition of total current cut-off, an additional short fuse (exploded in air) was added in series with fuse 2 (exploded in vacuum). The air fuse provided complete interruption of current in both series elements. This way, the voltage applied across the series fuses by the fuse 3 after delay time, Δt, provided a measure of the upper limit on the vacuum fuse resistance for Δt up to 10 μsec. It was found that the resistance remains low and the recovery field is negligibly low. This conclusion is based on the observation that neither of these parameters differed from the values obtained when only fuses in air were used. This is also consistent with the recombination time for singly ionized plasma where the 3-body collisions of atomic ions and electrons are dominant. Its rate coefficient[18] $\alpha_3 \simeq 8\times10^{-27}\ T_e^{-4.5}$ gives the scale decay time $\tau = 1/\alpha_3 n_e^2$. For expected density of the order of 10^{16} cm^{-3}, $\tau = 30\ \mu$sec, i.e., the low channel resistance persists for times that are longer than available for testing.

III. CONCLUSION AND COMMENTS

In the experiments described here, electrical characteristics of fuses exploded in air and vacuum were found to differ substantially. Behavior in air is distinct from that in other media where such effects as tamping of the fuse channel expansion influence the electrical properties. Fuse behavior in vacuum differs more fundamentally from other cases because of the presence of ionization, nearly simultaneously with vaporization, that cannot be effectively inhibited.

Other scalings, such as dependence of induced, restrike and recovery electric fields on the diameter and length of the fuse revealed no significant non-linearities over the relatively narrow range of parameters used in the experiments. The method for determining the recovery level of fuses, represented by the circuit diagram in Fig. 3 is derived from that developed for generation of very high power repetitive pulses with short pulse-to-pulse separation[19]. This method provides a convenient simulation of experiments where the replacement of fuse 3 in Fig. 3 by a plasma load would generate rapidly rising voltage due to increasing plasma impedance, such as large change of inductance in implosion experiments, or large increase in anomalous plasma resistivity, as in beam particle production experiments.

IV. REFERENCES

1. V. I. Bogdanova, V. A. Burtsev, I. V. Kalinin, O. L. Komarov, V. N. Litunovsky, Preprint K-0410, Efremov Institute (NIIEFA), Leningrad, USSR, 1978.

2. D. Conte, R. D. Ford, W. H. Lupton, I. M. Vitkovitsky, Digest of Technical Papers of the Second IEEE International Pulse Power Conference in Lubbock, Texas, IEEE Catalog No. 79CHI505-7, p. 276, (1979).

3. D. L. Smith, R. P. Henderson, R. E. Reinovskii, Digest of Technical Papers of the Second IEEE International Pulse Power Conference in Lubbock, Texas, IEEE Catalog No. 79CHI505-7, p. 287, (1979).

4. Yu. A. Kotov, B. M. Kovalchuk, N. G. Kolganov, G. A. Mesyats, V. S. Sedoi, A. L. Ipatov, Sov. Tech. Phys. Lett. 3, 359, (1977).

5. D. Conte, R. D. Ford, W. H. Lupton, I. M. Vitkovitsky, Proceedings of the Seventh Symposium on Engineering Problems of Fusion Research, Vol. II, IEEE Pub. No. 77CH1267-4-NPS.

6. V. A. Zheltov, A. V. Ivlev, A. V. Kibardin, A. S. Komin, A. V. Kuchinsky, Yu. A. Morozov, Preprint K-0297, Efremov Institute (NIIEFA), Leningrad, USSR (1976).

7. R. K. Borisov, V. L. Budovich, I. P. Kushekhin, Sov. Tech. Phys. Lett. 3, p. 516 (1977).

8. R. Fernsler, JAYCOR, Alexandria, VA, Private Communication.

9. W. G. Chace and K. Moore ed. "Exploding Wires" Vol. I, II, III, IV, Plenum Press, NY (1968).

10. B. Stenerhag, S. K. Händle, I. Holmstrom, Z. F. Physik, 198, 172 (1967).

11. I. Holmström, S. K. Händle, B. Stenerhag, J. Appl. Phys. 39, 2998, (1968).

12. B. Stenerhag, S. K. Händle, B. Göhle, J. Appl. Phys. 42, 1876, (1971).

13. U. Braunsberger, J. Salge, U. Schwarz, Proceedings of the Eighth Symposium on Fusion Technology, Noordwijkerhout, Netherland, June 1974 published by Commission of the European Communities, Luxemburg, (1974).

14. F. D. Bennett, G. D. Kahl, Ref. 9, Vol. IV, p. 1.

15. L. Spitzer, "Physics of Fully Ionized Gases", Interscience Publishers, NY (1967).

16. V. A. Burtsev, A. M. Bezdolny, V. A. Dubiansky, N. P. Yegorov, M. P. Kasatkina, A. B. Produvnov, I. V. Shestakov, "Investigation of Electrical Explosions of foils in Air", Efremov Science Research Institute of Electrophysical Apparatus, Preprint P-K-0451, Leningrad, USSR (1979). In Russian.

17. D. C. Chern and T. Korneff, Ref. 9, Vol. IV, p. 173.

18. Y. B. Zeldovich and Raizer, "Physics of Shock Waves", Vol. I, Academic Press, NY (1966).

19. R. D. Ford, I. M. Vitkovitsky, IEEE Trans. on Electron Devices Vol. ED-26, 1527, (1979).

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