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Terminated Capacitor Discharge Firing of Electroexplosive Devices

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Preface

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Abstract

By terminating the discharge of energy into an insensitive electroexplosive device, firing energy parameters can be determined. A simple capacitor discharge system providing exponential pulses terminated at an adjustable width is described. Development technique and application to testing are discussed.

Terminated Capacitor Discharge Firing of Electroexplosive Devices

I. Introduction

The initiator of an electroexplosive device (EED) employs a fine bridgewire in intimate thermal contact with an explosive mixture. An established procedure for characterizing the sensitivity of such a device is by capacitor discharge firing. For example, the mean firing energy for a device is the energy in joules (or ergs) required to fire 50% of the devices under test. This energy must be supplied adiabatically in this test method to preclude any heat loss or diffusion throughout the explosive mixture. When energy is delivered in a time less than one-tenth of the major thermal time constant, negligible cooling is apparent. Since most firing systems employ capacitor discharge power supplies, this energy parameter is applicable to the design of such systems. The apparatus and technique to be described are particularly applicable to high-reliability insensitive devices (i.e., 1 W/1 A no-fire) as encountered in spacecraft application.

Military type EEDs are, in general, less sophisticated, less expensive, and are produced in larger quantities (lots of 100,000 are not unusual) as compared to aerospace EEDs. These factors can justify using a 50- to 100-sample Bruceton type test to determine the energy requirements or sensitivity of the devices. This, however, is not true for aerospace EEDs, because the quantities (lots of about 1000) are small and costs become excessive. As an alternate procedure, the bridgewire of each aerospace EED fired during evaluation is electrically monitored. The energy to fire by constant current pulse is calculated on the basis of pulse start time to time of bridgewire burnout. A calculation on this basis contains an inherent error since sustained chemical reaction commences prior to bridgewire burnout. The estimate is on the conservative side, and this could lead to an unjustifiably large power supply with a resultant increase in weight and space requirements.

A typical aerospace EED would be capable of passing 1 W or 1 A continuously (whichever is greater) for safety considerations, but under impulsive firing conditions may require energies of 20 to 200 mJ, depending on the electrothermal design. The higher energy delivery requirements pose certain problems for the test apparatus. For example, a 2-mF capacitor at 160 V would have the same energy (25.6 mJ) as a 32-mF capacitor at 40 V. With a 1-Ω device, the discharge currents under ideal conditions would be 160 and 40 A, respectively. The problems of switching 160 A are obviously greater than those of 40 A. In addition, it seems more meaningful to test at a voltage level typically employed in the firing system. One method of assuring meaningful measurements is to ascertain that the energy stays constant for the range of test currents employed or the action integral ($A = \int i^2 dt$) is constant for low TCR (temperature coefficient of resistivity) bridgewire.[1]

Capacitor discharge firing with the larger capacitors required may call for polar types with increased losses when compared to the low-energy systems. The efficiency of energy transfer should be viewed conservatively, and the actual discharge waveforms must be monitored during the firing. Although mercury-pool type switches have an excellent performance record at low energy levels, there is little justification for their use since the high "di/dt" values will be limited by external circuitry. The thyristor or silicon-controlled rectifier (SCR) device is the typical system switch mechanism, and it appears wise to use this or an equivalent solid-state switch in a test apparatus. Although the switching efficiency is poorer, energy will be determined at the device terminals. The convenience and flexibility of a thyristor switch system far outweigh any disadvantages and are the basis of the switching and pulse termination system presented.

Another obvious system for delivering an energy burst could employ a transistor as a pass device in series with a regulated power source. The transistor would be driven into saturation with a one-shot gating pulse. Although faster rise and fall times are possible, the total complexity of this type system makes it less attractive than the thyristor system.

The testing apparatus to be described employs a charged capacitor (at 40 V) as the energy source and a high-quality thyristor as the switch. At some preset time after the discharge initiation, the current pulse is diverted away from the device under test, thus terminating the capacitor discharge energy. At termination, only the initial high-current, high-power region of the pulse is used and the low-energy tail is discarded. The desirable characteristics of a rectangular current burst and capacitor discharge simulation are provided in this method. Terminating the pulse clearly displays a region where the explosive reaction incubates to maturity. The simple circuitry employed will be described in detail.

II. Circuit Description

The circuit of Fig. 1 is the complete apparatus except for the power supply (40 V), which is noncritical and set constant. A capacitor bank C, consisting of three high-quality tantalum electrolytics, makes up the energy storage component of the firing circuit. Resistor R_1 controls the recycle rate and primarily limits the thyristor currents to below "holding" levels so that they turn off after a discharge cycle. Controlled rectifier T_1 is the main discharge device for the load consisting of the EED and a series ballast 1-Ω resistor, while T_4 is the bypass or discharge termination device. When S_1 is closed, a gate pulse limited by the size of R_2 fires T_1 and the energy is dumped at a time constant determined essentially by C_1 and the total load resistance. Typically, an EED of 1 Ω would result in a discharge time constant of 1350 μs. During discharge, the voltage appearing at point K is converted to a constant charging current for timing capacitor C_2. This is accomplished by the JFET transistor T_2 acting as a current regulator by means of source degeneration (Ref. 1). As the source resistance R_3 is varied from 0 to 5 kΩ, the current charging C_2 is varied from 3.5 mA to near zero. A fixed constant current diode device (e.g., Motorola IN5283-IN5314) would require some other timing mechanism such as a variable capacitor (C_2) or an adjustable unijunction firing voltage. As long as there is a voltage greater than 3 V at point K, a constant current charges the capacitor C_2. Timing is therefore based on the presence of a main discharge pulse, independent of the pulse waveform. Without the current regulator T_2, it would be possible to make the voltage at C_2 responsive to the discharge cycle waveshape.

The voltage at C_2 climbs in a linear manner according to constant current charging. Unijunction transistor T_3, having an interbase voltage of 14 V, will discharge at an emitter voltage of roughly 7 V. Variation of the interbase voltage would offer some control over the timing, if desired. Firing of T_3 triggers thyristor T_4 into conduction, which diverts the main capacitor discharge in "crowbar" fashion from the load. Thus the discharge of energy into the EED is terminated by means of the bypass procedure. Both rectifiers T_1 and T_4 in series totally discharge C_1, but since there is insufficient holding current, the capacitor is allowed to recharge. The typical linear continuous pulse width control is shown in Fig. 2 for the

[1]The TCR of a typical bridgewire material, Tophet A, at 25°C is 100×10^{-6} Ω/°C.

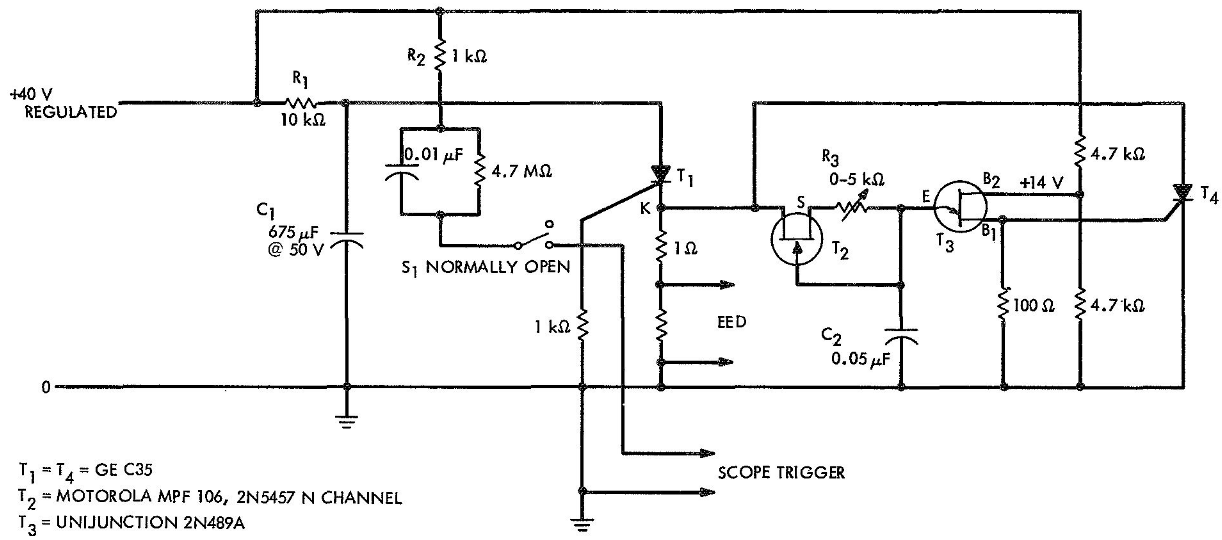

Fig. 1. Circuit diagram of the terminated capacitor discharge firing set

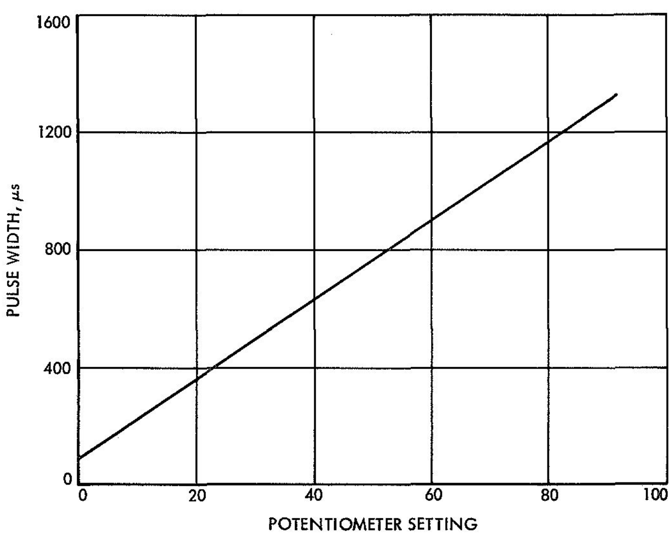

Fig. 2. Pulse width vs control setting

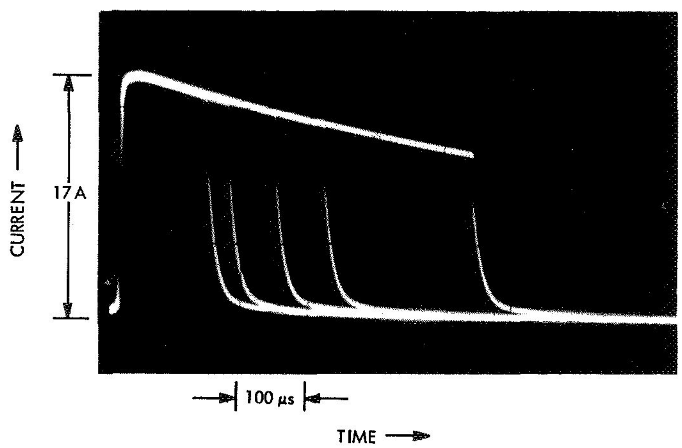

Fig. 3. Typical discharge traces

range of 100–1300 μs. The rheostat R_3 is of the composition variety, which accounts for some of the deviation from linearity.

It is essential to monitor the EED voltage by means of an oscilloscope at the device terminals. The scope trigger signal can be derived from the gate pulse for T_1. By increasing the ballast resistor from 1 Ω, the discharge current can be reduced from the nominal 20-A peak rate, with a corresponding longer discharge time constant.

A series of terminated pulses is shown in Fig. 3 for a 1-Ω dummy load replacing the EED. A 1-Ω ballast resistor is in series to limit the current to 17 A peak, and the termination behavior is apparent for a variety of pulse widths. A rise time of 5 μs and a fall time of 25 μs were measured. Since power varies as the square of the current amplitude, the energy termination is very rapid. From peak current measurements it was determined that the internal resistance of the discharge circuit was equivalent to 0.35 Ω. With a discharge time constant of 1350 μs, the current amplitude is down by 10% in 135 μs.

The two traces shown in Figs. 4a and 4b show the behavior of the timing circuit. In Fig. 4a a 200-μs pulse is "timed" out by the superimposed linear trace due to the charging of the unijunction capacitor. At 7 V on the

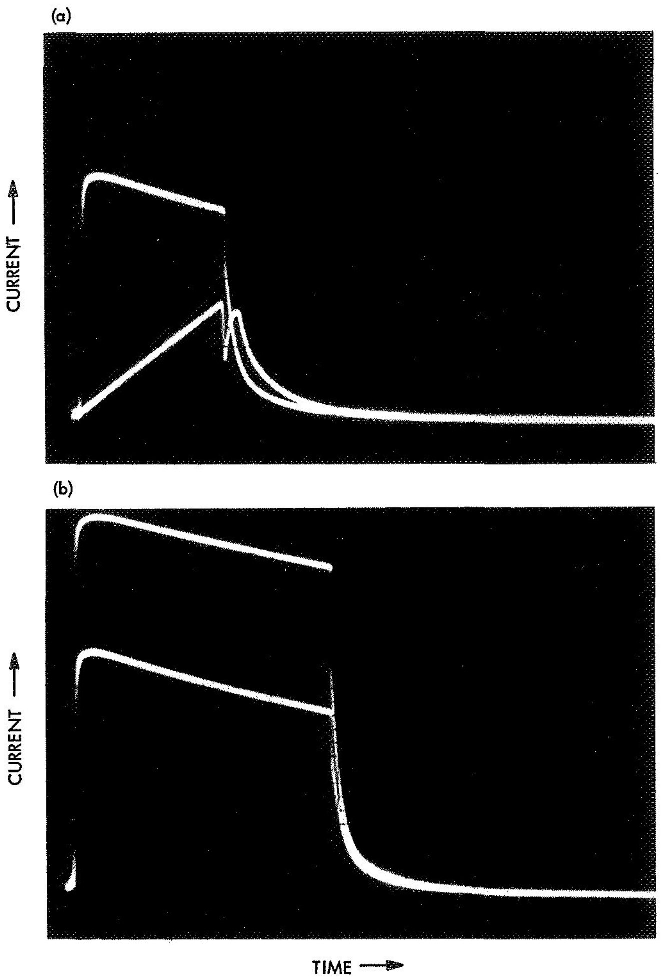

Fig. 4. Emitter voltage and bypass SCR. (a) The emitter voltage climbs in a linear manner until the bypass SCR is initiated; the pulse width is set at 200 μs. (b) Timing is independent of the pulse amplitude because of constant current charging for this 400-μs pulse width

emitter, the "dump" thyristor becomes active. The time control is independent of discharge waveshape as shown in Fig. 4b. For a discharge into 4 Ω (top) or 2 Ω (bottom), the identical pulse width of 400 μs is obtained.

III. Energy Calculations

The energy delivered to a constant resistance due to the exponentially decaying pulse can be determined from the observed scope trace. The initial current I_0, termination current I_1, and pulse width t_w are measured. With knowledge of the total load resistance, or a complete discharge cycle, an effective time constant τ can be established.[2] For an EED resistance of R ohms the energy delivered is

$$W = \int_0^{t_w} R\,(I_0 e^{-t/\tau})^2\,dt \qquad (1)$$

Integration results in

$$W = \frac{I_0^2 R \tau}{2}\,(1 - e^{-2t_w/\tau}) \qquad (2)$$

When the exponential term is expanded as a series,

$$W = \frac{I_0^2 R \tau}{2}\left[2\left(\frac{t_w}{\tau}\right) - 2\left(\frac{t_w}{\tau}\right)^2 \cdots\right] \qquad (2a)$$

Since I_1 is approximately $I_0\,[1 - (t_w/\tau)]$ for the region of linear droop, the equation reduces to:

$$W = I_0 I_1 R t_w \qquad (3)$$

If a longer portion of the decay is used, a correction is necessary. For example, Eq. (2) can be reduced to:

$$W = \left(\frac{I_0^2 - I_1^2}{\ln \frac{I_0}{I_1}}\right)\frac{R t_w}{2} \qquad (4)$$

A more exact way of deriving Eq. (3) shows the errors involved in terminating the series of Eq. 2(a). Since $I_1 = I_0 e^{-t_w/\tau}$, Eq. (2) can be shown to be

$$W = I_0 I_1 R \tau \sinh \frac{t_w}{\tau} \qquad (5)$$

It is desirable to eliminate the circuit discharge time constant by expanding the hyperbolic sine. The result is:

$$W = I_0 I_1 R \tau \left[\frac{t_w}{\tau} + \left(\frac{t_w}{\tau}\right)^3 \frac{1}{6} \cdots\right] \qquad (5a)$$

A corrected form of Eq. (3) can be extracted as

$$W = I_0 I_1 R t_w \left[1 + \left(\frac{t_w}{\tau}\right)^2 \frac{1}{6} \cdots\right] \qquad (3a)$$

As an example, if 20% of the exponential decay is used ($t_w/\tau = 0.2$), the energy as determined by Eq. (3) is low by 0.7%. This appears to be a trivial error.

[2]In a time interval of 0.1 τ, the amplitude falls by 10%.

In this analysis, the TCR of the bridgewire and pseudovariations in resistance which result in distorted exponential current decay waveforms have not been considered. In general, these distortions are quite small and will be considered later herein.

IV. Experimental Observations

By selecting the proper ballast resistor, we establish the initial discharge current (i.e., I_0). A reasonable step size in terms of pulse width t_w from some initial energy level is chosen based on the nominal energy requirements. Sufficient time must be allowed between firings to recharge the energy storage capacitor; an oscilloscope across the device provides the output information.

Figures 5a and 5b are typical observed traces. Unit 82180 (Fig. 5a) was fired at an I_0 level of 12.4 A; unit 41245 (Fig. 5b) was fired at 15.5 A. The last discharge corresponds to a fired condition, and the step size is obviously not sufficiently small for good resolution. In both traces there is a small pulse at a time after firing. The pulse is a result of the bridgewire opening at the time of destruction and is sensed by the "$L\ di/dt$" effect in the wire. A monitoring current could be used to accentuate this point in the firing cycle. It would appear that there is an incubation time during which the explosive reaction progresses through the device.

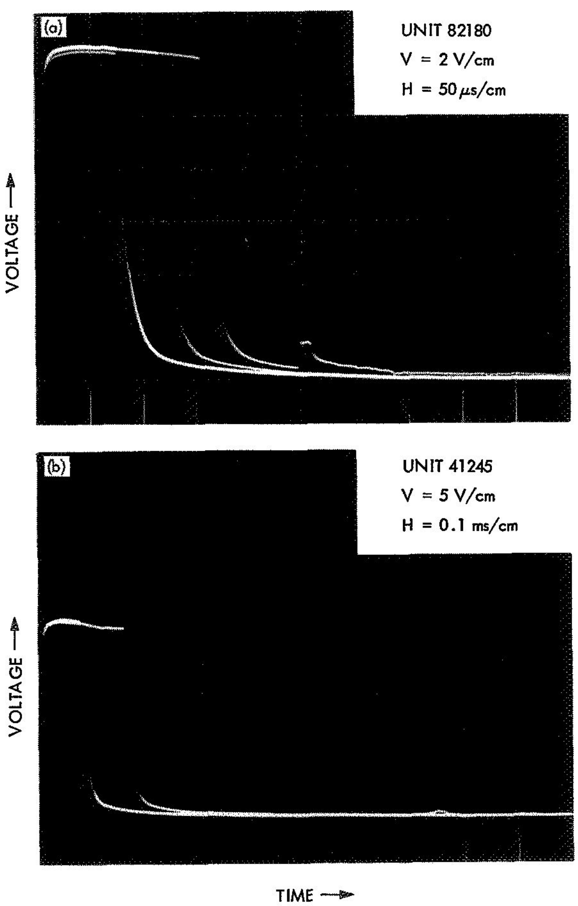

Fig. 5. Firing traces for two types of EEDs. (a) A nominal 23-mJ device with an incubation time to explosion of 300 μs. (b) A nominal 32-mJ device with an incubation time to explosion of 750 μs

A number of items were tested for firing energy, and the results are tabulated as group averages in Table 1. Individual resistances were used in the calculations in Table 1, and it should be noted that two manufactured groups are represented: ABC and DEF. For the small lot of samples tested, results clearly indicated a meaningful firing energy level over a current range of 2.4 to 1. The firing appears to be adiabatic in the constant action integral region. The second group, DEF, is clearly more sensitive than the first group tested.

During the discharge, EEDs in group ABC showed a change in discharge curvature (Fig. 5b) from the ideal decay. This may be due to a sudden cooling of the bridgewire (i.e., a drop in resistance) because it distorts and makes better thermal contact with the explosive. This change was not observed in group DEF. It was known that the loading density of the initiator charge in group ABC was slightly above bulk density, while the initiator charge in group DEF was pressed at a considerably higher density.

The obvious question as to the effects of repeated pulsing of the bridgewire on the performance must be

Table 1. Energy to fire based on capacitor termination tests

Group (samples)	I_0 level, A	t_w, μs	W energy to fire,[a] mJ
A-3	15.5	160	31.4
B-2	11.0	320	31.7
C-3	6.5	1050	31.6
D-1	12.4	155	22.5
E-1	18.5	74	23.0
F-1	8.2	400	21.7

[a]These values do not represent an exact energy requirement, because the time interval during "creep-up" to fire was large. A smaller time step could be used.

resolved. An item from group ABC was pulsed 30 times at a level of 25.3 mJ. The determined firing energy of about 32 mJ had been established. When the energy of the thirty-first pulse was increased to 31.6 mJ, the item fired. In another test an energy level of 20.5 mJ was dumped 50 times into an item of the first group. It was observed that the resistance increased from 1.16 to 1.29 Ω because of the repeated pulsing. This was a result of the bridgewire straining the weld and structure during thermal expansions accompanying pulsing (Ref. 2).

When the pulsing was continued at increasing pulse widths, the unit fired at a level of 29.1 mJ. Since the number of pulses was far in excess of the typical test procedure, it seems proper to assume that pulse testing the same item will not result in meaningful changes in performance. This may not be true for the case of sensitive devices (e.g., 5000-erg *all-fire*) and should be ascertained for any given item under test. When costly items are tested, the use of a smaller test sample lot can result in meaningful savings.

V. Conclusions

It appears that the terminated capacitor discharge test apparatus can provide meaningful measurements of the firing energy requirements for insensitive electroexplosive devices. The number of pulses of increasing width should be limited to less than 10 as a good procedure. Energy calculations are simple and sufficiently accurate. Details in the discharge trace may also give clues as to manufacturing variations and abnormalities.

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16. Abstract

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