

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Report 32-1556

*Evaluation of Electroexplosive Devices by
Nondestructive Test Techniques and
Impulsive Waveform Firings*

V. J. Menichelli

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JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

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Preface

The work described in this report was performed by the Propulsion Division of the Jet Propulsion Laboratory.

Acknowledgement

The author would like to acknowledge the helpful suggestions and cooperation of L.A. Rosenthal (Professor of Electrical Engineering, Rutgers University, New Brunswick, New Jersey and Consultant to JPL) and to H. Jefferies for their assistance in designing and conducting the experiments, and to L. Swanson for his help in conducting and monitoring the output tests.

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Abstract

Special requirements of the space industry necessitate more detailed knowledge of the quality and reliability of each electroexplosive device (EED) selected for use aboard a spacecraft. Statistical methods do not practically demonstrate the high reliability needed. To close this gap, nondestructive test techniques and instrumentation for 1-W/1-A no-fire devices have been developed. Several lots of squibs have been evaluated using these techniques and instrumentation. They yield data as to the quality and normal behavior of each electroexplosive device without firing or degrading the unit. Performance data were obtained by initiating the EED's with an impulsive waveform and sensing the initiation characteristics, sensitivity, and output.

Evaluation of Electroexplosive Devices by Nondestructive Test Techniques and Impulsive Waveform Firings

I. Introduction

Failure of an electroexplosive device (EED) during a space mission can result in partial or complete loss of the mission and perhaps loss of life. The selection of EED's for use aboard a spacecraft is usually made on a statistical basis. Statistical methods have been applied to the determination of reliability with some success. For example, predictions can be made as to the number and type of failures that can be expected to occur within a given lot of EED's. However, the statistical methods do not predict which specific unit will fail nor the failure mode. Although these methods are acceptable for some applications, they do not meet the high reliability needs of the space industry, whose special requirements necessitate more detailed knowledge of the quality of each EED to be used. The quantities required on a spacecraft are relatively small, i.e., less than 30 EED's are needed for a typical Mars exploratory mission. To demonstrate by statistical methods the high reliability needed, the destructive testing of many EED's would be necessary. For example, a demonstration of functioning reliability of 0.999 at 0.90 confidence would require 2303 firings without a failure. Despite the predicted reliability value obtained, some doubt about the particular EED's used will always remain.

The Jet Propulsion Laboratory has developed nondestructive test (NDT) techniques and instrumentation which yield data as to the quality and normal behavior of 1-A/1-W no-fire EED's without firing or degrading the unit. These techniques are limited to the bridgewire/explosive/header interface, which is considered the most critical link in the electroexplosive chain (Fig. 1). The quality of the EED beyond this interface can be evaluated to a certain degree by techniques such as weighing, X-ray, and neutron radiography.

A certain amount of destructive testing is required to determine the performance, sensitivity, and output of the EED's. In general, firing circuits for EED's aboard JPL spacecraft are of the capacitor discharge type. Instrumentation to simulate the impulsive energy delivered by capacitor discharge has been developed which allows the delivery of energy in an impulsive manner with control of pulse width and amplitude. Monitoring of the pulse leads to a quick calculation of the total energy applied and provides a visual display of the bridgewire behavior. Sensitivity can be determined with a relatively small sample. The output, in terms of pressure or work, can be obtained simultaneously with the sensitivity determination.

Nondestructive tests and impulsive firings have been applied to three groups of aerospace-type EED's. Two groups, A and B, were of the same design (single-bridgewire) but manufactured by different vendors. The third group, C, was a dual-bridgewire design. Figure 1 illustrates the configuration of the single-bridgewire EED. The dual-bridgewire design is, for all practical purposes, the same as that in Fig. 1, with the exception of having two bridgewire circuits.

A block diagram of the test program is shown in Fig. 2. All EED's were first subjected to the NDT's ("transient pulse" and "electrothermal follow" tests). Units were then selected for environmental conditioning (vibration, thermal shock, cold storage, and hot storage). The vibration test consisted of subjecting the EED's to six sinusoidal vibration scans from 8 to 2000 Hz. The test levels were at 10, 20, 30, 40, 50, and 60 g peak, except as limited by maximum exciter displacement and/or velocities at the low frequencies and by maximum exciter armature current at the higher frequencies. The sweep rate was 1/2 octave/min or approximately 16 min per run. The test program was applied to each of three orthogonal axes of the EED's. At the end of each vibration scan, a continuity check on the bridgewire resistance was made to verify that no damage or degradation had occurred as a result of the test. The vibration equipment consisted of a Ling 335 Vibration Exciter, MB C-126 Vibration Exciter, and Ling PP175/240 Power Amplifier and Control Console. No change in bridgewire resistance was observed throughout the test.

The thermal shock test was conducted between the limits of 394 and 77K (121 and -196°C). An aluminum plate, drilled and threaded to accept the EED's, was the

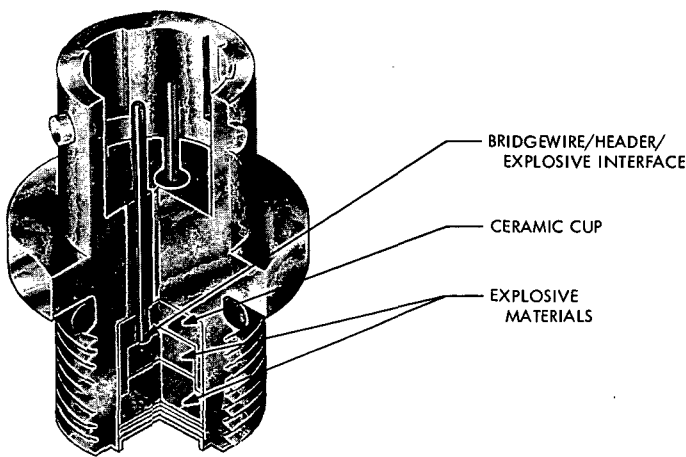


Fig. 1. Typical aerospace electroexplosive device

fixture used. A thermal shock consisted of conditioning the EED's at 394K for 30 min and then quickly submerging them in a liquid nitrogen bath (77K), where they remained for 30 min before being returned to the oven at 394K. A total of 18 cycles constituted the test. Between cycles, the bridgewire resistance of the EED's was monitored. During the test period, the EED's were twice stored overnight in the oven at 394K. No significant change in bridgewire resistances was noted throughout the test.

The hot and cold storage tests consisted of maintaining a group of EED's at 77K and a second group at 394K for a period of 1 week. No change in bridgewire resistance was observed during the storage.

At the completion of the environmental tests, the EED's were again subjected to the nondestructive tests. Finally, they were initiated by an impulsive waveform (half-sine-wave pulser) to determine functional characteristics, sensitivity, and output.

The purpose of the investigation was to

- (1) Evaluate the EED's nondestructively before and after environmental conditioning.
- (2) Demonstrate the utility of the nondestructive tests.

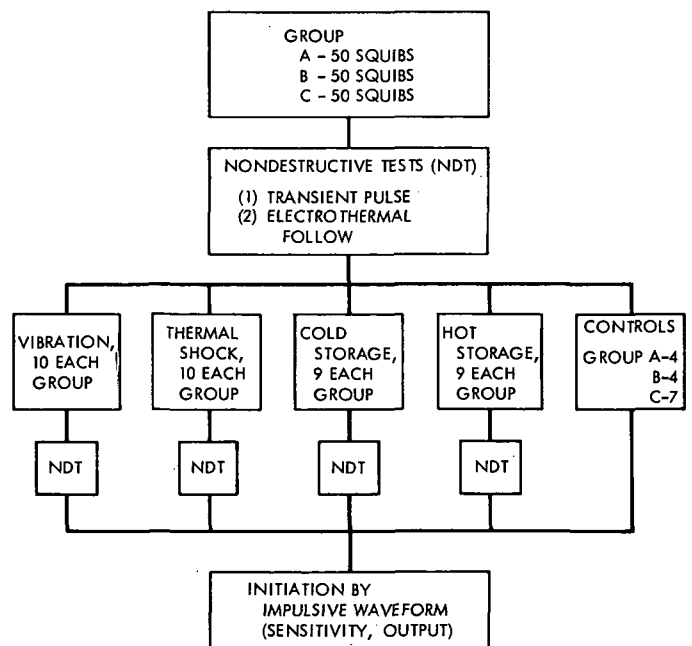


Fig. 2. Environmental conditioning test schedule

- (3) Determine performance characteristics of the EED's when initiated from an impulsive waveform.

This report summarizes the test results obtained for the three groups of EED's mentioned above. The tests and test program did not constitute a complete evaluation program but were arbitrarily designed to meet the objectives of the investigation.

II. Apparatus

Two nondestructive tests, referred to as transient pulse (Ref. 1) and electrothermal follow (Ref. 2), were applied to the EED's. For each instrument, the bridgewire of the EED becomes one arm of a Wheatstone Bridge. The transient pulse apparatus applies a step current waveform (approximately 50 ms on and 50 ms off) to the Wheatstone bridge circuit. The current pulse is small enough to avoid firing or degradation of the EED yet large enough to provide a meaningful electrothermal response. A particular EED design possesses a distinct and unique thermal capacity, thermal conductance, and thermal time constant. Because the bridgewire has a significant temperature coefficient of resistivity (TCR), the Wheatstone bridge unbalances as the bridgewire heats, and an error voltage is developed across the bridgewire terminals. A visual oscilloscope display of the error voltage (heating curve), which can be related to the temperature rise in the bridgewire, is observed during the test. Figure 3 shows a typical heating curve obtained from a normal EED. The instrumentation also allows a quantitative measurement of heat capacity, thermal conductance, thermal time constant, and the cold resistance of the bridgewire. The electrothermal equations used to calculate the values of the above parameters were derived from a lumped model thermal analysis of the bridgewire system (Ref. 3).

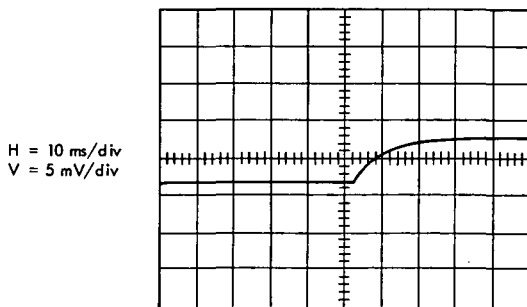


Fig. 3. Typical heating curve response from a normal EED as sensed by the voltage drop at the bridgewire

The second apparatus, electrothermal follow, employs a steady-state 10-Hz sinusoidal current to the Wheatstone bridge circuit. A self-balancing feature of the Wheatstone bridge takes the EED through a thermal cycle. The temperature excursion can be controlled and the bridgewire error signal displayed on an oscilloscope. The display shows how bridgewire heating unbalances the Wheatstone bridge in a cyclic manner, producing a Lissajous display (Ref. 4). This test is qualitative in nature and is best applied as a gross inspection tool. Figure 4 shows a typical Lissajous obtained from a normal EED.

Initiation of the EED's was accomplished with a power supply which generated an impulsive waveform and is referred to as the half-sine-wave pulser (Ref. 5). Practical firing systems, in most cases, operate in an adiabatic manner by discharging the energy stored on a capacitor. The energy is delivered adiabatically, that is, in a short time compared to the thermal time constant. Under these conditions, heat loss to the environment surrounding the hot bridgewire is at a minimum. An accurate measure of the energy required to initiate provides a useful sensitivity parameter. The half-sine-wave pulse is easily generated, and the energy content can be varied and readily calculated. A typical half-sine-wave pulse across a 1-Ω resistance is shown in Fig. 5. Energy is calculated using the following equation:

$$E = \frac{V_m^2 t_p}{2R}$$

where

V_m = maximum voltage observed

t_p = pulse width

R = bridgewire resistance

It was found that pulsing the squibs with subfiring energies did not alter the sensitivity of these devices by a measurable amount. Therefore, it is possible to progressively increase the pulse amplitude in modest steps until initiation takes place.

A measure of explosive output was obtained by two methods, pressure bomb and honeycomb (aluminum) crush. The pressure bomb method provides a measure of the time from the start of the initiation pulse to first pressure and time to peak pressure. The internal free volume of the bomb shown in Fig. 6 was $1.24 \times 10^{-6} \text{ m}^3$ (0.076 in.³) after insertion of the EED. An accelerometer was attached to the pressure bomb as a backup to monitor time to first pressure.

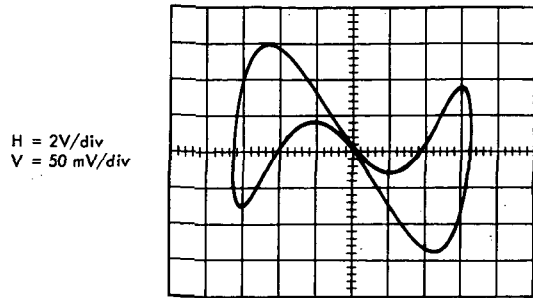


Fig. 4. Typical Lissajous response from a normal EED (H is proportional to drive current; V is proportional to bridgewire error voltage.)

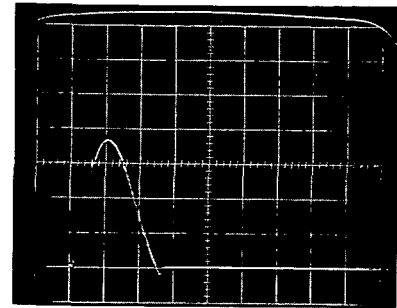


Fig. 5. Typical half-sine-wave pulse

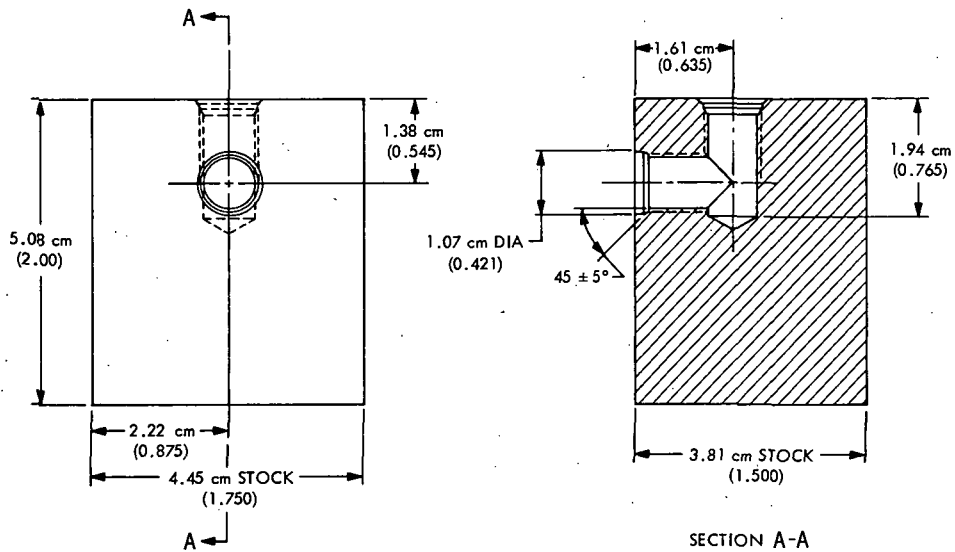


Fig. 6. Cross section of pressure bomb

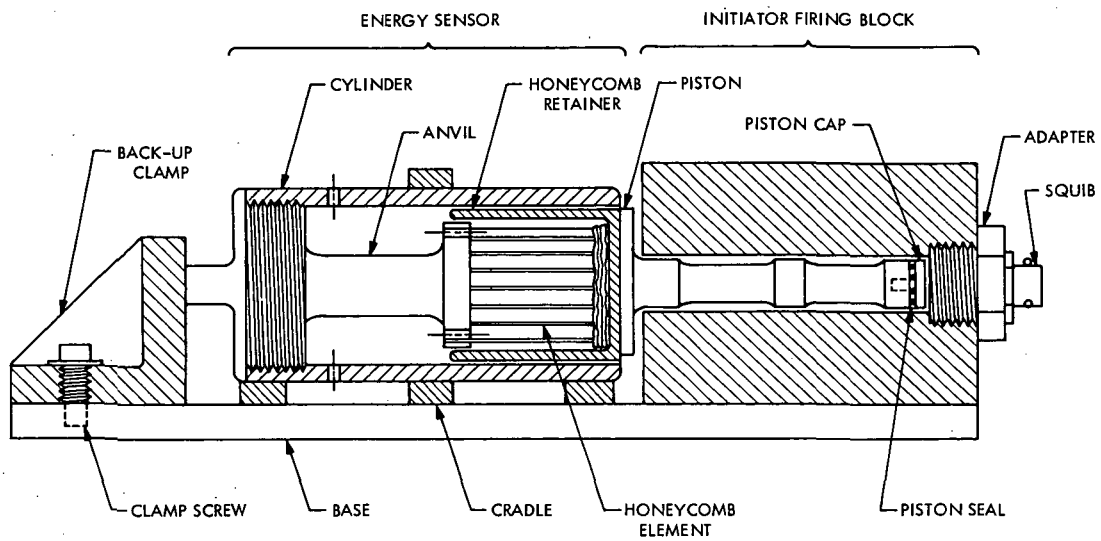


Fig. 7. MAC energy sensor output test fixture

The measure of output by the honeycomb crush method was carried out in a MAC energy sensor, described in Ref. 6 and illustrated in Fig. 7. The energy sensor is composed of four basic parts — a piston, a cylinder, an anvil, and a crushable aluminum honeycomb element. A method for determining the crush strength of the honeycomb is given in Ref. 6. Under test conditions, the EED is fired against the piston, which in turn acts upon the honeycomb element. The work output of the EED is then based on the reduction in the length of the honeycomb element.

III. Results

A. Nondestructive Tests

At the outset of this study, the three groups of test EED's (A, B, and C) were subjected to transient pulse and electrothermal follow nondestructive tests. Groups A and B produced normal heating curves. Typical examples for each group are given in Fig. 8. Figure 9 illustrates the type of heating curves obtained from group C, which varied considerably and are considered to be abnormal.

The abnormalities in group C are indicative of poor bridgewire welds and variations in intimacy of contact between the bridgewire and pyrotechnic mixture. The heating curves of Fig. 9 show the classical nonohmic and nonlinear responses verified with both the transient pulse and electrothermal follow apparatus. The nonohmic responses occur instantaneously and are known to result from poor weld fusion or oxide formations in the fusion. The nonlinear responses are time-dependent and result from bridgewire movement as the bridgewire heats. This movement affects the rate at which heat is lost to the surroundings, particularly if an air gap exists between the bridgewire and pyrotechnic mixture (Ref. 7). From the transient pulse apparatus, thermal parameters such as thermal time constant, thermal conductance, cold bridgewire resistance, and constant current flow through the bridgewire were calculated. A summation of these data is given in Table 1.

Comparison of groups A and B shows only slight differences on the average, which was expected, since they are of the same basic design. With the exception of bridgewire resistance, the values for group C are very different

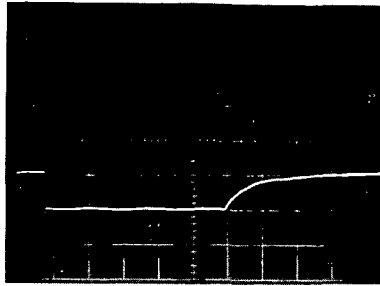
Table 1. Results of transient pulse testing before environmental conditioning

Group	Number of bridgewires	Mean	Standard deviation of mean	Coefficient of variation ^a	Maximum	Minimum	Range
Thermal time constant, ms							
A	50	5.03	0.63	12.58	7.21	4.28	2.93
B	50	5.78	0.52	8.97	7.20	3.55	3.65
C	100	8.04	1.30	16.18	11.88	5.17	6.71
Heat loss factor, W							
A	50	6.02	0.80	13.28	7.56	4.18	3.38
B	50	6.16	0.66	10.68	9.51	4.97	4.54
C	100	54.75	10.95	20.00	119.13	34.24	84.89
Cold bridgewire resistance, Ω							
A	50	1.02	0.03	3.19	1.08	0.94	0.14
B	50	1.00	0.04	3.99	1.17	0.93	0.24
C	100	1.06	0.02	1.66	1.11	1.02	0.08
Current through bridgewire to obtain a 5-mV error signal, mA							
A	50	325.4	16.5	5.1	359.5	287.4	72.1
B	50	331.0	7.6	2.3	349.5	310.1	39.4
C	100	665.8	37.3	5.6	744.3	562.3	182.1

^a(Standard deviation \times 100)/mean.

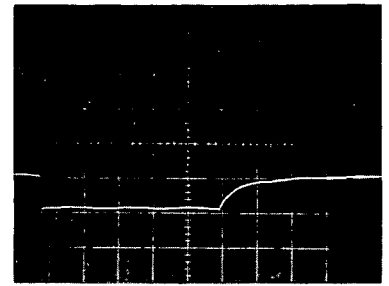
TRANSIENT PULSE

H = 10 ms/div
V = 5 mV/div



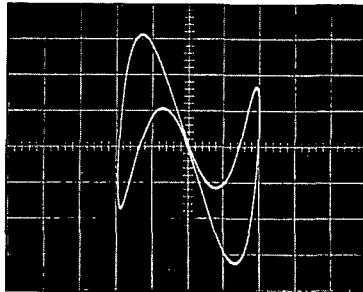
TRANSIENT PULSE

H = 10 ms/div
V = 5 mV/div



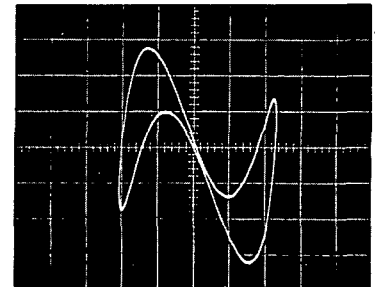
ELECTROTHERMAL FOLLOW

H = 2 V/div
V = 10 mV/div



ELECTROTHERMAL FOLLOW

H = 2 V/div
V = 10 mV/div



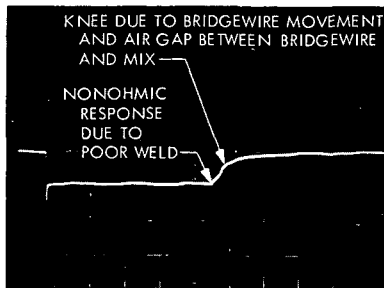
GROUP A

GROUP B

Fig. 8. Typical normal heating curves

TRANSIENT PULSE

H = 10 ms/div
V = 5 mV/div



ELECTROTHERMAL FOLLOW

H = 2 V/div
V = 10 mV/div

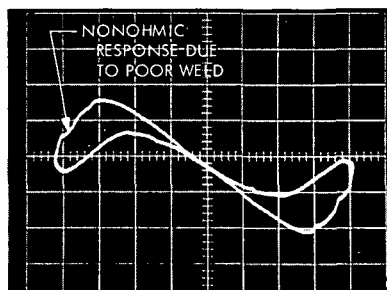


Fig. 9. Abnormal heating curves for group C

excepted) shows a great deal more scatter for Group C. This is substantiated by the abnormal heating curves displayed by group C.

After the completion of the NDT, the three groups of EED's were subjected to the environmental tests. The particular EED's which entered the different environments are noted in Table 2. After exposure to the conditioning schedules described earlier, the EED's were again nondestructively tested as before. The results are summarized in Tables 3, 4, 5, and 6. In each of these tables, the bridgewire resistance data have been omitted because no significant changes in bridgewire resistance resulted from the conditioning schedules.

A review of Table 3 shows no significant change in the electrothermal parameters due to vibration for groups A and B. However, group C does show changes, which were also reflected in the heating curves. On the average, the group C thermal time constant became longer and the heat loss factor was reduced, indicating that the intimacy of contact between the bridgewire and pyrotechnic mixture degraded. One could speculate from the heating curves and electrothermal data before and after conditioning that the intimacy of contact between the pyrotechnic mixture and bridgewire was low to start with and that the vibration schedule aggravated the condition.

from those of groups A and B. This is attributable to differences in bridgewire material, pyrotechnic material loaded onto the bridgewire, and the loading density of the pyrotechnic material. Comparison of the statistics for groups A and B with group C (bridgewire resistance

Table 2. Identification of EED's subjected to environmental testing

Test	Group		
	A	B	C
Thermal shock	236	153	41319
	237	545	41321
	238	547	41417
	239	551	41441
	241	553	41455
	243	557	41445
	245	562	41457
	246	619	41461
	247	620	41485
	784	703	42375
Hot storage 1 week at 394K	248	622	41501
	249	632	41502
	250	636	41555
	251	639	41588
	252	640	41612
	253	644	41635
	683	647	41675
	684	650	41710
	686	651	41771
Cold storage 1 week at 77 K	687	652	41822
	688	653	41857
	689	657	41864
	690	661	41890
	691	665	41917
	692	666	41927
	693	667	41931
	696	672	41953
	698	674	41966
Vibration	699	675	41990
	700	683	42005
	701	686	42059
	702	687	42123
	777	689	42144
	778	693	42235
	779	696	42253
	780	698	42254
	781	699	42265
782	702	42324	
Control	788	723	41889
	789	724	42431
	790	725	42493
	791	727	42494
			42502
		42506	
		42508	

Table 4 summarizes the electrothermal data resulting from the thermal shock test. The thermal time constants for groups A and B have decreased, which leads one to believe that heat sinking for the bridgewire has improved. Contrary to this hypothesis is the fact that for both groups the heat loss factor (thermal conductance) has also decreased. With an improvement in heat sinking, one would expect the heat loss factor to increase. The differences observed are small and, although a trend is indicated, they may not be significant.

A review of the heating curves obtained after thermal shock showed no changes in the profiles from the "before" test pictures. Group C electrothermal data resulted, on the average, in an increase in the thermal time constant and a decrease in the heat loss factor. This is as one would expect and indicates movement of the pyrotechnic mixture with respect to the bridgewire, resulting in poorer heat transfer away from the bridgewire. Comparison of the "before" and "after" heating curves showed differences which support the above contention.

The effect of hot storage on the electrothermal parameters (Table 5) showed small changes taking place in all groups, indicative of pyrotechnic movement with respect to the bridgewire. Group A had a slight increase in the thermal time constant and a corresponding decrease in the heat loss factor. In the case of Group B, the thermal time constant and heat loss factor increased slightly. The changes are much less than one standard deviation, so for all practical purposes, they can be considered insignificant. The heating curves of groups A and B obtained after hot storage showed no change in profiles when compared with the "before" curves. Group C showed a decrease in the thermal time constant and an increase in the heat loss factor, which is consistent with theory. The changes were relatively small but significant in light of the observable changes in the heating curve profiles when the "before" and "after" curves were compared. Enough evidence exists to state that, for group C, the pyrotechnic mixture is loosely coupled to the bridgewire. The effect of the hot storage would tend to cause the pyrotechnic mixture to expand, resulting in a movement of the mixture closer to the bridgewire. This would account for the decrease in the thermal time constant and an increase in the heat loss factor.

The electrothermal data in Table 6 and associated heating curves indicate that no significant changes occurred in any of the groups as a result of cold storage.

Table 3. Transient pulse test results for squibs subjected to vibration

Group	Number of bridgewires	Mean	Standard deviation of mean	Coefficient of variation	Maximum	Minimum	Range
Thermal time constant, ms							
A*	10	5.23	0.82	15.76	7.21	4.43	2.78
A	10	5.35	0.85	15.95	6.76	4.52	2.24
B*	10	5.74	0.20	3.51	6.00	5.43	0.58
B	10	5.71	0.21	3.72	6.06	5.37	0.69
C*	20	8.00	1.04	12.95	10.26	6.25	4.01
C	20	8.45	1.09	12.86	10.89	6.19	4.71
Bridgewire current, mA							
A*	10	320.6	20.7	6.5	349.3	287.4	61.9
A	10	324.2	18.5	5.7	355.7	291.9	63.8
B*	10	328.4	2.1	0.6	331.3	325.6	5.7
B	10	331.4	6.3	1.9	344.5	327.5	17.0
C*	20	658.8	38.3	5.8	719.5	562.3	157.2
C	20	679.8	36.9	5.4	725.9	592.3	133.7
Heat loss factor, W							
A*	10	5.84	0.99	16.88	7.03	4.19	2.85
A	10	5.73	0.90	15.77	7.06	4.40	2.66
B*	10	6.06	0.26	4.31	6.61	5.79	0.82
B	10	6.17	0.35	5.70	6.80	5.66	1.13
C*	20	55.18	9.87	17.89	67.05	35.26	31.79
C	20	54.06	8.05	14.89	65.46	38.24	27.22
*Controls.							

Table 4. Transient pulse test results for squibs subjected to thermal shock

Group	Number of bridgewires	Mean	Standard deviation of mean	Coefficient of variation	Maximum	Minimum	Range
Thermal time constant, ms							
A°	10	4.74	0.28	5.81	5.15	4.28	0.88
A	10	4.66	1.37	29.41	6.70	1.92	4.78
B°	10	5.94	0.56	9.40	6.87	5.13	1.74
B	10	5.28	0.62	11.77	6.35	3.93	2.42
C°	20	8.28	1.62	19.61	11.68	5.17	6.51
C	20	8.78	1.58	17.98	12.27	6.11	6.16
Bridgewire current, mA							
A°	10	331.3	6.1	1.8	343.2	320.3	22.9
A	10	336.3	12.9	3.8	353.5	315.3	38.2
B°	10	329.3	9.2	2.8	336.3	310.1	26.2
B	10	327.5	11.2	3.4	339.2	311.1	28.1
C°	20	666.7	46.3	6.9	744.3	582.0	162.3
C	20	599.7	38.6	6.4	658.0	511.9	146.2
Heat loss factor, W							
A°	10	6.32	0.41	6.59	7.13	5.68	1.45
A	10	6.04	0.76	12.62	7.42	4.76	2.66
B°	10	6.21	0.70	11.21	7.92	5.35	2.57
B	10	5.56	0.57	10.29	7.00	4.78	2.23
C°	20	50.48	9.50	18.82	65.86	34.24	31.61
C	20	42.15	8.45	20.04	54.28	22.66	31.62
°Controls.							

Table 5. Transient pulse test results for squibs subjected to hot storage

Group	Number of bridgewires	Mean	Standard deviation of mean	Coefficient of variation	Maximum	Minimum	Range
Thermal time constant, ms							
A°	9	4.73	0.73	15.38	6.64	4.33	2.31
A	9	4.82	0.65	13.49	5.60	3.62	1.98
B°	9	5.48	0.82	14.90	6.40	3.55	2.85
B	9	5.55	0.87	15.74	6.86	4.13	2.73
C°	18	8.06	1.07	13.33	9.91	6.19	3.72
C	18	7.26	1.46	20.13	11.74	5.80	5.94
Bridgewire current, mA							
A°	9	330.4	18.5	5.6	359.5	288.9	70.5
A	9	340.4	18.7	5.5	360.5	304.2	56.3
B°	9	331.8	6.0	1.8	342.6	324.3	18.3
B	9	327.3	13.0	4.0	350.9	313.5	37.4
C°	18	666.1	41.0	6.1	714.4	577.6	136.8
C	18	691.1	48.2	7.0	741.9	538.9	202.9
Heat loss factor, W							
A°	9	6.34	0.92	14.48	7.56	4.18	3.38
A	9	6.68	0.82	12.24	7.54	5.23	2.31
B°	9	6.66	1.11	16.64	9.51	5.90	3.62
B	9	5.75	1.10	19.13	8.49	4.85	3.64
C°	18	51.73	7.70	14.88	62.69	37.49	25.20
C	18	58.40	11.13	19.06	73.97	25.44	48.53
*Controls.							

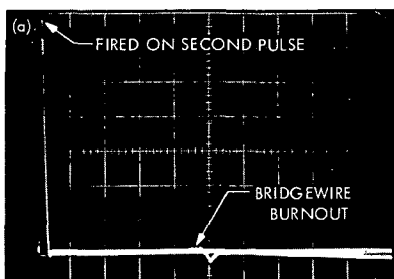
Table 6. Transient pulse test results for squibs subjected to cold storage

Group	Number of bridgewires	Mean	Standard deviation of mean	Coefficient of variation	Maximum	Minimum	Range
Thermal time constant, ms							
A*	9	5.06	0.65	12.92	6.41	4.38	2.04
A	9	4.94	0.62	12.48	6.18	4.27	1.91
B*	9	5.88	0.29	4.88	6.29	5.48	0.81
B	9	5.31	0.51	9.56	5.83	4.42	1.41
C*	18	8.17	1.33	16.27	11.88	5.80	6.07
C	18	7.11	1.55	21.76	11.49	5.15	6.33
Bridgewire current, mA							
A*	9	334.2	16.5	4.9	347.2	296.9	50.3
A	9	333.9	19.0	5.7	357.2	300.4	56.8
B*	9	337.7	4.6	1.4	349.5	334.8	14.7
B	9	335.7	4.8	1.4	344.9	331.6	13.3
C*	18	670.2	30.3	4.5	717.8	615.9	101.9
C	18	689.8	29.0	4.2	736.9	647.2	89.7
Heat loss factor, W							
A*	9	6.38	0.72	11.31	7.17	4.65	2.52
A	9	6.41	0.91	14.26	7.77	4.98	2.79
B*	9	6.07	0.38	6.26	6.74	5.47	1.27
B	9	6.05	0.31	5.07	6.51	5.65	0.86
C*	18	56.98	7.76	13.61	67.41	40.19	27.23
C	18	58.77	6.59	11.22	68.02	45.67	22.35
*Controls.							

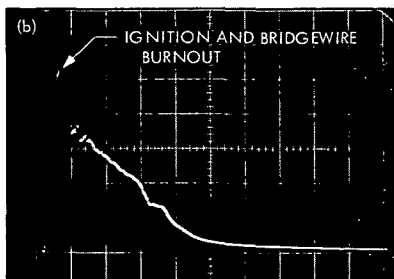
B. Sensitivity and Output

Energy to initiate and the work performed by the explosive device are useful parameters for characterizing the EED. The effect, if any, due to environmental conditioning may be reflected by a change in these parameters. Many EED initiation systems utilize a capacitor discharge power source. The advantage of an impulsive waveform is the fast delivery time of the energy when compared to the thermal time constant of the unit. The half-sine-wave pulser described earlier was used to initiate the EED's. The pulse width was kept constant at 25 μs , and the voltage varied. The exact amount of energy delivered could be calculated from photographed oscilloscope traces. The voltage was adjusted to deliver the approximate 50% firing energy. If the unit failed to initiate, the voltage was

H = 100 $\mu\text{s}/\text{cm}$
V = 10 V/cm
TEMP = 293 K



H = 20 $\mu\text{s}/\text{cm}$
V = 40 V/cm
TEMP = 77 K



H = 0.5 ms/cm
V = 689 $\text{N}/\text{m}^2 \times 10^4$ (1000 psi/cm)
TEMP = 293 K

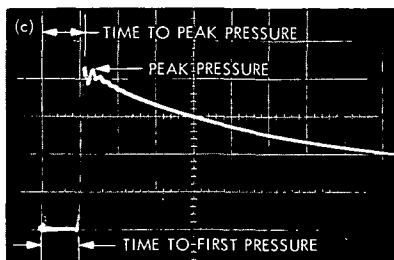


Fig. 10. Typical oscilloscope records for sensitivity testing of groups A, B, and C: (a) Ignition of an EED from a complete half-sine-wave pulse, (b) Ignition of an EED prior to completion of the half-sine-wave pulse, (c) Typical pressure bomb output record

increased and the unit re-pulsed. Sometimes the increments were larger than necessary, but an approximate estimate of the sensitivity was obtained. Of equal interest, in this series of tests was the behavior of the EED when pulsed with a very high current input (greater than 100 A). There has been some concern at low temperatures (77K) that if a high current pulse is applied to the bridgewire in a short time period (25 μs) the bridgewire can burn out and open the circuit before enough heat to start ignition has transferred from the bridgewire to the explosive, thus resulting in a dud. In some cases during the firing of the EED's, the maximum output (160 V for a 1- Ω load) was used to initiate the EED. No duds were experienced because of the high current pulse. This subject will be discussed in more detail later (see Figs. 10a and 10b).

Output was obtained simultaneously with the sensitivity testing. In one case, a pressure bomb was used in which the pressure profile was monitored (see Fig. 10c). A second technique involved measuring the work done. A calibrated aluminum honeycomb element was crushed by the EED output in a controlled manner and the work done calculated from the amount of crush incurred. Tables 7, 8, and 9 summarize the results obtained when the honeycomb output test was applied.

The firing energy for group A (Table 7) ranged from 37.2 to 61.8 mJ. The true all-fire sensitivity for this group is probably closer to the 37.2-mJ level because in most cases the units fired on the first pulse. The advantage of creeping up to the true firing energy was lost because the increments were too large. Bridgewire burnout time varied but was always longer than the pulse time (25 μs). The considerable scatter found in the output data is consistent with this particular test.

Group B (Table 8) yielded results similar to those of group A, which was expected. One noticeable difference was bridgewire burnout time. The time to bridgewire burnout in group B was on the average longer than in group A. This is attributable to the thermal coupling between the bridgewire and explosive material. The longer the bridgewire burnout time, the better the thermal coupling.

Group C (Table 9), as expected, behaved differently from groups A and B. The item is more sensitive, requiring approximately 30 mJ of energy to initiate, and the

Table 7. Results of sensitivity and output testing for group A

Item number	V_m	$t_B, \mu s$	Firing energy, mJ	Output energy		Preconditioning
				J	in. lb	
788	62	>500	50.6	35.5	314.2	Control
789	67	260	55.0	34.3	303.6	Control
701	54	60	37.2	28.3	251.0	Vibration
779	71	190	61.8	33.5	297.0	Vibration
692	68	200	58.3	31.8	281.8	Cold storage
693	65	130	52.3	29.0	256.5	Cold storage
253	62	200	49.0	26.0	230.0	Hot storage
683	65	60	53.9	30.0	266.0	Hot storage
245	63	>500	47.3	33.4	295.8	Thermal shock
246	61	>500	48.5	36.1	320.0	Thermal shock

- Notes:
1. Sensitivity determined with half-sine-wave pulser.
 2. Output energy obtained with MAC energy sensor.
 3. Half-sine-wave pulse width is 25 μs .
 4. Tests conducted at ambient temperature.
 5. V_m = maximum voltage to initiate.
 6. t_B = time to bridgewire burnout.

Table 8. Results of sensitivity and output testing for group B

Item number	V_m	$t_B, \mu s$	Firing energy, mJ	Output energy		Preconditioning
				J	in. lb	
723	53	>1000	37.0	25.8	228.1	Control
724	68	250	56.1	31.9	282.2	Control
675	66	310	53.9	33.8	299.8	Vibration
699	66	550	54.5	34.1	301.9	Vibration
666	64	770	51.7	30.4	269.1	Cold storage
667	78	190	76.1	28.8	255.0	Cold storage
644	76	275	75.2	26.3	233.3	Hot storage
647	70	200	61.3	29.5	260.9	Hot storage
562	68	450	55.6	29.0	257.0	Thermal shock
619	63	540	50.1	30.3	268.3	Thermal shock

- Notes:
1. Sensitivity determined with half-sine-wave pulser.
 2. Output energy obtained with MAC energy sensor.
 3. Half-sine-wave pulse width is 25 μs .
 4. Tests conducted at ambient temperature.
 5. V_m = maximum voltage to initiate.
 6. t_B = time to bridgewire burnout.

work output energy is approximately half that of groups A and B. One of the control units in group C had no measurable output, although electrically it responded like the others. It is possible that there was an equipment failure, but there was no visible evidence to support such an assumption. Because of the age (5 years) and design of this group of EED's, the result is not surprising. Four units in group C were pulsed at the maximum voltage of the test set (160 V for a 1- Ω resistance), causing ignition to occur before the half-sine-wave pulse was completed. It was expected that bridgewire burnout would occur in less than 100 μ s. However, bridgewire burnout times were longer than 100 μ s and, in general, longer than those experienced in groups A and B. There was no apparent effect on functioning and output for the three groups resulting from the environmental conditioning.

The data obtained when the pressure bomb output technique was used are summarized in Tables 10, 11, and 12. Some of the data were obtained at liquid nitrogen temperature (77K). All units initiated at the maximum input voltage setting (160 V for a 1- Ω load) and cold temperature (77K). The sensitivity and time to bridgewire burnout values were consistent with the data in Tables 7, 8, and 9. Reduction of the pressure bomb data shows

times to first pressure being less than 1 ms when the maximum voltage setting was used to initiate. However, when marginal energy was used to initiate the EED's, the times to first pressure were scattered up to 8.3 ms. The longest times to first pressure were associated with testing at liquid nitrogen temperature.

The difference in time between first pressure and peak pressure was fairly consistent for groups A and B (tables 10 and 11), being approximately 0.2 ms. For group C (Table 12), the time difference between first pressure and peak pressure was more scattered and averaged about 0.3 ms. Peak pressures for groups A and B were quite similar, averaging about $2896 \text{ N/cm}^2 \times 10^4$ (4200 psi), while group C averaged about $2758 \text{ N/cm}^2 \times 10^4$ (4000 psi). An accelerometer was attached to the pressure bomb to indicate when the end seal of the EED ruptured. The times to first pressure and the accelerometer times are in good agreement. Curiously enough, there appears to be a correlation between bridgewire burnout and the accelerometer time. Accelerometer times appear to be equal to or slightly longer than bridgewire burnout times. No significant effects on sensitivity or output resulted from the environmental conditioning or cold temperature tests for any of the three groups.

Table 9. Results of sensitivity and output testing for group C

Item number	V_m	t_B, μ s	Firing energy, mJ	Output energy		Preconditioning
				J	in. lb	
42431	48	>100	26.7	—	—	Control
42493	55	520	34.4	13.9	123.5	Control
42494	52	640	31.3	19.0	168.4	Control
42254	51	825	30.4	14.1	124.5	Vibration
42059	*	>100	—	31.5	279.2	Vibration
41931	*	>100	—	17.9	158.5	Cold storage
41927	52	570	31.9	18.5	163.6	Cold storage
41675	*	>500	—	16.4	145.5	Hot storage
41635	48	>1000	27.4	12.5	110.3	Hot storage
41457	53	>1000	33.1	15.5	137.7	Thermal shock
41461	*	220	—	21.1	187.1	Thermal shock

- Notes:
1. Sensitivity determined with half-sine-wave pulser.
 2. Output energy obtained with MAC energy sensor.
 3. Half-sine-wave pulse width is 25 μ s.
 4. Tests conducted at ambient temperature.
 5. V_m = maximum voltage to initiate.
 6. t_B = time to bridgewire burnout.

*Maximum input voltage setting.

Table 10. Results of sensitivity and pressure bomb output testing for group A^a

Item number	V_m^b	E, mJ^c	$t_B, \mu\text{s}^d$	t_{FP}, ms^e	t_p, ms^f	P_m^g		$Acc, \mu\text{s}^h$	T, K	Preconditioning
						$\text{N/m}^2 \times 10^4$	psi			
684	64	51.2	185	0.2	0.4	3103	4500	208	298	Hot storage
686	70	61.3	>1000	---	---	---	---	5330	77	Hot storage
247	70	61.3	160	0.20	0.4	2896	4200	181	298	Thermal shock
784	72	64.8	1200	1.2	1.4	3103	4500	1208	77	Thermal shock
700	*	---	---	0.070	0.16	2827	4100	52	298	Vibration
777	*	---	---	0.08	0.25	3448	5000	61	77	Vibration
696	*	---	---	0.1	0.2	3103	4500	56	77	Cold storage
790	56	39.2	660	1.4	1.6	2620	3800	655	298	Control
791	76	72.2	300	0.4	0.5	3448	5000	333	77	Control

^aInternal free volume of pressure bomb = $1.25 \times 10^{-6} \text{ m}^3$ (0.076 in.³); half-sine-wave pulsewidth = 25 μs ; *denotes maximum input voltage setting.

^b V_m = maximum voltage delivered by half-sine-wave pulser.

^c E = calculated energy delivered.

^d t_B = time from start of pulse to bridgewire burnout.

^e t_{FP} = time from start of pulse to first pressure.

^f t_p = time from start of pulse to peak pressure.

^g P_m = peak pressure.

^h Acc = time to function accelerometer or end seal rupture.

Table 11. Results of sensitivity and pressure bomb output testing for group B^a

Item number	V_m^b	E, mJ^c	$t_B, \mu\text{s}^d$	t_{FP}, ms^e	t_p, ms^f	P_m^g		$Acc, \mu\text{s}^h$	T, K	Preconditioning
						$\text{N/m}^2 \times 10^4$	psi			
650	68	57.8	310	0.35	0.5	2034	4400	318	298	Hot storage
620	68	57.8	470	0.5	0.6	2965	4300	466	298	Thermal shock
687	*	---	50	0.60	0.16	2758	4000	45	298	Vibration
727	*	---	---	0.08	0.26	2896	4200	69	298	Control
674	*	---	70	0.08	0.28	2896	4200	70	298	Cold storage
691	*	---	---	0.4	0.6	3034	4400	364	77	Vibration
672	*	---	---	0.6	0.8	3103	4500	547	77	Cold storage
703	70	61.3	2500	3.8	4.0	3103	4500	2892	77	Thermal shock
651	64	51.2	2000	2.5	2.7	---	4350	2430	77	Hot storage
725	60	45.0	>200	---	---	2999	---	---	77	Control

^aInternal free volume of pressure bomb = $1.25 \times 10^{-6} \text{ m}^3$ (0.076 in.³); half-sine-wave pulsewidth = 25 μs ; *denotes maximum input voltage setting.

^b V_m = maximum voltage delivered by half-sine-wave pulser.

^c E = calculated energy delivered.

^d t_B = time from start of pulse to bridgewire burnout.

^e t_{FP} = time from start of pulse to first pressure.

^f t_p = time from start of pulse to peak pressure.

^g P_m = peak pressure.

^h Acc = time to function accelerometer or end seal rupture.

Table 12. Results of sensitivity and pressure bomb output testing for group C^a

Item number	V_m^b	$E, \text{ mJ}^c$	$t_B, \mu\text{s}^d$	$t_{FP}, \text{ ms}^e$	$t_p, \text{ ms}^f$	P_m^g		Acc, μs^h	T, K	Preconditioning
						$\text{N/m}^2 \times 10^4$	psi			
41485	52	33.8	>1000	>2	>2	—	—	5192	298	Thermal shock
41710	50	31.3	>1000	1.1	1.6	2896	4200	1077	298	Hot storage
41771	*	—	—	0.7	1.0	2896	4200	656	77	Hot storage
41889	51	32.5	1450	1.6	—	—	—	1541	298	Control
41953	58	42.1	2700	3.1	3.5	2482	3600	2954	77	Cold storage
41966	52	33.8	960	1.2	—	—	—	1092	298	Cold storage
42235	53	35.1	900	1.0	—	—	—	1033	298	Vibration
42327	57	40.6	2300	3.0	3.3	2689	3900	2908	77	Vibration
42375	58	42.1	6600	8.3	8.9	2551	3700	8358	77	Thermal shock
42502	*	—	—	0.14	0.4	2620	3800	127	298	Control
42506	53	35.1	720	0.83	0.96	2206	3200	825	298	Control
42508	*	—	—	0.4	0.7	2758	4000	301	77	Control

^aInternal free volume of pressure bomb = $1.25 \times 10^{-6} \text{ m}^3$ (0.076 in.³); half-sine-wave pulsewidth = 25 μs ; *denotes maximum input voltage setting.

^b V_m = maximum voltage delivered by half-sine-wave pulser.

^c E = calculated energy delivered.

^d t_B = time from start of pulse to bridgewire burnout.

^e t_{FP} = time from start of pulse to first pressure.

^f t_p = time from start of pulse to peak pressure.

^g P_m = peak pressure.

^hAcc = time to function accelerometer or end seal rupture.

IV. Discussion

A large quantity of data was generated in this study. Most of the results are explainable and conform to previous experience. However, some new phenomena did occur that warrant discussion. A considerable amount of development effort was put into the three groups of EED's tested. They were primarily developed for space applications (manned or unmanned). The maintenance of very high quality control standards and the use of statistical testing techniques implied high reliability and confidence. Groups A and B are of recent vintage (about 2 years old), while group C is approximately 6 years old. The higher quality demonstrated by groups A and B as compared to group C is not believed to be due to the aging of group C but rather to an advancement in the state-of-the-art. Group C demonstrated abnormalities arising from poor bridgewire welding to the pins, poor explosive compaction on the bridgewire, and movement of the explosive material as a result of environmental conditioning. In the interval between the time group C was fabricated and the fabrication of groups A and B, it ap-

pears that bridgewire welding techniques and EED design have advanced.

A fear of burning out a bridgewire under extreme cold conditions (77K) without igniting the pyrotechnic material when a high-current, short-duration pulse is used has prevailed for some time. In fact, some EED specifications exist which limit the maximum current to about 20 A and the minimum duration of the pulse to 10 ms because of this fear. Theoretically, it may be possible to burn out the bridgewire without igniting the EED, especially if a very fine, low-melting-point bridgewire is used, or if the pyrotechnic mixture on the bridgewire is desensitized and extreme cold conditions exist. However, using the presently employed pyrotechnic mixtures and EED designs in conjunction with conventional power supplies, it is unlikely that high enough currents can be delivered in a short enough time to cause dudding. The dudding phenomenon was studied during this investigation using impulsive waveforms (capacitor discharge and half-sine-wave) with amplitudes as high as 160 A deli-

vered in times as short as 25 μ s at liquid nitrogen temperature (77K). When the half-sine-wave pulser (at 160 A and 25 μ s) was used to initiate the EED's, bridgewire burnout consistently occurred before completion of the pulse at about 10 μ s. No duds were experienced in more than 100 tests under these conditions. Review of the oscilloscope impulsive waveforms leads one to believe that functioning would be more reliable and functioning times more consistent when the highest current available is used. The data generated so far concerning the dudding phenomenon indicate that if a failure to ignite occurs under conditions of high current and extreme cold, the failure is attributable to a design or fabrication defect in the device.

In those cases in which the EED's were initiated from the half-sine-wave pulser set for 160 A and 25 μ s, bridgewire burnout occurred in approximately 10 μ s. Assuming that ignition occurred at the time of bridgewire burnout, the energy deposited up to that time was always about three times greater than the energy necessary to initiate at the all-fire level. For the lower energy requirement, the bridgewire temperature does not reach the melting point of the bridgewire material but does reach a temperature high enough to start the chemical reaction. The bridgewire burns out later as a result of pyrotechnic reaction. The increase in energy to fire under high current inputs is believed to be due to a large increase in the bridgewire resistance at or near the melting point of the bridgewire. The TCR of typical bridgewire materials is fairly constant from ambient to about 800K but increases considerably beyond this temperature (Ref. 8).

Based on the results of the nondestructive testing and functioning characteristics it can be inferred that groups A and B represent a well designed, highly reliable device. Certainly, according to the nondestructive test results, the items are very uniform, which is indicative of good quality control. Group C demonstrated poor uniformity and abnormalities. Any abnormality must be viewed with

suspicion and considered as a possible failure mode. Even though some of the abnormalities may not interfere with the device functioning at this point in time, they could become progressively worse with time and eventually result in a failure. This consideration becomes vital when the devices are to be kept in long-term storage and even more so when they are used on space missions which may last as long as 10 years.

V. Conclusions

The study has shown that the nondestructive tests can provide useful information as to the condition of the bridgewire/header/pyrotechnic interface. Basic abnormalities such as poor-quality welds (of the bridgewire to the pins) and inadequate thermal contact between bridgewire and pyrotechnic material were observed. The NDT techniques can be applied to in-process quality control, evaluation of EED's, and the optimization of new EED designs. The quantitative data can be used to further normalize a sample by taking a parameter such as the thermal time constant and selecting units within a narrow bandwidth. Higher reliability and confidence with a minimum of destructive testing will be realized with these techniques.

Functional and output characteristics of EED's, such as the energy to fire adiabatically, time to bridgewire burnout, time to end seal rupture, total work, and peak pressure are important parameters. The impulsive waveform used to initiate the EED's and the output measurement techniques yielded valuable information as to unit performance. Practical firing systems generally operate in an adiabatic manner. An accurate measure of this energy and the rate at which it is applied can be used in the design of any impulsive firing system. The data provided by the two output measuring techniques are useful when EED's are used in devices such as cable cutters, pinpuffers, and release mechanisms.

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