Effects of Nuclear Radiation and Elevated Temperature Storage on Electroexplosive Devices

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Aerospace type electroexplosive devices (EEDs) were subjected to nuclear radiation. Components and chemicals used in the EEDs were also included. The kind of radiation and total dosage administered were those which may be experienced in a space flight of 10 years duration, based on information available at this time. After irradiation, the items were stored in elevated constant-temperature ovens to accelerate early effects of the exposure to radiation. Periodically, samples were withdrawn for visual observation and testing. Significant changes occurred which were attributed to elevated-temperature storage and not radiation.

Nomenclature

R_0 = bridgewire resistance, ambient temp
θ = thermal resistance
τ = thermal time constant

Introduction

A SPACECRAFT designed for a long-term mission to the outer planets (e.g., 10 years) would probably be equipped with a radioisotope thermal generator (RTG). The spacecraft, after launch, would be exposed to several sources of radiation: 1) RTG radioactive decay, 2) the planetary radiation belts, and 3) the cosmic background. Such environments contain gamma rays, neutrons, protons, alpha particles, electrons, and heavy ions. The effect on the long-term reliability of electroexplosive devices (EEDs) of these environments is of interest. An engineering approach was taken in which mission radiation conditions are reproduced and the effects of radiation and aging are accelerated by elevated-temperature storage. The primary objective of the study was to develop information pertaining to the effect of low-level, long-term nuclear radiations on selected aerospace type EEDs.

Experimental Procedures

Fully assembled EEDs, substances composing EEDs, and a homogeneous composite of all materials making up the EED were exposed to radiation. The dosage levels used in this study were based on 10-yr estimates of the RTG radioactive decay, planetary radiation belts, and cosmic background information known at this time. Since then, however, new evidence of the proton and electron environments of Jupiter has been published.[1] Because the original estimates were rough calculations, two dosage levels were used in the study: the estimated level and five times the estimated level. A review of the new evidence indicates that the higher dosage level used would satisfy conditions expected in the Jovian environment. Table 1 lists the characteristics and total dosage to which the test specimens were subjected. Irradiation of the test specimens with alpha particles and heavy ions was omitted because a) the fluences of these particles are expected to be relatively small and b) the EED's explosive charges are contained in a metallic case and further shielded in a metallic device which provides an effective shield under these conditions. An insignificant amount of energy will be imparted to the EED pyrothechnic material. Electrons were omitted because by appropriately combining the damage effects caused by neutrons and gamma rays, one could arrive at the expected damage due to electrons. Test specimens were irradiated with neutrons, gamma rays, and protons.

The explosive material in the EED, upon exposure to radiation, would present the weakest link. That is, the explosive material could decompose, resulting in a change in sensitivity and output. The explosive material may become more sensitive so as to initiate inadvertently from a spurious signal or become desensitized so as not to initiate when the proper signal is applied. There are other elements of the EED which are of concern. For example, the fine bridgewire (0.05-mm diam) welded to the EED pins, the integrity of the glass-to-metal seal which maintains circuit insulation and hermetic sealing, and, in general, weld areas. Degradation of the bridgewire seals and glass seals could lead to incipient failures. It was not expected that the effects of radiation would be direct and obvious. Rather, ions would result from the radiation and migrate. This could result in interactions leading to chemical degradation and structural breakdown. To accelerate the process, the test specimens were stored in elevated-temperature chambers (120°C) after irradiation. Withdrawals were made periodically and the specimens subjected to various tests (to be discussed later).

Test Specimens

Most aerospace type EEDs are of the 1-amp, 1-W no-fire sensitivity. Their construction consists of a steel shell containing a glass-to-metal connector for hermetic sealing and

Table 1 Characteristics of radiation applied to test specimens

Radiation	Average energy, MeV	Time of exposure	Fluence, $N \times cm^2$	Exposure, r
High neutron (HN)	1	6 hr	25×10^{12}	
Low neutron (LN)	1	1.2 hr	5×10^{12}	
Proton	144		4×10^{12}	
High gamma (HG)	1.2	35 days		25×10^4
Low gamma (LG)	1.2	7 days		5×10^4
High neutron, high gamma (HNG)	1.1	35 days, 6 hr	25×10^{12}	25×10^4
Low neutron, low gamma (LNG)	1.1	7 days, 1.2 hr	5×10^{12}	5×10^4

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Index category: Reliability, Quality Control, and Maintainability.

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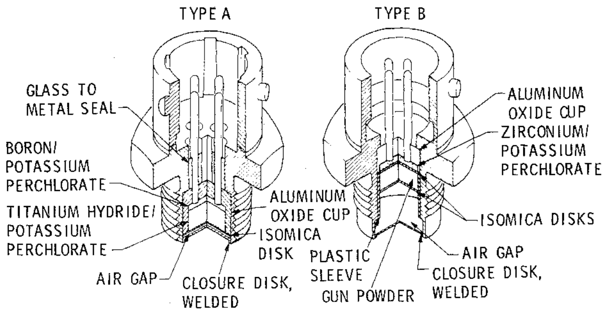

Fig. 1 Electroexplosive devices used in the study.

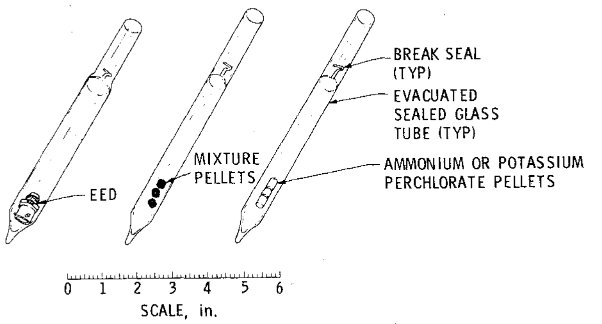

Fig. 2 Method for encapsulating specimens under vacuum.

electrical isolation of the bridgewire circuits. The bridgewire circuit is a fine nichrome wire (0.05-mm diam) welded to pins approximately 1-mm diam. The circuit is flush mounted on an alumina substrate, and a pyrotechnic mixture (usually a metal/metal oxide/binder) is loaded onto the wire. This is usually followed by a pressed pyrotechnic output charge. A closure disk is then welded to the body. Two different EEDs, Type A and Type B (illustrated in Fig. 1), were used. Type A contained a boron, potassium perchlorate, viton prime mix and a titanium hydride, potassium perchlorate, viton output charge. The Type B EEDs contained a zirconium and potassium perchlorate prime mixture and a gunpowder output charge. In addition, pellets (5-mm diam, 5-mm long) of ammonium perchlorate, potassium perchlorate, and a mixture (see Table 2) containing all the elements comprising the Type A EEDs were studied. The percent composition of the mix approximates the internal conditions of the EED. The pellets were pressed at 69×10^6 N/m^2 (10K psi).

Table 2 Mixture composition

Material	%
Viton A	5
$KClO_4$ (Mil-P-217A)	40
TiH_2 (<325 mesh)	20
Boron (90-92% purity)	20
Inconel (<80 mesh)	6
Al_2O_3 (<48 mesh)	5
Armstrong Adhesive 828 (cured and ground)	2
Armstrong Adhesive 7004 (cured and ground)	2

Table 3 Test specimens

Specimen	Type of radiation						Controls
	LN[a]	LNG	HN[b]	HNG	LG[c]	HG[d]	
Type A EEDs				20			
Type B EEDs	15	15	15	15	45	45	45
NH_4ClO_4 pellets	15	15	15	15	45	45	45
$KClO_4$ pellets	15		15		45	45	45
Mixture pellets	15		15		45	45	45

[a] 5×10^{12} N/cm^2 – 1 hr; [b] 25×10^{12} N/cm^2 – 6 hr; [c] 5×10^4 roentgens – 7 days; [d] 25×10^4 roentgens – 35 days.

The number of test specimens prepared for irradiation are listed in Table 3. All specimens were encapsulated in evacuated, sealed glass tubes, as shown in Fig. 2. The test specimens were then irradiated, as outlined in Table 1. After irradiation, some of the items in each group were examined before elevated-temperature storage. About 40% of the items from each group were subjected to a temperature ramp of 0.555°C/day from 35-160°C and held at 160°C thereafter. The remainder was stored at 120°C.

Techniques to Monitor Effects

The assessment of the effects of radiation and aging or the combination of the two was based on a measurement of the change in the physical and/or chemical properties of the materials and devices under study. Destructive and nondestructive test techniques were employed. The nondestructive tests are listed as: 1) visual and microscopic examination of the pellets, EED glass seals and welds; 2) continuity—bridgewire resistance; 3) X-ray, neutron radiography; 4) helium leak test; 5) "thermal transient"—this test gives qualitative and quantitative information about the bridgewire/explosive/header interface; 6) "electrothermal follow"—a qualitative test yielding information about the bridgewire/explosive/header interface. The "thermal transient" and "electrothermal follow" tests are of recent technology.[2-4]

The destructive tests were primarily a measure of sensitivity (using a "creep-up" approach) and output (pressure bomb). Some units were dissected for visual examination. The closure seals of some EEDs were punctured to determine whether gases were formed internally, the amount, and the species. Sensitivity and output tests were conducted simultaneously. The EEDs were initiated by pulsing the bridgewire from a "half-sine wave" generator.[5] This instrument allowed incremental steps of pulsed energy to be applied until the EED fired. The starting pulse was selected close to the firing energy so that initiation occurred within three pulses. At the time of initiation, the EED was located in a pressure bomb so that a pressure/time history was also obtained.

Test Results

Specimens from each group (Table 3) were tested approximately every 40 days. The total sampling period covered approximately 8 months. The glass tubes (Fig. 2) were attached to a pressure measuring device and mass spectrometer. After breaking the seal, it was found that the amount of gas evolved from the pellets and EED bodies was extremely small. Visual and microscopic examination of the pellets over the 8-month period revealed no significant surface changes compared to the control pellets. Dimensional measurements did not indicate shrinkage or swelling of the pellets. Visual examination of the EEDs showed no changes taking place at the glass-to-metal interface nor at the end closure welds. Leak test data before and after conditioning showed the EEDs meeting the original seal standards. With increasing storage time, it was observed that the EED closure disks began to bulge outward, indicating a buildup of internal gas pressure. A technique was devised to puncture the closure disk and direct the released gases to a mass spectrometer for analysis. The mass spectrometer data for the Type B EED's are summarized in Table 4.

Benzene appeared in all samples analyzed, and speculation is that it may have been used in conjunction with a binder (viton A) or is a byproduct of the adhesive used in the

Table 4 Mean mole percent of gases generated in Type B EEDs

Mole %						
Benzene	CO_2	N_2	Ar	H_2O	CH_4	H_2
0.33	31.4	4.9	0.12	0.25	0.55	62.4

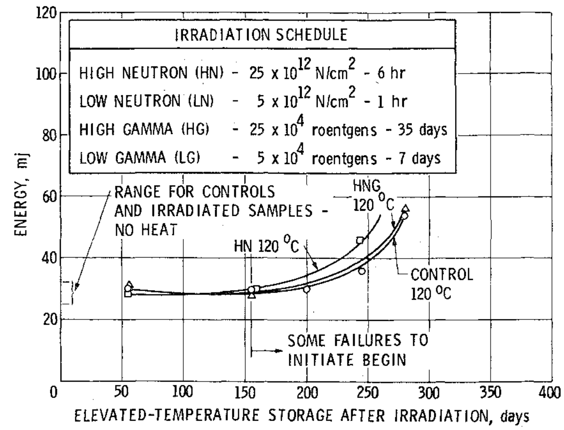

Fig. 3 Energy to initiate Type B EEDs vs time.

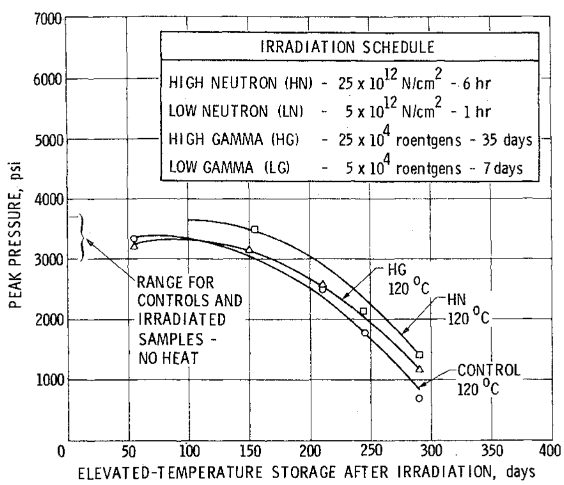

Fig. 4 Peak pressure for Type B EEDs vs time.

fabrication of the EEDs. The Type A EED mass spectrometer data did not identify benzene but showed a high mole percentage of nitrogen (approximately 50%). The sample of type A EEDs analyzed was too small to permit reaching any definitive conclusions. Because the controls and nonirradiated samples behaved in the same manner as the irradiated samples, it is believed that the results are due to heat and not radiation.

The thermal transient and electrothermal follow nondestructive tests yielded qualitative and quantitative data about the EEDs. Examination of the oscilloscope responses showed changes taking place at the bridgewire/explosive/header interface. Electrothermal measurements were obtained on parameters such as bridgewire resistance (R_0), thermal time constant (τ), and thermal resistance (θ).

The Type A EEDs showed less change over the test period that the Type B. Electrothermal data indicated that movement of the pyrotechnic material at the bridgewire interface was taking place. That is, the intimacy of contact between the bridgewire and the pyrotechnic material varied. Changes in the thermal time constant (τ) values and *N*-ray photographs supported this hypothesis. In both EED designs, an air gap exists between the last increment of pyrotechnic and the closure disk. Also, the pyrotechnic mixtures contain viton A, which can behave like a lubricant. These conditions plus the evolution of gas led to the movement of the pyrotechnic material. The Type A EEDs were much less affected than the Type B. Individual thermal time constants (τ) for the Type B EEDs continued to increase (indicating separation of the pyrotechnic from the bridgewire). It could be predicted that, as the thermal time constant increased, a point would be reached where failure to initiate would occur when the EED was properly pulsed. Several EEDs which developed abnormally long thermal time constants did indeed fail to initiate when properly pulsed. Failure occurred because the bridgewire was not in intimate contact with the pyrotechnic and opened without transferring heat to the pyrotechnic. Also, the sensitivity of Type B EEDs decreased with time. The decreased sensitivity is believed due to a loss of bridgewire-pyrotechnic intimacy rather than a complete degradation of the prime charge. Figure 3 shows the change in sensitivity for Type B EEDs as a function of time. Small changes in thermal time constant values were experienced for Type A EEDs but no failures to initiate were observed.

Simultaneous with the sensitivity measurements was a measure of output by recording the peak pressure obtained in a closed bomb. After approximately 150 days of elevated-temperature storage, degradation in peak pressure values began to occur. Figure 4 illustrates peak pressure degradation for Type B EEDs. Output degradation was also observed in Type A EEDs but to a lesser extent.

Throughout the period of the experiment, a small but gradual increase in bridgewire resistance was observed in both groups of EEDs. The increase was less than a tenth of an ohm and is believed due to strain relaxation.

The observation of the closure disk bulging due to gas evolution was also coincident with changing thermal time constant (τ) values, some higher, some lower. It was hypothesized that the gases being released were acting on the pyrotechnic so as to move it against or away from the bridgewire. To test this hypothesis, two type B EEDs, which had bulged end seals and exhibited abnormally long thermal time constants, were punctured to release the gas. The EEDs were then fitted into a fixture, in which an external gas pressure (N_2) was applied to the punctured end of the EEDs. Increasing gas pressure gave increasingly lower thermal time constant values, indicating that the pellet was being moved against the bridgewire. Removal of the gas pressure did not affect the final thermal time constant value. It was concluded that the formation of gas in combustion with the air gap in the EED caused the movement of the pyrotechnic.

The effects of extended gamma irradiation (45 megarads) on EEDs was also studied. Fifteen Type A EEDs were subdivided into groups as shown in Table 5. All squibs were nondestructively tested using the thermal transient and electrothermal follow techniques prior to the start of the experiment and approximately every 30 days thereafter. At the end of 13 months, groups A and B had received 45 megarads of irradiation from a cobalt 60 source. During this period, the "controls" (group D) and the "gamma only" (group B) EEDs showed no significant changes. Groups A and C, "gamma plus heat" and "heat only," showed no significant changes. Groups A and C, "gamma plus heat" and "heat only," showed significant changes such as a continuing increase in bridgewire resistance and fluctuating electrothermal

Table 5 Type A EED gamma irradiation assignment

Type A EED's	Sample size	Environment
Group A	7	Gamma plus heat (120°C)
Group B	3	Gamma only
Group C	3	Heat only (120°C)
Group D	2	Controls

Table 6 Mean values observed before and after proton irradiation

Electrothermal parameter	Before proton irradiation	After proton irradiation
Bridgewire resistance (R_0), (Ω)	1.08	1.08
Thermal time constant (τ), msec	2.70	2.49
Thermal resistance (θ), W/°C	139.00	144.00

parameters. Fluctuating electrothermal parameters, e.g., thermal time constant τ and thermal resistance θ are indicative of internal movement of the pyrotechnic material. It was also observed that the closure disks on the squibs of groups A and C began to bulge outward, indicating internal gas pressure. The above observations support the reasoning that gamma irradiation had little or no effect on the EEDs and that the changes observed in groups A and C can be attributed to elevated-temperature storage (120°C).

Another group of eight Type A EEDs were subjected to proton irradiation (12×10^{12} P/cm^2). The squibs were nondestructively tested before and after irradiation. The results are given in Table 6. There were no significant electrothermal changes resulting from proton irradiation.

Conclusions

The small samples of Type A EEDs used in the program revealed no major problems due to elevated-temperature storage or irradiation. The Type B EEDs deteriorated to the point of failure. The thermal transient test showed that internal movement of the pyrotechnic material was taking place in both types of EEDs tested. The pellets emitted some gas but appeared to hold up quite well throughout the program.

The data show that the type and amount of radiation used in this program had little or no effect on the items tested. The deterioration which occurred in the type B EED's can be attributed to elevated-temperature storage. Based on the design of the EED it is reasonable to assume that internal movement of the pyrotechnic was taking place, which eventually lead to failure. Also, the decreasing output with time demonstrated a deterioration of the output charge. These changes occurred only when heat was involved and were not observed in the control or irradiated samples.

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