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GALILEO INTERNAL ELECTROSTATIC DISCHARGE PROGRAM*

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The Galileo spacecraft which will orbit Jupiter in 1988 will encounter a very harsh environment of energetic electrons. These electrons will have sufficient energy to penetrate the spacecraft shielding, consequently depositing charges in the dielectric insulating materials or ungrounded conductors. The resulting electric field could exceed the breakdown strength of the insulating materials, producing discharges. The transients produced from these Internal Electrostatic Discharges (IESD) could, depending on their relative location, be coupled to nearby cables and circuits. These transients could change the state of logic circuits or degrade or even damage spacecraft components, consequently disrupting the operation of subsystems and systems of the Galileo spacecraft during its expected mission life. An extensive testing program was initiated for the purpose of understanding the potential threats associated with these IESD events. Data obtained from these tests were used to define design guidelines.

INTRODUCTION

The Galileo spacecraft will be launched in late 1986. Galileo is to perform a far more intensive and comprehensive investigation of the Jupiter system than was possible with Voyager. Its design has benefited from the experience of the Voyager spacecrafts. The Voyager 1 spacecraft, as it entered Jupiter's magnetosphere, experienced a number of Power on Resets (POR). An extensive study was carried out to determine the cause of PORs. A study of the environment was performed. The environment consists of low energy (<100 keV) plasma and intense high energy (>100 keV) electrons. Our investigation showed that the time for the occurrence of PORs did not correlate with the severity of the plasma environment. The plasma instrument onboard the spacecraft also confirmed that significant surface charging did not occur. An investigation of the radiation electron environment indicated that the PORs occurred during the time that the flux of radiation electrons was at its peak. Consequently, internal discharges induced by the penetrating electrons were proposed as a possible cause of PORs (Ref.1).

In order to prevent the occurrence of PORs during the Galileo mission, a test program was initiated to investigate the effect of penetrating electrons on

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electronic circuits. The program consists of two phases. In the initial phase, the phenomena of IESD were investigated through analysis and testing. This was done with contractor support from General Electric and JAYCOR. Analysis and tests during this phase demonstrated that some of the dielectric insulation of spacecraft components did discharge when they were irradiated by an electron beam with a flux level corresponding to the levels they would experience in the Jovian environment. To ensure that IESD related anomalies will not occur during Galileo's encounter with Jupiter, the second phase of this program was to acquire the necessary data to generate the required design guidelines for the Galileo spacecraft. The design guidelines are on the material selection, grounding criterion, transient characteristics and coupling of discharge energy into circuits.

This paper discusses the test configuration, the test results, and the application of test results for design guideline generation.

GENERAL TEST PROGRAM

The tests were performed in the dynamitron facility of the Jet Propulsion Laboratory. The dynamitron is capable of delivering an electron beam in the energy range of 0.8-2.5 Mev. To simulate the environment that the dielectrics would experience in space, it was decided that a high vacuum system would be required. This system uses a standard diffusion pump with a cold trap provided to control oil contamination (Figure 1). The dynamitron electron beam enters the test chamber through a 75 μm stainless steel diaphragm. The sample holder is located inside the vacuum chamber and is situated perpendicular to the electron beam. A Faraday cup is mounted in the plane of the sample specimen so that the flux levels at the test sample could be accurately monitored. Pressures of 2×10^{-5} torr or less are required before initiating the test.

The occurrence of discharges are monitored by current transformers placed along the possible paths of discharge currents. Another diagnostic for the discharge is a plasma current detector, which is a thin sheet (50 μm thick) of aluminium with a diameter slightly smaller than that of the chamber. This plasma current detector is placed right in front of the test sample and hence it detects the presence of charged particles generated during discharges. In some of the tests, the test items (such as cables and circuit traces) were used as detectors for the occurrence of discharges. The transient signals induced on these detectors are transmitted outside the vacuum chamber through coaxial cables. These signals are displayed on storage scopes or transient digitizers. The length of coaxial cable used in our experiments are about 10 m. The effect of long cables on the transient signals was investigated by applying a pulse on one end of the cable and receiving the pulse at the other end. No significant amplitude loss or waveform distortion was observed.

The flux level used in our experiment was determined by the expected inflight deposited flux levels at the samples. The expected inflight deposited flux level as well as the dynamitron deposited flux levels were both determined by Monte Carlo computer calculations. The test fluence for our test is usually chosen as Jupiter Orbit Insertion (JOI) plus 5 orbit fluence. This selection is based on the fact that JOI+5 orbits are the minimum required for a successful mission. Due to the constraint of time and cost, the flux level used to achieve this fluence was usually at least a factor of three higher than the anticipated worst-case level.

The test items chosen for this test program were parts of the Galileo spacecraft. They were either components with dielectric insulation or components with floating conductors. The criteria for test sample selection are based on: (1) the intensity of the expected deposited flux level, and (2) the proximity of the components to sensitive circuits. Initial tests were performed to determine if breakdown was possible. If breakdown did occur, then tests were performed to determine the transient parameters. The transient parameters of importance are rise time, pulse width, and peak voltage. The electron beam had previously been charted inside the chamber to determine its uniformity. The results indicated that the beam was uniform over the surface of the sample holder (36-cm diameter). Before any radiation tests were initiated in the chamber, a dry run was performed at a very high flux level. This was done in order to determine if there existed any dielectric in the chamber that might break down producing unwanted data. The results of the tests were negative.

Table 1 presents the test samples and the results of radiation tests performed on these items. This table does not include the results on circuit boards and cables; the results on these two items are presented in more detail in the next section. This table provides information on the electron beam energy and the flux level. If discharges occurred, the associated worst-case IESD parameters are also presented. Note that the flux levels used in testing the connectors were far greater than the anticipated environment. We were interested in acquiring as much information on the transient parameters and, therefore, it was decided to greatly increase the flux level.

DESIGN GUIDELINE TEST

It was determined that the greatest hazard existing to the subsystems and systems of Galileo originated from the circuit boards (Ref. 2) and flight cabling. Extensive testing was performed on these items to determine the effects of discharge on nearby circuitry.

Different circuit board designs were fabricated to determine the effects of electron radiation on floating circuit traces of various area, spacing, and length. The boards were fabricated out of FR4 material. Circuit board A (Fig. 2a) was designed to determine the effects of the floating trace area on the characteristics of discharges. The areas varied from 5×5 cm (25 cm^2) to a plated-through hole (elements 1 to 5). In addition, the effects of spacing between the nearest grounded conductor was investigated using elements 6, 7, and 8 on board A. Board B (Fig. 2b) was designed to determine the effects of spacing and length variation on IESD events.

During each test, only one element of a circuit was left floating while the other elements were connected to strips which were grounded through 50-ohm resistors. Two grounded strips on each board were monitored for signs of an IESD event. The discharge current collector was used to monitor the blowoff electrons resulting from discharges. The boards above were tested under two different configurations. In the first configuration the board was bare, and in the second configuration it was coated with Solithane (a conformal coating).

Tests were also designed to characterize the transient signals generated by discharge of the cables. The cabling employed on Galileo uses two different types of insulation, Kapton and Teflon. Previous results obtained from the irradiation of Kapton (Refs. 3, 4, and 6) and Teflon (Refs. 4 and 5) materials indicate that they will break down under Jupiter's anticipated flux level. The concern raised was the voltage and energy levels associated with the transient induced on the center conductors. Typical flight-like cabling of both Kapton and Teflon material were obtained for testing. The length of the Kapton and Teflon cables varied from 15 to 300 cm. The center conductors were terminated with an impedance of 50 ohms, and they were also used as discharge detectors.

In some of the cables that we have tested, some conductors were accidentally left floating. The transient characteristics generated by cables with floating conductors were found to be vastly different from cables with all conductors grounded. The cables with floating conductors included cables inside a Teflon bundle cable and cables from the Data Management Subsystem (DMS) of the Galileo spacecraft. The wires associated with the DMS cable were nonshielded single conductors. The length of the wires tested were approximately 30 cm.

The electron beam employed in testing the circuit boards ranged from 0.85 to 1.75 MeV. The current density of the beam varied from 4 to 26 pA/cm². The position of the circuit traces was perpendicular to the incoming beam. The Faraday cup was positioned at the sample level of the circuit board such that the appropriate current density could be maintained.

The Kapton and Teflon cables were coiled on the surface of the sample holder around the Faraday cup. In this way the cable surface was perpendicular to the incoming electrons. The DMS cable, due to its limited length, was positioned along the length of the sample holder. The beam energy used in testing the cables ranged from 1.45 to 1.65 MeV. The current density of the electron beam varied from 160 to 320 pA/cm² for the Kapton and Teflon cable bundles. The current density used in the case of the DMS cable was 16 pA/cm².

DESIGN GUIDELINE TEST RESULTS

Several types of discharges were observed in the circuit board tests. Small discharges were usually observed at the beginning of irradiation of a "fresh" circuit board. This could have been due to the occurrence of discharges within the imperfections of the circuit board. The transient voltage coupled to the nearby grounded conductor was usually very small (<1 V) and was of narrow pulse width (<20 ns). Large amplitude (>5 V) signals were usually not observed until the circuit board had been irradiated for a period of 2-4 hours. Therefore, the magnitude of transients depends on the time history of the irradiation. Consequently, there was a great deal of variation in the transient characteristics associated with the discharges of each circuit trace. Table 2 displays the worst-case transient parameters observed during the irradiation of the A board. In the case of element A4 (Table 2), the small voltage of 0.8 V was observed at the beginning of the electron beam irradiation; if we had rerun the test again at a later period we would expect the observed voltage to be much higher than 0.8 V. The average rise time of the pulses observed ranged from 5-10 ns.

The signals coupled to nearby grounded conductors during big discharges indicated that there were two different discharge processes. In one process, a negative spike with a narrow pulse width (40 ns) was induced on a nearby grounded conductor (Fig. 3). The negative signal was probably due to the flow of electrons from the floating trace to the grounded trace. In another process, the transient signal coupled to a nearby conductor consisted of two distinct parts. The first part was the negative narrow pulse width signal (Fig. 4a) with characteristics similar to the previously mentioned signal. The second part of the signal consists of a positive signal with a wide pulse width (400 ns). The negative portion of this signal was again due to the floating circuit trace discharge. However, this discharge also caused the expulsion of electrons stored in the circuit board material. These blowoff electrons, which were many times greater in number than the electrons stored in the floating circuit trace, were collected by the plasma detector. This process was confirmed by the negative wide pulse width signal on the plasma current collector (Fig. 4b). The positive signal detected by the grounded trace was due to the return current of the electrons stored in the circuit board.

Experiments with conformal coated circuit board A indicated the maximum energy and voltage of the transient was reduced by a factor of 2 or more. The reduction is due to the fact that the conformal coating reduces the efficiency of coupling by eliminating the direct couple path.

After performing a variety of tests on Kapton and Teflon flight cabling, it became obvious that the danger lay not in the dielectrics of the cabling but the problems associated with floating conductors that may exist in the cabling. Induced transients with voltages of 4-6 V were observed when the dielectric insulation of the cable discharged. However, due to engineering changes or undetermined plans, wires within the cable bundle may end up not being used. These wires would exist as floating conductors inside the bundle during the Galileo mission. Once in the Jovian environment the bundle would be exposed to penetrating radiation. The wires could then be charged to high enough potentials to breakdown the insulation of the wires or the connectors. Typical discharge signals associated with grounded and floating conductors inside cable bundles are shown in Figs. 5a and 5b. This signal was detected by a grounded (through 50 ohm) conductor in the cable bundle. Notice the difference in magnitudes of transient signals between the two cases.

It was found that when one varied the impedance of the monitored wire the effect was to alter the pulse width of the induced transient. The amplitude of the transient remained at basically the same level. This seems to indicate that the governing impedance of the detection system actually depends on the source impedance of the discharge itself.

DESIGN GUIDELINE DISCUSSION

From the measured waveforms, the energy that can be coupled to a load of impedance R is given by the following equation:

$$E = \frac{V^2}{4R} T$$

Where V_{pp} is the peak voltage, R is the impedance, and T is the pulse width. Since most of the observed waveforms resemble a damped sine wave, to add some conservatism in the energy calculation T is the e-folding pulse width. This method was applied to calculate the energy of all transient pulses observed.

In the discharge of each circuit trace, pulses of different magnitudes were observed. As an engineering approach, only the pulses with the highest magnitude (Table 2) were used for the correlation study. The energy and voltage data are plotted in Figs. 6a and 6b. In both plots, the data obtained from circuit trace element #4 were omitted. Figures 6a and 6b do indicate a trend, i.e. the voltage and energy that can couple to a load increases with the area of the circuit traces.

The results obtained for elements 6-8 on the noncoated A circuit board did not display any consistency in terms of floating trace spacing and the resulting transient parameters. Tests performed on circuit board B indicated that the transient parameters did not show any correlation with either the spacing or the length of the circuit traces. With additional statistics it may be possible to determine some relationships.

As mentioned in the previous section, the cable tests indicated that the breakdown of cable insulation would induce a 4-6 V transient on the conductors of the cables. This low voltage level is acceptable to Galileo spacecraft subsystems since all the circuits are designed to withstand a 10-V transient voltage. However, the breakdown of cables with floating conductors can induce voltage in excess of 10 V into circuitry; therefore, a design requirement is needed for cables with floating conductors. In order to derive this requirement, the results from the Teflon cable bundle test and the DMS cable test were used. Figures 7a and 7b display the voltage and energy that were coupled to a 50-ohm load, respectively. The upper data point is for the Teflon cable bundle. There were several floating conductors in both the Teflon and the DMS cable bundles. Because of the wide pulse width of the observed discharges, the discharges were most likely caused by more than one floating conductor. The error bars in Figs. 7a and 7b indicate the uncertainties in the total length of floating conductor involved in the observed discharges.

Steps were taken to define design guidelines based on the information derived from the tests. The raw data provided a margin of one. However, for engineering purposes a safety factor of two was incorporated into the design guidelines. These design guidelines had their origin in the assumption that an IC would not be damaged by a transient having a voltage of 20 V and an energy of 4 μ J. The two design guidelines derived are:

- (1) All individual wires exceeding 25 cm in length within subsystem wire harnesses, Orbiter system wire harnesses, and assembly-to-system interface cabling shall have a conductive path to ground with 1×10^8 ohm resistance when measured in air or 1×10^{12} ohm resistance when measured in vacuum.
- (2) All radiation shields, circuit traces, and conductor with a surface area greater than 3.2 cm^2 shall be electrically grounded unless one of the following conditions can be verified:
 - (a) The conductive element and circuit is identical to Voyager and is approved by the Environmental Requirements Engineer and Orbiter Manager to be an acceptable risk.

- (b) The conductive element is verified by test or analysis to have $<1 \times 10^8$ ohm resistance to ground in air or 1×10^{12} ohm resistance in vacuum.

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TABLE 1. = RESULTS OF ELECTRON IRRADIATION TESTS FOR VARIOUS GALILEO SPACECRAFT COMPONENTS

TEST ITEM	ELECTRON BEAM ENERGY (MeV)	FLUX (pA/cm ²)	WORST-CASE IESD TRANSIENT PARAMETERS				COMMENTS
			VOLTAGE (V)	RISE TIME (ns)	PULSE WIDTH (ns)	ENERGY (J)	
SIGNAL AND TOROIDAL POWER TRANSFORMERS	2.50	29	—	—	—	—	TRANSIENT NOT OBSERVED
SYNTACTIC FOAMS	1.45 - 2.50	16 - 80	—	—	—	—	TRANSIENT NOT OBSERVED
ANTENNA MATERIAL	1.45	64	0.3	5	200	3.6×10^{-10}	TRANSIENT SIZE AREA DEPENDENT
BOOM MATERIAL	1.85 - 2.50	53 - 106	1.6	—	6000	3.8×10^{-7}	TRANSIENT SIZE LENGTH AND ANGLE OF INCIDENT DEPENDENT
COAX CABLE (RG 142/U)	1.00 - 1.25	80 - 160	8	10	1000	3.2×10^{-7}	MEASURED ACROSS 50 Ω
STANDARD DENSITY CONNECTOR DS 313-22-55	1.60 - 2.50	640	5.8	5	50	8.4×10^{-9}	MEASURED ACROSS 50 Ω
HIGH DENSITY CONNECTOR ST-11949-12-35	1.60 - 2.50	640	5.3	5	30	4.2×10^{-9}	MEASURED ACROSS 50 Ω
FLEX PRINT CONNECTOR ST-11493-50	1.60 - 2.50	160 - 640	28	10	70	2.7×10^{-7}	MEASURED ACROSS 50 Ω

TABLE 2. - TRANSIENT PARAMETERS OBSERVED DURING DISCHARGE OF ELEMENTS OF NONCOATED BOARD A

ELEMENT NO.	WORST-CASE IESD TRANSIENT PARAMETERS		
	VOLTAGE (V _{pp})	PULSE WIDTH (ns)	ENERGY (J)
1	60	339	6.1×10^{-6}
2	25	510	1.6×10^{-6}
3	10	375	6.1×10^{-7}
4	0.8	19	3.2×10^{-11}
5	6	52	9.4×10^{-9}

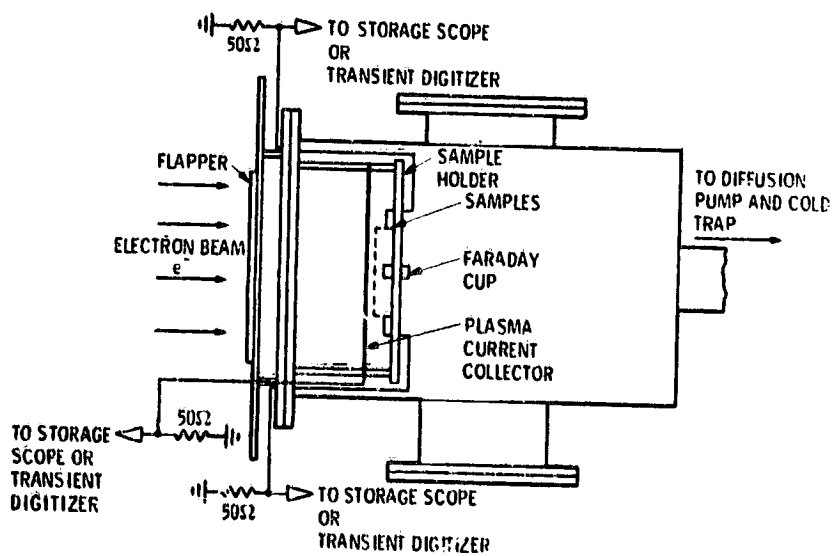
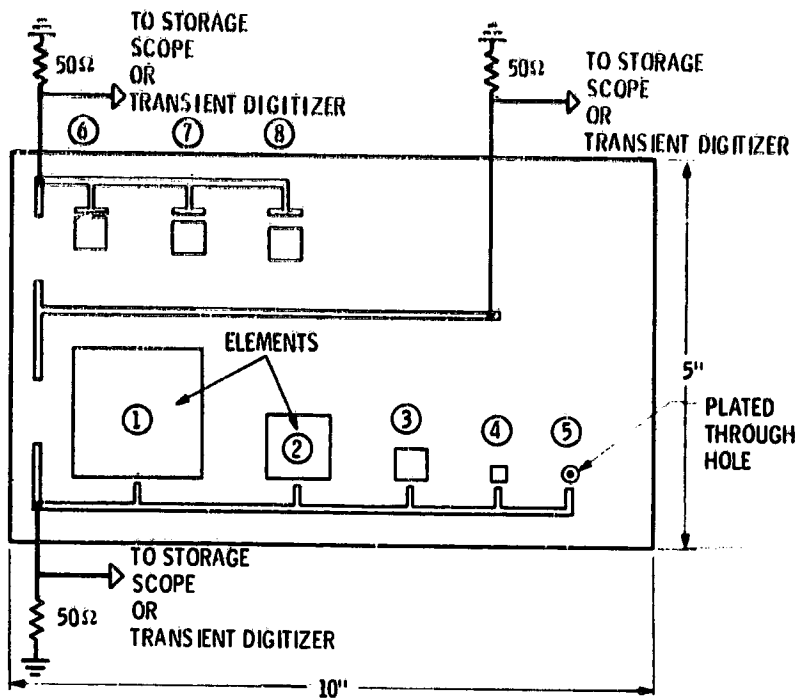
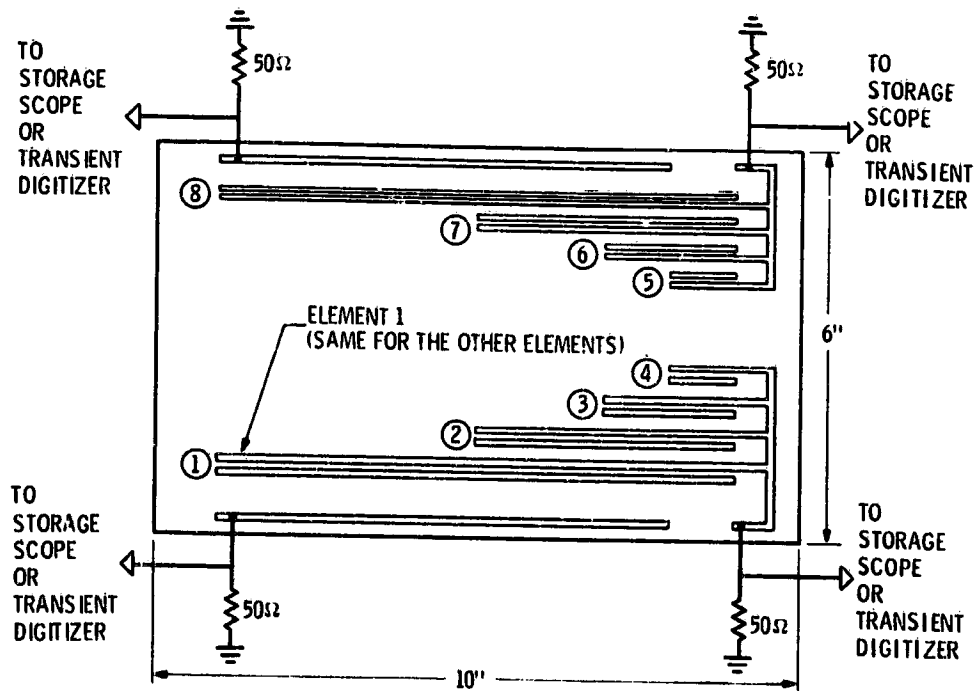


Figure 1. - Target chamber and fixtures.



(a) Board A.



(b) Board B.

Figure 2. - Trace length and spacing variation.

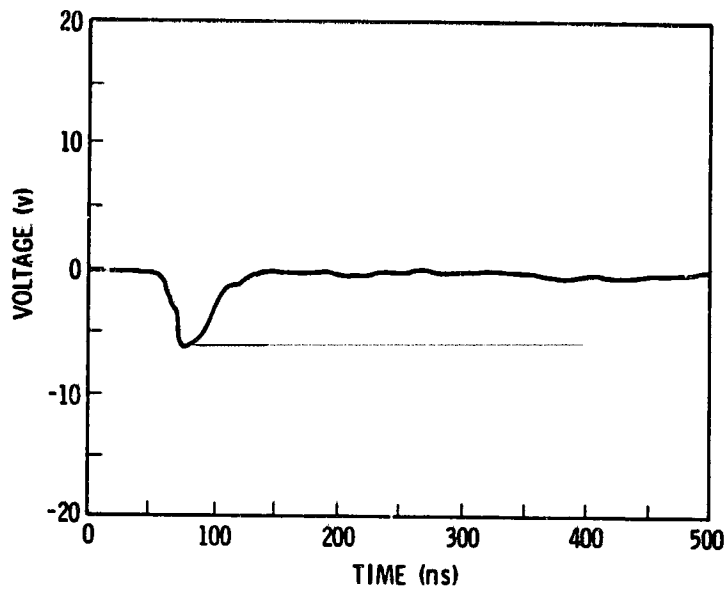
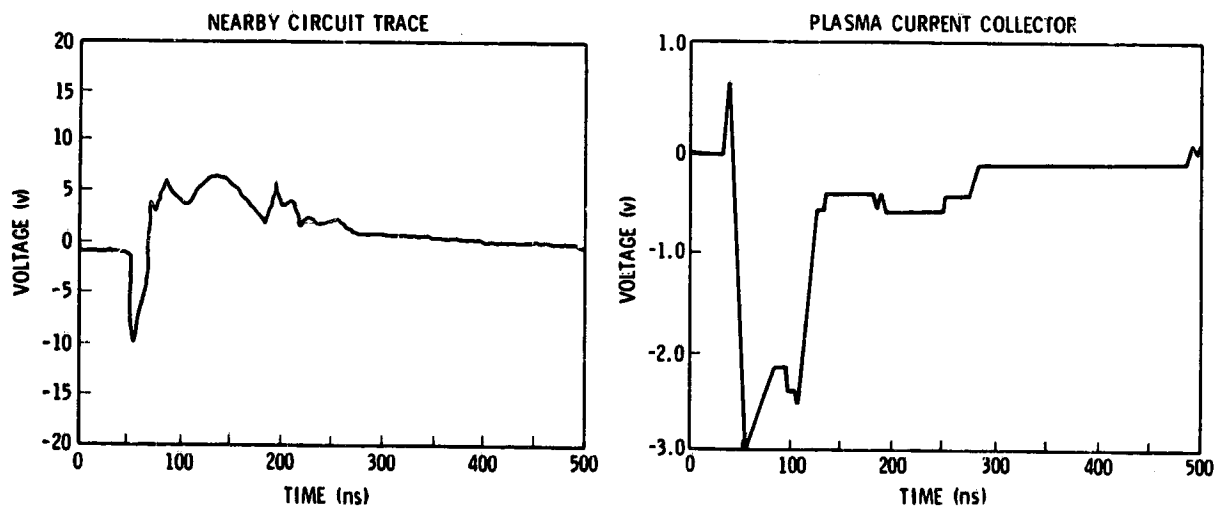


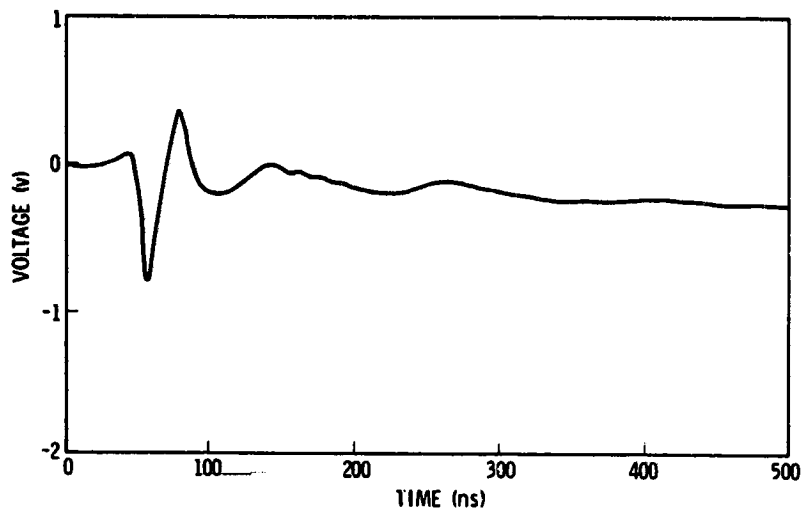
Figure 3. - An intermediate discharge pulse observed during electron beam irradiation of circuit boards with floating circuit trace. Detector is a nearby grounded trace.



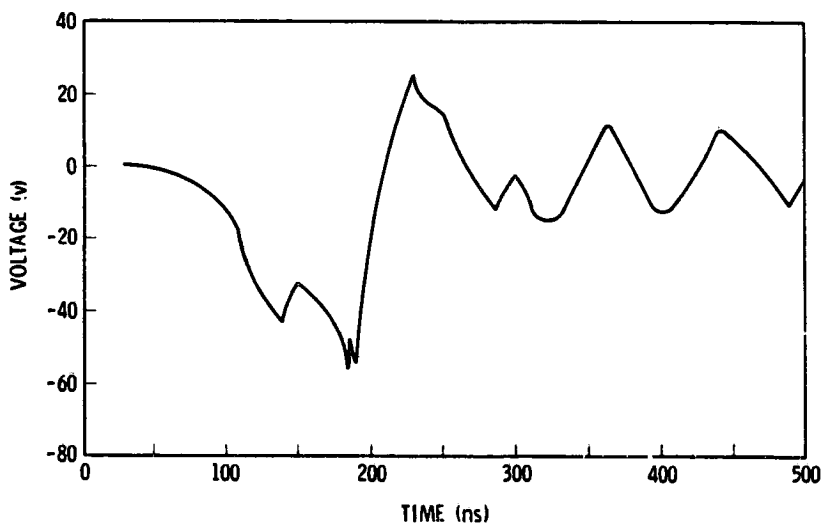
(a) Detector, nearby grounded trace.

(b) Detector, plasma current detector.

Figure 4. - Large discharge pulse observed during electron beam irradiation of circuit board with floating traces.

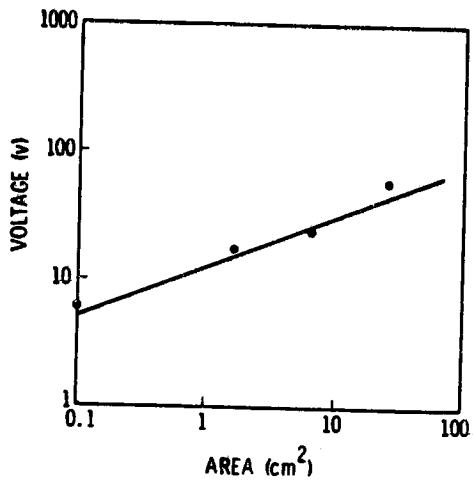


(a) Grounded conductors.

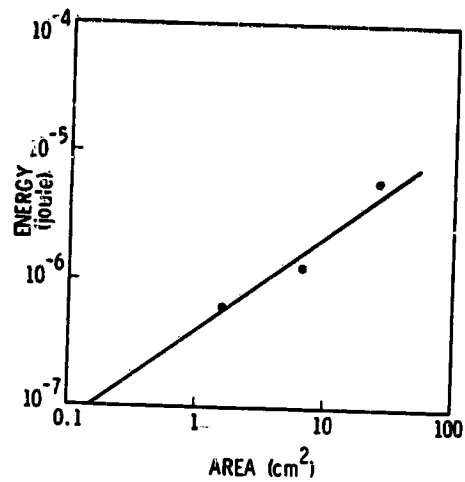


(b) Floating conductors.

Figure 5. - Discharge pulses observed during electron beam irradiation of Teflon cable bundle. Detector in both cases was a grounded conductor within cable bundle.

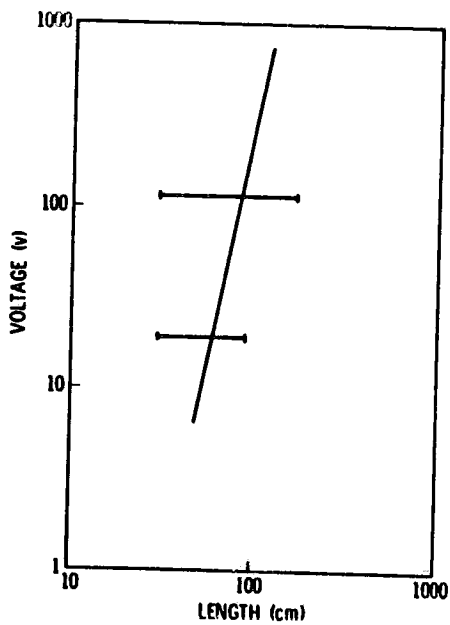


(a) Voltage versus area.

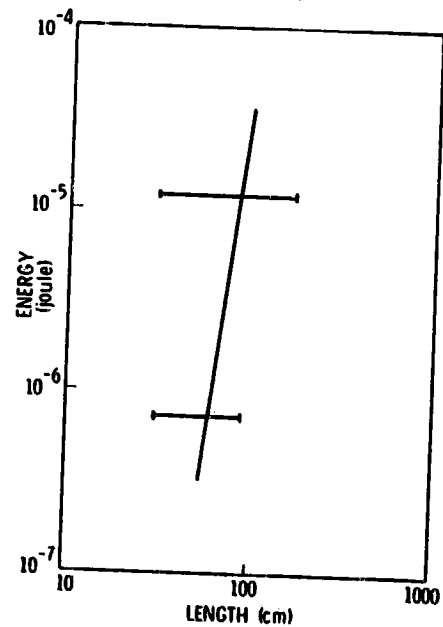


(b) Energy versus area.

Figure 6. - Dependence of transient parameters on circuit trace area.



(a) Voltage versus length.



(b) Energy versus length.

Figure 7. - Dependence of transient parameters on floating conductor length.