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EFFECTS OF SHUNT CAPACITANCE ON TRANSIENT EFFECTS CAUSED BY ELECTRON IRRADIATION OF A POLYETHYLENE TEREPHTHALATE INSULATED RIBBON WIRE

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SUMMARY

An investigation of the effects of external "shunt" capacitance upon the electron irradiation induced voltage pulses from a 20.3-centimeter strip of polytheylene terephthalate insulated ribbon wire irradiated with 60 keV electrons is reported. Both the average and the maximum pulse heights observed varied inversely with the total capacitance in the system. A change in load resistance caused a negligible variation in average and maximum pulse heights. After irradiation, electron discharge patterns known as Lichtenberg figures were found in the polyethylene terephthalate insulation. Rough calculations indicate that the power density along the discharge path is adequate to produce the observed physical damage.

INTRODUCTION

The radiation belts surrounding the earth pose a problem in the use of certain components on satellites. One such problem, investigated in reference 1, involves dielectric materials that produce voltage pulses when exposed to electron irradiation.

The present investigation was made to obtain effects of electron irradiation on polyethylene terephthalate insulated ribbon wire. More specifically, the present investigation was instituted to study the effects of "shunt" capacitance upon the radiation-induced discharges described in reference 1. To this end, the sample was subjected to 60-keV electron irradiation at room temperature while systematic changes were made in the external circuit. The behavior of the ribbon wire was monitored throughout the irradiation.

The results of these tests are given in the form of maximum and average pulse heights observed during irradiation. The results of a microscopic post-irradiation examination of the ribbon wire sample are also presented.

EXPERIMENTAL ARRANGEMENT

The irradiations were carried out with a 1.0 MeV cascaded rectifier electron accelerator of the type described in reference 2. The experimental arrangement used for the tests is shown in figure 1. The electron beam entered from the accelerator and was spread laterally by a single quadrapole lens. After being spread, the beam was swept vertically by the scan magnets at a rate of approximately 10 cycles per second. The beam then impinged upon the target inside an independently pumped vacuum target chamber. The vacuum in the target chamber during irradiations was 0.9 to 2.0×10^{-6} torr $\left(1.20 \times 10^{-4}\right.$ to 2.67×10^{-4} newton/meter^2) as measured by a Bayard-Alpert ionization gage.

The beam uniformity was found by cobalt glass dosimetry to be within ±5 percent over an area of 7 by 30 centimeters. Monoenergetic electrons with an incident energy of 60 keV were used for these tests. The kinetic energy of the electron beam was determined by using a surface-barrier silicon solid-state detector, which had an energy resolution of 18 keV (full width at half-maximum) which, in turn, was calibrated against suitable internal conversion electron-emitting isotopes. The energy spread and short-term energy drift of the accelerator was sufficiently below the resolution of the solid-state detector that they could not be determined. The electron dose and dose rate were monitored by a 1- by 2-centimeter aluminum plate, which was suspended inside the vacuum target chamber (fig. 1). The electron current and the total dose incident upon the plate were measured by an integrating electrometer. The dose rate used throughout these tests was 3.1×10^{10} electrons/centimeter^2-second. Each of the irradiations was carried to a total dose of 1.0×10^{14} electrons/centimeter^2.
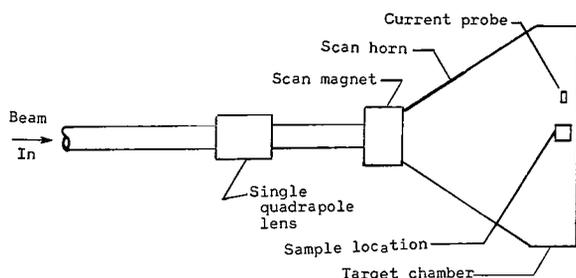

Figure 1.- Experimental setup for tests on insulated wire.

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Figure 2.- Ribbon-wire sample ready for mounting.

The test sample as tested is shown mounted on an electrical feedthrough plate in figure 2. The sample was a strip 0.762 centimeter wide of polyethylene terephthalate. Two flat copper conductors were imbedded in the polyethylene terephthalate. The thickness of the sample was 0.127 millimeter (5 mil) and the length was 20.3 centimeters. The copper conductors were 1.5 millimeters wide and 0.0762 millimeter thick and were separated by 1.5 millimeters. The insulation was stripped from the ends of the piece of ribbon wire for a distance of approximately 1.5 centimeters. The ribbon wire was then coiled and the ends were soldered to the electrical feedthroughs on the plate. Figure 3 shows the sample in place in the vacuum target chamber, as viewed from a point behind the target. The rigidity of the ribbon wire was such that no external means of support was necessary.
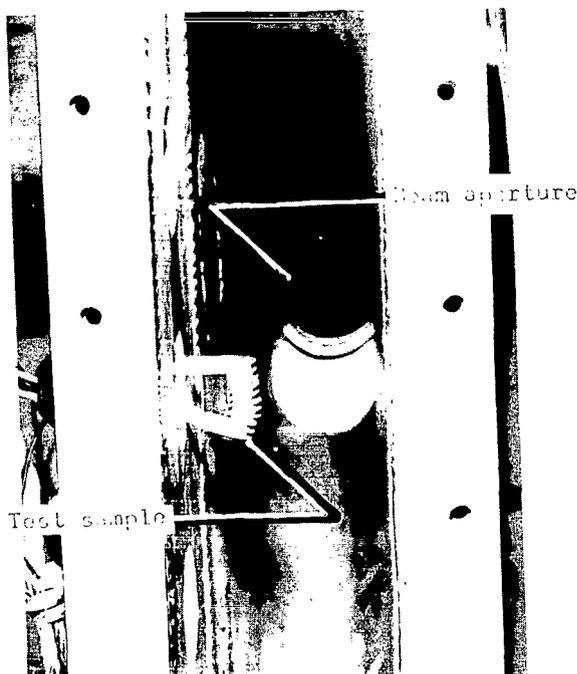
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Figure 3.- Sample mounted in target chamber.

The test circuit used for the ribbon-wire irradiation tests is shown in figure 4. The electron beam impinged only on the coiled ribbon wire. Shunt capacitance and load resistance were installed external to the target chamber. For most of the tests the load resistance was 3000 ohms. The size of the capacitive shunt was varied over several orders of magnitude (0.0001 to 1.0 microfarad) during the tests. The measured capacitance of the external circuit without shunt capacitance was 0.001 microfarad. The capacitance of the sample was 4 picofarads. A 45-volt battery was placed in the circuit with negative polarity at ground (ref. 1). The radiation-induced voltage pulses from the ribbon wire were amplified by an alternating-current coupled 0.01-microsecond rise-time preamplifier in the oscilloscope. The voltage pulse displayed on the cathode-ray tube of the oscilloscope was recorded on film by a manually operated camera on the oscilloscope.
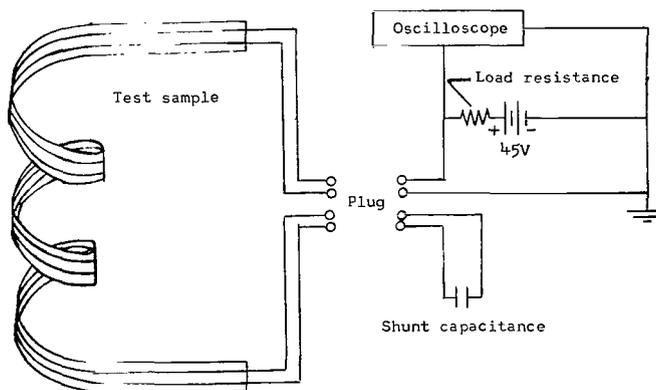
Figure 4.- Circuit used for tests.

The oscilloscope was used in the single sweep mode so that each voltage pulse could be recorded separately. The trigger level of the oscilloscope was set at approximately 0.5 volt. Many pulses with direct-current amplitudes less than 0.5 volt were obtained with this system. In these cases, the oscilloscope was triggered by brief ringing at the leading edge of the signal. (See fig. 5.) The direct-current level of all pulses obtained was used in determining the average pulse heights.
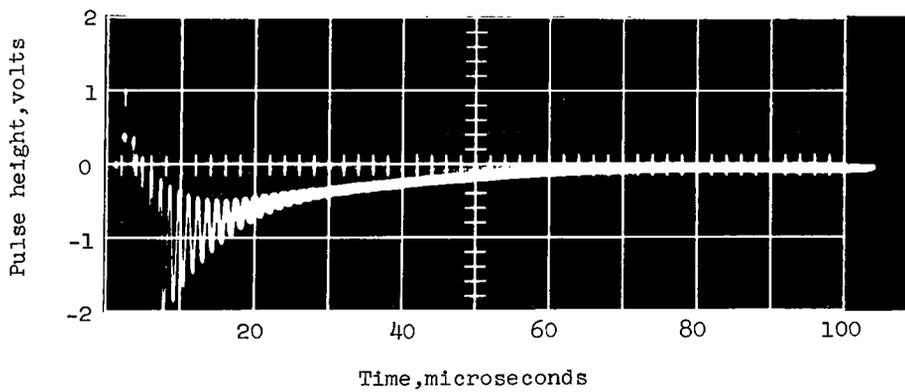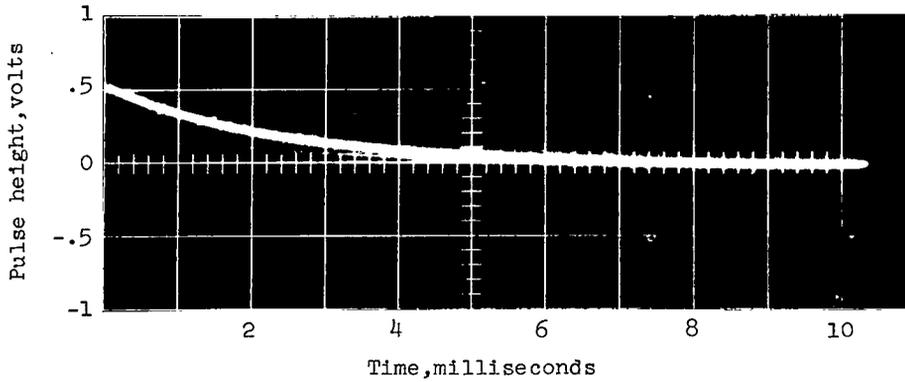

Figure 5.- Two typical pulses obtained from test sample.

RESULTS

Distribution of Voltage Pulses

A typical pulse-height distribution for the sample tested is shown in figure 6. At the higher pulse heights, relatively few pulses were observed. For each test, the average pulse height was found by summing the absolute voltage of each pulse and dividing the result by the total number of pulses observed in that test. The total number of pulses for each test was approximately the same as that shown in figure 6; however, the integral pulse height varied as a function of the total capacitance of the system. Examination of the data showed the voltage pulses to be irregular with respect to time and pulse height.

Effect on Average Pulse Height

Effect of shunt capacitance on average pulse height.- The effect of total circuit capacitance on the average observed pulse height is shown in figure 7. The absolute magnitudes of both positive and negative pulses were used to obtain the average pulse height. The average pulse height decreased from 5.1 volts at a total circuit capacitance of 1.1×10^{-9} farads to less than 0.01 volt at a total capacitance of 1.0×10^{-7} farads.

Effect of load resistance on average pulse height.- The effect of increasing load resistance R_L on the average pulse height at a total capaci-
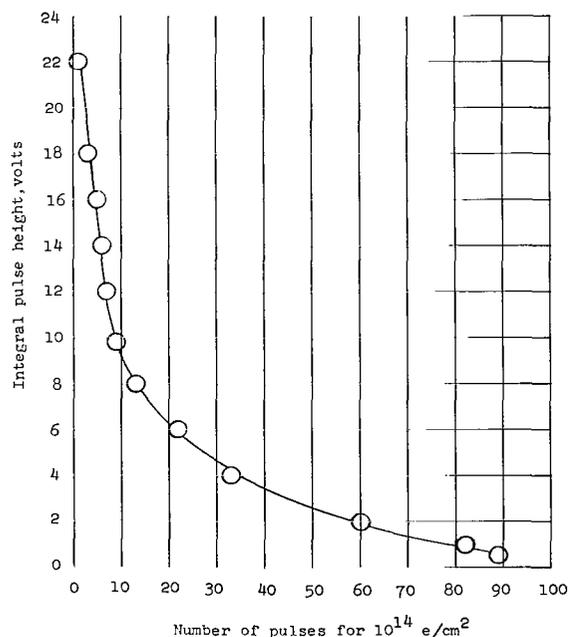

Figure 6.- Number of pulses above a given voltage from the polyethylene terephthalate insulated ribbon wire. Plot is for a 0.0022-microfarad data point.

tance of 1.0×10^{-8} farads is also shown in figure 7. Increasing the load resistance by two orders of magnitude from 3 000 ohms to 300 000 ohms produced less than an order of magnitude change in the average pulse height measured.

Effect on Maximum Pulse Height

Effect of shunt capacitance on maximum pulse height.- The effect of increasing total capacitance on the maximum pulse height observed is shown in figure 8. The maximum pulse height decreased from 35 volts at a total capacitance of 1.1×10^{-9} farads to approximately 0.2 volt at a total capacitance of 1.0×10^{-7} farads.
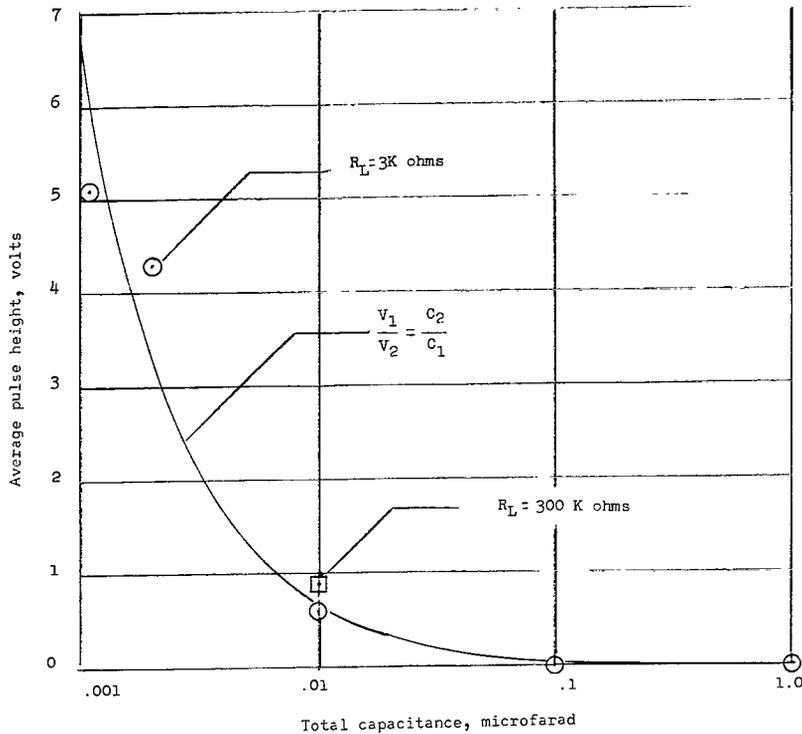
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$$\frac{v_1}{v_2} = \frac{c_2}{c_1}$$

Figure 7.- Average pulse height obtained for a given total capacitance.
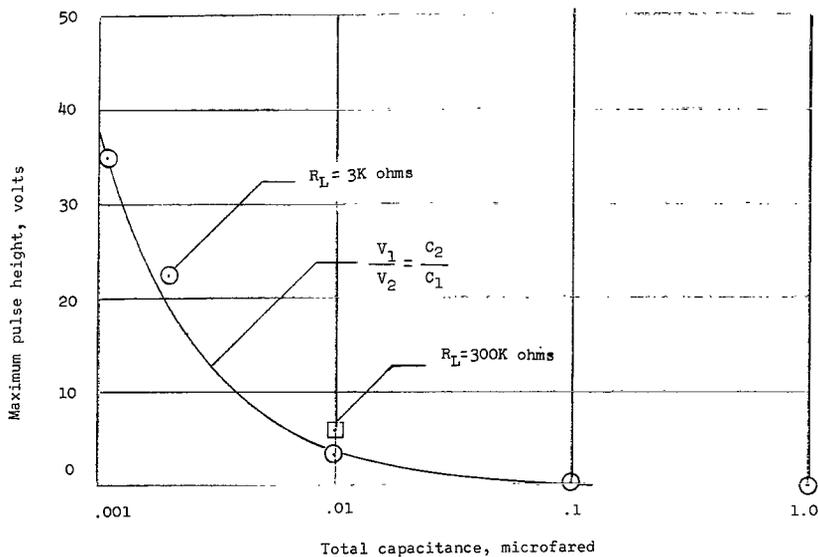

$$\frac{v_1}{v_2} = \frac{c_2}{c_1}$$

Figure 8.- Maximum pulse height obtained for a given total capacitance.

Effect of load resistance on maximum pulse height.- The effect of increasing the load resistance on the maximum pulse height observed at a total capacitance of 1.0×10^{-8} farads is shown in figure 8. The maximum pulse height observed also increased by less than an order of magnitude with an increase of load resistance by two orders of magnitude (from 3 000 ohms to 300 000 ohms).

Visible Radiation Effects

After the irradiations it was noted that the portions of the coiled polyethylene terephthalate insulated ribbon wire that had been exposed to the direct electron beam exhibited a slight foggy white discoloration. The polyethylene terephthalate was examined under a microscope and was found to contain a large number of microscopic Lichtenberg figures. Figure 9 shows three of these Lichtenberg figures in the polyethylene terephthalate terminating at the copper conductor of the ribbon wire. The thickest part of the discharge trunk is on the order of 15 microns. In the thickest part of the trunk there is usually a region (on the order of 50 to 100 microns in diameter) that is different in size and shape from the rest of the

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discharge trunk. This bulbous region may have been vaporized by the discharge. This effect is shown in figure 9. Large Lichtenberg figures have been noted in polymethyl methacrylate (ref. 3), borosilicate glass (ref. 4), and radiation shielding glass (ref. 5) following electron irradiation.

<div align="center">DISCUSSION</div>

<div align="center">Origin of Pulses</div>

Reference 1 postulates that a portion of the incident electrons are stopped and stored within the dielectric material. This charge increases as the sample is irradiated. At some point in time, this charge is released and is transported to the conductor, at which time the charge becomes observable as a voltage pulse.

Once the charge passes from the dielectric to the metallic plate formed by the wire, the charge sees the entire capacitance of the system. The voltage measured by the external circuit will then be

$$V = \frac{Q}{C} \tag{1}$$

where

V   circuit voltage

Q   quantity of charge released

C   total circuit capacitance

Furthermore, if the same discharge were observed in two different external circuits having different capacitances (denoted by the subscripts 1 and 2), then the ratio of the observed pulse heights will be

$$\frac{V_1}{V_2} = \frac{C_2}{C_1} \tag{2}$$

A curve satisfying equation (2) has been fitted to the data shown in figures 6 and 7. Within the accuracy of measurement this curve fits the data quite well and thus supports the postulate of reference 1.
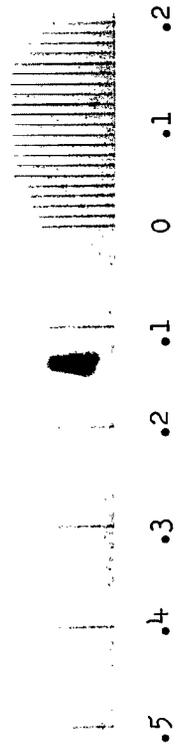
Since equation (2) is a satisfying fit to the observed pulse heights, equation (1) may be used to obtain an indication of the magnitude of the charge transfer involved in the discharges. Thus, an average charge transfer for the data presented in figure 7 is of the order of 6.6×10^{-9} coulombs and the maximum charge transfer indicated by the data of figure 8 is on the order of 44×10^{-9} coulombs. Calculations indicate that this latter charge would have been adequate to produce an 11 000-volt pulse in the 4-picofarad sample of wire if there had been no external capacitance at all.
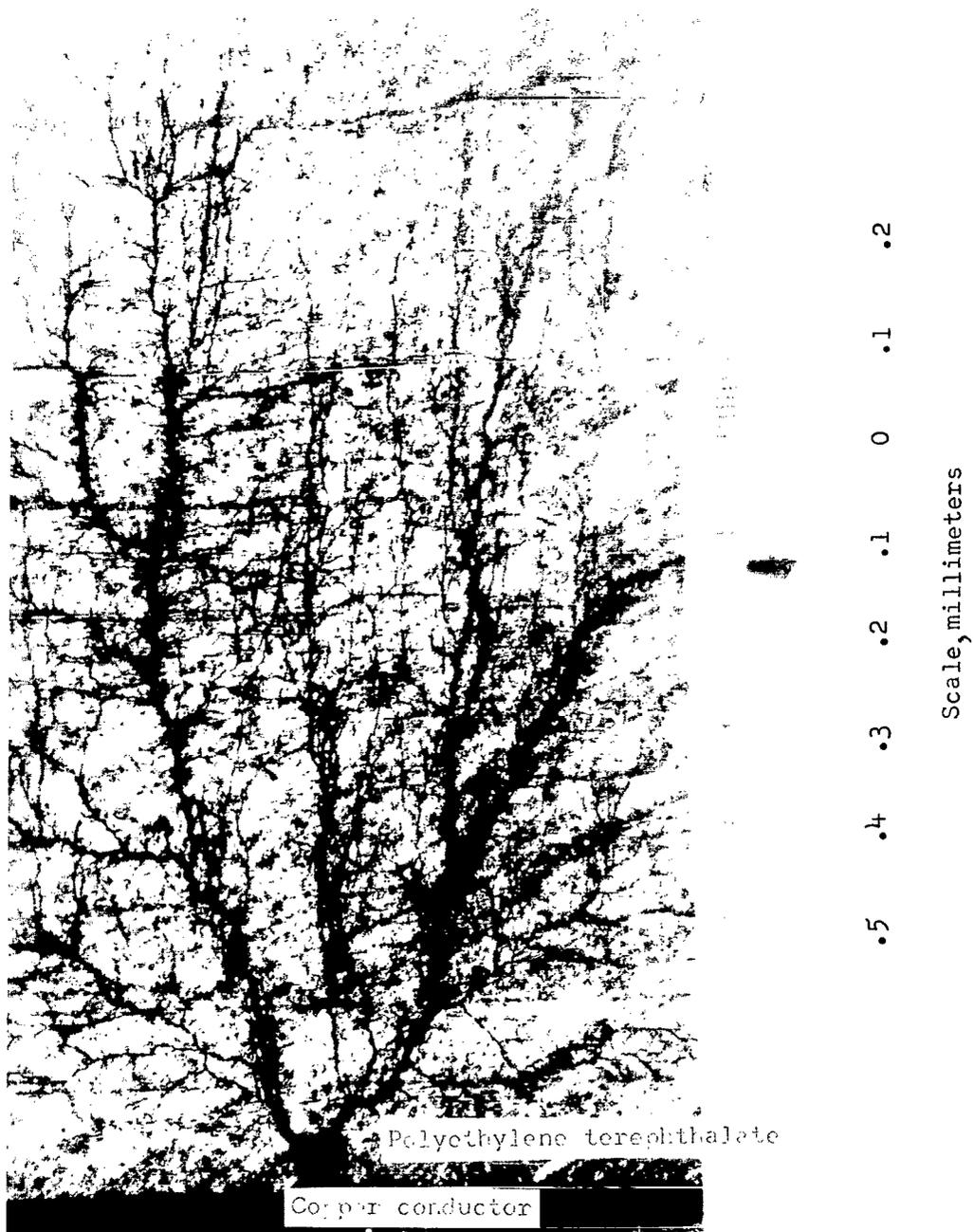
Scale, millimeters

(a) Specimen showing no bulb.   L-65-9022

Figure 9.- Discharge pattern in polyethylene terephthalate irradiated
with 60 KeV electrons.

(b) Specimen showing bulb.   L-65-9023

Figure 9.- Concluded.

It is evident from the extent of the Lichtenberg figures produced in .the dielectric (fig. 9) that the discharge from the dielectric is from a relatively small region of the material. Thus, an extension of the above calculations to a sample of dimensions on the order of those of the Lichtenberg figures would result in voltages substantially in excess of the aforementioned values.

It is of interest to make a rough calculation of the power density along the trunk of the discharges shown in figure 9. The energy transferred is of the order of 11×10^3 volts times 44×10^{-9} coulombs, or 5×10^{-4} watt-seconds. The trunk diameter of the discharge as evidenced by the damage indicated in figure 9 is on the order of 15 microns; that is, the local energy density along the trunk during the discharge is on the order of 270 watt-seconds/centimeter^2. Now, the discharge is accomplished during the rise time of the signal. This rise time is so short that it cannot be resolved on an oscilloscope with a rise time of 0.01 microsecond. If 0.01 microsecond is accepted as the discharge time, the local power density along the track is found to be on the order of 3×10^{10} watts/centimeter^2. Power densities of this order of magnitude should be capable of producing the damage indicated in figure 9, judging from evidence obtained with laser beams given in reference 6.

Effect of Load Resistance

The load resistance in the circuit acts as a path to ground for the voltage pulse. For the values of load resistance used in this experiment the change in pulse height as a function of load resistance is a second-order effect. Increasing the load resistance by two orders of magnitude results in less than an order-of-magnitude increase in the average and maximum pulse heights observed.

CONCLUSIONS

This study of the effect of shunt capacitance on the electron radiation-induced voltage pulses from a length of polyethylene terephthalate insulated ribbon wire indicates that:

1. Both the average and maximum pulse heights observed vary as the inverse of the total capacitance in the system, as postulated.

2. The discharge of stored electrons produces Lichtenberg figures in the polyethylene terephthalate dielectric. Rough calculations indicate that power densities along the discharge tracks are adequate to produce the observed damage.

3. The actual pulse height of the discharges as calculated can be as high as 11 000 volts. For a sample with dimensions on the order of those of the Lichtenberg figures, calculations indicate that voltages substantially in excess of this value may be produced.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., November 26, 1965.

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