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EXPERIMENTAL STUDY OF TRANSIENT EFFECTS IN DIELECTRIC MATERIALS CAUSED BY ELECTRON IRRADIATION

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SUMMARY

Voltage pulses in capacitors and insulated wires during low-energy electron irradiation were studied. Various dielectric materials (polyethylene terephthalate, polytetrafluoroethylene, polystyrene, ceramic, polypyromellitimide, regenerated cellulose, polyvinyl alcohol, a copolymer of polyvinyl chloride and polyvinylidene chloride, mica paper, and silicone-impregnated mica paper) were tested over a range of incident electron kinetic energies, temperatures, and dose rates. Some dielectrics were found to have relatively few voltage pulses occurring as a result of irradiation, whereas others pulsed rapidly and with large amplitudes. The number of pulses was found to vary with the incident electron kinetic energy. Because of the thinness of most of the samples tested, the greatest number of pulses was obtained at the lower energies (30 to 100 keV), and, in all cases, the number of pulses decreased markedly as the electron energy was increased. Temperature also had a profound effect on the number of pulses. Irradiation at low temperatures resulted in a greater number of pulses. Dose-rate effects on the number of pulses were significant except at the lowest temperatures at which the tests were conducted. Some of the present results are compared with results obtained from previously published work on the X-ray induced conductivity in dielectric materials. A degree of qualitative correlation was found with this prior work; that is, those materials found to possess long postirradiation current decay time constants in the X-ray work tended to be more susceptible to electron-induced transients.

INTRODUCTION

The characteristics and performance of many electronic components and materials which are being used in satellites have been seriously affected by continuous exposure to radiation. Gamma-radiation, electron, proton, and neutron studies have been carried out on a variety of components and materials. (See refs. 1 and 2.) Since electrons are a prime constituent of the radiation belts (refs. 3 to 5), the effects of electron irradiation are of particular interest.

The effect of electrons on capacitors and insulating materials under varying conditions has been studied in many prior investigations. Changes in both physical and electrical properties of dielectric materials have been noted. (See refs. 1 and 2.) In particular, changes in volume resistivity, color, and hardness have been reported. On the other hand, relatively little information has been obtained on any transient effects that might occur during a steady irradiation process. The purpose of the present investigation is to study transient effects that occur during low-energy electron irradiation of dielectrics at total doses far too small to cause any significant permanent changes in the characteristics of most dielectric materials. (See refs. 1 and 2.)

Commercial capacitors, insulated wires, and specially prepared sandwich capacitors were irradiated with monoenergetic electron beams having kinetic energies ranging from 20 to 1000 keV. Three types of commercial capacitors utilizing polyethylene terephthalate, ceramic, and polystyrene dielectrics were studied. The three types of insulated wires tested had polyethylene terephthalate, polytetrafluoroethylene, and polypyromellitimide insulation. The specially prepared capacitors were made from a variety of dielectric materials: polyethylene terephthalate, regenerated cellulose, polypyromellitimide, polyvinyl alcohol, a copolymer of polyvinyl chloride and polyvinylidene chloride, mica paper, and mica paper impregnated with silicone (methyl phenyl siloxane). In most cases, the thinnest sample of the given material that was commercially and rapidly available was used in the specially prepared capacitors. The effects of temperature, battery voltage, and electron dose rate on the observed transients was noted for the commercial capacitor insulated with polyethylene terephthalate. The effect of temperature on the transients was also studied in tests on the specially prepared capacitors. The effect of dose rate was noted in the specially prepared polyethylene terephthalate, polypyromellitimide, and silicone-impregnated mica-paper insulated capacitors and the polypyromellitimide insulated wire. The results from the electron irradiation of various capacitors and insulated wires were compared with the results of experiments on X- and gamma-ray induced conductivity in insulating materials.

The International System of Units (SI) (ref. 6) is used throughout the paper. However, the U.S. Customary Units are also given for some measurements. An appendix is included for the purpose of relating the two systems.

APPARATUS AND TESTS

Accelerator

The samples were bombarded with monoenergetic electrons from a cascaded-rectifier potential-drop accelerator of the type described in reference 7. Electrons with incident kinetic energies from 20 to 1000 keV were used. The accelerator energy was calibrated by using a solid-state radiation detector which, in turn, was calibrated with suitable radioactive isotopes. The energy as determined by this technique is believed to be within 1.0 percent of the nominal value stated. The energy spread within the beam and the short-term

energy fluctuations were sufficiently below the 18-keV resolution (full width at half-maximum) of the detector; therefore, the fluctuations and the spread could not be determined.

Beam-Handling System

Electrons from the accelerator pass through an evacuated beam tube into beam-handling and target-chamber systems. (See fig. 1.) The beam is first widened horizontally to approximately 7.6 centimeters by a single quadrupole magnetic lens. Next, the beam travels through the field of two electromagnets which are fed by a triangular wave. As a result of this varying field, the beam is scanned vertically at a rate of approximately 10 cycles per second in a fan-shaped scan horn. The swept beam then enters the target chamber.

Target Chamber

Targets are mounted within a chamber 76.2 centimeters high, 7.6 centimeters wide, and 30.5 centimeters deep. The target chamber is independently evacuated and contains a bucket, or finger, which may be filled with liquid nitrogen or hot water in order to control the temperature of the specimens under test. During the tests the target-chamber vacuum ranged between 2×10^{-8} torr $\left(2.67 \times 10^{-6} \text{ N/m}^2\right)$ and 10^{-5} torr $\left(1.33 \times 10^{-3} \text{ N/m}^2\right)$, depending primarily upon the temperature of the control finger. The most usual pressure range during tests was from 1×10^{-6} to 2×10^{-6} torr $\left(1.33 \times 10^{-4} \text{ to } 2.67 \times 10^{-4} \text{ N/m}^2\right)$. The vacuum in the target chamber was determined by an ionization gage mounted approximately 45 centimeters above and across the target chamber from the inlet of the diffusion pump.

Beam-Current Density

The beam current was monitored by an aluminum plate having a thickness of 1.27 centimeters and a rectangular area of 2 square centimeters (1 by 2 cm). This plate was glued to a glass chip (5 mm thick) which was in turn glued to the temperature-control bucket. Current collected by this plate was fed through an integrating electrometer (accuracy within 1 percent of indicated value) to ground to measure the dose rate in electrons per square centimeter per second $(e/cm^2\text{-sec})$ and the total dose in electrons per square centimeter (e/cm^2). A bare wire lead was used within the chamber to connect to this plate. The error between the current density on the sample and that picked up by the probe is comparatively small and should not affect the interpretation of the results of this experiment.

Beam-Current Uniformity

As mentioned previously, the beam-handling equipment spreads the beam horizontally 7.6 centimeters and scans it vertically approximately 45 centimeters at the target area. The uniformity of the beam was determined by cobalt-glass

dosimetry and was checked periodically by using polyvinyl chloride film, a film which darkens under electron irradiation. From the cobalt-glass dosimetry, the beam pattern was found to be vertically uniform over the test samples and current probe to within ± 5 percent when the test samples were mounted on the temperature-control finger. Laterally, the beam-current density was approximately 20 percent less near the edges than in the center. The lateral nonuniformity of beam-current density is due to the lenticular cross section of the beam under the action of the quadrupole lens. Since the current probe was mounted on the center line of the target area, it indicates the maximum value of the beam-current density.

Test Samples

Each type of commercial capacitor that was selected for testing had a rated capacitance of 0.01 μF. This particular value of capacitance was arbitrarily chosen. Because of limited time, extensive tests on a variety of capacitances could not be made. One sample of each type of capacitor was taken apart in order to determine the internal construction. The polyethylene terephthalate commercial capacitor was cylindrical in shape, with a base diameter of approximately 0.3 centimeter and a length of about 1.1 centimeters. The capacitor consisted of two superimposed polyethylene terephthalate strips, each 0.0064 mm (1/4 mil) thick and 68.6 centimeters long. Each strip was vapor deposited with aluminum over two-thirds of the width of the strip, and the resulting one-third overlap of aluminum vapor deposit in the center of the strips provided the two plates of the capacitor. The strip was wound to about 120 turns, and each end of the strip was in contact with the external leads through a conducting glue. A single layer of plasticized paper, 0.0762 mm (3 mils) thick, provided the outer wrap of the capacitor. The ceramic commercial capacitor was found to consist of four metal plates embedded in ceramic dielectric material. The sample measured 0.6 centimeter by 0.6 centimeter by 0.08 centimeter thick. The samples that were tested were chosen for similarity in capacitance dissipation and resistance values (usually several thousand megohms), as well as for their closeness to the commercially stated values of capacitance (0.01 μF). A simple commercial polystyrene capacitor was also tested. The polystyrene capacitor consisted of two layers of polystyrene, 0.0254 mm (1 mil) thick, alternated with a vapor deposit of aluminum. The resulting sandwich was rolled into a cylinder having a diameter of 0.8 centimeter and a height of 1.9 centimeters. The various capacitors were either mounted on the electrical feedthrough plate or glued to the temperature-control finger (fig. 2) with a silicone-based glue or a silver paint. Tests indicated that the silicone-based glue had a negligible effect on the results.

The insulated wires were also mounted either directly on an electrical feedthrough plate or on the temperature-control finger. The ribbon wire consisted of two flat copper wires surrounded and electrically insulated by polyethylene terephthalate. The dielectric in the two samples tested was approximately 20.3 centimeters long, 0.8 centimeter wide, and 0.0762 mm (3 mils) thick. One strip of the ribbon wire was coiled and mounted to the electrical feedthrough plate, and another strip was attached to the temperature-control finger with silicone glue. (See figs. 3(a) and (b).) Two lengths of

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polytetrafluoroethylene insulated wire were twisted about each other and formed into a circle having a diameter of approximately 5 centimeters (fig. 3(c)) to insure that all the wire was in the beam. The insulated length of the wires was 53.3 centimeters and the coating was approximately 0.1905 mm (7.5 mils) thick. Similarly, two lengths of polypyromellitimide insulated wire were twisted and formed into a circle approximately 4 centimeters in diameter. (See fig. 3(d).) Almost the entire 38-centimeter length of each wire was coated with polypyromellitimide insulation 0.0254 mm (1 mil) thick. Both the polytetrafluoroethylene and polypyromellitimide insulated wires were mounted to electrical feedthrough plates.

With the exception of the polyethylene terephthalate insulated capacitor, the specially prepared flat sandwich capacitors were made by gluing the dielectric to two 5.1- by 7.6-centimeter aluminum plates, each 0.0254 mm (1 mil) thick, with a very thin layer of glue. The polyethylene terephthalate insulated capacitor had a vapor deposit of aluminum (25μ in. or 0.635 micron thick) on one side of the dielectric and an aluminum plate 0.0254 mm (1 mil) thick glued to the other side. A variety of dielectrics were obtained, each of the smallest thickness that was commercially and rapidly available: polyethylene terephthalate, 0.0064 mm (1/4 mil); regenerated cellulose, 0.0381 mm $\left(1\frac{1}{2} \text{ mils}\right)$; polypyromellitimide, 0.0254 mm (1 mil); polyvinyl alcohol, 0.0762 mm (3 mils); a copolymer of polyvinylidene chloride and polyvinyl chloride, 0.0127 mm (1/2 mil); mica paper, 0.0127 mm (1/2 mil); and methyl phenyl siloxane impregnated mica paper, 0.0190 mm (3/4 mil). Leads were glued to both aluminum plates with silver-loaded epoxy cement, and the test samples were bonded to the temperature-control finger with a silicone-based glue. (See fig. 4.)

Test Circuits

The samples that were tested were connected to an active detection circuit. Transients were detected as voltage pulses in these circuits.

In tests on the commercial capacitors, one plate of the capacitor was connected directly to ground. The other plate was connected either directly to a storage oscilloscope or first to the negative side of a battery (15 or 45 volts) and then to a storage oscilloscope (fig. 5). The readout circuit was completed to ground through the 1-megohm internal resistance of the oscilloscope. Since two samples each of the commercial polyethylene terephthalate and ceramic capacitors were tested simultaneously, two separate readouts were used.

In tests on the insulated wires, essentially the same circuit was maintained, except that a 0.01-μF capacitor was connected between the two wire segments external to the target chamber. (See fig. 6.) The capacitor was placed in the circuit in order to slow the recovery response of the transients so that they were compatible with the writing speed of the oscilloscope. A 45-volt battery was kept in series with the test specimen and the oscilloscope.

All tests on the specially prepared capacitors utilized a discriminator circuit connected to a direct-writing oscillograph with a flat response to

400 cycles per second. (See fig. 7.) The discriminator circuit accepted only positive pulses of 1.0 volt or greater and shaped them into a standard-size pulse which was transmitted to the oscillograph. No information on the size of the pulse was obtained other than the fact that the magnitude of all pulses was greater than 1.0 volt.

Photographs of the shape and size of many transients were taken with an open-shutter camera in combination with a fast oscilloscope (with a sweep speed as low as 0.1 μsec/cm and with a rise time of 12 nsec). The oscilloscope had a built-in signal delay of 0.25 μsec and was set to trigger the sweep circuits upon receiving a transient pulse greater than a given voltage. Sample photographs of pulses from most of the test components were obtained.

RESULTS AND DISCUSSION

General

Because of the amount and nature of the information obtained, results from each sample are presented separately. In addition, information on the nature of the transients is given. Table I lists all the samples tested along with some of the conditions under which the tests were carried out. It may be noted that the effect of electron dose rate on the number of transients was determined only for a few samples because of the large amount of time that must be expended to obtain data at low dose rates.

Nature of Transients

Sample photographs of the wave form of the transients were taken during the tests. Figure 8 shows typical oscilloscope traces. The pulse shapes were essentially of the same character regardless of the sample from which the pulses were obtained. The pulses are characterized by a very fast rise time (on the order of a few nanoseconds), followed by a relatively slow decay corresponding to the resistance-capacitance time constant of the circuit. (See fig. 8 for relative times.) Severe ringing was observed in the pulses obtained from many of the samples. This ringing is believed to be caused largely by inductance in the test samples; however, some contribution to the ringing may be due to imperfectly matched lines to the oscilloscope used in these measurements.

Both positive and negative pulses were obtained, and the following convention is used throughout this paper to designate whether pulses are positive or negative. If the direction of rise of the transient pulse was the same as the direction of rise of a pulse obtained from shorting the capacitor in the circuit shown in figure 5, then the pulse is designated positive. If the direction of rise of the transient pulse was opposite to that of a shorting pulse, it is designated negative. In the tests reported herein in which it was possible to observe positive and negative pulses simultaneously, the positive pulses far outnumbered the negative pulses.

In many of the test samples, the pulse heights of the transients exceeded the "impressed" battery voltage. Indeed, pulses having amplitudes as great as 6 volts were obtained from commercial polyethylene terephthalate insulated capacitors when there was no battery in the detection circuit. Thus, the observed transients cannot be explained on the basis of dielectric breakdown as a result of the combined effects of impressed voltage and radiation.

Instead, the pulses that were observed are believed to be due to the release of charges stored in the dielectric as a result of irradiation. Electrons impinging upon the targets are slowed down in the target and some are trapped in the dielectric material. (The mechanism of trapping and the subsequent discharge of the trapped charges is not well understood. This point is discussed at length in a later section of this paper.) After a sufficient charge density is built up within the dielectric material, an avalanche discharge is triggered, draining a portion of the charge to the detection circuit.

Polyethylene Terephthalate Commercial Capacitors

Two commercial capacitors which had polyethylene terephthalate as a dielectric were tested, and the circuit shown in figure 5 was used. The effects of incident electron kinetic energy, battery voltage, temperature, and electron dose rate on the number of transient pulses were obtained. These results are seen in figures 9 to 12. A relatively small number of negative pulses was obtained (less than 5 percent of the total number of pulses). In one sample 68 out of a total of 2803 pulses were negative, and in the other sample 144 out of a total of 2648 pulses were negative.

Effect of electron kinetic energy.- Incident electron kinetic energies were varied from 35 to 900 keV. The number of pulses obtained increased to a maximum between 40 and 80 keV and then decreased to zero as the energy was further increased. (See figs. 9 to 11.) This decrease in the number of pulses obtained at the higher energies corresponds to increased transmission through the test sample and, consequently, to less deposition of electrons in the dielectric.

Effect of battery voltage.- The effect of battery voltage on the number of pulses obtained over the range of incident electron kinetic energies (40 to 265 keV) was investigated twice during the experiment. The capacitors were mounted on electrical feedthrough plates and remained at room temperature (294° K). All pulses greater than 1 volt were counted. A 15-volt battery, no battery, and a 45-volt battery were put in series with the capacitor and oscilloscope in the first group of tests. The number of pulses for a fixed electron dose $\left(10^{14} \text{ e/cm}^2\right)$ as a function of energy is shown in figure 9. As may be seen, the number of pulses obtained in the two samples, as well as the variation in number as a function of battery voltage and kinetic energy, is different. This order of variation between ostensibly identical samples was found to be rather common throughout all the tests reported herein. The variation of the number of pulses with voltage is small when compared with other variables. A few negative pulses were obtained that were greater than 1 volt

in magnitude. The total number of negative pulses for figure 9(a) was 12 and the total for figure 9(b) was 2.

In order to check the repeatability of the data, this entire series of tests was rerun, and the results are shown in figure 10. Again, the same variability was observed between the two samples and between the different battery voltages. The total number of negative pulses for figure 10(a) was zero and the total for figure 10(b) was 78. A comparison of figures 9 and 10 indicates a substantial increase in the number of pulses recorded in the second set of tests at energies from 100 to 240 keV over the number of pulses recorded in the initial tests. This increase in the number of pulses may have been due to the variability in the response to radiation in these capacitors. Possibly, the increase may have been due to the dose received. After completion of the tests for which data are shown in figure 10, each sample had received a total dose of approximately 7×10^{15} e/cm^2.

Effect of temperature.- The effect of temperature was investigated by gluing the capacitors to the temperature-control finger and by conducting tests at liquid nitrogen (77° K) and hot water (363° K) temperatures. The temperature was monitored by a copper-constantan thermocouple attached to the finger just above the test samples. (See fig. 2(a).) The 45-volt battery was maintained in the circuit.

The number of pulses obtained for different incident electron kinetic energies was investigated, and the results are presented in figure 11. Included are curves obtained from runs at room temperature when the capacitors were mounted on electrical feedthrough plates. It is believed that these curves may be included even though the geometrical configurations are slightly different.

Figure 11 indicates that the number of pulses obtained at 363° K is markedly less than the number obtained at 77° K. At 363° K, no pulses were observed at electron kinetic energies greater than 85 keV; at room temperature (294° K), no pulses were obtained at energies above 155 keV; at liquid nitrogen temperature (77° K), pulsing continued up to incident electron kinetic energies of 600 keV. Both positive and negative pulses were obtained, with most of the negative pulses being obtained at the higher energies. These results indicate a profound effect of temperature on the number of pulses obtained from capacitors under electron irradiation, the lowest temperatures producing the greatest number of transient pulses.

Effect of dose rate.- A study was made of the effect of dose rate on the amount of pulsing in the polyethylene terephthalate capacitors. The samples were mounted on electrical feedthrough plates and irradiated at room temperature (294° K). Irradiation did not measurably change the temperature of the test sample. A 45-volt battery was used in the circuit. Three different dose rates were used: 3.2×10^{10} e/cm^2-sec, 3.1×10^9 e/cm^2-sec, and 3.1×10^8 e/cm^2-sec. At the two higher dose rates, a total dose of 10^{14} e/cm^2 was employed. At the lowest dose rate, a total dose of 1.7×10^{13} e/cm^2 was used. The kinetic energy of the bombarding electrons was 85 keV in each case. Figure 12 shows the dependence of the number of pulses on the dose rate for the

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two samples; both positive and negative pulses are included. The number of pulses obtained at a total dose of 1.7×10^{13} e/cm^2 is given for all three dose rates. The number of pulses for a total dose of 10^{14} e/cm^2 is given for the two higher dose rates. Figure 12 indicates that there is a substantial dose-rate effect at room temperature, particularly for dose rates below 10^9 e/cm^2-sec. However, some pulses might have been obtained had the sample that was tested at a dose rate of 3.1×10^8 e/cm^2-sec been given the same total dose $\left(10^{14} \text{ e/cm}^2\right)$ as in the other tests. The subject of dose-rate effects at temperatures other than 294° K is discussed more fully in a later section of this paper.

Polyethylene Terephthalate Insulated Ribbon Wire

All runs were conducted to a total dose of 10^{14} e/cm^2 at an average dose rate of 3.2×10^{10} e/cm^2-sec. The energy of the bombarding electrons was varied from 35 keV up to the energy for which no further pulses were obtained from the ribbon wire. All pulses that were counted were of 1-volt magnitude or greater. The circuit in figure 6 was used to detect the pulses; a 45-volt battery was used in this circuit.

In the first series of tests, a coiled sample of ribbon wire, 20.3 centimeters in length, was kept at room temperature (294° K) and mounted in the beam on an electrical feedthrough plate. Figure 13 shows the dependence of the number of pulses for a fixed dose on the incident electron kinetic energy. The maximum number of pulses was obtained at approximately 40 keV, and, subsequently, the number dropped as the energy was increased. This decrease in the number of pulses again corresponded to increased transmission of the electrons completely through the polyethylene terephthalate insulation and, consequently, less storage in the dielectric at the higher energies. Some negative pulses (a total of 12, all less than 4 volts) were observed.

In addition, it was observed that the ribbon wire pulsed with greater amplitudes at the lower energies (35 keV to 45 keV) than at the higher energies. This trend may be seen in the pulse-height profiles at different kinetic energies shown in figure 14. Pulse heights as great as 30 volts were obtained at a kinetic energy of 44 keV. It is believed that the pulse heights would have been much greater if it were not for the 0.01-μF capacitor in parallel with the 4-picofarad capacitance of the ribbon wire. Since the charge q is related to the capacitance C and voltage V by the equation

$$q = CV$$

the amplitude of a transient in volts is inversely proportional to the capacitance for a given amount of charge released. Thus, a transient generated in the low-capacitance ribbon wire would immediately be divided in voltage by the ratio of the total capacitance to the irradiated capacitance. Thus, if no external capacitance had been used and if sufficiently fast electronics had

been available, it is possible that very short pulses having amplitudes as great as 75 000 volts might have been observed.

In another series of tests, a different strip of ribbon wire, approximately 20.3 centimeters in length, was mounted to the control finger (fig. 3(b)) and was maintained at liquid nitrogen temperature. Fewer pulses were obtained in this configuration, although the same general features were observed in the data. (See fig. 15.) The peak number of pulses occurred between 40 and 60 keV with a subsequent decrease as the energy was increased. Because of different test configurations, nothing can be concluded about a temperature effect.

A pulse-height profile for several energies is seen in figure 16. No negative pulses were obtained. The greater amount of pulsing from the ribbon wire in comparison with that from the polyethylene terephthalate commercial capacitor was probably because the insulation on the wire had no shielding from the impinging electrons.

After tests were completed, the ribbon wire was closely examined with a microscope. Discharge patterns known as Lichtenberg figures were readily visible in the polyethylene terephthalate insulation. The tree-like paths of discharge terminated at the copper wires embedded in the polyethylene terephthalate.

Ceramic Capacitors

The next type of commercial capacitor that was tested had ceramic material as the dielectric. Two samples were mounted in the electron beam on electrical feedthrough plates (fig. 2(c)) and were irradiated at room temperature. Forty-five-volt batteries were kept in series with each capacitor and the oscilloscope (fig. 5). The capacitors were exposed to a total dose of 10^{14} e/cm^2 at a rate of 3.2×10^{10} e/cm^2-sec for each energy.

All pulses that were counted were positive and over 1 volt in magnitude. Figure 17 shows the number of pulses obtained for different incident electron energies in each capacitor. Again the typical curve showing the dependence of the number of pulses on incident electron kinetic energy was obtained. All pulses were less than 3 volts.

Polystyrene Capacitor

A single commercial polystyrene insulated capacitor was tested at a temperature of 297° K. The capacitor was mounted to the temperature-control finger (fig. 2(d)) by a silver-loaded epoxy glue, and the temperature was monitored by a thermocouple. The pulse-detection circuit was similar to that seen in figure 5; tests were made with a 45-volt battery in this circuit.

All pulses that were counted were positive and were 1 volt and greater in height. Figure 18 shows the effect of incident electron kinetic energy on the number of pulses. Each data point represents the number of pulses obtained for

a dose of 10^{14} e/cm^2. The rate at which the dose was delivered to the capacitor was approximately 3.2×10^{10} e/cm^2-sec. The shape of this curve is similar to that obtained from the other components tested.

Polytetrafluoroethylene Insulated Wire

All tests were conducted to a total dose of 10^{14} e/cm^2 at an average dose rate of 3.2×10^{10} e/cm^2-sec for each incident electron kinetic energy. The wires were twisted, mounted on an electrical feedthrough plate (fig. 3(c)), and irradiated at room temperature. Two series of tests were made. In the first series (configuration 1), one of the polytetrafluoroethylene insulated wires was connected to ground and the other to the battery and oscilloscope (fig. 6). In the second series of tests (configuration 2), the leads were reversed.

Figure 19 shows the effect of incident electron kinetic energy on the number of pulses for both configurations. Approximately four times as many pulses were obtained with configuration 2 as with configuration 1. There is no immediately apparent reason for this difference in the number of pulses obtained with the two electronic configurations. In each case, the peak number of pulses was obtained between 40 and 65 keV.

Figure 20 shows the pulse-height profile at several energies for both configurations. In figure 20(a) it can be seen that the largest pulses were obtained at the lowest energy (45 keV). Here, also, it appears that a large number of pulses were obtained because the insulation was not shielded.

Polypyromellitimide Insulated Wire

The effect of incident electron kinetic energy and electron dose rate on the number of pulses was studied in tests on polypyromellitimide insulated wire. Pulses were detected using the circuit shown in figure 6. The temperature of the test sample was irradiated at approximately 294° K. The total dose given the sample for each data point obtained was 10^{14} e/cm^2.

For the study of the effect of electron kinetic energy, the dose rate was 3.1×10^{10} e/cm^2-sec. A series of tests was made with two different readout configurations - one with the readout as shown in figure 6 and the other with the polarity of the battery shown in figure 6 reversed. The pulses that were obtained were between 1 and 2 volts negative. Relatively few pulses were obtained in comparison with the number obtained from both the polyethylene terephthalate and polytetrafluoroethylene insulated wires. Table II gives the results of tests on the polypyromellitimide insulated wire.

Three additional tests were made at a lower dose rate of 3.1×10^9 e/cm^2-sec with electrons having incident kinetic energies of 44 and 55 keV. In one test at 44 keV, the battery polarity was reversed from that shown in figure 6. No pulses over 1 volt in magnitude were obtained. Although relatively little data

were obtained, it appears that there might be a dose-rate effect. Further tests are necessary in order to yield any certainty. Regardless, this series of tests indicates that polypyromellitimide insulated wire would serve well in an electron-radiation environment.

Specially Prepared Flat Capacitors

General.- The specially prepared capacitors were attached to the temperature-control finger. (See fig. 4.) Readout of the data was accomplished through a discriminator circuit (fig. 7) which accepted pulses only over 1 volt and subsequently transmitted a shaped signal pulse to a direct-writing oscillograph. For tests determining the effect of incident electron kinetic energy on the number of pulses, the various capacitors were maintained at room (297° K) and liquid nitrogen (77° K) temperatures. The effect of dose rate on the number of pulses was observed in the specially prepared polyethylene tereph-thalate, polypyromellitimide, and silicone-impregnated mica-paper capacitors at various temperatures.

Regenerated cellulose.- Figure 21 shows the effect of incident electron kinetic energy on the number of pulses from the regenerated cellulose insulated capacitor at both room and liquid nitrogen temperatures. The number of pulses fell off rapidly as the kinetic energy was increased above 35 keV. The capac-itor was found to have bubbled severely as a result of the high vacuum and rad-iation and was partially delaminated from the aluminum cover plates.

Polypyromellitimide.- The effect of incident electron kinetic energy on the number of pulses from the polypyromellitimide capacitor is seen in fig-ure 22 for liquid nitrogen temperature. Very few pulses were obtained at the lower temperature, and no pulses were obtained at room temperature and at a dose rate of 3.1×10^{10} e/cm^2-sec. An additional test for an incident electron kinetic energy of 50 keV and at a dose rate of 3.1×10^9 e/cm^2-sec showed no pulses even at liquid nitrogen temperature. The total dose was 1.72×10^{14} e/cm^2.

Polyvinyl alcohol.- A large number of pulses was obtained from the poly-vinyl alcohol capacitor. Figure 23 shows the pulse dependence on the incident electron kinetic energy at two temperatures (297° K and 77° K). Apparently, because of the thickness of the dielectric (0.0762 mm or 3 mils), a large number of pulses was obtained at the higher energies. More electrons at higher ener-gies were stopped and stored in the dielectric because of its thickness. In this capacitor, the effect of temperature was most noticeable. Many more pulses at higher kinetic energies were obtained at 77° K. No pulses were obtained above 85 keV at 297° K, whereas, at 77° K, pulses were being obtained at a kinetic energy of 240 keV. Severe delamination, presumably due to radiation-induced gas evolution in a high-vacuum environment, occurred in this capacitor.

Copolymer of polyvinyl chloride and polyvinylidene chloride.- Two capaci-tors with a copolymer of polyvinyl chloride and polyvinylidene chloride as the dielectric were tested at 77° K and 297° K. Figure 24 shows the effect of the

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incident electron kinetic energy on pulsing for the two capacitors at liquid nitrogen temperature. No pulses were obtained at room temperature.

Mica paper.- Figure 25 shows the effect of electron kinetic energy on the number of pulses from the mica-paper capacitor at both liquid nitrogen and room temperatures. Relatively few pulses were obtained at either temperature. No pulses were obtained above 60 keV at 77° K.

Silicone-impregnated mica paper.- Very few pulses were obtained at 77° K from the mica-paper capacitor impregnated with silicone (methyl phenyl siloxane). No pulses were obtained in a single test at an incident kinetic energy of 35 keV and a temperature of 297° K. Figure 26 shows the effect of incident electron kinetic energy on the number of pulses.

An investigation of the effect of dose rate on the number of pulses was made next. Tests were performed at liquid nitrogen temperature. Two tests, one at an incident kinetic energy of 55 keV and the other at 65 keV, were conducted to a total dose of 3.28×10^{14} e/cm^2 at a dose rate of 3.1×10^{10} e/cm^2-sec. Two and five pulses, respectively, were obtained from the test capacitor in these tests. Another two tests were then made at a dose rate of 3.1×10^9 e/cm^2-sec in which the test at 55 keV was conducted to a total dose of 1.9×10^{14} e/cm^2 and the other test at 65 keV was to a total dose of 1.57×10^{14} e/cm^2. At this dose rate and at these energies, no pulses were obtained. Although the test was not conducted to a high enough total dose to yield real certainty, it appears that there may be a significant dose-rate effect in the silicone-impregnated mica paper.

Polyethylene terephthalate.- The effect of incident electron kinetic energy on the number of pulses obtained from the polyethylene terephthalate capacitor at 77° K is seen in figure 27. The number of pulses was at its maximum at approximately 40 keV and subsequently decreased with an increase in the electron kinetic energy. A relatively large number of pulses was obtained from the polyethylene terephthalate capacitor in comparison with the other specially prepared capacitors, even though it was considerably thinner (0.0064 mm or 1/4 mil).

The effect of dose rate on the number of pulses was also studied. The kinetic energy of the incident electrons was maintained at 55 keV. Tests were conducted at temperatures of 77° K, 297° K, and 363° K. At 77° K, dose rates of 3.1×10^7 e/cm^2-sec, 3.1×10^8 e/cm^2-sec, 3.1×10^9 e/cm^2-sec, and 3.1×10^{10} e/cm^2-sec were used to irradiate the target. For the lowest dose rate, the test was conducted to a total dose of only 8.1×10^{12} e/cm^2 as opposed to a total dose of 3.75×10^{13} e/cm^2 for the tests at higher dose rates. The number of pulses obtained from the test conducted to the lower total dose were prorated to what might be expected if the runs were conducted to a total dose of 3.75×10^{13} e/cm^2.

To check the validity of the proration, additional tests were made by using a dose rate of 3.1×10^9 e/cm^2-sec. One test was conducted to a total dose of approximately 8.0×10^{12} e/cm^2 and the other, to a total dose of 3.75×10^{13} e/cm^2. The prorated number of pulses as determined by a simple direct proportion (41 pulses) agreed closely with the number of pulses (41, 43, and 44) obtained for the higher total dose. A similar check on the validity of the proration was made for a dose rate of 3.1×10^8 e/cm^2-sec. Again the prorated number of pulses (41) agreed closely with the number obtained for the higher total dose (39).

Tests at 297° K and 363° K were conducted to a total dose of 3.75×10^{13} e/cm^2 with dose rates of 3.1×10^{10} e/cm^2-sec and 3.1×10^9 e/cm^2-sec. Results at the various temperatures for the different dose rates are shown in figure 28. At 77° K, there appears to be relatively little dependence of the number of pulses on the dose rate within the range of these tests. For the lowest dose rate at 77° K, the number of pulses decreases slightly from the number obtained at the higher dose rates. This decrease may be due solely to a statistical fluctuation in the number of pulses. It is also possible that this slight decrease is an indication of a dose-rate effect. At both 363° K and 297° K, there appears to be a significant dependence on the dose rate.

Comparison With Work on X-Ray Induced Conductivity

General.- It is believed that some correlation can be made between the results of the present experiment and the results of experiments on X- or gamma-ray induced conductivity in dielectric materials. (See refs. 8 to 10.) There exists some direct evidence that such a qualitative comparison can be made. It was found in reference 11 that capacitors having dielectrics of paper film and a terephthalate polymer underwent transient breakdowns below their rated voltage when irradiated with gamma rays; however, dose rates as high as 2×10^{10} rads/second were necessary to initiate the breakdowns.

Even though the same problems are not involved in electron and electromagnetic radiations, the basic processes that occur are believed to be similar - particularly, the behavior of charge carriers that are produced as a result of either type of radiation. A physical model of these processes has been described in reference 8, along with results of an experiment concerned with the X-ray induced conductivity in dielectric materials. A brief summary of some of that work is presented here.

X-ray conductivity experiment: The behavior of charge carriers in an applied electric field is measured as a radiation-induced current. In particular, the experiment described in reference 8 has shown that the leakage current increases abruptly upon commencing radiation and then quickly reaches a steady-state level of conduction. The steady-state value of the radiation-induced current is dependent on the dose rate; that is,

$$I \propto R^\triangle$$

where I is the radiation-induced current, R is the dose rate, and Δ is a quantity characteristic of the material and whose value generally lies between 0.50 and 1.00.

After irradiation is stopped, the induced current decreases quickly at first and then decays more slowly to the value of the static, or dark, current. From the essentially hyperbolic current decay, a characteristic time constant can be determined for each dielectric material. From the investigation reported in reference 8 values for Δ and the current decay time constant for several materials have been obtained experimentally at a temperature of 293° K. Some results of this investigation are reproduced in table III. It may be noted that those materials with long decay time constants generally have values of Δ close to 0.50 and those materials with short decay times have values of Δ close to 1.00.

Physical model: Free electrons, many of which may have thermal energy, are produced in a dielectric as a result of irradiation. These conduction electrons may become trapped in local electrostatic potential sites, or traps, from which they are later thermally released back into conduction levels, thus giving rise to time constants which may be very long. These traps are assumed to be accessible only to electrons in the conduction levels, and the electrons are released again only into conduction levels. The presence of a large number of traps would decrease the number of electrons available for conduction. For many dielectrics, the concentration of traps necessary to explain their low

static conductivities is 10^{13} to 10^{20} traps/cm^3. By analogy with crystal phosphors, the retention times of electrons in traps of a depth of 1 eV may be expected to be 10^3 seconds and as long as 10^7 seconds for 1.5-eV traps.

The electron-band model of conduction is applied to dielectrics (even though some are completely amorphous) since it suggests a continuous distribution of traps. If a particular distribution of traps is assumed, a characteristic Δ can be calculated. For example, if a uniform distribution of traps below the conduction band to a certain depth is assumed, the value of Δ is found to be 1.00. If an exponential distribution in depth is assumed, the value of Δ is found to be 0.50. Hence, some idea as to a possible distribution of traps in various dielectrics can be obtained if Δ is experimentally determined.

Comparison.- In the present experiment, it may be noted that those materials (polyethylene terephthalate, polytetrafluoroethylene, and polystyrene) that pulsed rapidly and with large amplitudes are those which reference 8 has shown to possess comparatively long decay time constants (table III). Further, those materials (mica paper and silicone-impregnated mica paper) that pulsed relatively little are related to a material (mica) that was shown in reference 8 to have a short time constant. These results may be very significant. These results tend to indicate that X- and gamma-ray conductivity experiments may provide a good screening test for determining the relative susceptibility of various dielectrics to electron-radiation-induced transient effects.

Such tests may be desirable since they require far less and simpler equipment and instrumentation than necessary to obtain the present results. Indeed,

in certain cases, the needed data can be found in published literature. Consequently, such a screening test could be used to restrict future electron-irradiation tests to only those dielectric materials which appear to be promising for use in a radiation environment.

CONCLUSIONS

An investigation of the voltage pulses originating in various capacitors and insulated wires because of low-energy electron irradiation indicates the following conclusions:

1. Voltage pulses occurred in capacitors and insulated wires. These pulses were characterized by a very fast rise time (on the order of a few nanoseconds) and a subsequent decay corresponding to the resistance-capacitance time constant of the detection circuit.

2. The kinetic energy of the incident electrons has a profound effect on the number of pulses. As the incident kinetic energy was increased, the number of pulses either increased and subsequently decreased or simply decreased, depending on the sample tested. The decrease in the number of pulses as the energy increased was apparently due to greater transmission through and less deposition of electrons within the dielectric material.

3. The number of pulses obtained also varied considerably with temperature, irradiation at lower temperatures giving a greater number of pulses.

4. More than a simple conduction effect is involved since pulses were obtained with no battery in the circuit. Changes of battery voltage in the test circuit with the polyethylene terephthalate commercial capacitors seemed to have little effect on the number of pulses. The mechanism for the observed voltage pulses is believed to be the trapping and subsequent release of electrons from within the dielectric.

5. Lower dose rates appeared to lower the number of pulses obtained for a given dose from various test samples at temperatures of 294° K and above; however, in the specially prepared polyethylene terephthalate capacitor at a temperature of 77° K, the number of pulses obtained for a given total dose was not noticeably affected by lowering the dose rate from 3.1×10^{10} e/cm^2-sec to 3.1×10^7 e/cm^2-sec.

6. In tests on the polyethylene terephthalate and polytetrafluoroethylene insulated wires, the size of the voltage pulses was found to depend on the incident electron kinetic energy. Greater pulse heights were obtained at kinetic energies between 35 and 45 keV than at higher energies.

7. Very few transient pulses were observed to have originated within the polypyromellitimide and the silicone-impregnated mica paper. These materials would apparently serve best in capacitors and insulated wires that must be exposed to electron irradiation.

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8. Comparison with previous work appears to indicate that X-ray conductivity experiments may provide a good screening test for determining the relative susceptibility of various dielectrics to pulsing as a result of electron irradiation.

Langley Research Center,
      National Aeronautics and Space Administration,
          Langley Station, Hampton, Va., June 9, 1965.

APPENDIX

CONVERSION OF U.S. CUSTOMARY UNITS TO SI UNITS

The International System of Units (SI) was adopted by the Eleventh General Conference on Weights and Measures, Paris, October 1960, in Resolution No. 12 (ref. 6). Conversion factors for the units used herein are given in the following table:

Physical quantity	U.S. Customary Unit	Conversion factor (*)	SI Unit
Length . . . . . {	mil	2.54×10^{-5}	meter (m)
	inch	2.54×10^{-2}	meter (m)
Pressure	torr	1.33322×10^{2}	newtons per square meter (N/m^2)

*Multiply value given in U.S. Customary Unit by conversion factor to obtain equivalent value in SI Unit.

Prefixes to indicate multiples of units are as follows:

Prefix	Multiple
mega (M)	10^{6}
kilo (k)	10^{3}
centi (c)	10^{-2}
milli (m)	10^{-3}
micro (μ)	10^{-6}
nano (n)	10^{-9}
pico (p)	10^{-12}

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11. Compton, D. M. J.; and Poll, R. A.: Transient Radiation Effects. GA-4164 (Contract No. DA-49-186-ORD-939), Gen. Dyn., Apr. 12, 1963. (Available from DDC as AD No. 440292.)

TABLE I.- TEST SAMPLES AND PARAMETERS

Sample	Mounting	Parameter		
		Temperature, $^\circ K$	Incident kinetic energy range, keV	Dose rates, e/cm^2-sec
Commercial capacitors:				
Polyethylene terephthalate	Feedthrough, bucket	77, 294, 363	35 to 730	3.1×10^8, 3.2×10^9, 3.1×10^{10}
Ceramic	Feedthrough	294	35 to 150	3.2×10^{10}
Polystyrene	Bucket	297	100 to 1000	3.2×10^{10}
Insulated wires:				
Polyethylene terephthalate	Feedthrough, bucket	77, 294	35 to 210	3.2×10^{10}
Polytetrafluoroethylene	Feedthrough	294	35 to 210	3.2×10^{10}
Polypyromellitimide	Feedthrough	294	32 to 210	3.1×10^{10}, 3.1×10^9
Specially prepared capacitors:				
Regenerated cellulose	Bucket ⟶	77, 297	35 to 210	3.1×10^{10}
Polypyromellitimide		77, 297	35 to 110	3.1×10^{10}, 3.2×10^9
Polyvinyl alcohol		77, 297	35 to 240	3.1×10^{10}
Copolymer of polyvinyl chloride and polyvinylidene chloride		77, 297	35 to 210	3.1×10^{10}
Mica paper		77, 297	35 to 130	3.1×10^{10}
Silicone-impregnated mica paper		77, 297	35 to 110	3.1×10^7, 3.1×10^8, 3.1×10^9
Polyethylene terephthalate		77, 297, 363	20 to 250	3.1×10^9, 3.1×10^{10}

TABLE II.- RESULTS OF TESTS ON POLYPYROMELLITIMIDE

INSULATED WIRE

Incident kinetic energy, keV	Number of pulses for 10^{14} e/cm^2	
	With battery polarity as in figure 6	With battery polarity reversed
32	0	0
44	1	0
55	0	0
66	0	0
77	0	0
88	0	0
99	0	0
110	0	0
130	0	1
150	0	0
170	0	1
190	0	1
210	0	0

TABLE III.- VALUES OF Δ AND CURRENT DECAY TIME

CONSTANT FOR VARIOUS DIELECTRIC MATERIALS

[Obtained from reference 8]

Material	Δ	Time constant
Polytetrafluoroethylene	0.63	19 hours
Polyethylene terephthalate	.83	8.5 hours
Polystyrene	.65	13 hours
Polystyrene (United States sample)	.75	1800 seconds
Mica	.95	10 seconds
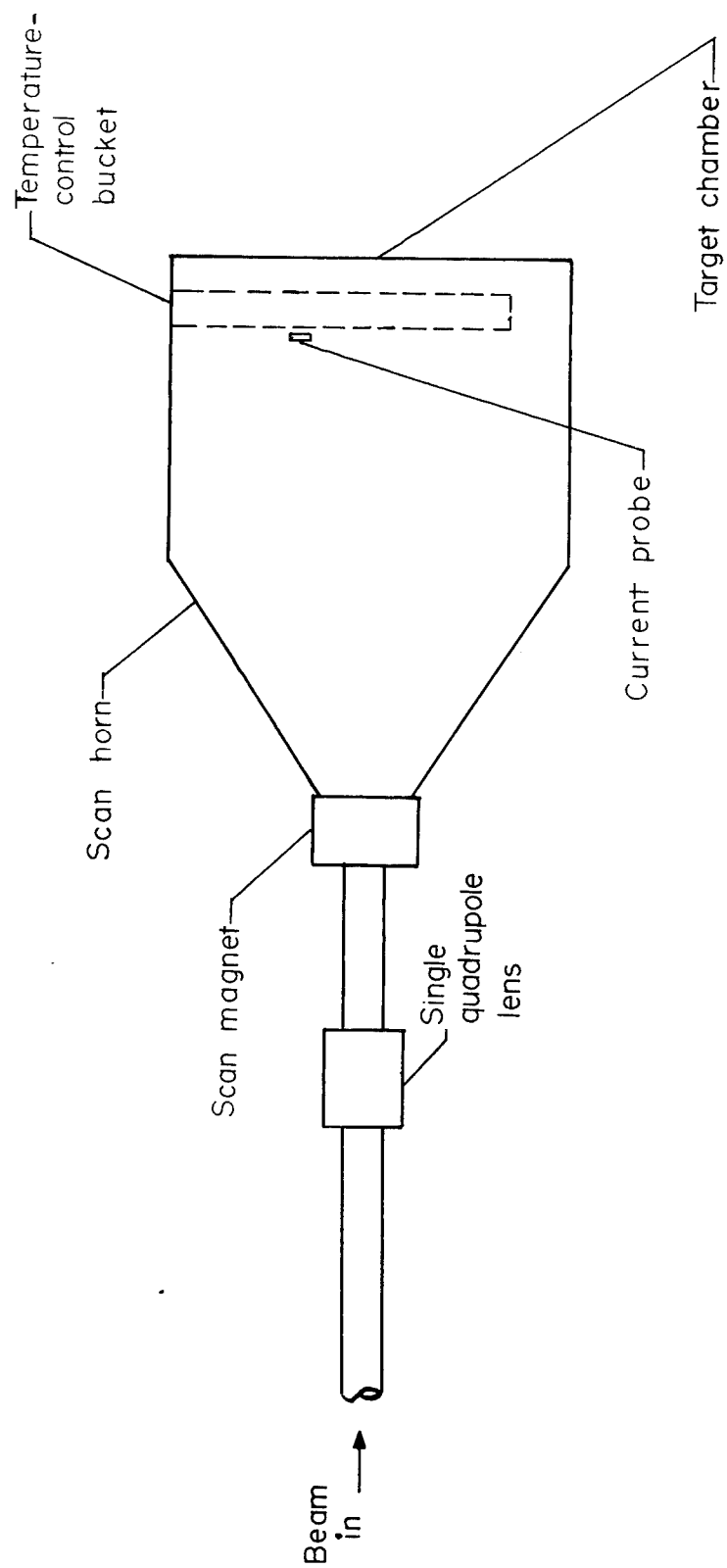
Figure 1.- Experimental arrangement for tests on capacitors and insulated wires.
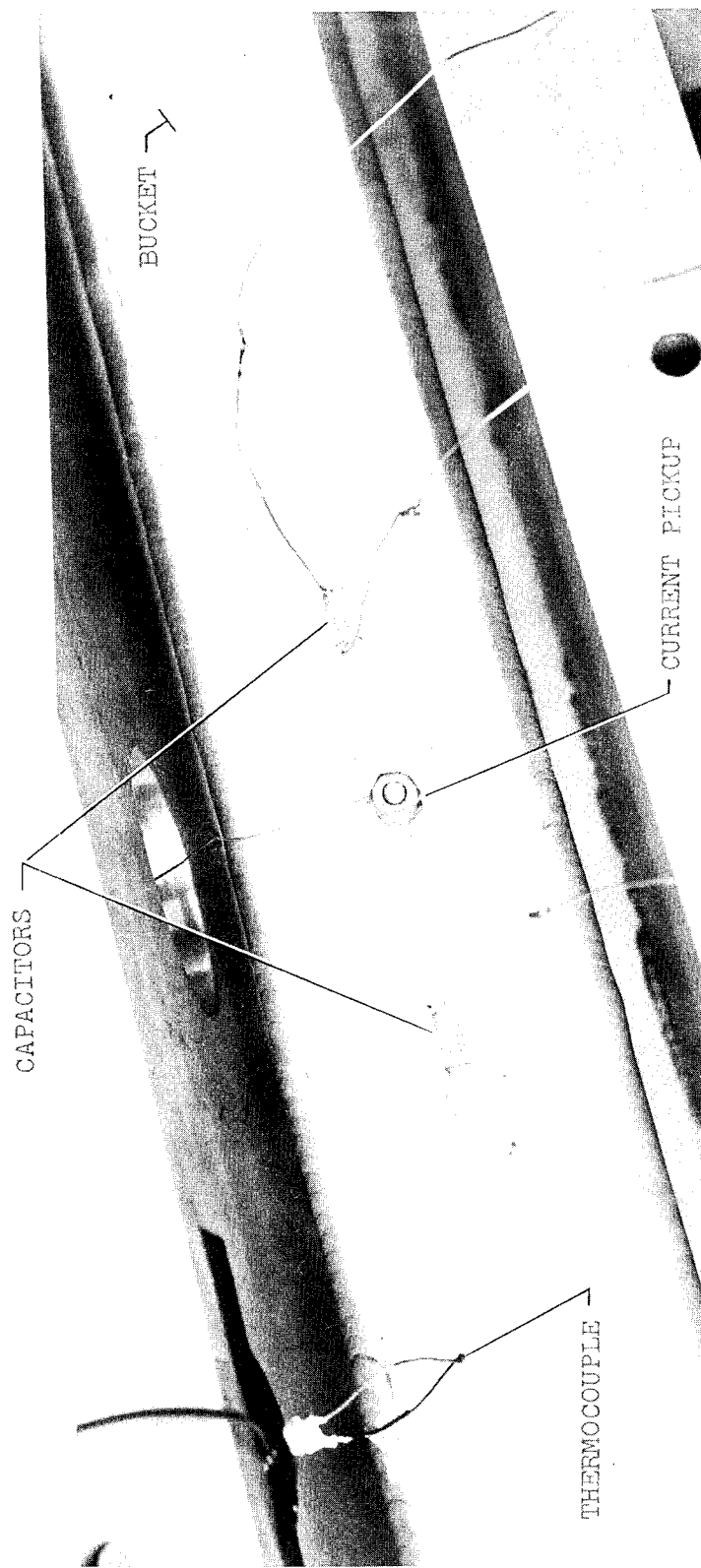
CAPACITORS

BUCKET

THERMOCOUPLE

CURRENT PICKUP

L-63-9720.1

(a) Polyethylene terephthalate insulated capacitor mounted on temperature-control bucket in target chamber.

Figure 2.- Commercial capacitor test samples.

23
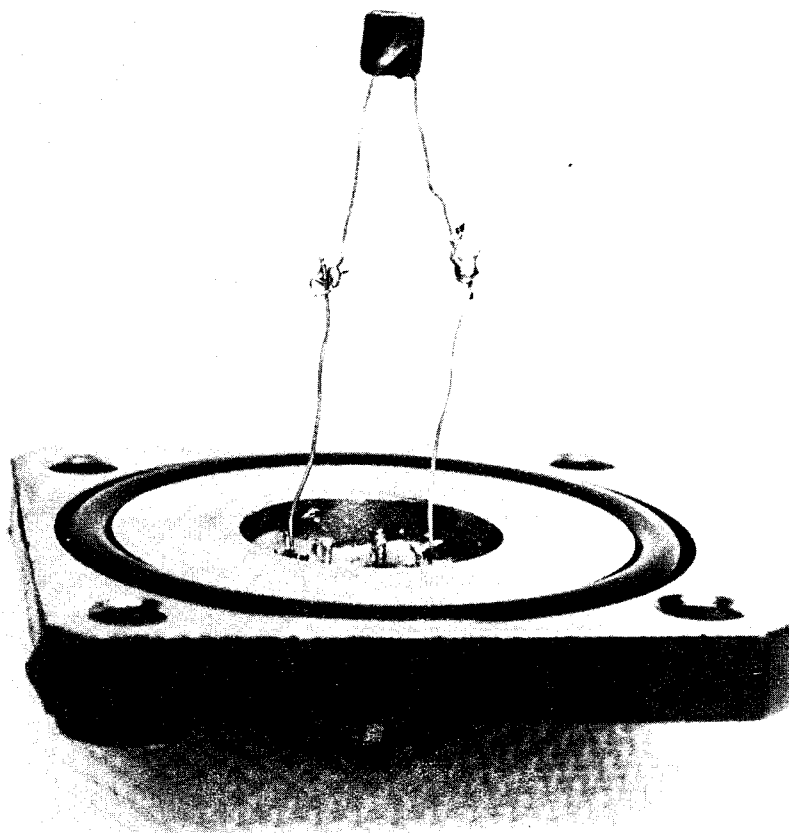
(b) Ceramic capacitor mounted to electrical feedthrough plate.

Figure 2.- Continued.
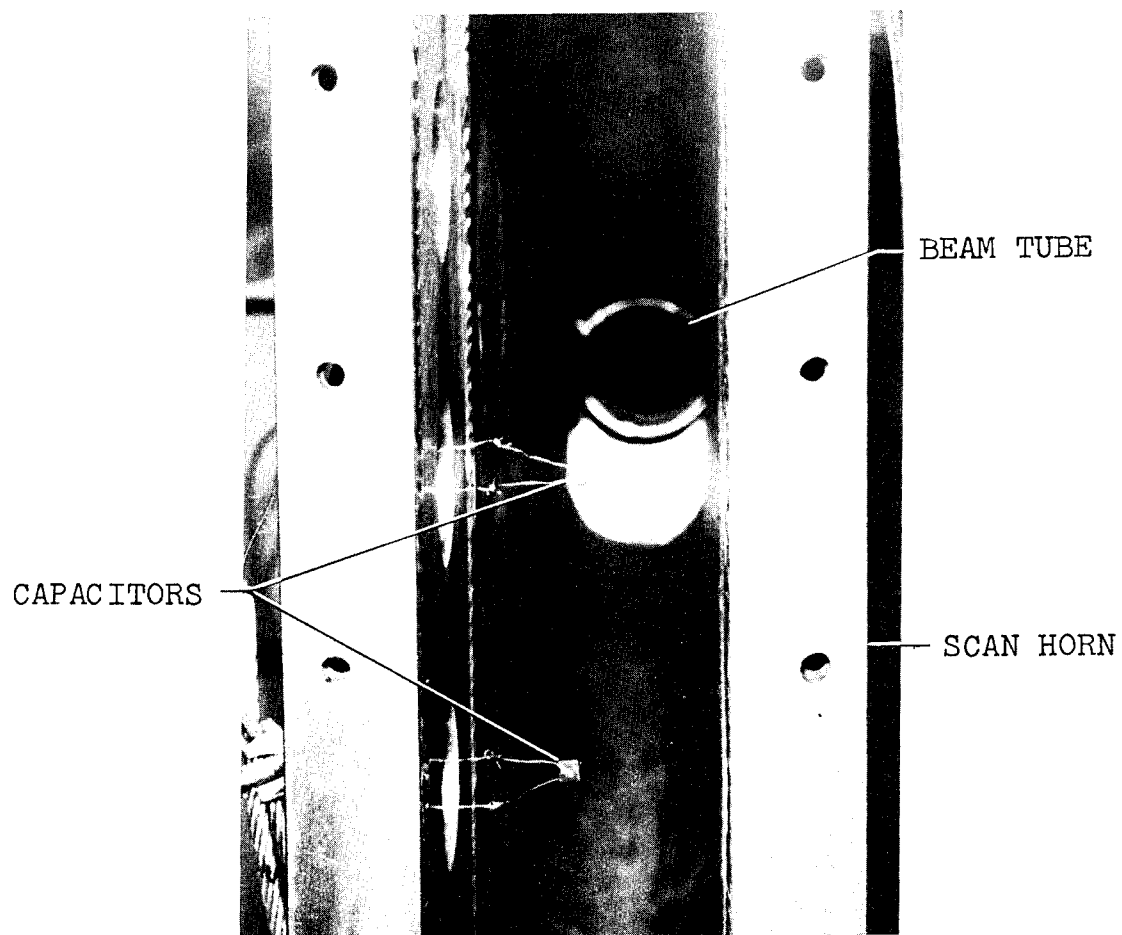
L-65-138
(c) Ceramic capacitor mounted in target chamber.

Figure 2.- Continued.

TARGET CHAMBER

CURRENT PICKUP

CAPACITOR

THERMOCOUPLE

BUCKET

INCHES
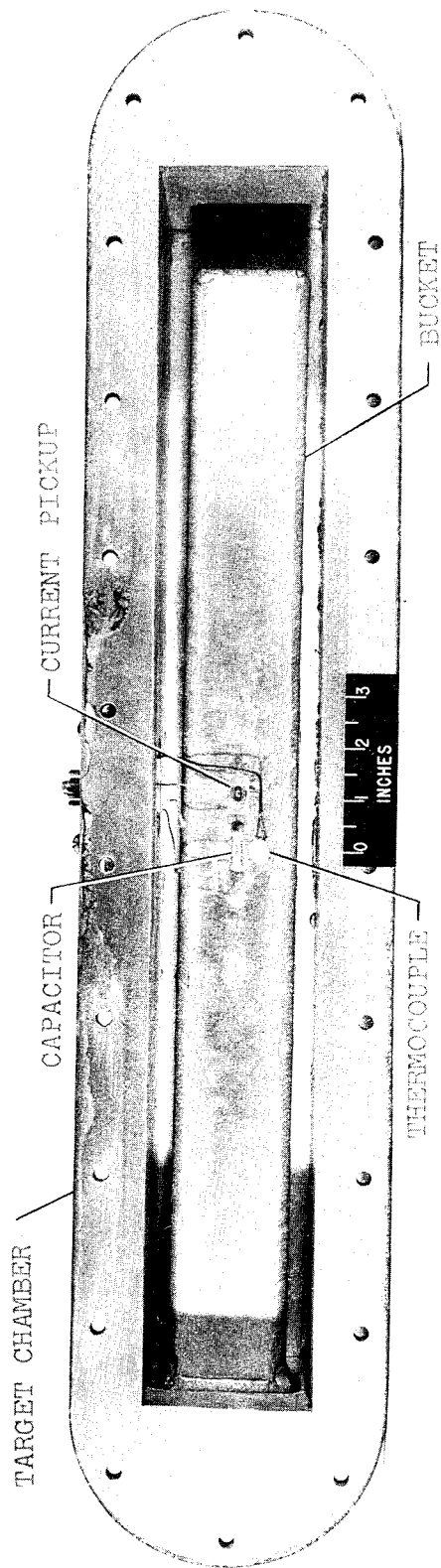
L-65-278.1

(d) Polystyrene insulated capacitor mounted on temperature-control bucket.

Figure 2.- Concluded.
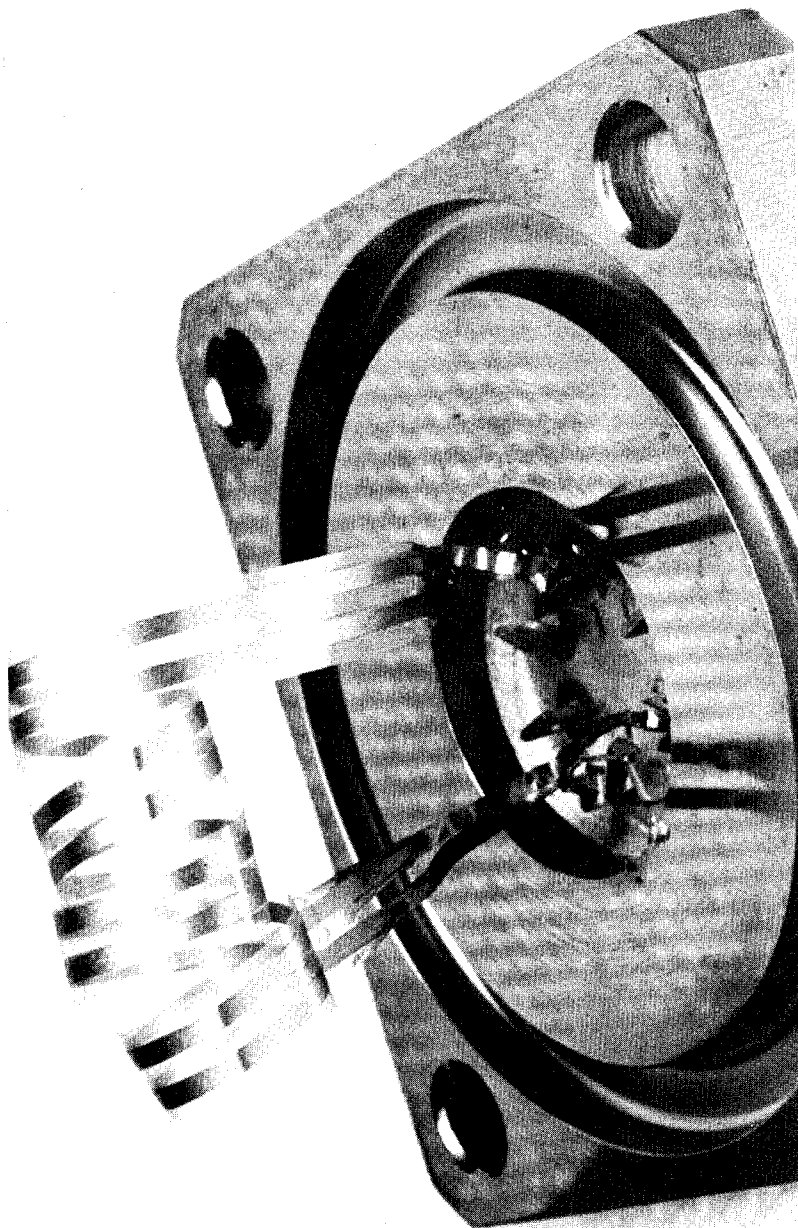
(a) Polyethylene terephthalate insulated ribbon wire mounted to electrical feedthrough plate.

Figure 3.- Insulated wire test samples.

27

CURRENT PICKUP

BUCKET

RIBBON WIRE

TARGET CHAMBER

INCHES
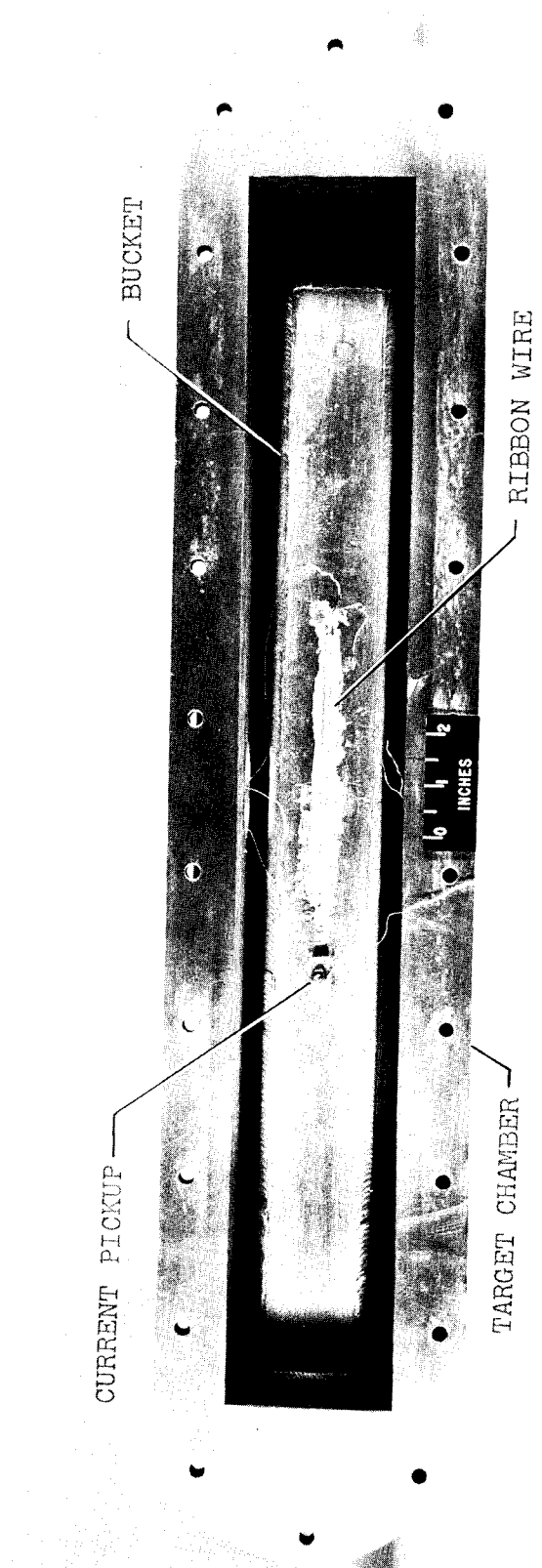
(b) Polyethylene terephthalate insulated ribbon wire mounted on temperature-control bucket.   L-64-8076.1

Figure 3.- Continued.

(c) Polytetrafluoroethylene insulated wire mounted to electrical feedthrough plate.
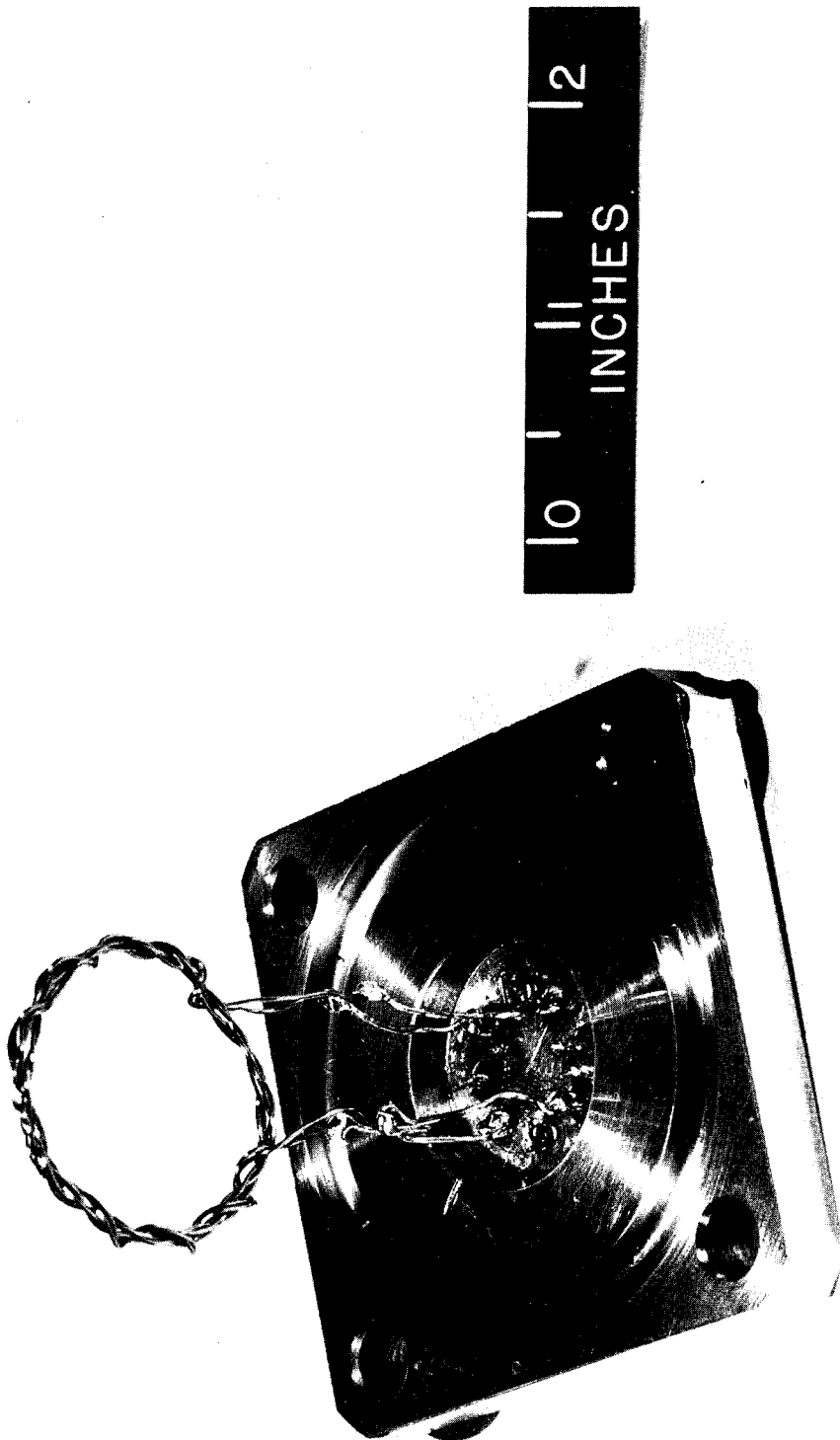
Figure 3.- Continued.

(d) Polypyromellitimide insulated wire mounted to electrical feedthrough plate.

Figure 3.- Concluded.

L-64-8851
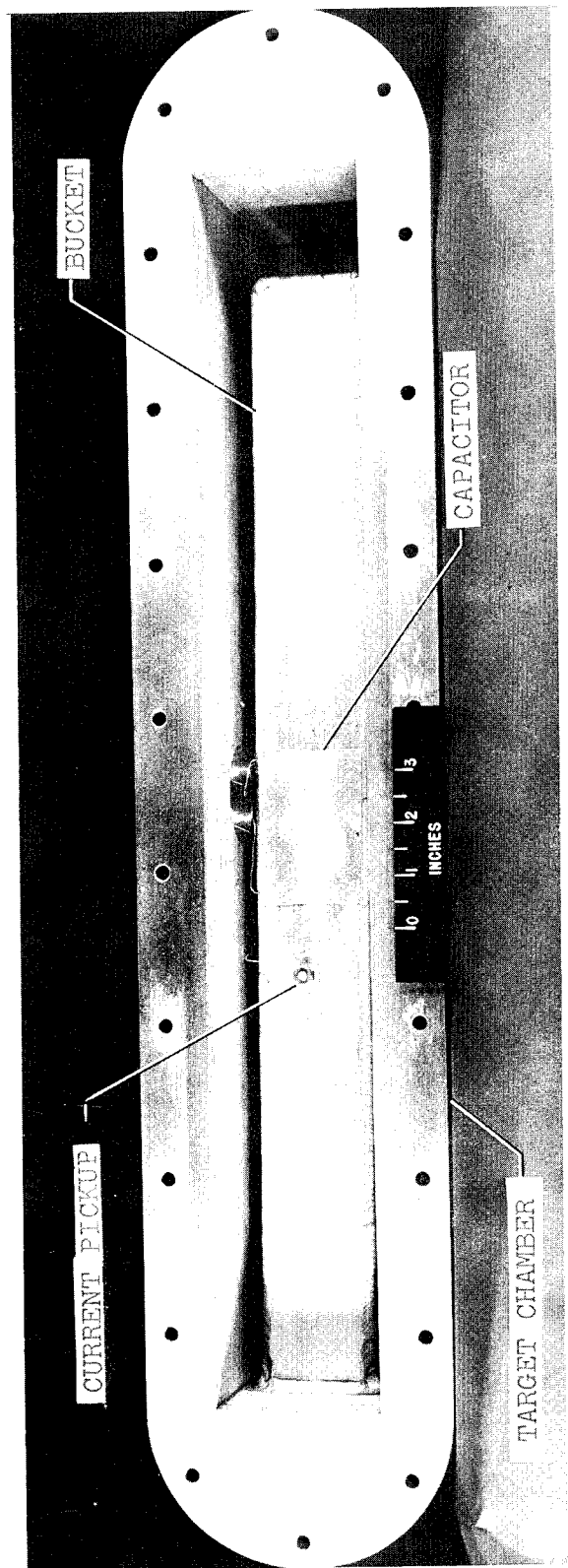
Figure 4.- Specially prepared capacitor mounted on temperature-control bucket.

L-64-3380.1

Sample
.01μF

Battery

1MΩ

Storage
oscilloscope
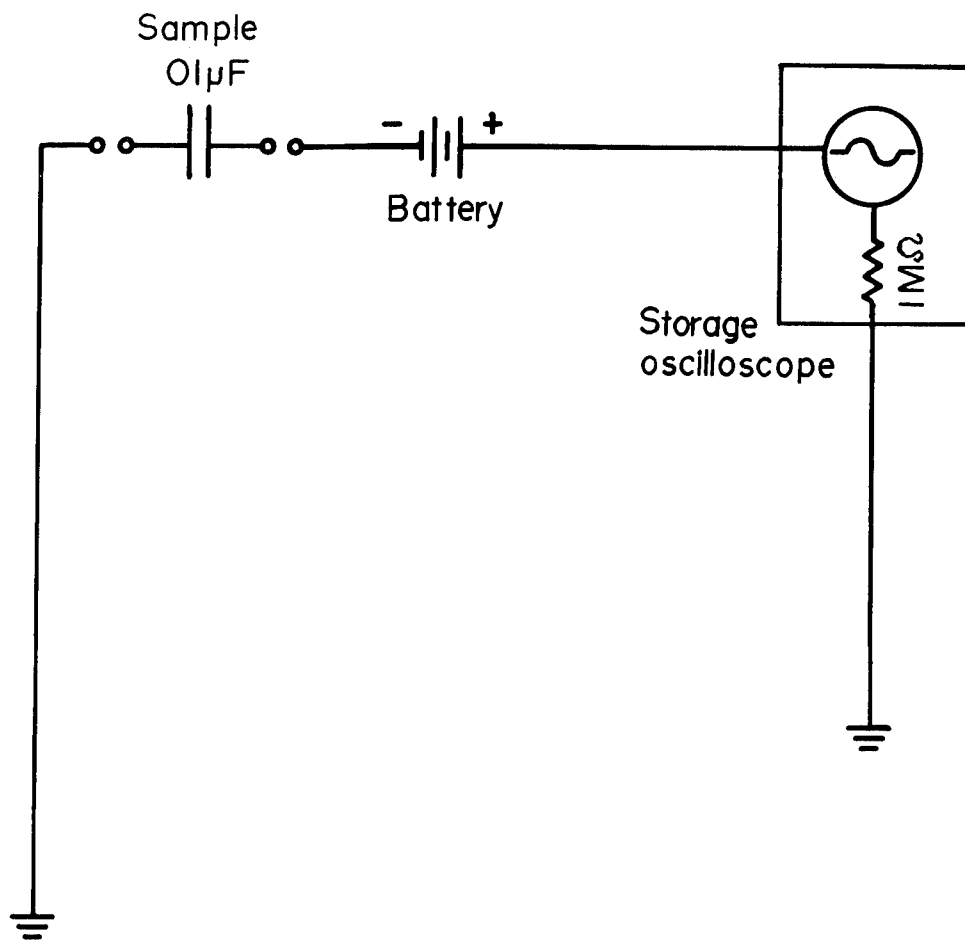
Figure 5.- Circuit used during commerical capacitor tests.
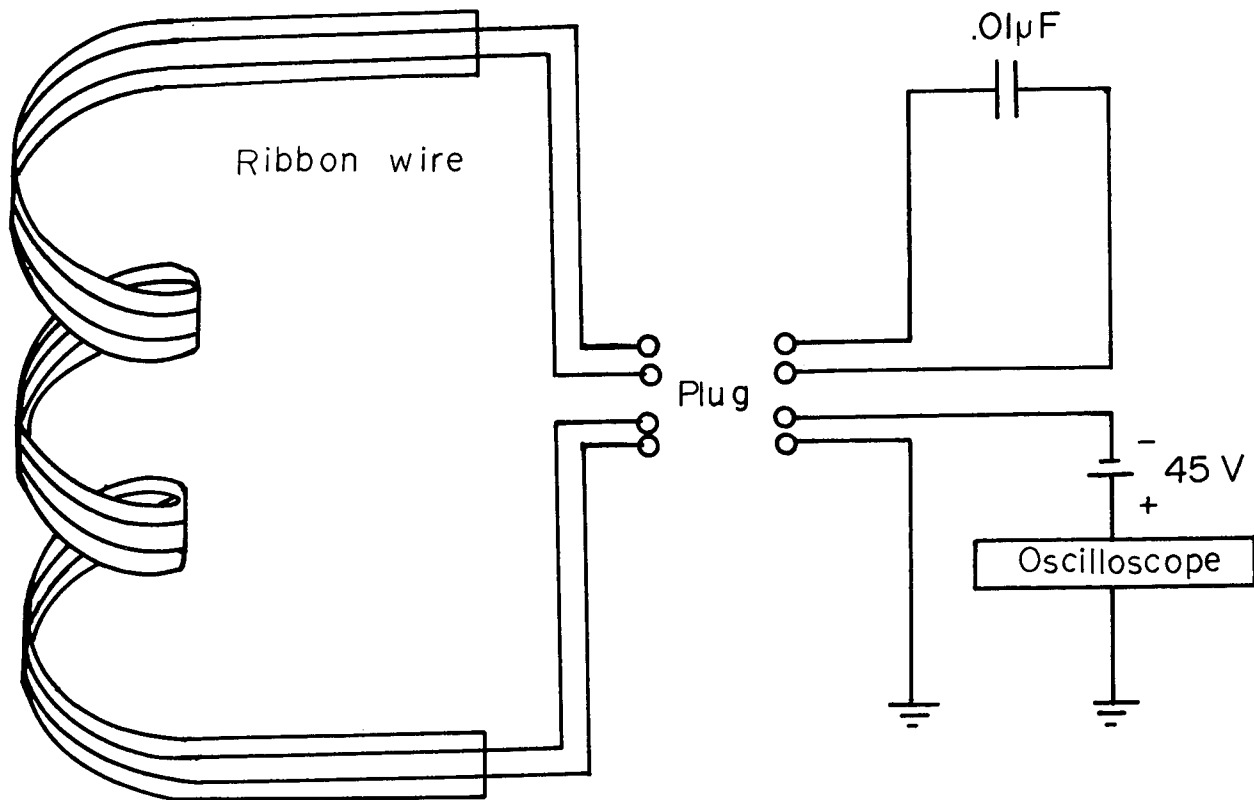
Figure 6.- Circuit used during insulated wire tests.
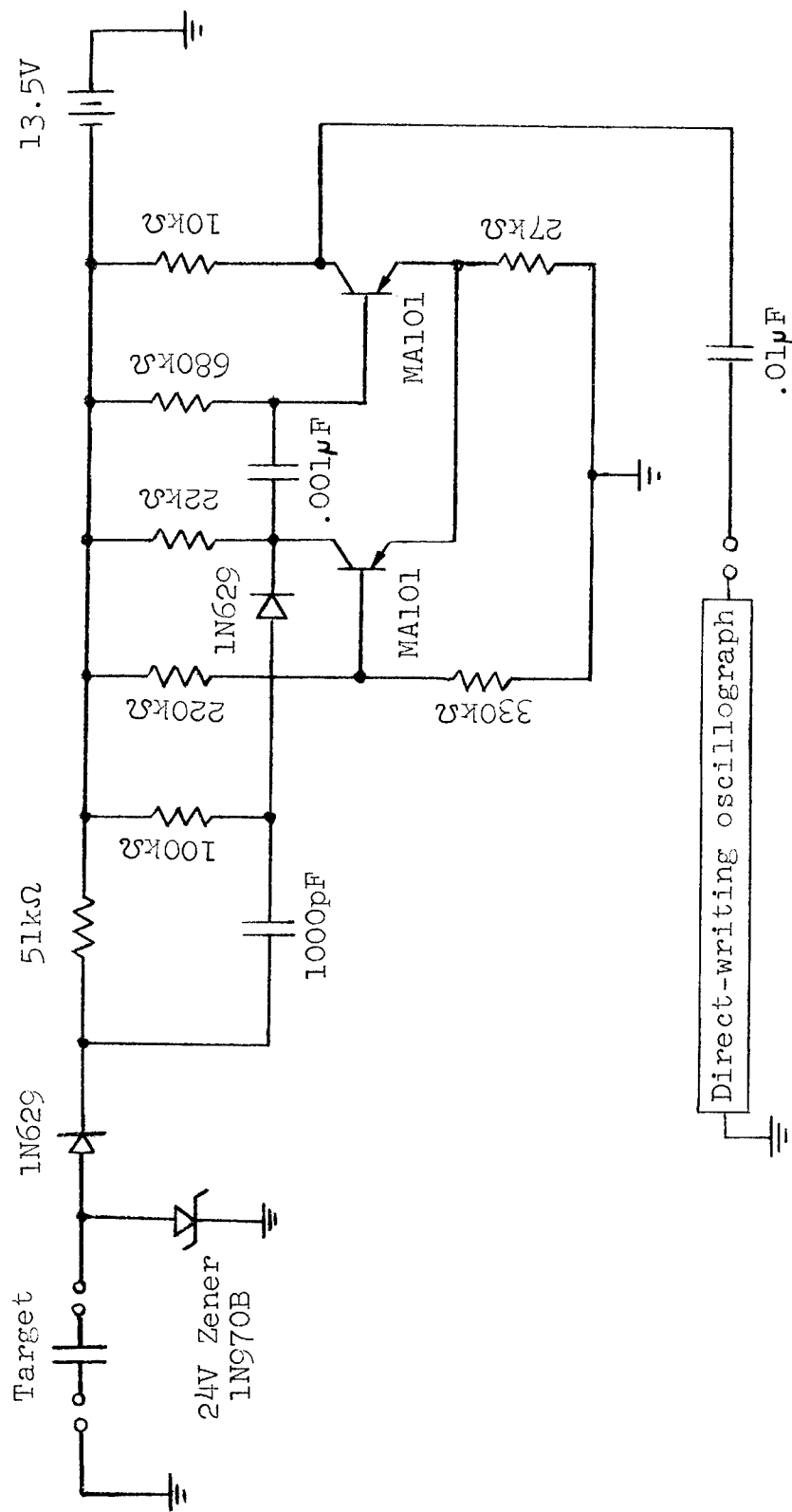
Figure 7.- Discriminator circuit used for recording pulses from specially prepared capacitors.
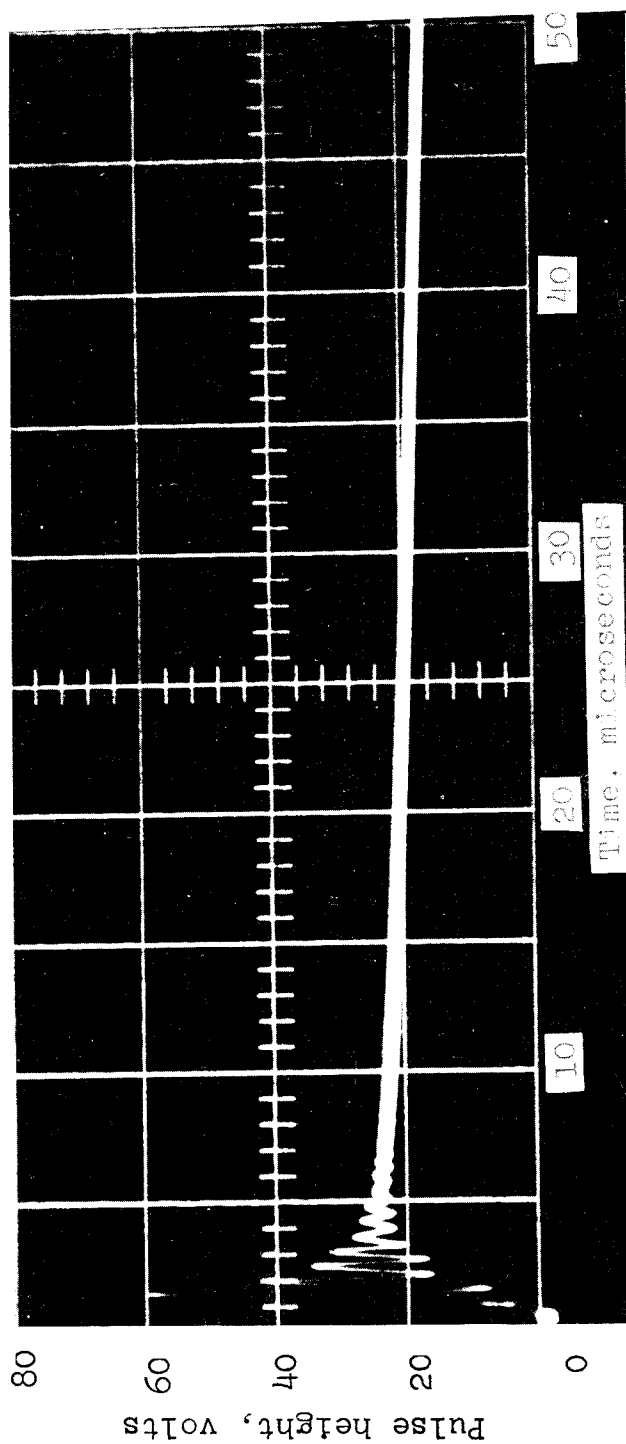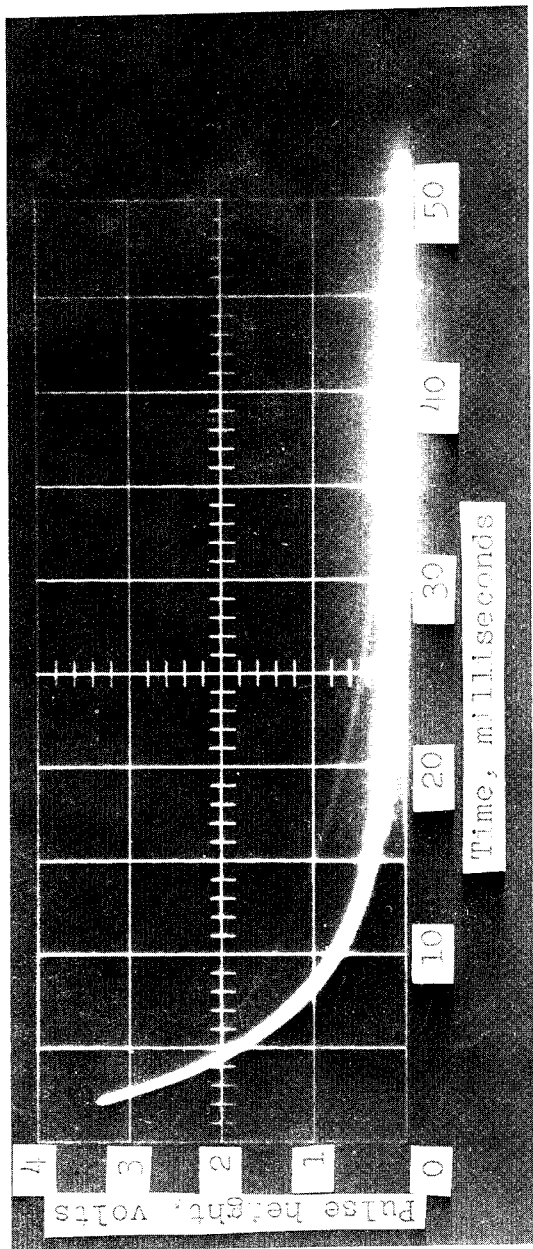
Figure 8.- Two typical pulse traces obtained from test samples.
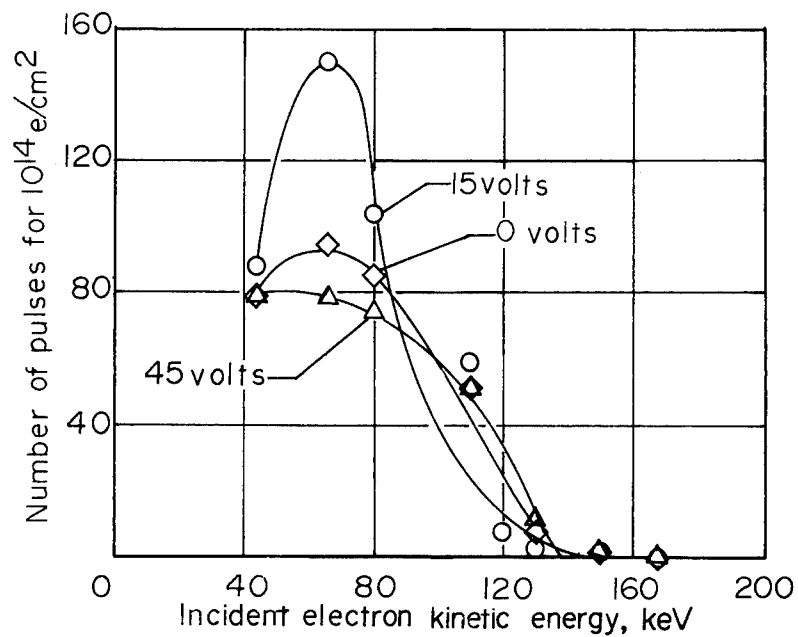
(a) Sample 1.
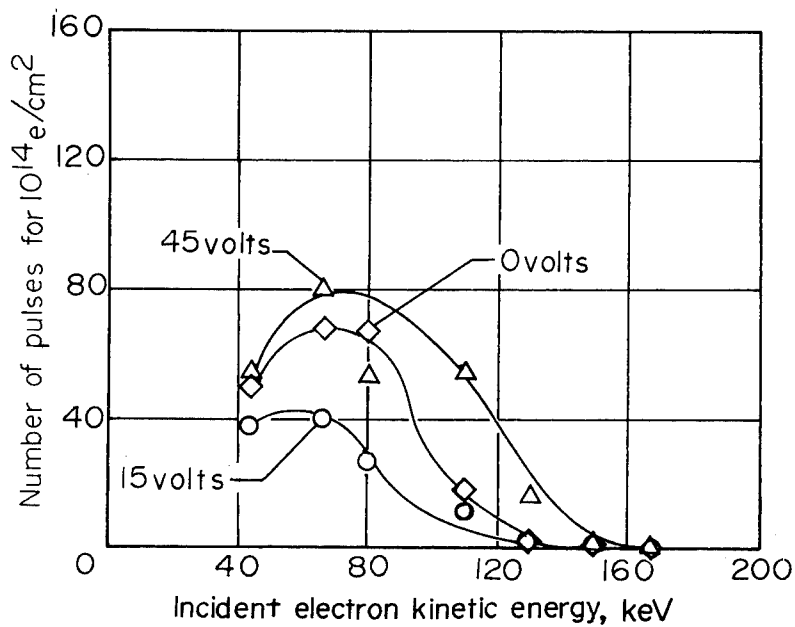
(b) Sample 2.

Figure 9.- Dependence of number of pulses on battery voltage over range of incident energies for two commercial polyethylene terephthalate insulated capacitors in initial series of tests. Dose rate = 3.2×10^{10} e/cm^2-sec at 294° K.
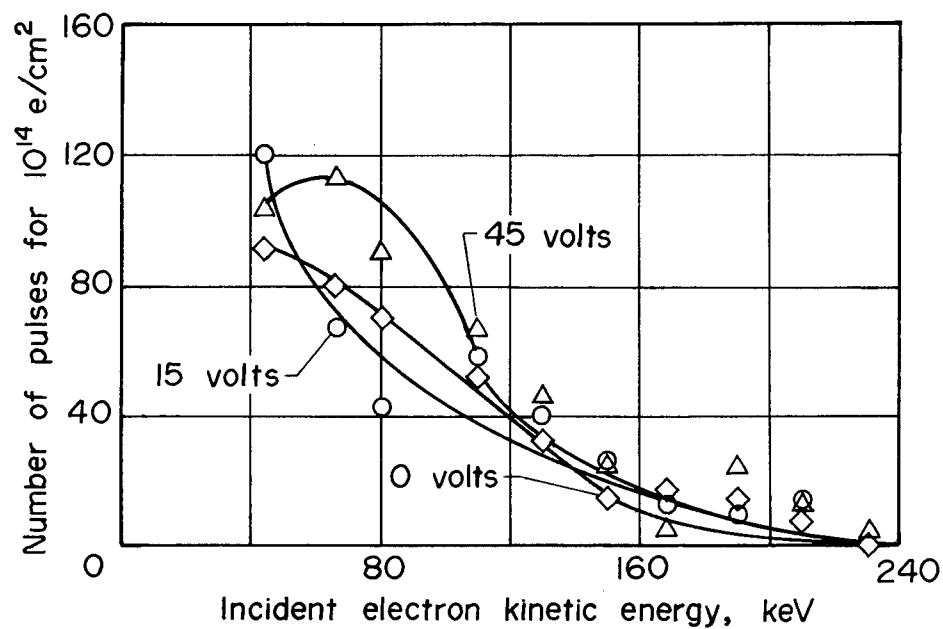
(a) Sample 1.
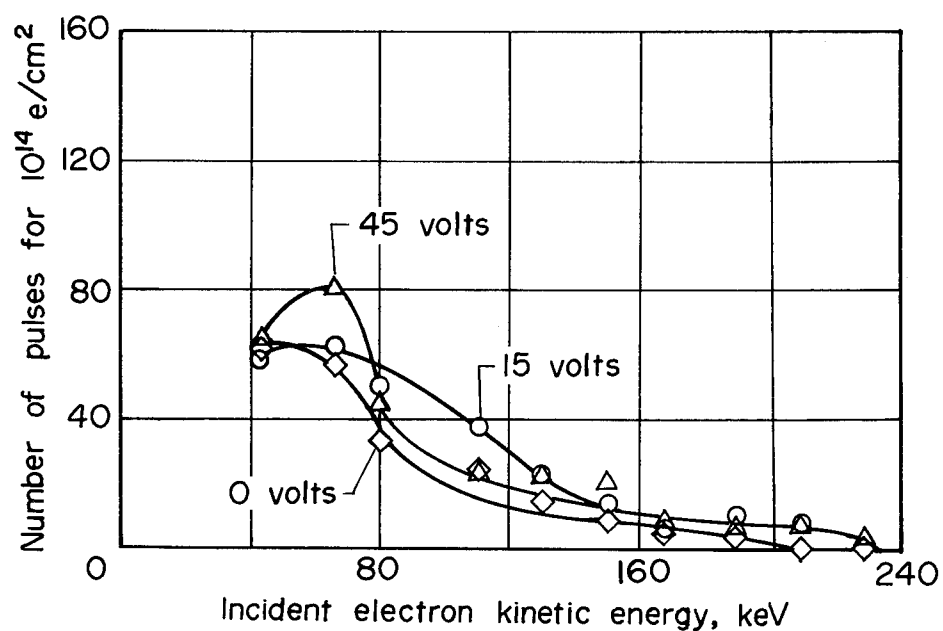
(b) Sample 2.

Figure 10.- Dependence of number of pulses on battery voltage over range of incident energies for two commercial polyethylene terephthalate insulated capacitors in second series of tests.   Dose rate = 3.2×10^{10} e/cm^2-sec at 294° K.
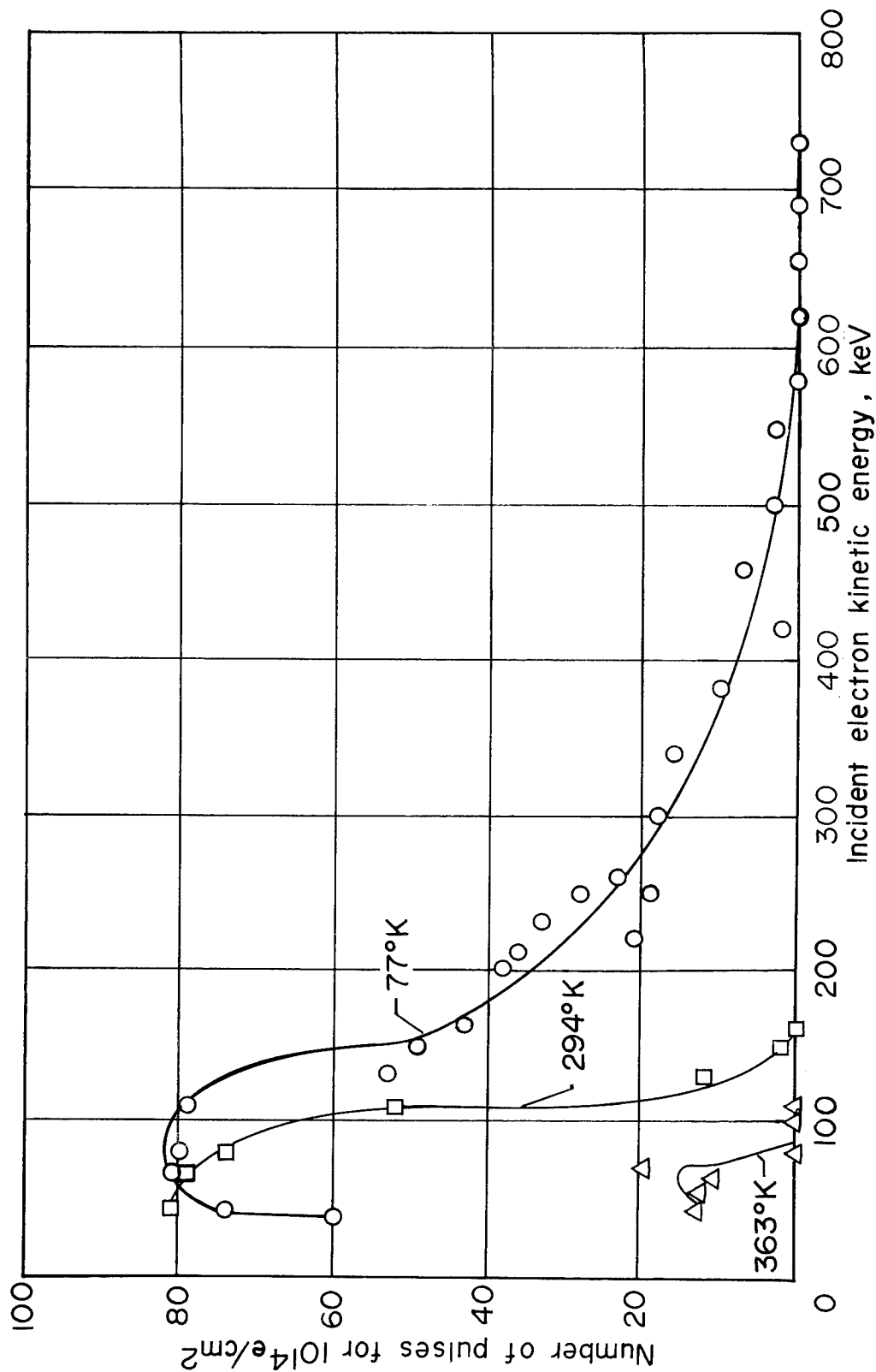
Figure 11.- Dependence of number of pulses on electron energy and temperature for two commercial polyethylene terephthalate insulated capacitors. Dose rate = 3.2 × 10¹⁰ e/cm²-sec. (Sample was mounted on feedthrough plate for tests at 294° K rather than on temperature-control bucket.)

(a) Sample 1.

Incident electron kinetic energy, keV

Number of pulses for 10^{14} e/cm²

77°K

294°K

363°K
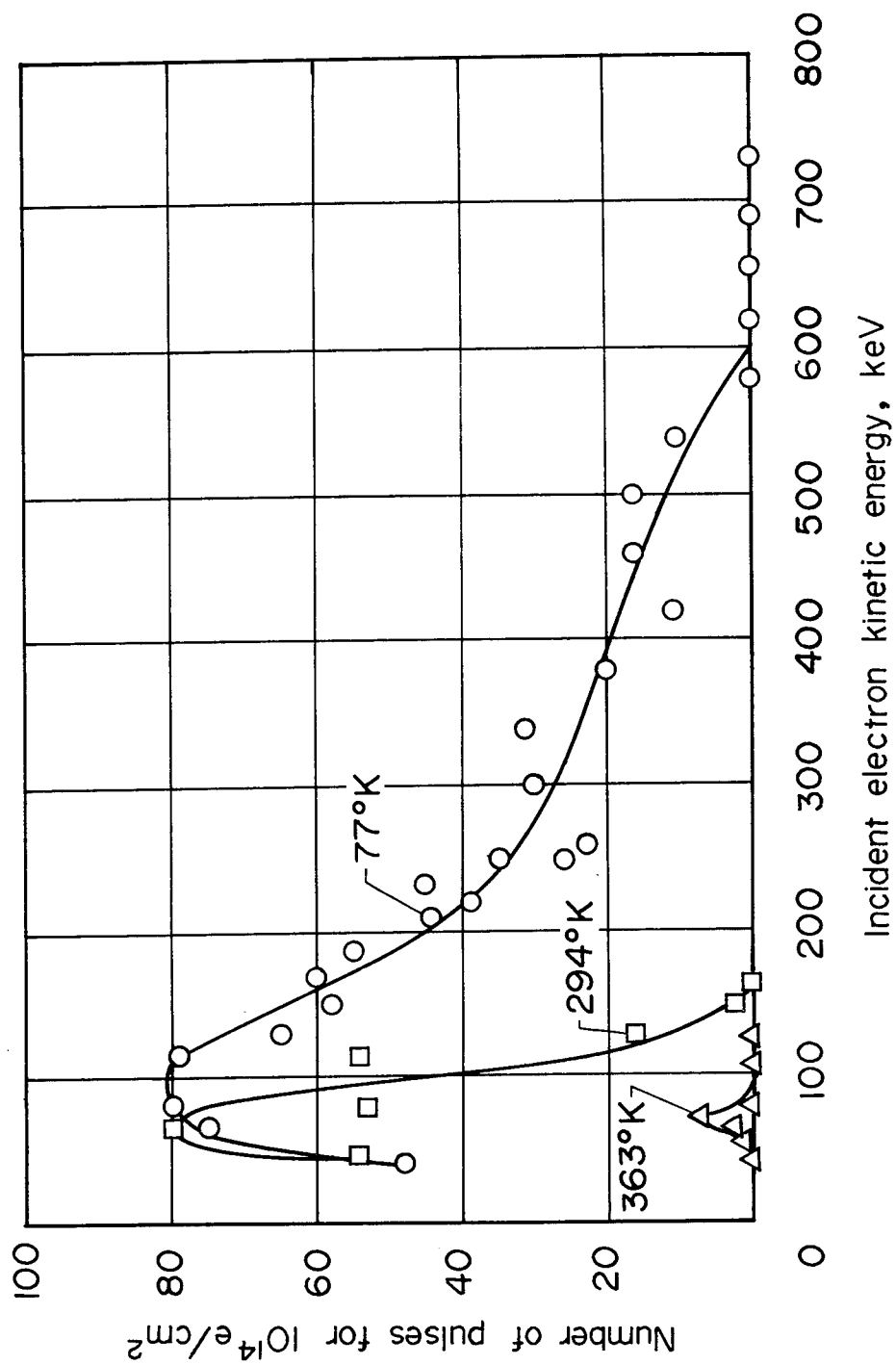
(b) Sample 2.

Figure 11.- Concluded.

39
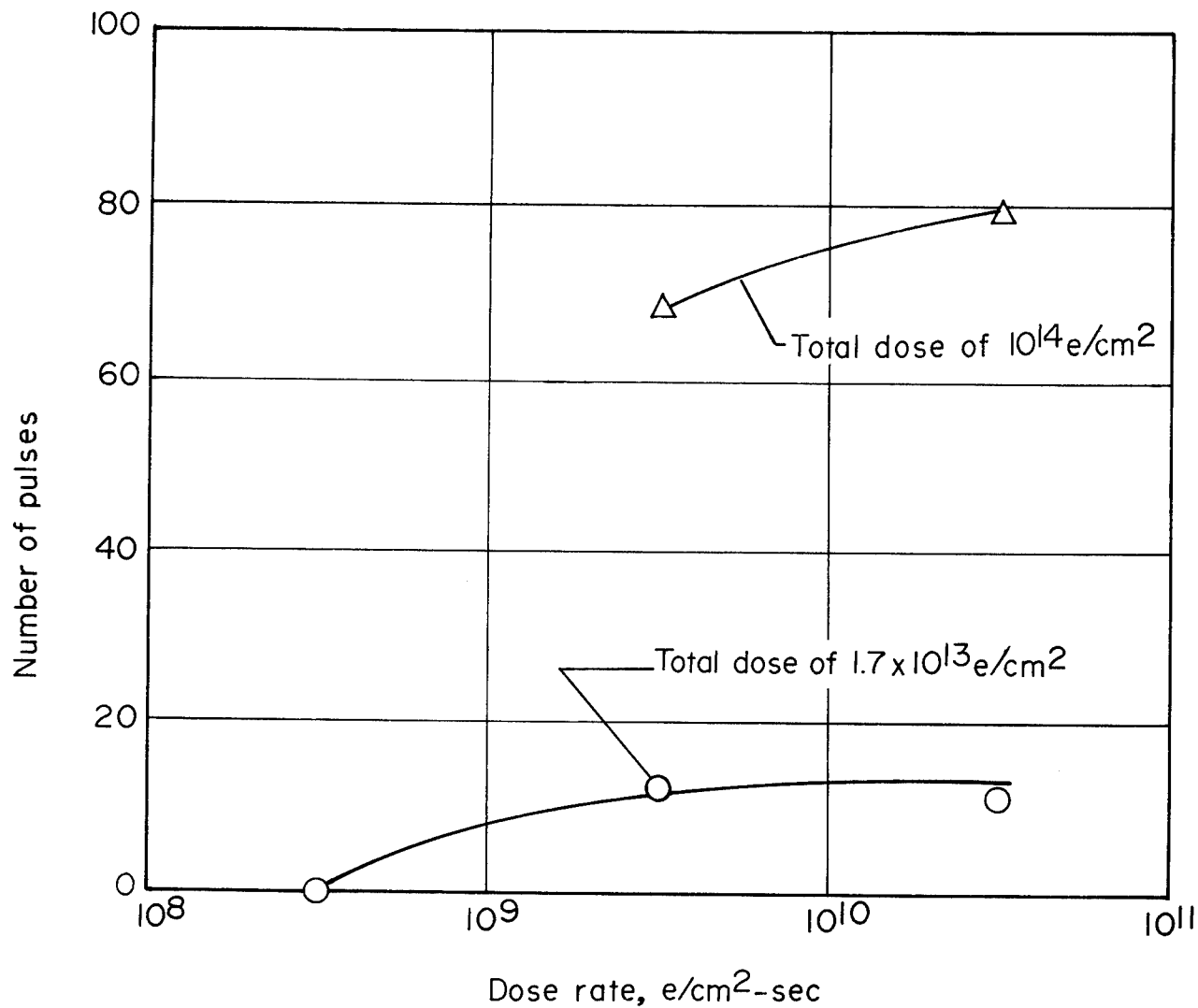
(a) Sample 1.

Figure 12.- Dependence of number of pulses on electron dose rate for two commerical polyethylene terephthalate insulated capacitors. Incident electron kinetic energy = 85 keV at 294° K.
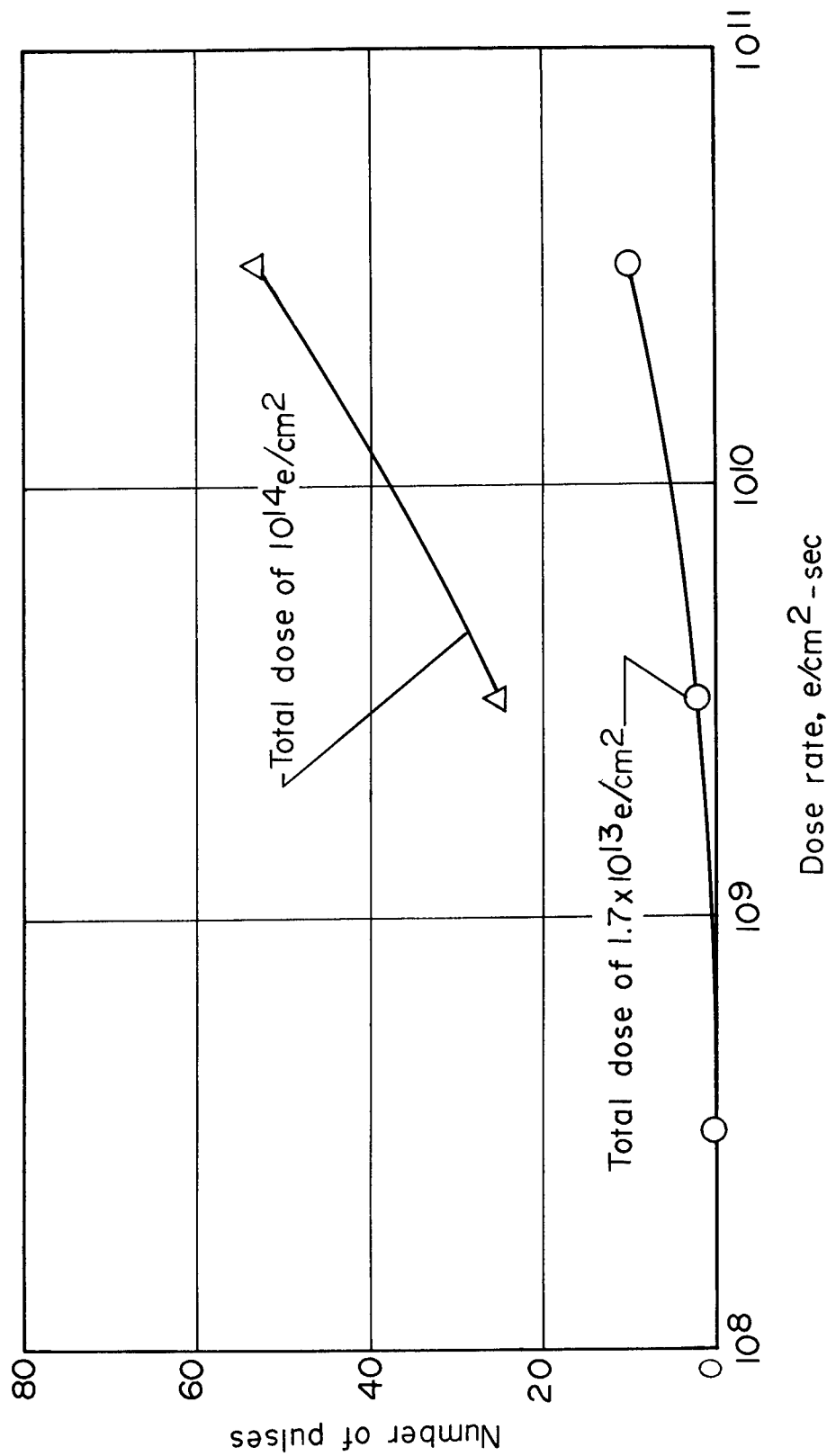
(b) Sample 2.

Figure 12.- Concluded.
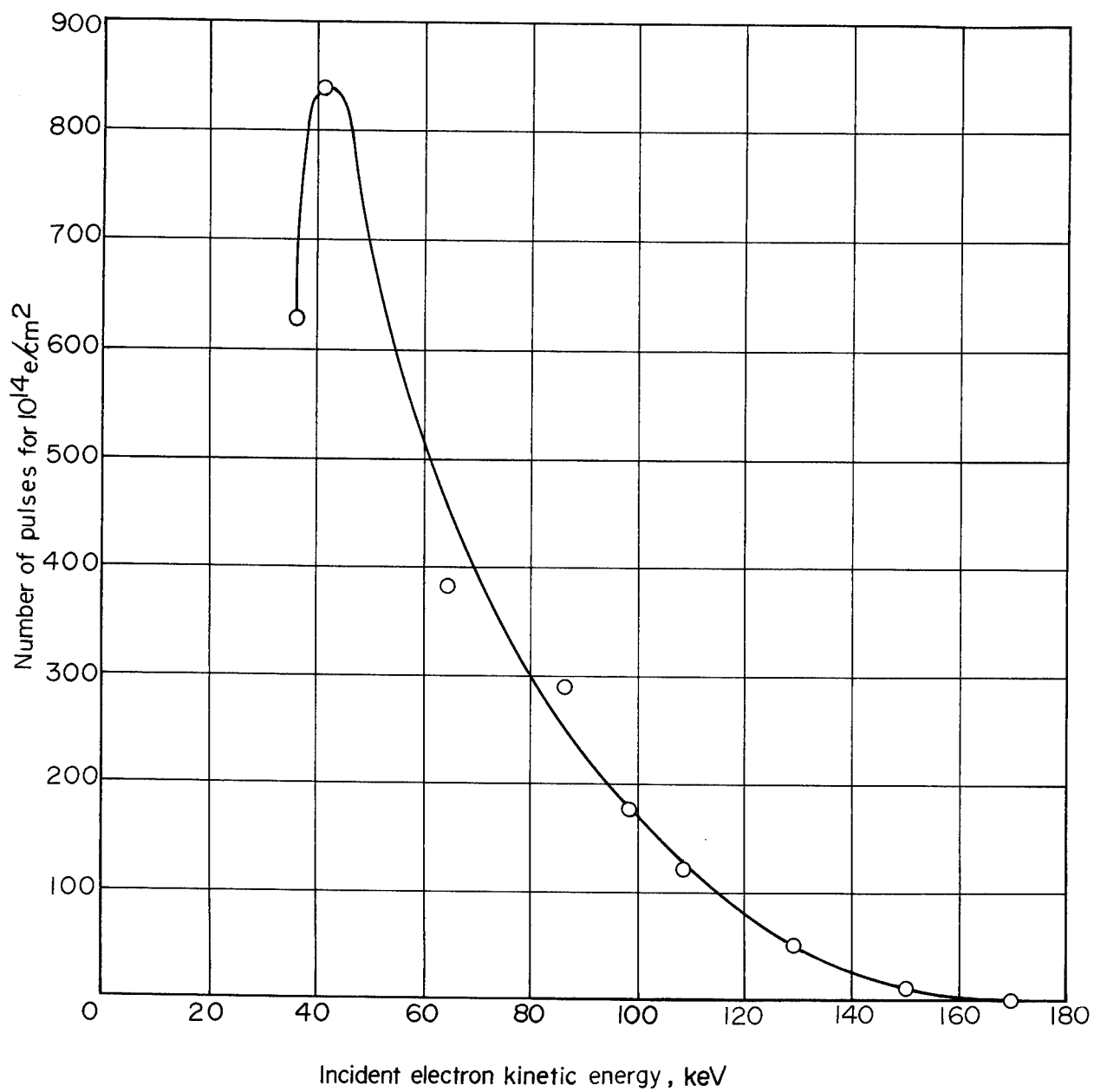
Figure 13.- Dependence of number of pulses on electron energy for polyethylene terephthalate insulated ribbon wire mounted on feedthrough plate. Dose rate = 3.2×10^{10} e/cm^2-sec at 294° K.
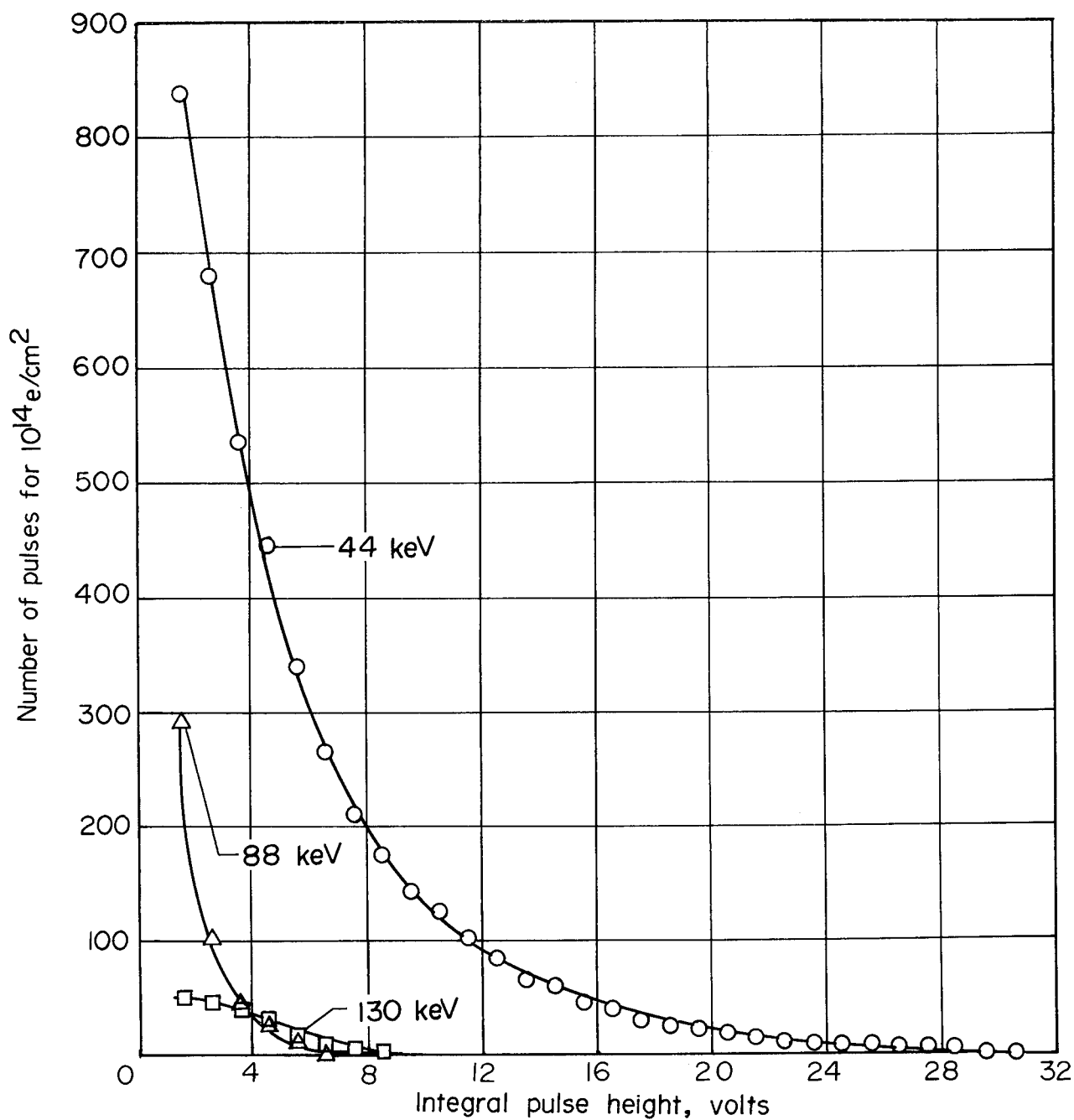
Figure 14.- Number of pulses above a given voltage obtained from polyethylene terephthalate insulated ribbon wire mounted on feedthrough plate. Dose rate = 3.2×10^{10} e/cm^2-sec at 294° K.
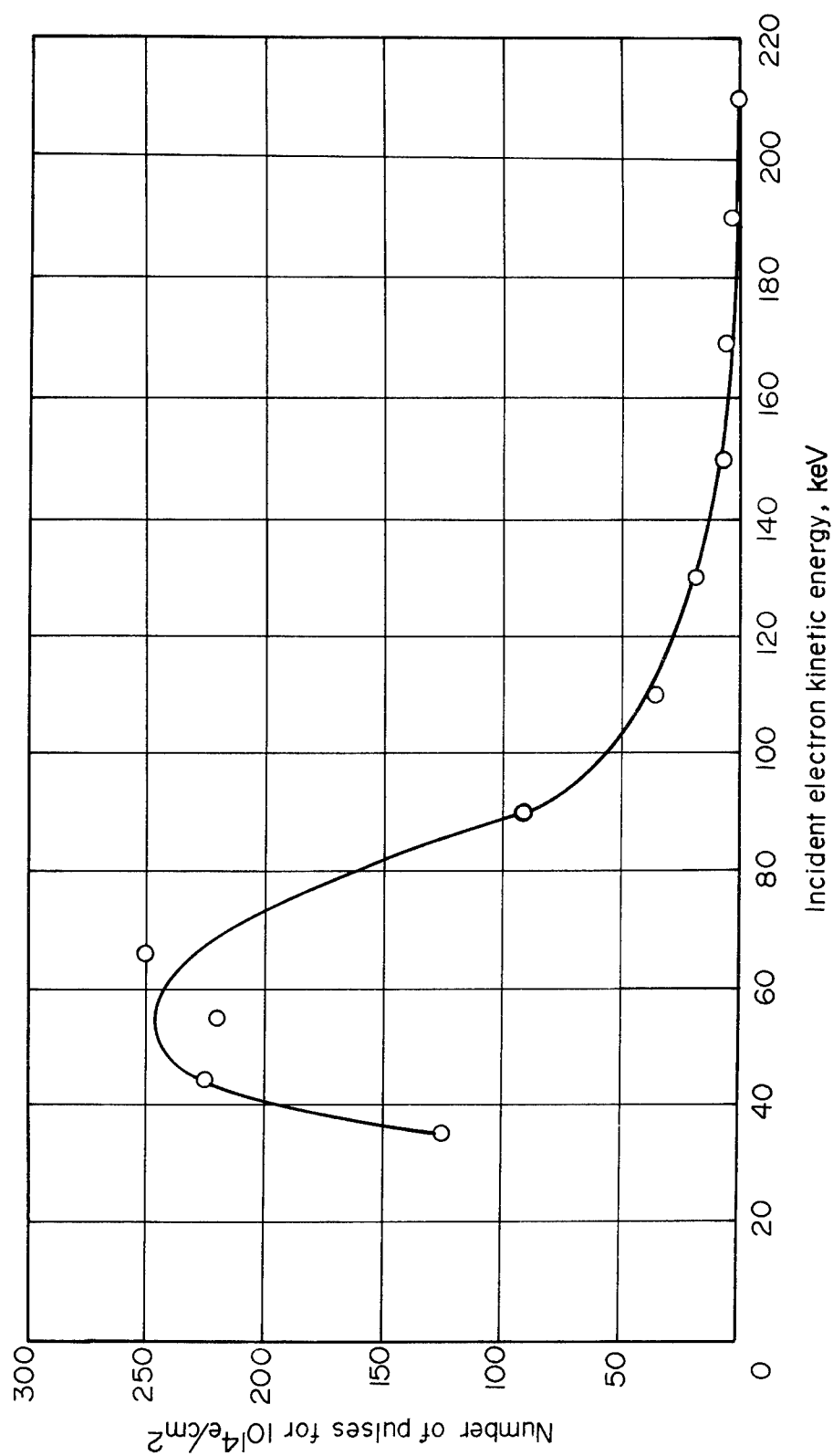
Figure 15.- Dependence of number of pulses on electron energy for polyethylene terephthalate insulated ribbon wire glued to temperature-control bucket. Dose rate = 3.2 × 10^{10} e/cm^2-sec at 77° K.
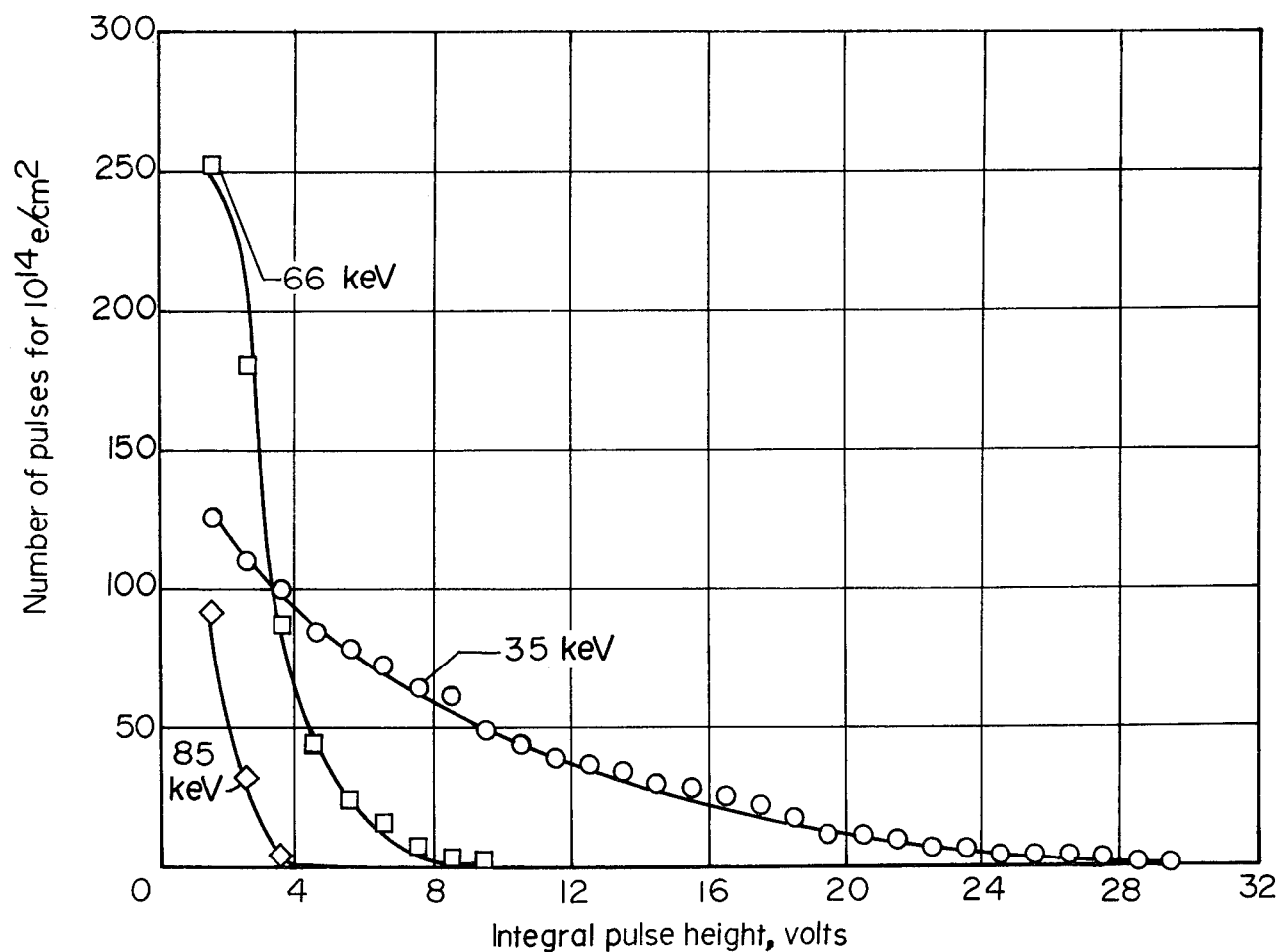
Figure 16.- Number of pulses above a given voltage obtained from polyethylene terephthalate insulated ribbon wire glued to temperature-control bucket.

Dose rate = 3.2 x 10^10 e/cm^2-sec at 77° K.
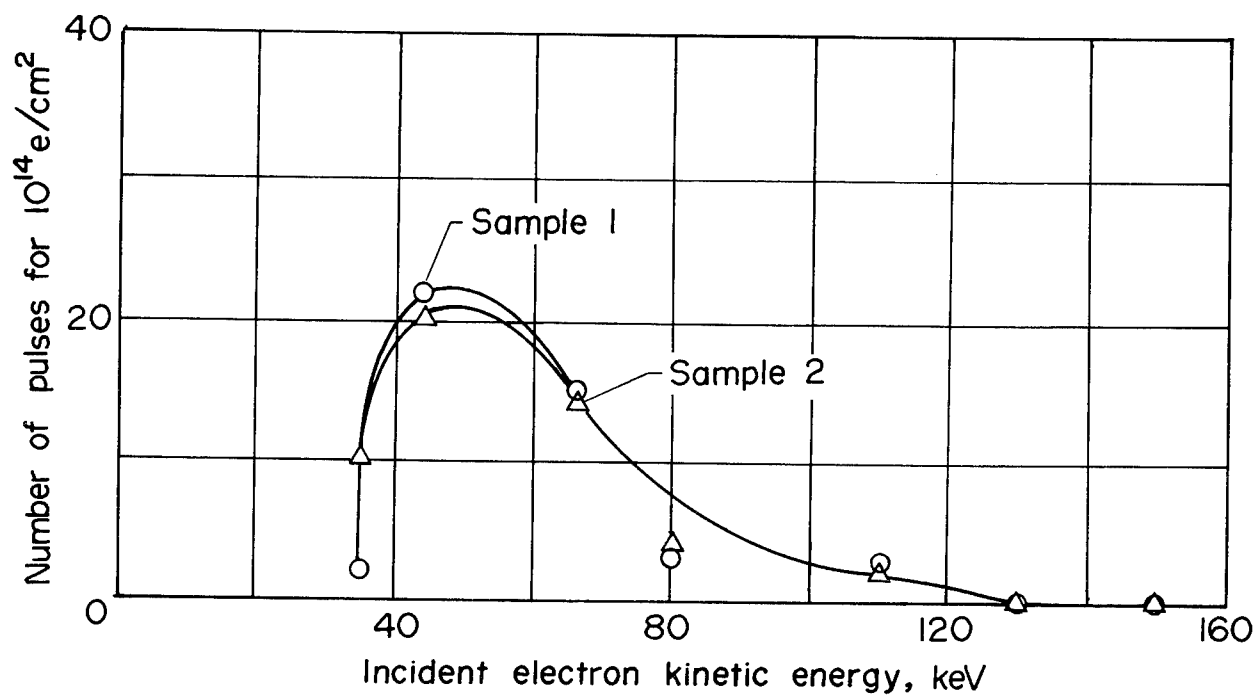
Figure 17.- Dependence of number of pulses on electron energy for two commercial ceramic insulated capacitors. Dose rate = 3.2×10^{10} e/cm^2-sec at 294° K.
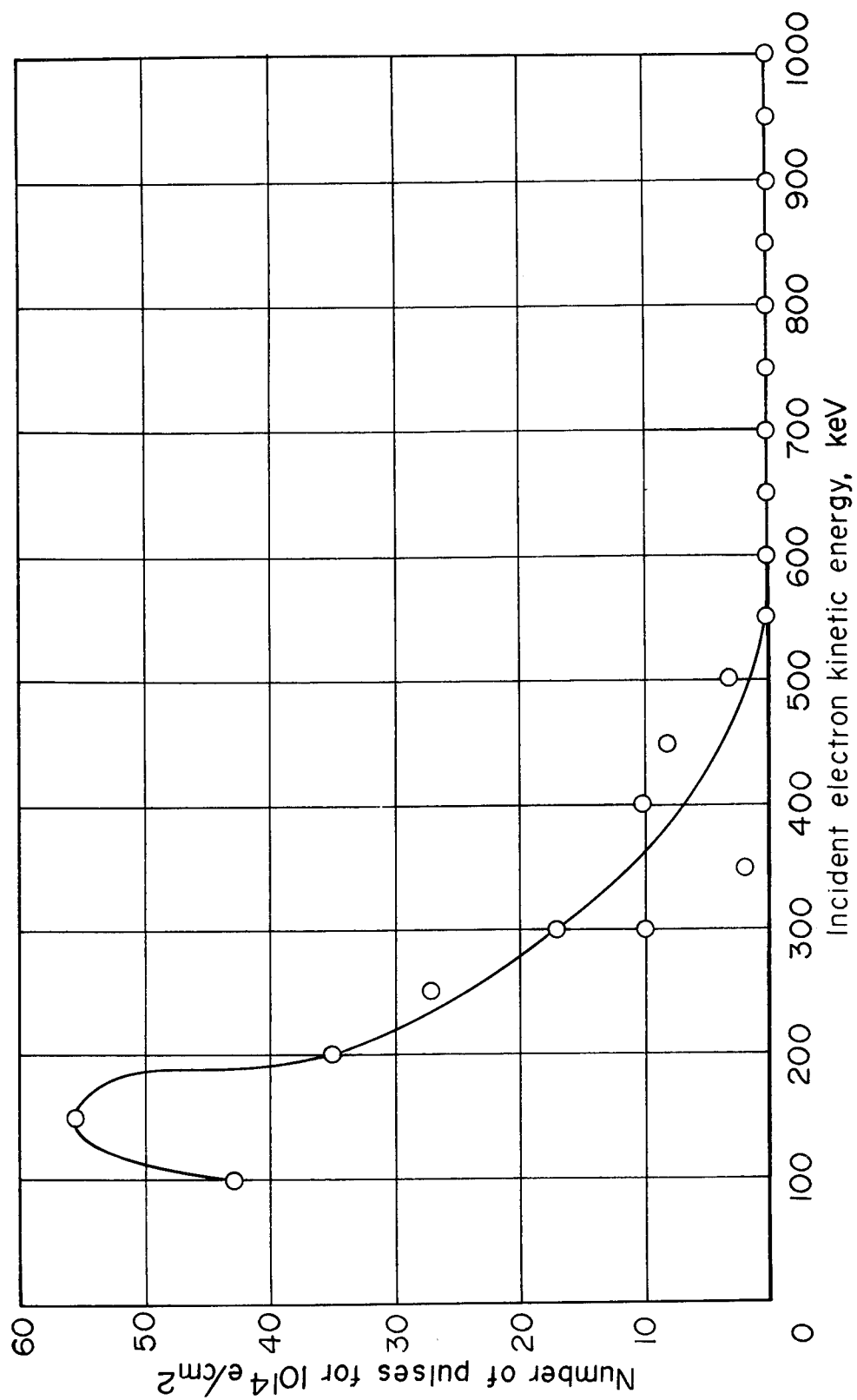
Figure 18.- Dependence of number of pulses on electron energy for commercial polystyrene insulated capacitor. Dose rate = 3.2×10^{10} e/cm^2-sec at 297° K.
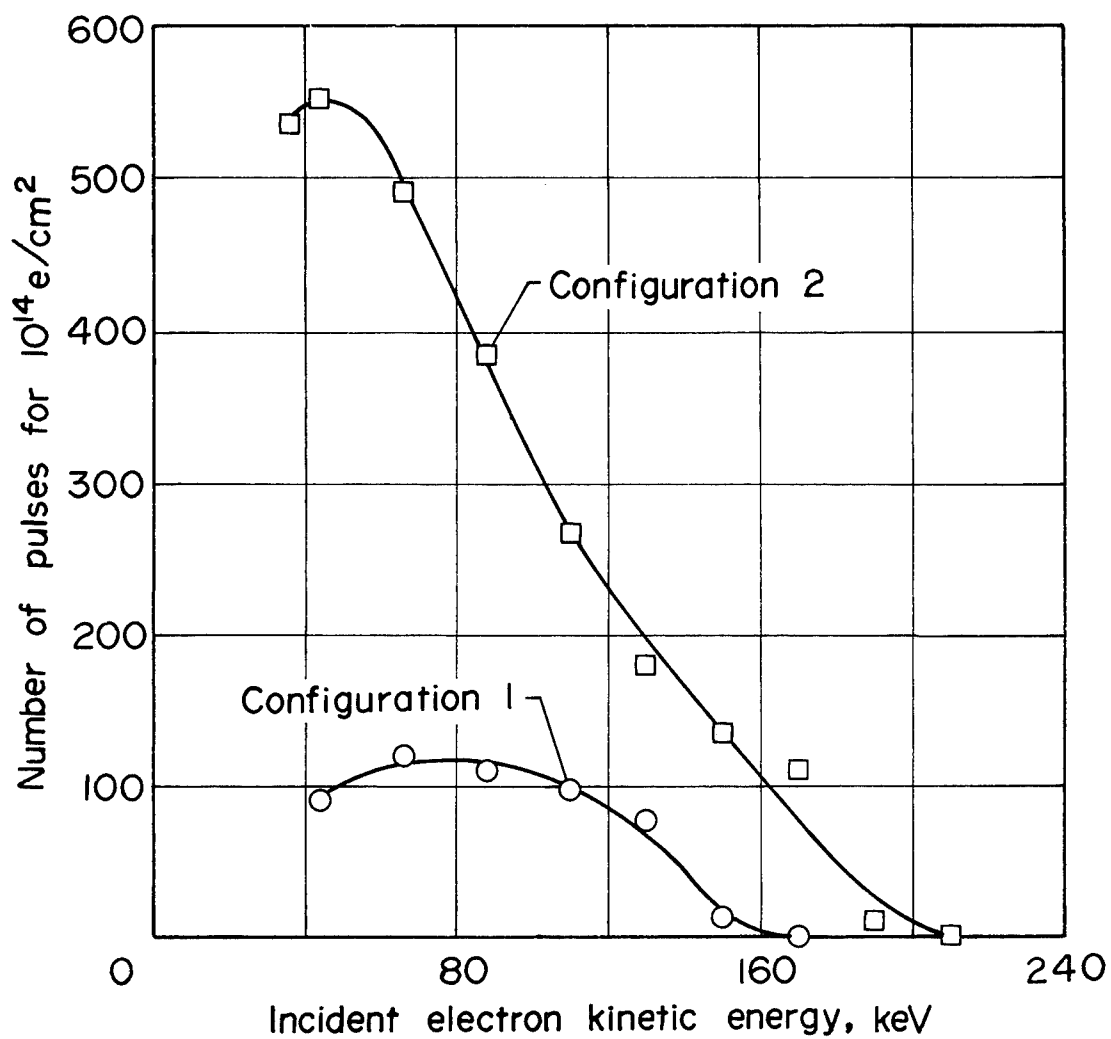
Figure 19.- Dependence of number of pulses on electron energy for polytetrafluoroethylene insulated wire in two different electronic configurations. Dose rate = 3.2×10^{10} e/cm^2-sec at 294° K.
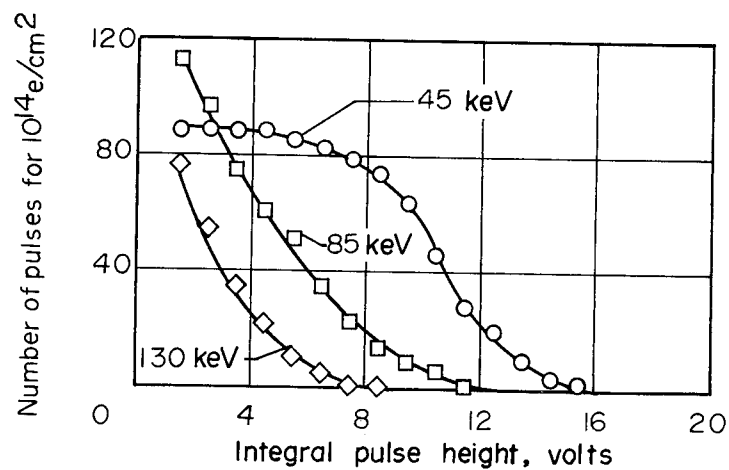
(a) Configuration 1.
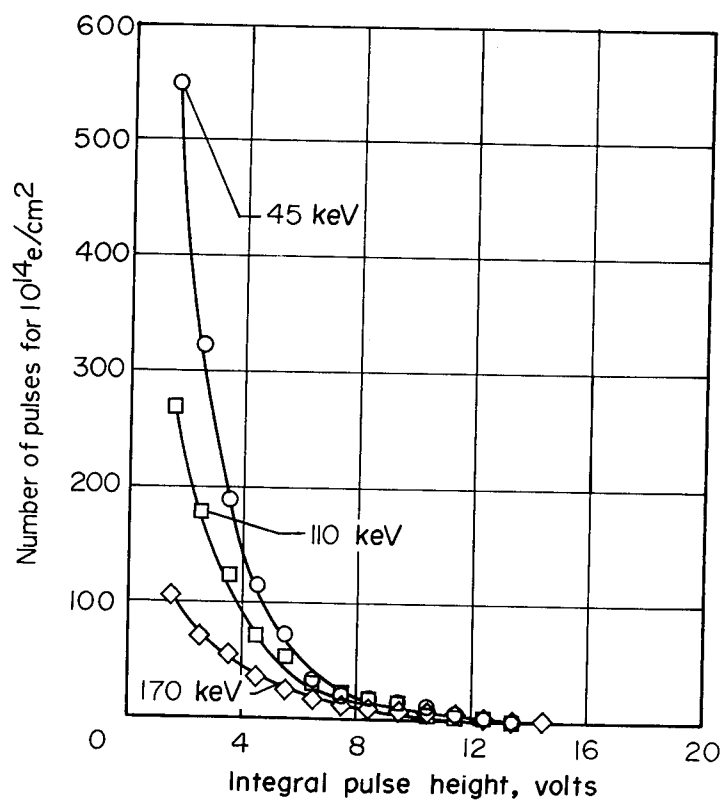
(b) Configuration 2.

Figure 20.- Number of pulses above a given voltage obtained from polytetra-
fluoroethylene insulated wire in two configurations. Dose rate =
3.2×10^{10} e/cm²-sec at 294° K.
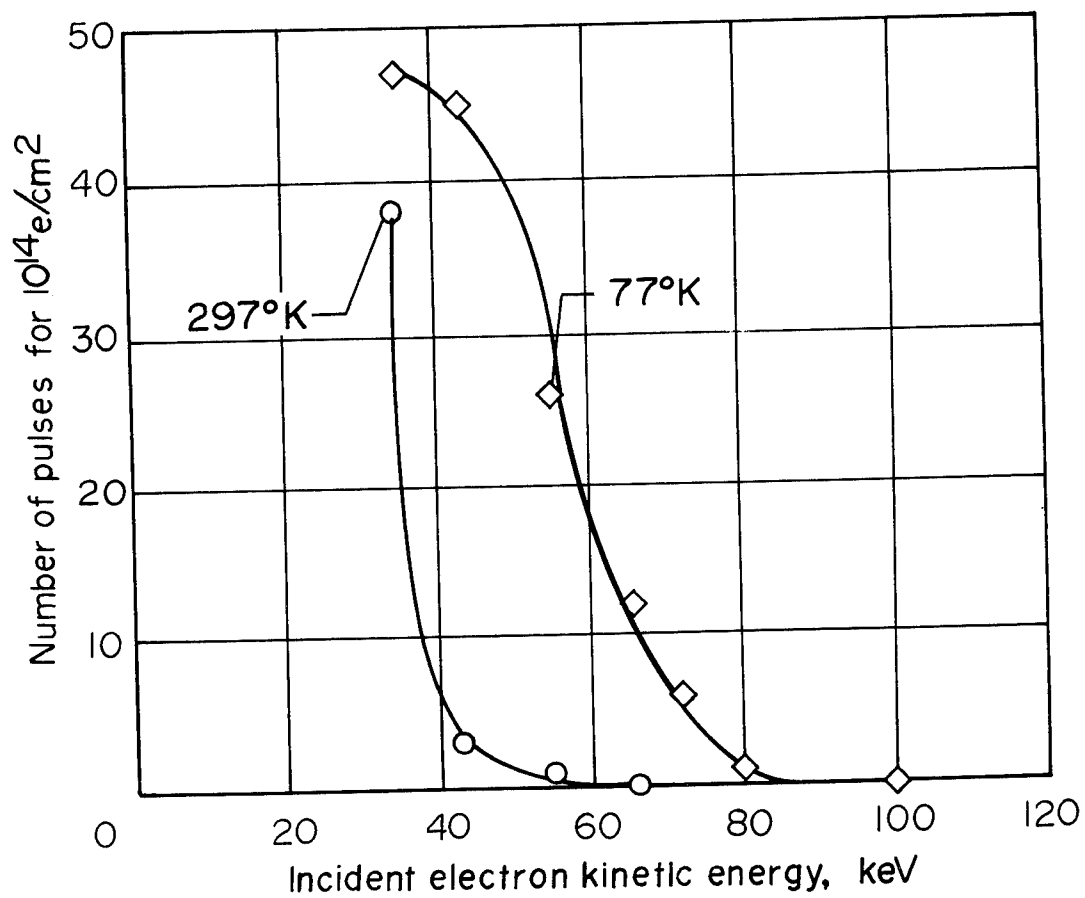
Figure 21.- Dependence of number of pulses on electron energy at 297° K and 77° K for specially prepared regenerated cellulose capacitor. Dose rate = 3.1×10^{10} e/cm^2-sec.
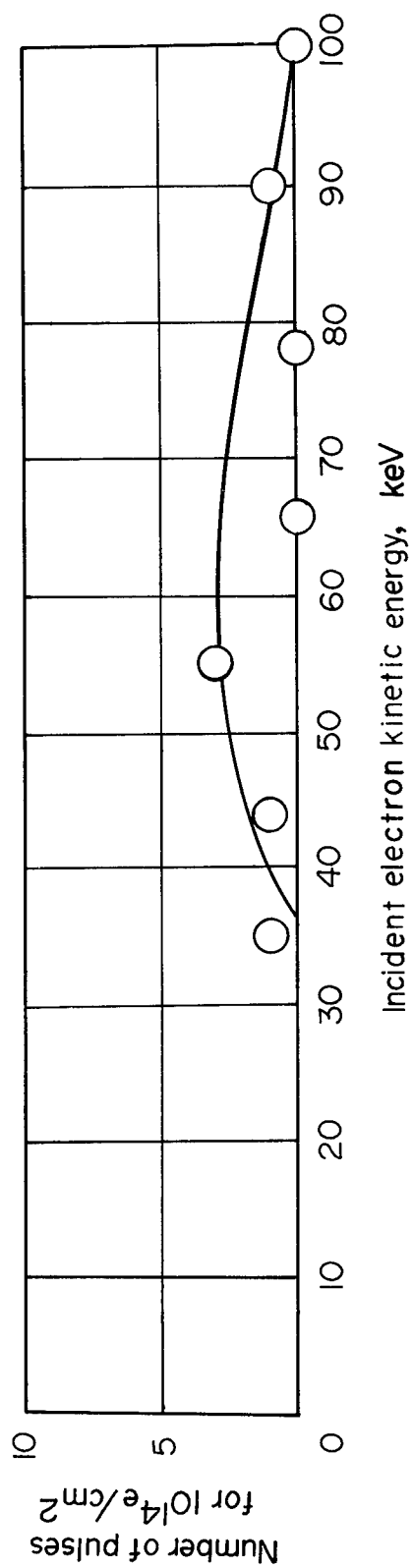
Figure 22.- Dependence of number of pulses on electron energy for specially prepared polypyromellitimide capacitor. Dose rate = 3.1×10^{10} e/cm^2-sec at 77° K.
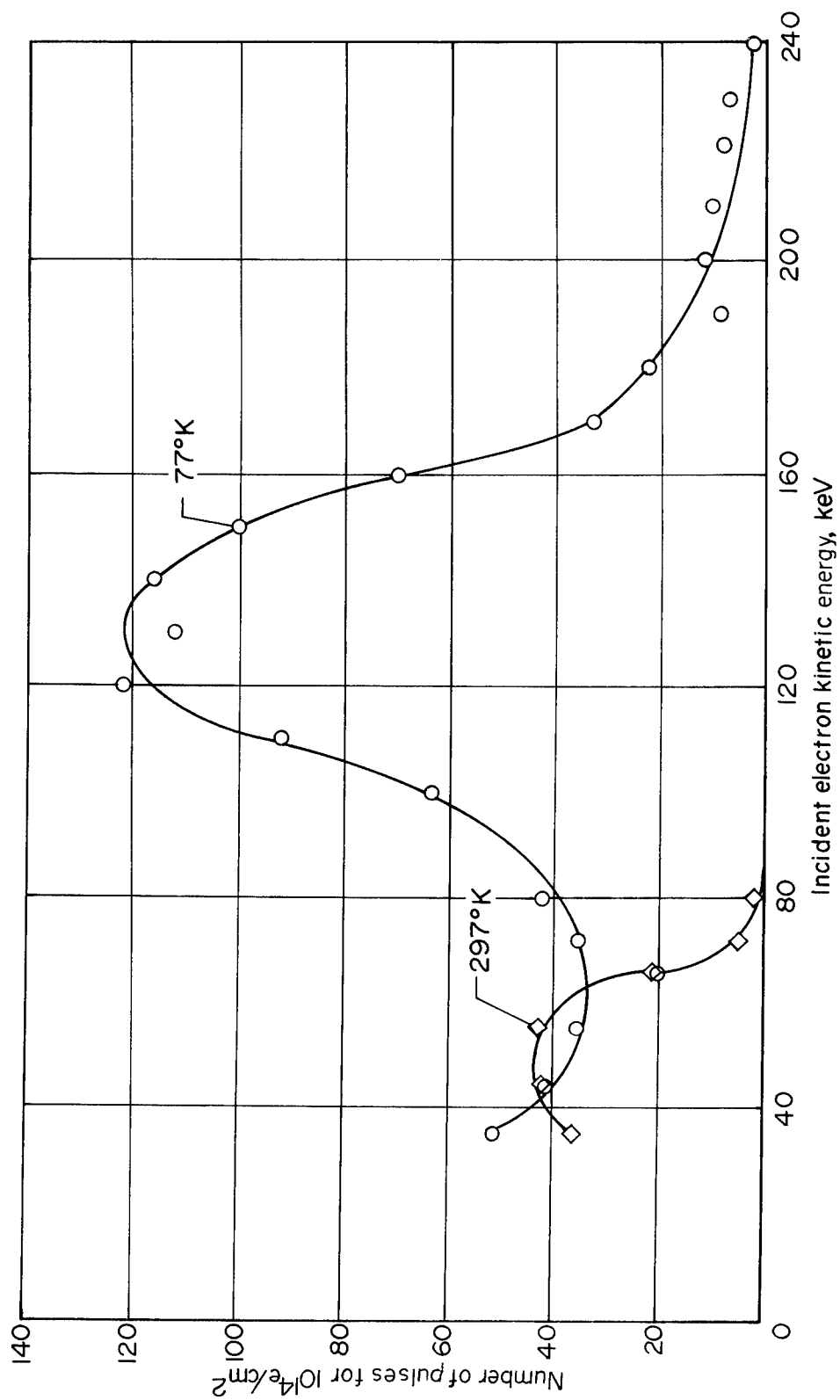
Figure 23.- Dependence of number of pulses on electron energy at 77° K and 297° K for a specially prepared polyvinyl alcohol capacitor. Dose rate = 3.1×10^{10} e/cm²-sec.

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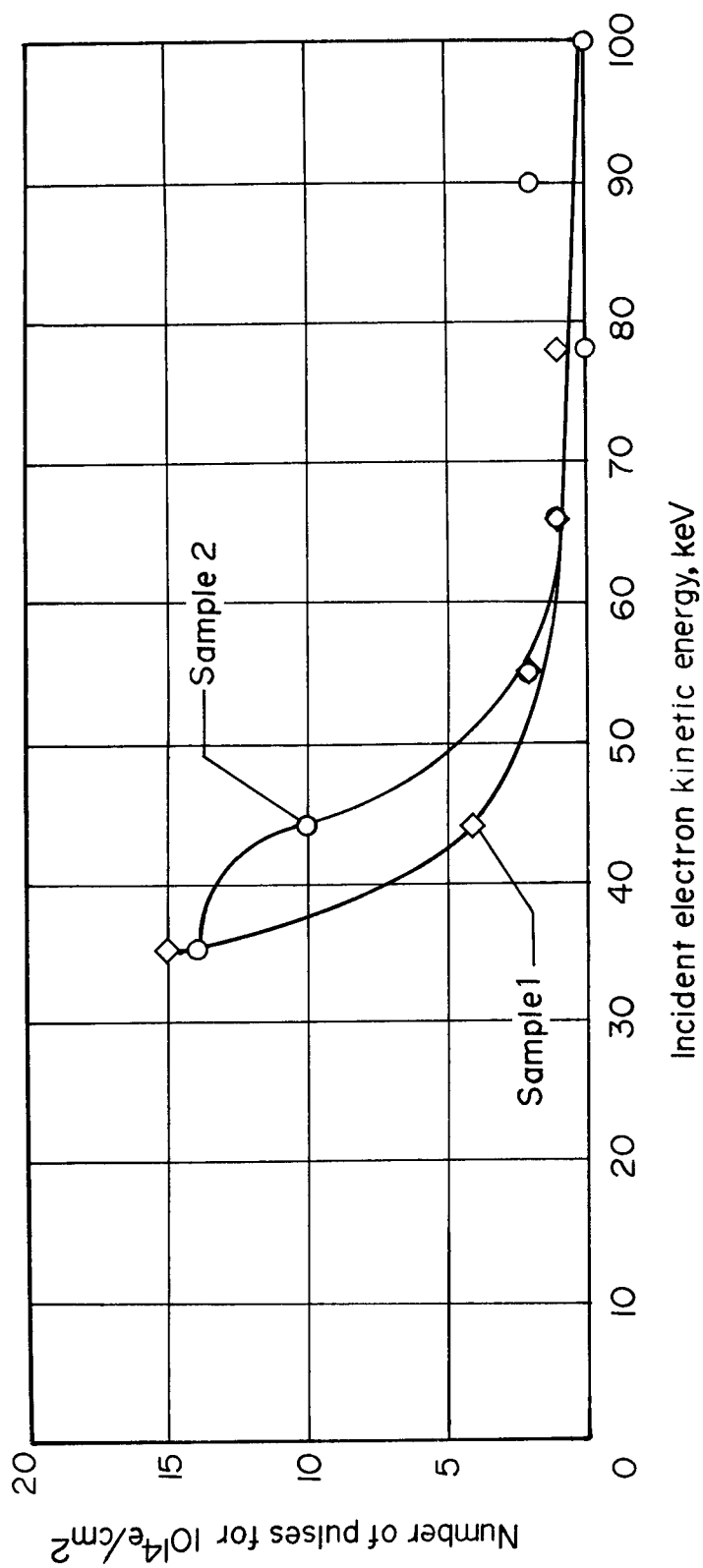
Figure 24.- Dependence of number of pulses on electron energy at 77° K for two specially prepared capacitors insulated with a copolymer of polyvinyl chloride and polyvinylidene chloride. Dose rate = 3.1×10^{10} e/cm²-sec.
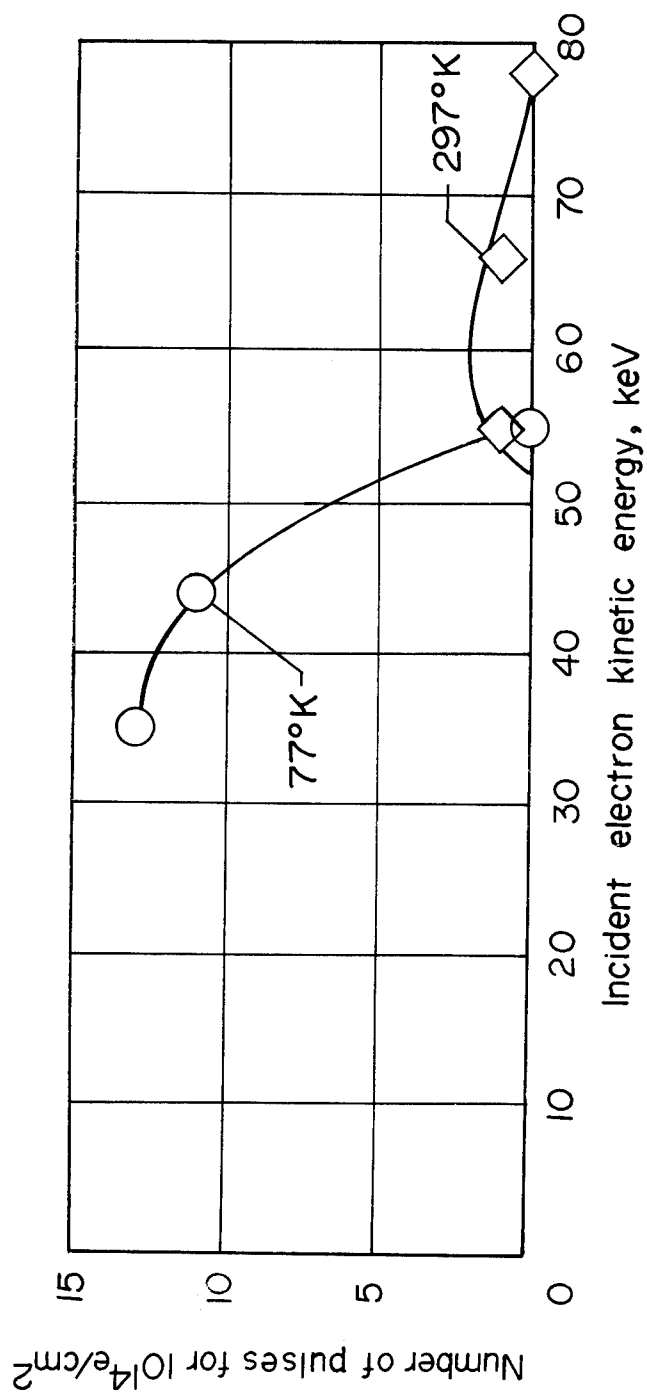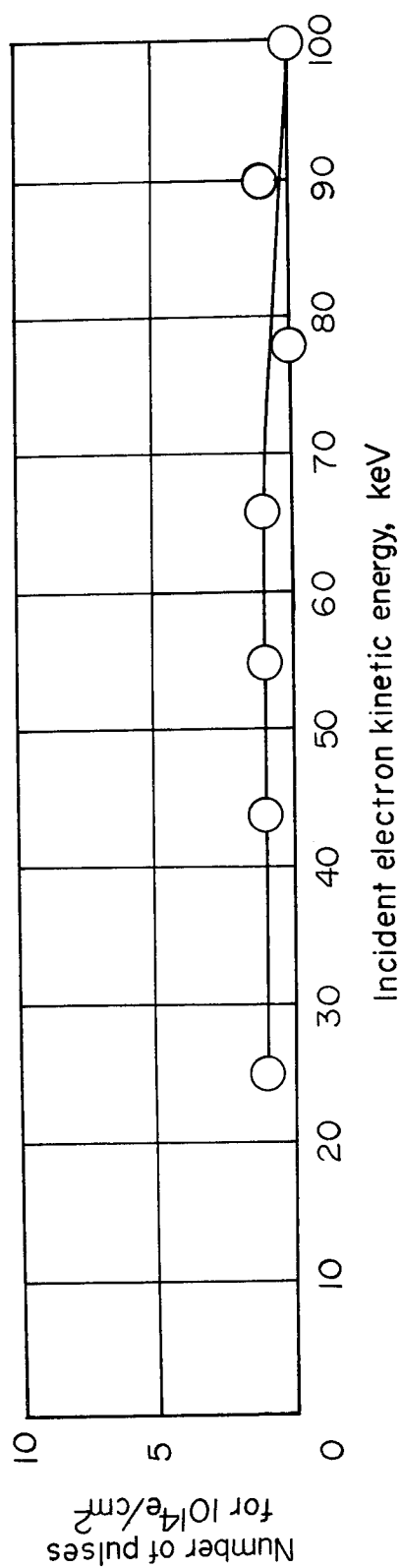
Figure 25.- Dependence of number of pulses on electron energy at 77° K and 297° K for specially prepared mica-paper capacitor. Dose rate = 3.1×10^{10} e/cm²-sec.

Figure 26.- Dependence of number of pulses on electron energy for specially prepared silicone-impregnated mica-paper capacitor. Dose rate = 3.1×10^{10} e/cm^2-sec at 77° K.
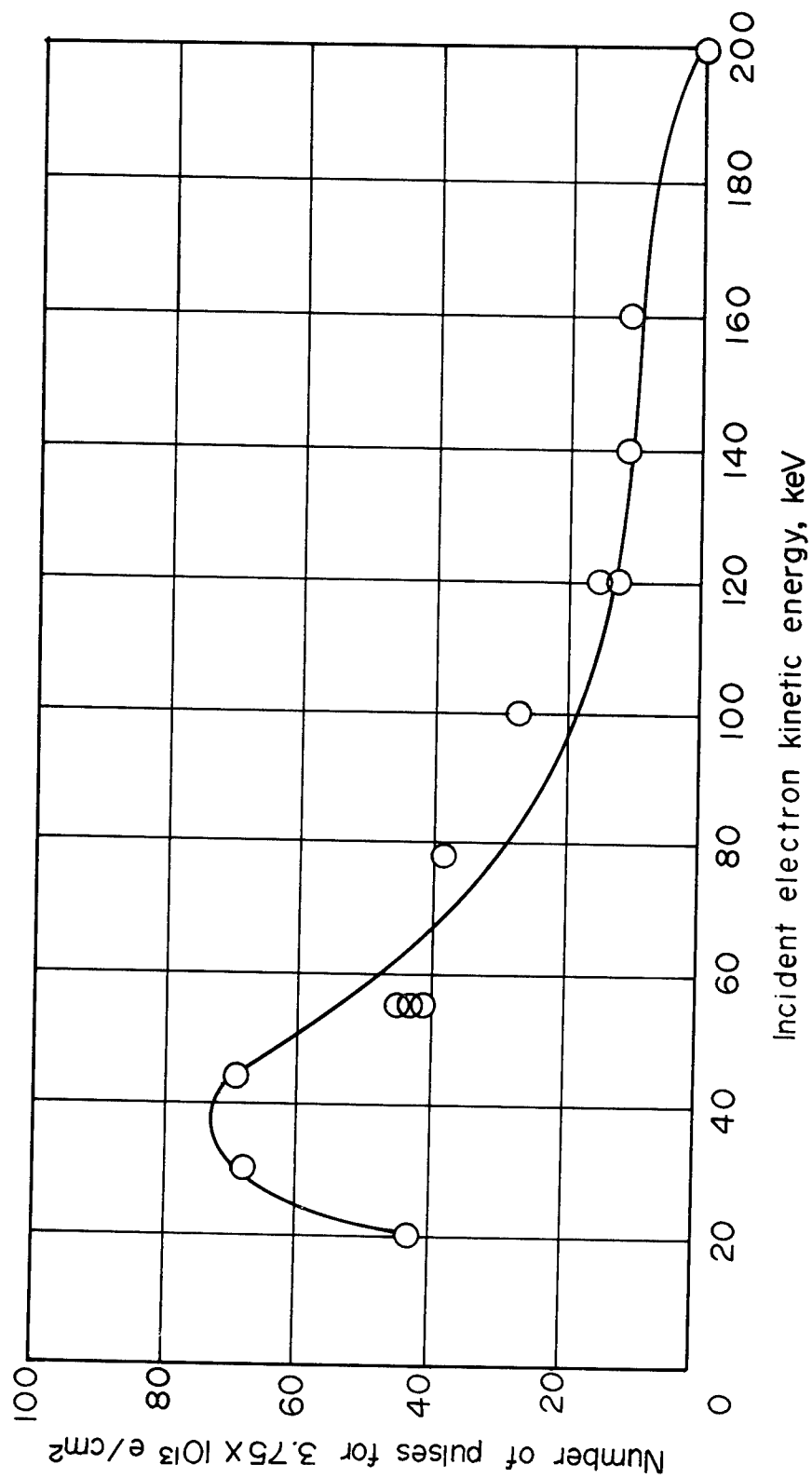
Figure 27.- Dependence of number of pulses on electron energy for specially prepared polyethylene terephthalate capacitor. Dose rate = 3.1×10^9 e/cm^2-sec at 77° K.
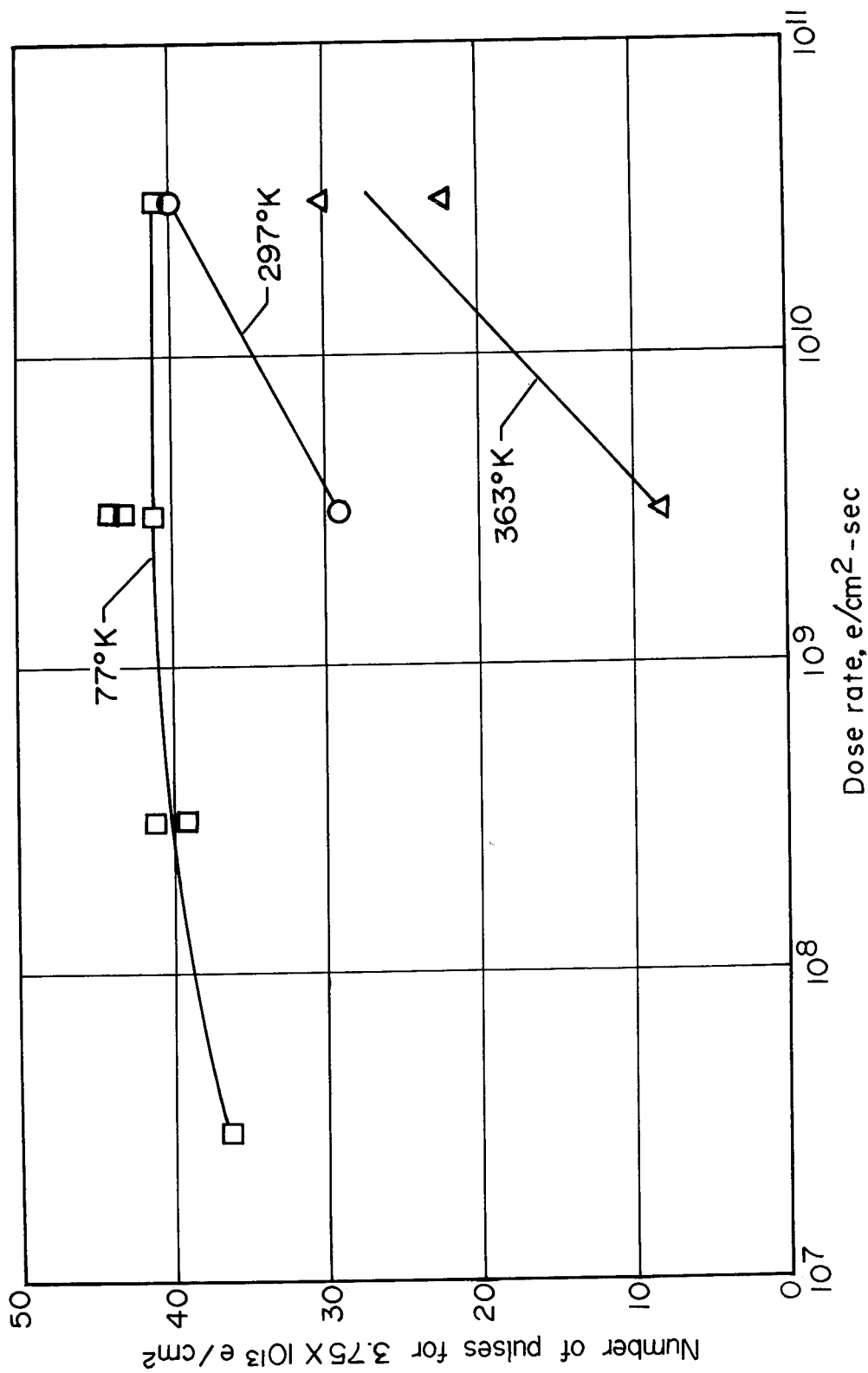
Figure 28.- Dependence of number of pulses on electron dose rate at incident kinetic energy of 55 keV and at temperatures of 77° K, 297° K, and 363° K for specially prepared polyethylene terephthalate insulated capacitor.