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RADIATION EFFECTS DESIGN HANDBOOK

**Section 3. Electrical Insulating Materials
and Capacitors**

by C. L. Hanks and D. J. Hamman

Prepared by
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16. Abstract This document contains summarized information relating to steady-state radiation effects on electrical insulating materials and capacitors. The information is presented in both tabular and graphical form with text discussion. The radiation considered includes neutrons, gamma rays, and charged particles. The information is useful to design engineers responsible for choosing candidate materials or devices for use in a radiation environment.					
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PREFACE

This document is the third section of a Radiation Effects Design Handbook designed to aid engineers in the design of equipment for operation in the radiation environments to be found in space, be they natural or artificial. This Handbook will provide the general background and information necessary to enable the designers to choose suitable types of materials or classes of devices.

Other sections of the Handbook will discuss such subjects as transistors, solar cells, thermal-control coatings, structural metals, and interactions of radiation.

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SECTION 3. ELECTRICAL INSULATING MATERIALS AND CAPACITORS

ELECTRICAL INSULATING MATERIALS

INTRODUCTION

Dielectric and insulating materials as applied to electronic circuitry are second only to semiconductor devices, such as integrated circuits, transistors, diodes, in sensitivity to radiation. Consideration of this sensitivity and what effects might occur as a result are of primary importance to the circuit designer and application engineer in designing a system that includes radiation as an environmental condition. The purpose of this report is to assist in providing information regarding the radiation tolerance of various insulating materials and the degradation of their electrical properties. Degradation of mechanical properties, however, is also a consideration to the extent that in many applications the mechanical failure of an insulator or dielectric will adversely affect its electrical characteristics. If the reader's interest is such that he requires more information than is presented herein concerning changes in the basic mechanical characteristics of organic insulating materials or the damage mechanisms involved, he is directed to the elastomeric and plastic components and materials section of this handbook.

It is impractical to attempt to compile within this document the detailed information that would be directly applicable to all circuit requirements and environmental conditions. Often the damage experienced by an insulating or dielectric material is dependent upon environmental conditions present in addition to the radiation, such as temperature and humidity. The fabrication method used by the manufacturer can also be a factor in determining the amount of damage that might occur. For these reasons, this report is limited to generalized "ballpark" type information which is applicable to early design considerations. Where information on a material is insufficient for "ballpark" generalization, however, details of specific irradiations are presented.

The effects of radiation as presented in this report are often identified as damage threshold and/or 25 percent damage dose. These terms relate to changes in one or more physical properties, i. e., tensile strength,

elongation, etc., with damage threshold being the dose where the change is first detected. The 25 percent damage dose is that where a 25 percent change in property occurs.

The scope of this report has been limited to the effects of steady-state and space radiation and excludes information concerning transient radiation or pulse-radiation effects with the exception of the next few pages where transient effects are used for illustration. The information presented is separated by the configuration of the test item, i. e., bulk or sheet materials, wire and cable insulation, encapsulating compounds, connectors and terminals, and capacitors. Introductory paragraphs on organic and inorganic insulators discuss the effects of radiation in general terms on these two basic categories of insulating materials. Also, the information on the effects of radiation on bulk or sheet-type specimens is considered applicable to other configurations of the same material, keeping in mind what effect the different configuration may have in regard to the type of damage that occurs.

Conversion factors for converting electron fluences to rads, and procedures to calculate ionization due to neutrons and protons are available in the handbook section entitled "Radiations in Space and Their Interaction with Matter".

RADIATION EFFECTS ON ORGANIC MATERIALS

Organic insulating and dielectric materials experience both temporary and permanent changes in characteristics when subjected to a radiation environment such as that found in space or the fields of a nuclear reactor or radioisotope source. Data indicate that the temporary effects are generally rate sensitive with a saturation of the effect at the higher radiation levels. The enhancement of the electrical conductivity is the most important of the temporary effects; increases of several orders of magnitude are observed. The magnitude of the increase is dependent upon several factors including the material being irradiated, ambient temperature, and the radiation rate.

Absorption of energy, excitation of charge carriers from nonconducting to conducting states, and the return of these carriers from conducting to nonconducting states are considered responsible for the induced conductivity. S. E. Harrison, et al, ⁽¹⁾ have demonstrated that, with steady-state gamma irradiation between 10^{-3} and 10^4 rads (H_2O)/s, the excess

conductivity has distinct characteristics in three time intervals which are denoted as A, B, and C in Figure 1. The conductivity increases exponentially in response to a step increase in gamma dose rate, $\dot{\gamma}$, during Interval A and is characterized by

$$(\sigma - \sigma_0) = A \left(1 - e^{-t/\tau_0} \right) , \quad (1)$$

where

σ_0 = initial conductivity

σ = conductivity at time t

A = empirical constant

$\tau_0 = k_0 \dot{\gamma}^{-\mu}$ = time constant of the response as a function of gamma dose, gamma equivalent ionizing dose, or dose rate k_0 and μ being empirical constants (see Figure 2).

During Interval B, the induced conductivity is at equilibrium, and its value is determined by the rate of exposure and temperature for a specific material. This condition is characterized to a good approximation by

$$(\sigma - \sigma_0) = A_\gamma \dot{\gamma}^\delta , \quad (2)$$

where

A_γ and δ = empirical constants (see Table 1) and

$\dot{\gamma}$ = gamma or gamma equivalent (ionizing) exposure rate in rads (H_2O)/s.

The equilibrium or saturation of the radiation induced conductivity is attributed to two conditions: (1) equal rates of free-carrier generation and carrier annihilation through recombination, and (2) the rate of free-carrier capture in trapping states equals that of trapped-carrier decay.

The induced conductivity gradually decreases following the termination of the irradiation. The measured conductivity of Interval C has been characterized for several organic materials by

$$\sigma(t-b) = \sigma_{eq} \sum_{i=1}^n k_i e^{-(t-b)/\tau_i} \quad (3)$$

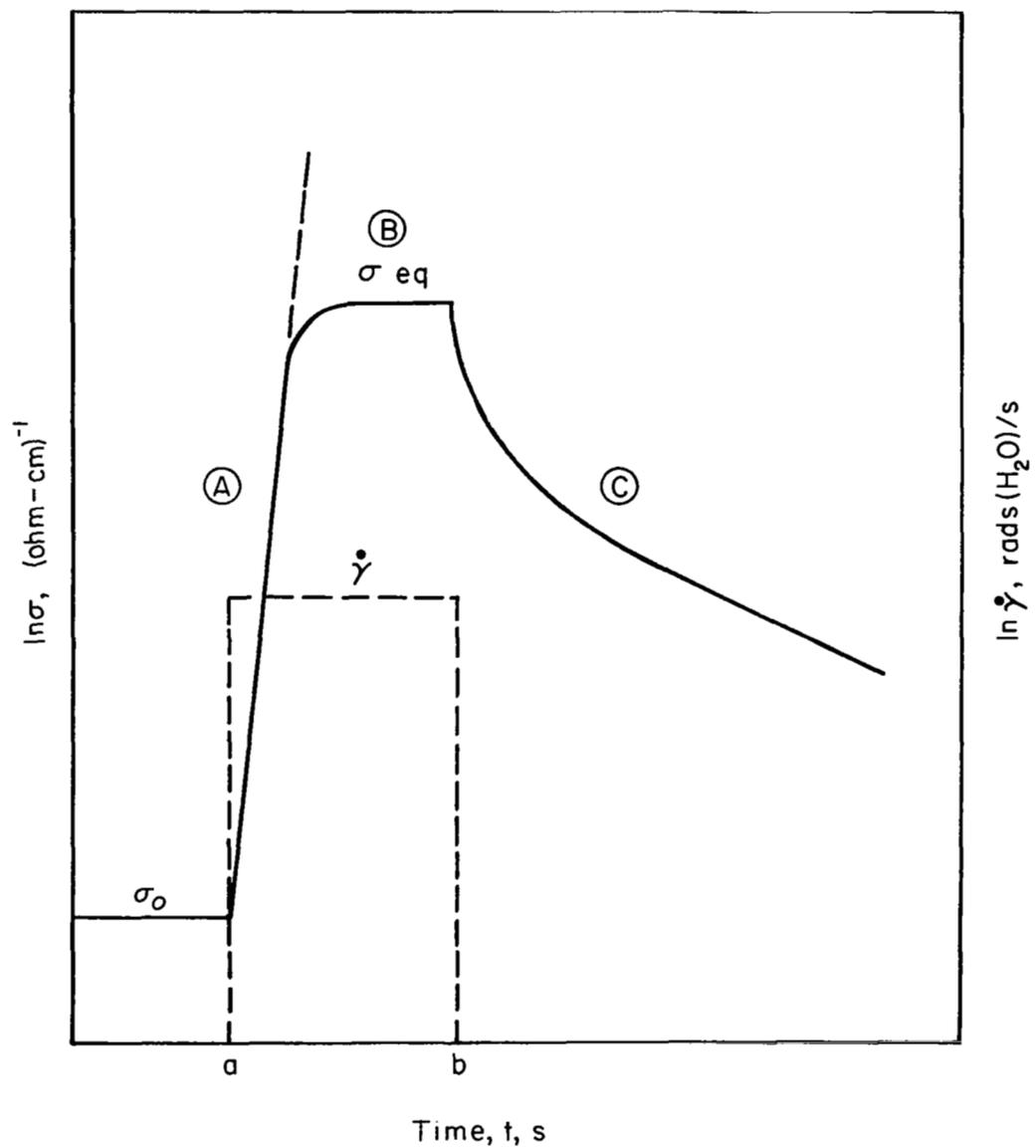


FIGURE 1. TYPICAL BEHAVIOR OF CONDUCTIVITY IN RESPONSE TO A RECTANGULAR PULSE OF GAMMA-RAY DOSE RATE⁽¹⁾

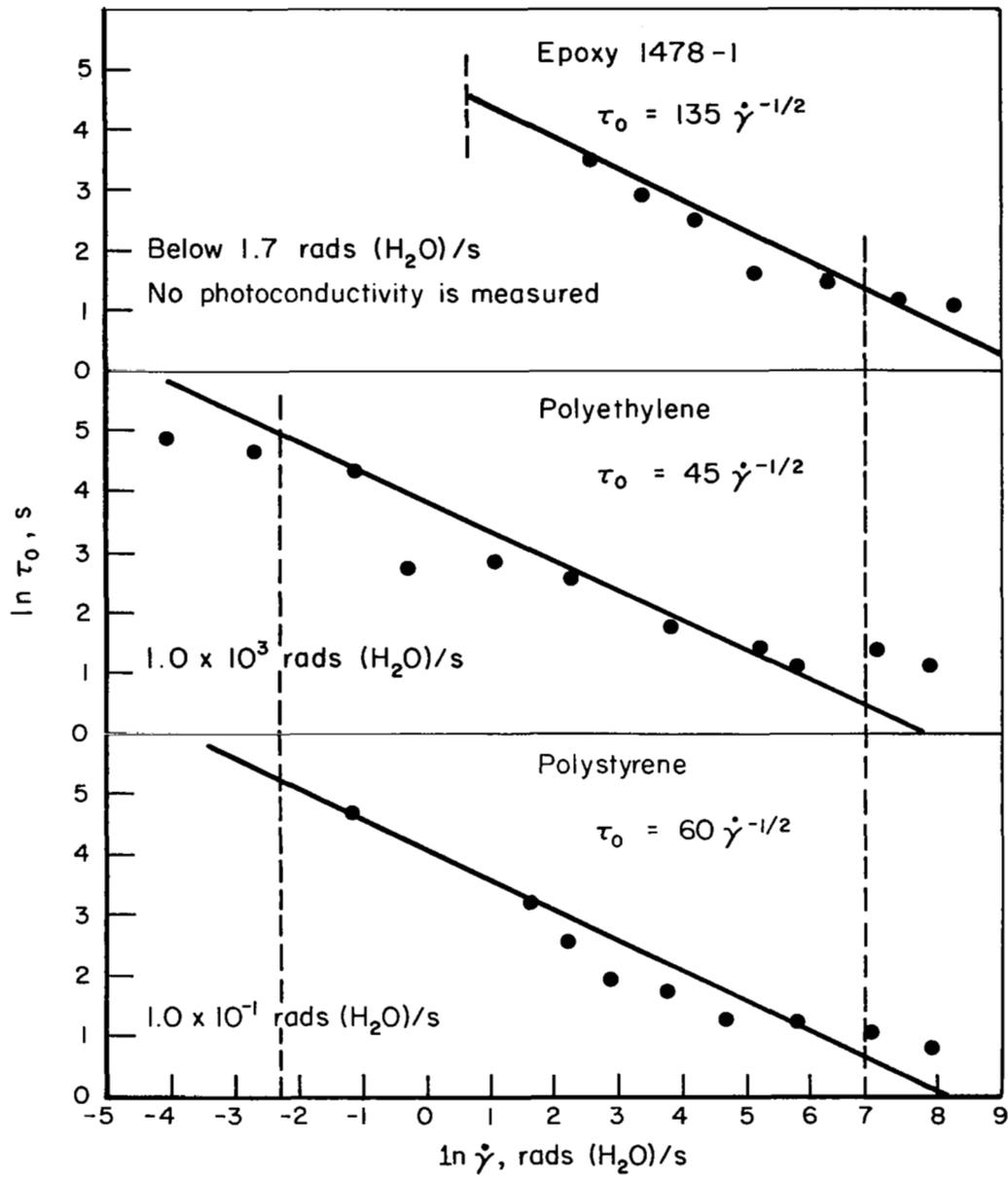


FIGURE 2. LOGARITHM OF TIME CONSTANT VERSUS LOGARITHM OF GAMMA-RAY DOSE RATE FOR POLYETHYLENE, POLYSTYRENE, AND EPOXY 1478-1 AT 38 C⁽¹⁾

TABLE 1. MEASURED VALUES OF $A_{\dot{\gamma}}$ AND δ FOR EIGHT MATERIALS AS DEFINED BY $(\sigma - \sigma_0) = A_{\dot{\gamma}} \dot{\gamma} \sigma$ (a)

Material(b)	Temperature(c), C	δ	$A_{\dot{\gamma}}$	Range of $\dot{\gamma}$, rads (H ₂ O)/s
Polystyrene	38	0.97	4.0×10^{-17}	1.7×10^{-2} to 5.0×10^3
	49	0.97	4.0×10^{-17}	1.7×10^{-2} to 5.0×10^3
	60	0.97	4.0×10^{-17}	1.7×10^{-2} to 5.0×10^3
Polyethylene	38	0.74	5.2×10^{-16}	8.3×10^{-2} to 1.7×10^3
	49	0.74	6.3×10^{-16}	8.3×10^{-2} to 1.7×10^3
	60	0.74	1.6×10^{-15}	8.3×10^{-2} to 1.7×10^3
Epoxy 1478-1	38	No measurable photoconductivity below $\dot{\gamma} = 1.7$		
		1.0	3.3×10^{-17}	1.7 to 4.2×10^3
	49	No measurable photoconductivity below $\dot{\gamma} = 9.0$		
		1.0	3.3×10^{-17}	9.0 to 4.2×10^3
	60	No measurable photoconductivity below $\dot{\gamma} = 7.5 \times 10^1$		
		1.0	3.8×10^{-17}	7.5×10^1 to 4.2×10^3
Polypropylene	38	0.88	3.8×10^{-17}	1.8×10^{-3} to 6.0×10^3
H-film	38	1.1	5.8×10^{-18}	1.8×10^{-3} to 6.0×10^3
Teflon	38	1.0	1.2×10^{-16}	1.8×10^{-3} to 6.0×10^3
Nylon	38	No measurable photoconductivity below $\dot{\gamma} = 8.0$		
		1.3	2.8×10^{-18}	8.0 to 6.0×10^3
Diallylphthalate	38	0.30	2.1×10^{-16}	1.8×10^{-3} to 3.0×10^2
		1.7	8.0×10^{-20}	3.0×10^2 to 6.0×10^3

(a) Data taken under steady state conditions after 1.8×10^3 seconds of electrification.

(b) Temperature is ± 1 C.

(c) Fifteen samples of polyethylene, polystyrene, and Epoxy 1478-1 and three samples of the other materials were measured.

where

$$\sigma_{eq} = \sigma_0 + A_\gamma \dot{\gamma}^\delta = \text{equilibrium conductivity}$$

n = number of discrete decay-time constants in the recovery process

τ_i = decay-time constants of the recovery

k_i = weighting factors associated with the $i^{\text{th}} \tau_i$. (2)

A generalized expression for conductivity in insulating materials utilizing the "unit-step function", $U(t)$, was combined with the three basic characterizations presented above for Intervals A, B, and C by S. E. Harrison, et al⁽¹⁾, to yield an equation which has been modified⁽²⁾ to

$$\sigma(t, \dot{\gamma}) = \left[U(t) - U(t-b)\sigma(t-b) \right] \sigma_0 + \left[U(t-a) + U(t-b)\sigma(t-b) \right] A_\gamma \dot{\gamma}^\delta \left(1 - e^{-(t-a)/\tau_0} \right) \quad (4)$$

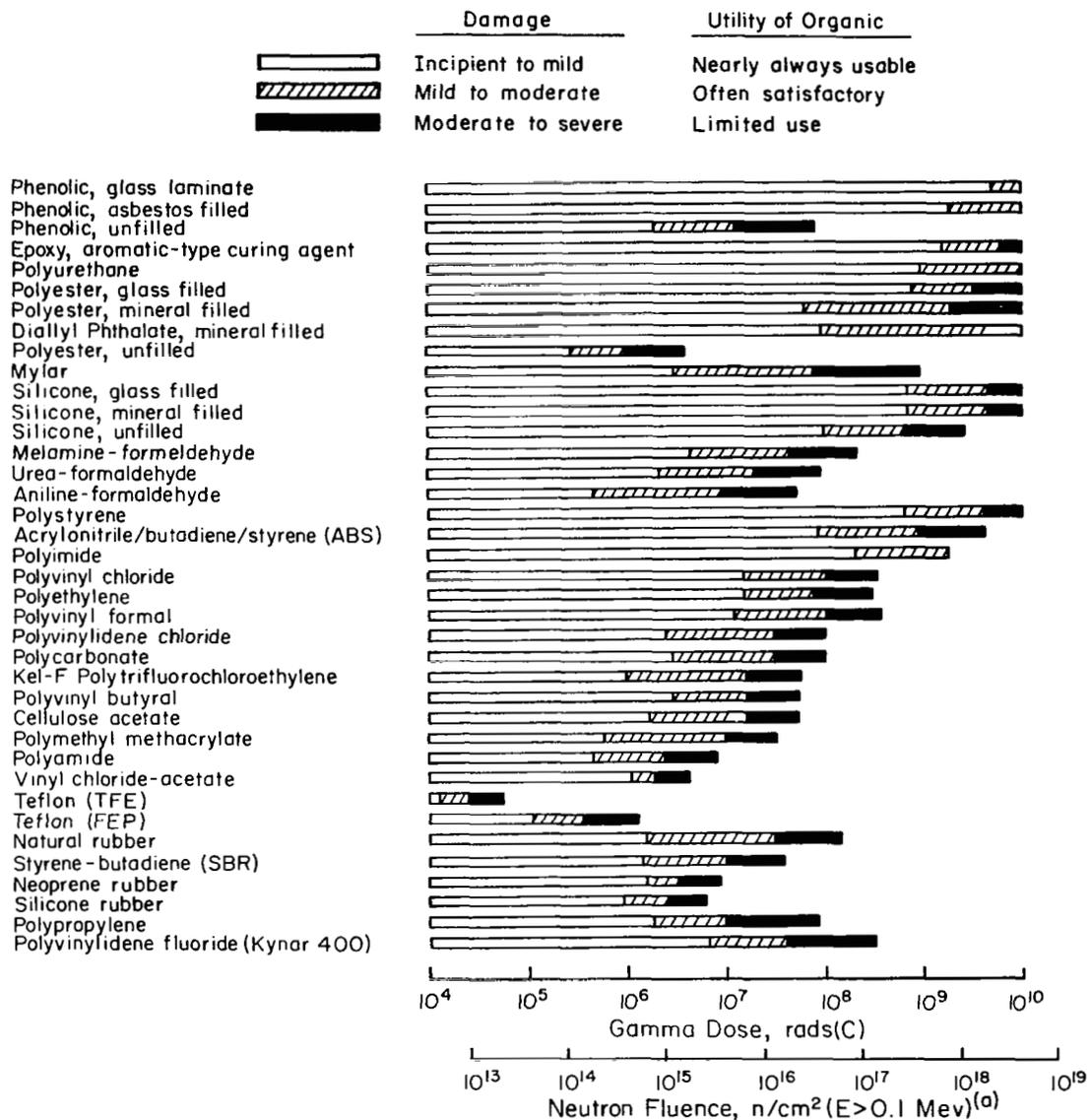
The cumulative results of the temporary effects pertaining to the electrical parameters of insulating materials are a reduction in breakdown and flashover voltages as well as an increase in leakage current or conductance - the latter also being identified as a decrease in the materials insulation resistance. However, these temporary changes in electrical characteristics are often not large enough to prevent the use of organic insulators and dielectrics in a radiation environment. This is especially true if the designer considers these changes and makes allowances to minimize their effects. However, where the designer is under severe space limitations or the application includes a high radiation-exposure rate, it may be necessary to limit insulating-material considerations to the inorganics since they tend to have a larger dose tolerance than organics for the same ionizing rate.

Permanent effects of radiation on organic insulating and dielectric materials are normally associated with a chemical change in the material. Most important among these chemical reactions that occur are molecular scission and crosslinkage. These chemical reactions or changes modify the physical properties of the material. A softening of the material, decreases in tensile strength and melting point, and a greater solubility could be the result of chain scission. Crosslinking leads to hardening, an increase in strength and melting point, a decrease in solubility, and an increase in density. Thus, the permanent effects of radiation on organic materials is predominantly a change in the physical properties. This

physical degradation, however, may also be disastrous to the electrical characteristics of a component part such as printed circuit boards, wire insulation, and connectors. Radiation-induced embrittlement of insulating structures, such as these, where the insulation cracks or flakes, in turn, could, cause a circuit to fail electrically through an "open" or "short" circuit. This is often the case when an insulator or dielectric material fails in a radiation environment, i. e., physical degradation followed by failure of electrical properties. Changes in dielectric loss or dissipation factor and insulation resistance have also been recorded as permanent effects from exposure to a radiation environment. These changes, however, are often quite small, and it would be an uncommon application where they would offer any problem.

A comparison of the relative resistance of organic insulating materials to permanent effects is presented in Figure 3. Another reaction that may occur when an organic insulator or dielectric is irradiated is gas evolution. Gas evolution from the solid organic polymers is less than that for liquids because of a greater possibility of recombination and limited diffusion. It is unlikely, therefore, that the volume of gas would be of serious concern except for organic fluids when sufficient pressure may be produced to distort or rupture a sealed enclosure. Another problem with some evolved-gas species is that they are corrosive. This is true of the gases produced during the irradiation of halogenated hydrocarbons such as polytetrafluoroethylene (Teflon) and Kel-F. Although failure from other causes is likely to occur before the corrosion would become a problem, some consideration in this area may be advisable when selecting sealed parts - like miniature relays - that contain electrical contacts.

Environmental conditions other than radiation contribute to the degradation of organic insulators and dielectrics. Temperature and/or humidity may be important for some materials, and the gaseous content of the ambient atmosphere is of serious import to others. For example, the absence of oxygen is known to increase the tolerance of tetrafluoroethylene to radiation by one to two orders of magnitude. This could be an important factor when considering its possible use in a radiation application.



(a) Approximate fluence (1 rad(C) = 4 x 10⁸ n/cm²)

FIGURE 3. RELATIVE RADIATION RESISTANCE OF ORGANIC INSULATING MATERIALS BASED UPON CHANGES IN PHYSICAL PROPERTIES

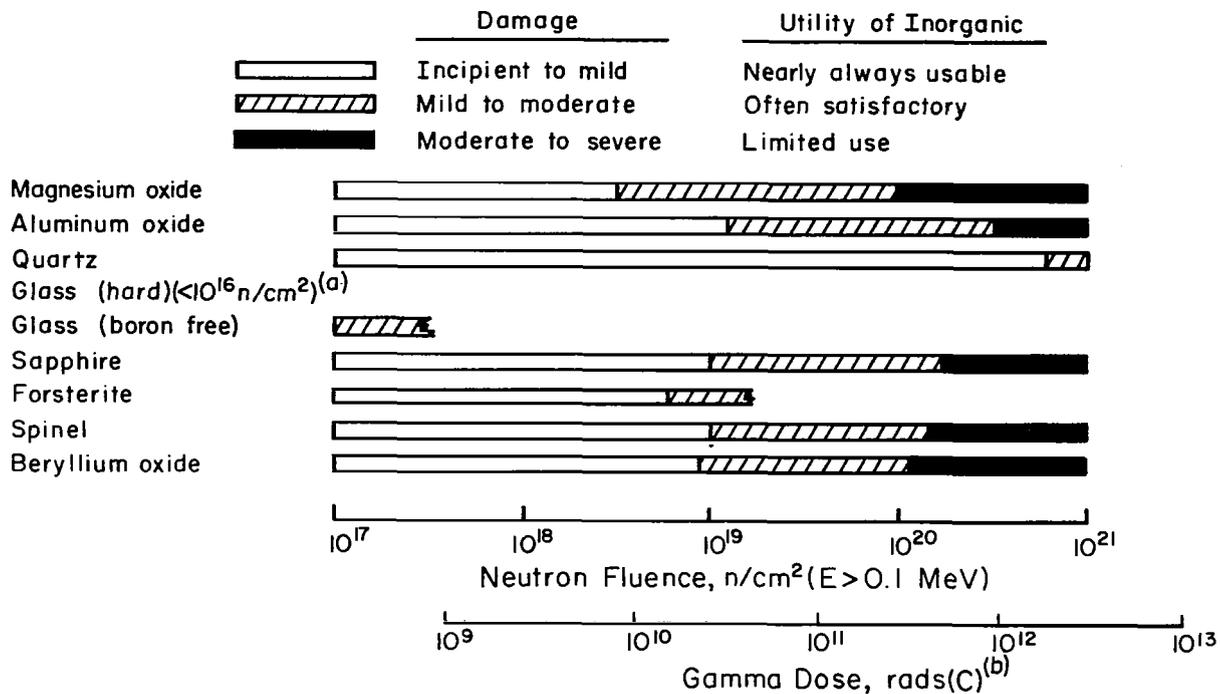
RADIATION EFFECTS ON INORGANIC MATERIALS

Inorganic insulating and dielectric materials are, in general, more resistant to radiation damage than are the organic insulators. Atomic displacements are responsible for nearly all of the permanent damage that occurs in inorganic insulators, but constitutes only a small part of the damage in organic insulators. No new bond formations are produced by the irradiation of the inorganic insulating materials, and they are left unaltered chemically.

A large part of the energy of incident radiation is absorbed through electronic excitation and ionization which produce a strong photoconductive effect in inorganic ceramics. A higher mobility of charge carriers in the inorganic compounds and the excitation-produced quasi-free electrons are responsible for this photoconductive effect. The generalized expression for conductivity in insulating materials, Equation (4), is applicable to the inorganic materials as well as the organics. The value of δ is almost always 1 for inorganics and $A\gamma$ is approximately $10^{-16} < A\gamma < 10^{-18}$. (2)

Atomic displacements lead to permanent changes in crystalline inorganic insulators which are manifested as changes in density, strength, and electrical properties. The density of crystalline insulators decreases from exposure to fast neutrons. Amorphous insulators, such as fused quartz and glass, experience a breakdown of their bonds. Change in resistivity is the predominant effect on electrical properties; little or no change occurs in a-c characteristics.

A comparison of the relative radiation resistance of inorganic insulators to permanent damage is presented in Figure 4.



(a) Unsatisfactory at $10^{16} n/cm^2$

(b) Approximate gamma dose ($4 \times 10^8 n/cm^2 = 1$ rad(C))

(c) Varies greatly with temperature

FIGURE 4. RELATIVE RADIATION RESISTANCE^(c) OF INORGANIC INSULATING MATERIALS

Based upon changes in physical properties.

RADIATION EFFECTS ON SPECIFIC BULK, SHEET, AND FILM INSULATIONS

Electrical insulations of the bulk, sheet, and film type have been investigated as to the effect of radiation on their physical and electrical properties by a number of experimenters. This section of the report summarized the results of these investigations.

Polytetrafluoroethylene (PTFE)

Polytetrafluoroethylene (commonly identified as Teflon TFE, but also including the trades names Halon TFE, Tetran, Fluon, Polyflon and Algotlon) has demonstrated a rather high susceptibility to radiation damage, which is quite apparent from the degradation of physical properties when it is irradiated. The rapid degradation of these properties by ionizing radiation is primarily attributed to a prevalence of main-chain scission by liberated fluorine atoms and the production of entrapped fluorocarbon gases. Tensile strength and ultimate elongation decrease, and the material becomes embrittled through the main-chain scission. The embrittlement becomes severe with extended irradiation [10^7 rads (C)] and the polytetrafluoroethylene crumbles and/or powders. The approximate damage threshold and the 25 percent damage dose are 1.7×10^4 rads (C) and 3.4×10^4 rads (C), respectively.

There is evidence that the damage observed when polytetrafluoroethylene is irradiated is a function of several factors. These include the various types of polytetrafluoroethylene such as TFE and the copolymer FEP, the ambient atmosphere, and the test temperature. It had been demonstrated that Teflon-FEP is more radiation resistant than TFE. In vacuum, 10-mil-thick FEP has retained its elongation properties for a factor-of-10 higher radiation exposure than similar TFE-7 film.⁽³⁾ In air, there was a factor-of-16 difference between the doses at which FEP and TFE-7 Teflon retained equivalent elongation properties. These differences are illustrated in Figures 5, 6, and 7 which also give a comparison between the effects of irradiation in vacuum and air at room temperature for various sample thicknesses. The absence of air or oxygen improves the radiation resistance of Teflon. These data also show a trend in the damage-thickness relationship.

The effect of elevated temperature in combination with irradiation is to accelerate the degradation of the polytetrafluoroethylene's physical properties. For example, in one study only negligible damage was observed at -65 F after a dose of 2.6×10^5 rads (C), while the tensile strength decreased 40 and 60 percent after similar doses at 73 and 350 F.⁽⁴⁾

Polytetrafluoroethylene also experiences changes in electrical properties when it is subjected to a radiation environment. The electrical parameters that have shown a sensitivity to radiation include dissipation factor or loss tangent, volume resistivity, dielectric constant, and dielectric strength. The changes observed are often insignificant in many

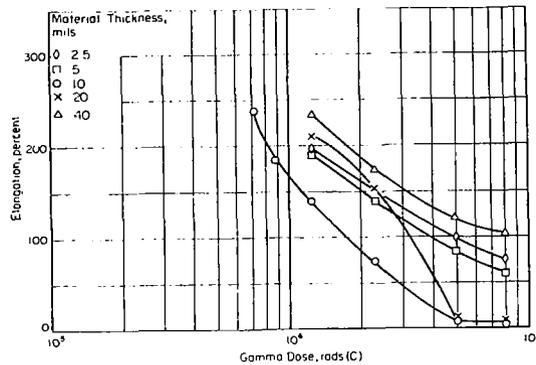


FIGURE 5. COMPARISON OF ULTIMATE ELONGATION VALUES OF VARIOUS THICKNESSES OF TEFLON TFE-7 IRRADIATED IN VACUUM(3)

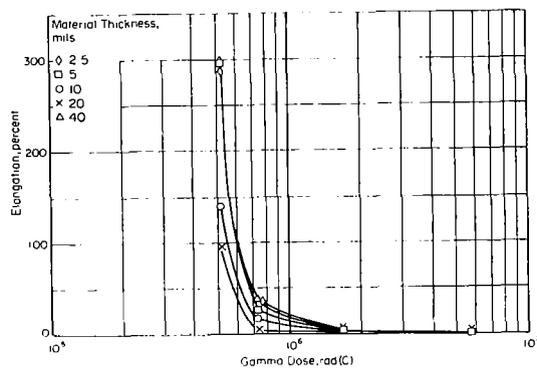


FIGURE 6. COMPARISON OF ULTIMATE ELONGATION VALUES OF VARIOUS THICKNESSES OF TEFLON TFE-7 IRRADIATED IN AIR(3)

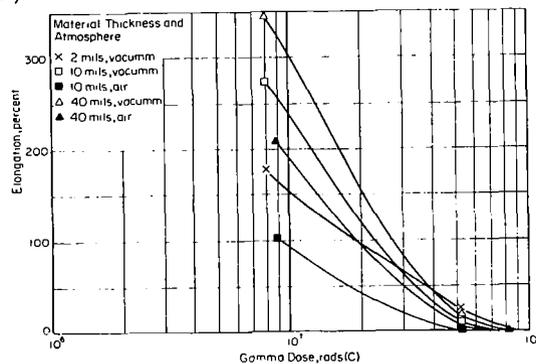


FIGURE 7. COMPARISON OF ULTIMATE ELONGATION VALUES OF VARIOUS THICKNESSES OF TEFLON FEP IRRADIATED IN VACUUM AND AIR(3)

practical applications as long as the materials mechanical integrity is maintained. Therefore, even though changes in electrical properties do occur, the degradation of physical properties is the criteria often used in determining the acceptability of this material for use in a specific application.

The volume resistivity of polytetrafluoroethylene decreases two or three orders of magnitude from initial values between 5×10^{17} and 1×10^{18} ohm-cm or greater when irradiated under vacuum conditions to total doses of 10^6 rads (C) and higher. The degradation may continue after the radiation exposure is terminated with an additional decrease of one or two orders of magnitude over a period of several days. Recovery may also occur with the volume resistivity approaching its preirradiation value several weeks after the irradiation.

Dielectric-constant measurements of polytetrafluoroethylene during and following exposure to a radiation environment have shown increases of less than 15 percent when irradiation in air or vacuum to respective doses of 8×10^6 and 10^8 rads (C). Recovery is essentially complete within a day or two after the irradiation. Similar results have also been obtained under vacuum conditions at cryogenic temperatures to a dose of 7×10^6 rads (C).⁽³⁾ However, when this test was terminated at 9.5×10^7 rads (C), the greatest value for the dielectric constant during exposure was approximately 22 percent higher than the initial cryotemperature value. Recovery to within 0.4 percent of the initial value occurred after the irradiation was terminated.

Significant increases of between two and three orders of magnitude occur in the low-frequency dissipation factor (60-100 Hz) or loss tangent of Teflon TFE when irradiated. This is true for irradiations at normal atmospheric conditions (air) and in vacuum at room temperature as illustrated by the example shown in Figure 8. Exposure to radiation in an air environment results in an increase to a maximum value which is then maintained during the irradiation. Irradiation in a vacuum environment produces a similar increase in dissipation factor; however, upon reaching a maximum value, this dissipation factor gradually decreases. The absorbed dose at which the maximum occurs appears to be a function of the exposure rate in that the peak occurs at a higher total dose with an increase in the rate of exposure.

The recovery characteristics of the dissipation factor of Teflon irradiated in air and vacuum are quite different. That of vacuum irradiated Teflon recovers rapidly and is essentially complete as long as it remains

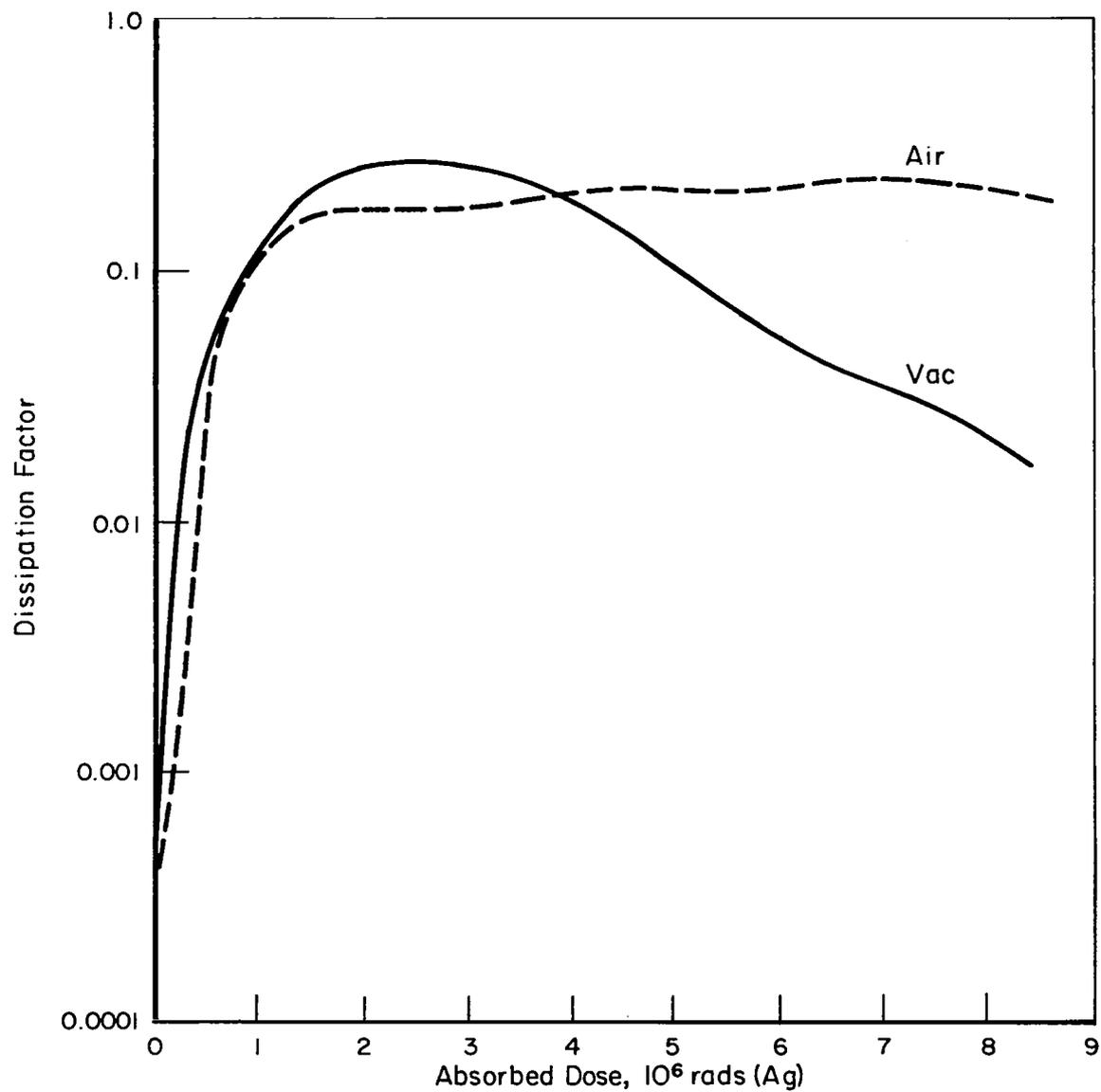


FIGURE 8. EFFECT OF X-RAY IRRADIATION ON TFE-6⁽⁵⁾

in the vacuum environment, while the dissipation factor of Teflon irradiated in a normal atmosphere recovers gradually over several days or weeks. If the vacuum-irradiated Teflon is exposed to air or nitrogen after its recovery under vacuum conditions the dissipation factor increases sharply. Following this increase, there is a more gradual recovery. Examples of these recovery characteristics are presented in Figure 9 after the exposure shown in Figure 8.

Limited information on the effect of radiation on the dissipation factor of different Teflon types indicate a difference in sensitivity in radiation. The a-c loss characteristics of the copolymer Teflon FEP-100 did not change significantly when this material was irradiated to a total dose of 3.08×10^6 rads (Ag).⁽⁶⁾ It has been assumed that this dose and that in Figure 8 are in rads silver since the calorimeter target used in measuring the dose was silver and no other material is mentioned in the documents in describing the radiation environment. Similar radiation exposure caused substantial increases to 0.408 and 0.169 in the dissipation factors for TFE-6 (extrusion resin) and TFE-7 (molding resin), respectively, in this same study.

Dielectric breakdowns induced in Teflon FEP by electron irradiation to a given fluence are both flux and temperature sensitive.⁽⁷⁾ An increase in temperature or a decrease in electron flux tends to decrease the number of breakdowns observed. Approximately twice as many breakdowns were observed for a fluence of 10^{13} e/cm² ($E_k = 40$ keV) and a flux of 10^{11} e/(cm²·s) than for a similar fluence and a flux of 10^{10} e/(cm²·s), and the number of breakdowns at liquid nitrogen temperature was seven to eight times greater than at room temperature.

Similar exposures of Teflon TFE to a proton environment including a flux range of 1×10^9 to 2×10^{11} p/(cm²·s), and a proton fluence of up to 5×10^{14} p/cm² did not result in dielectric breakdown at the test temperatures of -134 C or 27 C.⁽⁸⁾ A large recombination of trapped charges appears to take place in this and other materials with proton energies of 0.4 to 2.15 MeV at these fluxes and fluences and thus eliminates the dielectric breakdown effect observed with electron irradiation.

Polychlorotrifluoroethylene (Kel-F)

Polychlorotrifluoroethylene, another fluoroethylene polymer, also experiences severe degradation of its physical properties when exposed to a radiation environment. It is reported to have a damage threshold of

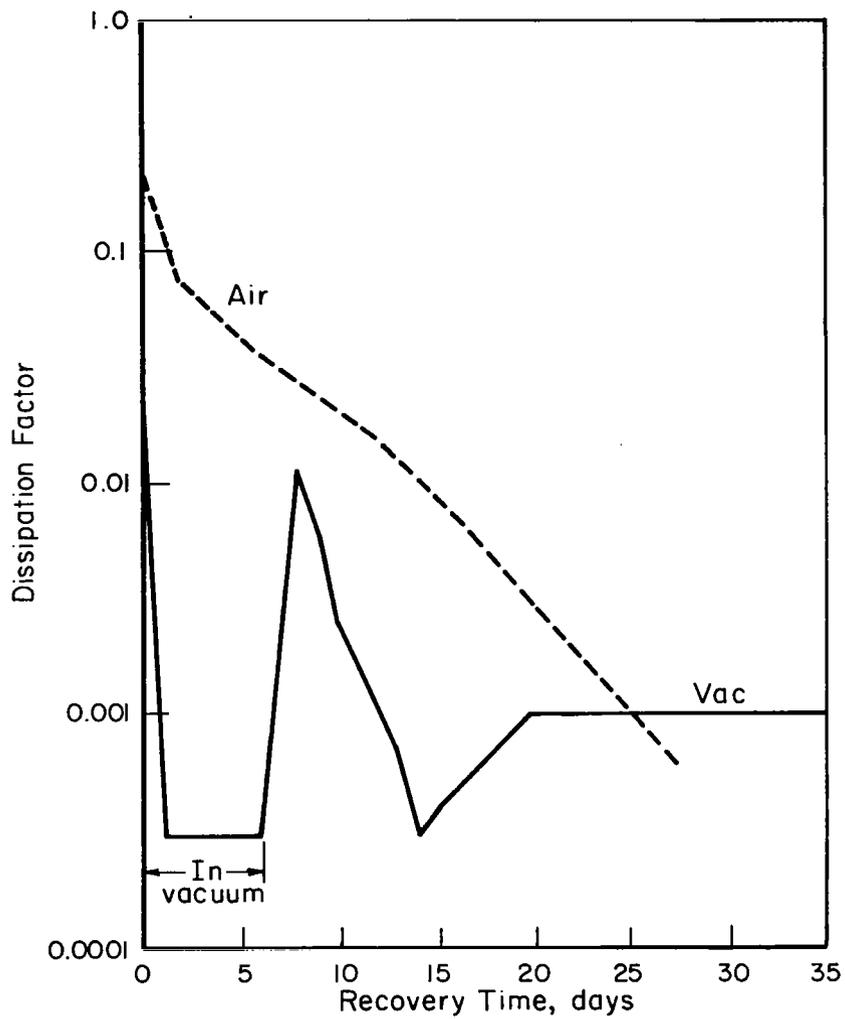


FIGURE 9. RECOVERY CHARACTERISTICS OF TFE-6 SPECIMENS AFTER X-RAY IRRADIATION AS SHOWN IN FIGURE 8⁽⁵⁾

1.3×10^6 rads (C) and a 25 percent damage dose of 2×10^7 rads (C)(4). The elongation of this material increased 47 percent and the impact strength decreased 16 percent when it was subjected to a total dose of approximately 2.4×10^7 rads (C).(9) The ultimate tensile strength was unaffected.

Electron irradiation with a total of 3.67×10^{16} e/cm² (E = 1.0 MeV) at 60 C so seriously degraded a specimen of polychlorotrifluoroethylene that it could not be measured as to its physical and electrical properties.

The degradation of the electrical properties of polychlorotrifluoroethylene from exposure to radiation includes a reduction in volume and surface resistivity. Decreases of between one and two orders of magnitude have been observed in both of these parameters during X-ray irradiation to a total dose of 2.1×10^7 rads (Ag) in a vacuum environment.(6) Essentially, no recovery was observed following the irradiation.

Measurements of dissipation factor during and following the irradiation of this material has actually shown decreases or improvement in this characteristic. Low values of 0.001 after 1920 hours of recovery in air were observed.(6)

A Russian study that included a total bremsstrahlung dose of 5.3×10^7 rads (C) produced similar reductions in volume resistivity.(10)

Polyethylene

In some respects, polyethylene improves with exposure to radiation in that its softening-point temperature increases for exposures of less than 10^7 rads (C). In addition, the tensile strength also increases until approximately 10^8 rads (C), after which it decreases and is 25 percent below the initial value at approximately 10^{10} rads (C).(4) The damage threshold is greater than 10^7 rads (C).

There are some differences in the results obtained from the irradiation of polyethylene; thinner films degrade at lower radiation doses than thicker films. This difference in behavior is attributed, at least in part, to the oxidation of the polyethylene when it is irradiated. Other factors that contribute to differing results are the various densities in which this material is produced and the addition of fillers.

A study where polyethylene of low and high densities and another which was carbon-black filled were exposed to an electron dose of

5.8×10^{16} e/cm² (E = 1.0 MeV) at 60 C illustrates the differences these factors make.⁽¹¹⁾ The hardness and stiffness in flexure of the high-density material decreased as a result of the irradiation, and the low-density and carbon-filled materials experienced increases in these properties. The high-density polyethylene also increased in tensile strength and the others decreased.

The electrical properties of polyethylene also degrade when it is exposed to a radiation environment. Measurements of the insulating qualities such as volume resistivity, surface resistivity, and insulation resistance indicate that a decrease of up to three orders of magnitude occurs in these parameters during irradiation with permanent decreases of one order of magnitude when subject to a total dose of 5.8×10^{16} e/cm² (E = 1.0 MeV). The dissipation factor at 1 KHz increases one to two orders of magnitude as a result of irradiation, and the dielectric constant changes less than ± 5 percent.

Electron-radiation-induced dielectric breakdown in polyethylene is sensitive to the flux to which the polyethylene is exposed; the number of observed breakdowns increases with an increase in electron flux.⁽⁷⁾ Exposure to a flux of 1×10^{11} e/(cm²·s) resulted in 20 breakdowns for a fluence of 2×10^{13} e/cm² (E_k = 30 keV) while only 12 breakdowns were observed for a similar fluence at 5×10^{10} e/(cm²·s) and none at 1×10^{10} e/(cm²·s).

Proton irradiation of polyethylene over a flux range of 10^9 to 10^{10} p/(cm²·s) for a fluence of 10^{13} p/cm² at each rate with energies of 1.15 and 1.65 MeV produced no breakdowns in the material.⁽⁸⁾

Polystyrene

Irradiation studies of polystyrene have shown it to be one of the most radiation-resistance plastics among those used for insulating purposes in electronic circuitry. It has a damage threshold of 10^8 rads (C) and does not experience 25 percent damage to its physical properties below 4×10^9 rads (C). Polystyrene is subject to postirradiation oxidation that continues for several weeks, however, oxidation plays little or no part in the radiation damage that occurs.

Electron irradiation to a fluence of 5.8×10^{16} e/cm² (E = 1.0 MeV) at 60 C has resulted in decreases of approximately 50 percent in the tensile strength and ultimate elongation.⁽¹¹⁾ The hardness and the stiffness in

flexure also decreased 1 percent and 13 percent, respectively, during this same study. These results indicate polystyrene becomes more flexible and softer as a result of the irradiation.

The insulating quality of polystyrene appears to be the only electrical property that is affected by exposure to radiation. Permanent decreases of one and two orders of magnitude have been observed in the volume resistivity and insulation resistance of this material following doses as low as 4.5×10^6 rads (C) and as high as 1×10^8 rads (C). Other electrical parameters, such as dielectric constant and dissipation factor, have shown little or no change from exposure to a radiation environment within this range of total dose.

Polyethylene Terephthalate

Polyethylene terephthalate (Mylar) has shown improvement in its physical properties when exposed to limited radiation doses with very little degradation in electrical properties. There is, however, some disagreement concerning the dose at which the trend toward improved physical properties is reversed and degradation begins. Based upon available information, the best estimate for the dose at which this reversal occurs is 10^6 to 10^7 rads (C) for X-ray and reactor irradiation. Radiation exposure to doses of 10^8 rads (C) and above causes severe embrittlement of polyethylene terephthalate to a degree that properties are unmeasurable.

Degradation of the electrical properties of polyethylene terephthalate with the doses described above, 10^6 to 10^7 rads (C), is insignificant. Changes in the insulation resistance, volume resistivity, and surface resistivity as a result of irradiation are limited to approximately one decade. The dielectric constant and dissipation factor remain, essentially, unchanged.

Exposure to a proton fluence of 10^{13} p/cm² at various energies between 0.8 and 3.25 MeV and flux of 10^9 to 10^{10} p/(cm². s) did not induce adielectric breakdown in Mylar at temperatures of -134 C and 27 C. (8)

Polyamide

Polyamide (nylon) sheet or film insulation changes in both physical and electrical properties when subjected to a radiation environment. This

material experiences threshold damage at a dose of 8.6×10^5 rads (C) and 25 percent damage at 4.7×10^6 rads (C). These doses are based upon losses in ultimate elongation and impact strength. Another property of polyamide that deteriorates from radiation exposure is stiffness in flexure, which has increased between 52 and 181 percent, depending upon the nylon type, after exposure to an electron dose of 5.8×10^{16} e/cm² (E = 1.0 MeV) at 60 C⁽¹¹⁾. This same exposure improved the tensile strength by 49 to 107 percent. These results agree with other radiation studies which have shown increases in tensile strength of 25 percent for doses over 10^9 rads (C).

Information on the effects of radiation on the electrical properties of polyamide is limited to results of the electron irradiation mentioned above. Exposure to this radiation environment produced an increase of approximately one order of magnitude in the insulation resistance and a decrease of less than an order of magnitude for the dissipation factor. A decrease in dielectric constant was insignificant at 1 MHz and varied between 5 and 32 percent at 1 KHz, depending on the polyamide type.

Diallyl Phthalate

Diallyl phthalate with various fillers such as glass or Orlon has shown exceptional radiation tolerance for a plastic insulating material. Little or no permanent degradation of physical or electrical properties have been observed with radiation exposures to doses of between 10^8 and 10^{10} rads (C). Insignificant changes are observed in the hardness and flexibility of this material when irradiated to these total doses. The ultimate elongation and tensile strength of Orlon-filled diallyl phthalate actually increased or improved with exposure to an electron dose of 5.8×10^{16} e/cm² (E = 1.0 MeV) at 60 C.

The electrical properties of diallyl phthalate such as dielectric constant, dissipation factor, and insulation resistance are affected by exposure to a radiation environment such as described above. The amount of degradation or change in these parameters because of this exposure is of little practical significance. Permanent changes in dielectric constant were less than 6 percent while the dissipation factor recovered to below the initial value. Increases in insulation resistance during exposure are followed by complete recovery within approximately 1 hour after the irradiation is terminated.

Polypropylene

Polypropylene is subject to a severe loss in physical properties when exposed to a radiation environment. Above a total dose of 1×10^7 rads (C) this material becomes embrittled and experiences decreases in tensile and impact strengths that approach 60 and 75 percent, respectively, at a dose of 5×10^7 rads (C). An electron fluence of 5.8×10^{16} e/cm² ($E = 1.0$ MeV) at 60 C resulted in decreases of 87 to 96 percent in ultimate elongation and tensile strength.⁽¹¹⁾ This electron fluence also produced a decrease in hardness of 25 percent which is in agreement with results from other studies where polypropylene became increasingly softer and more flexible with doses of between 2.6×10^8 and 8.7×10^8 rads (C) when lower doses caused embrittlement of the material.⁽¹²⁾ The suggested mechanism for this reversal in the effect of radiation is that at higher doses some of the polypropylene chains have become low in molecular weight from chain cleavage and this lower molecular weight material plasticized the remainder of the polymer.

The permanent degradation or change in electrical properties that occurs when polypropylene is irradiated to the above doses is of little or no practical significance. The dielectric constant decreases slightly and the insulation resistance decreases less than an order of magnitude. Measurements of a-c loss such as power factor and dissipation factor at 1 KHz to 1 MHz have varied from no observable change to an increase from between 0.0005 and 0.0008 to between 0.002 and 0.003. No information concerning temporary changes that might occur during irradiation is available.

Electron-irradiation-induced dielectric breakdown of polypropylene appears to be sensitive to the electron flux to which it is exposed for a specific fluence.⁽⁷⁾ The maximum number of breakdowns observed at room temperature with a flux of 1×10^{11} e/(cm². s) for a total fluence of 5×10^{13} e/cm² ($E_k = 30$ keV) was 40, while that for a flux of 1×10^{10} e/cm² was 8 for a similar fluence and temperature.

Polyurethane

Polyurethane has shown good stability in both physical and electrical properties when exposed to a radiation environment. Irradiation to doses up to 7×10^8 rads (C) has caused very little change in flexure strength or modulus.⁽¹³⁾ A weight loss of 1 percent (a physical change)

between this dose and 1.75×10^8 rads (C) indicates the possibility of approaching a damage threshold. No information is available above this dose, with exception of the results from an electron fluence of 5.8×10^{16} e/cm² (E = 1.0 MeV) at 60 C.⁽¹¹⁾ Serious deterioration of physical properties occurred from this radiation exposure and included a 67 and 176 percent increase in hardness and stiffness in flexure, respectively. A 59 percent decrease in tensile strength and a 99 percent decrease in ultimate elongation were also noted following irradiation to this electron fluence.

Information concerning the effect of radiation on the electrical properties of polyurethane is limited to results from two radiation studies: the electron irradiation mentioned above and a reactor exposure to a neutron fluence of 1.2×10^{14} n/cm² (E > 0.5 MeV) and gamma dose of 1.4×10^6 rads (C) at 16 C to 29 C.⁽¹⁴⁾ Insignificant permanent changes in the insulating properties, volume resistivity, or insulation resistance of less than one order of magnitude were observed as a result of these two studies. The dissipation factor at 1 MHz was essentially unchanged while that at 1 KHz increased approximately 30 percent in the reactor study (~6.0 to 7.4) and doubled in the electron irradiation study (0.02 to 0.04). The only disagreement in the results of the two studies was the dielectric constant which decreased 6-1/4 percent at 1 KHz from the electron irradiation and increased approximately 16 percent from the reactor exposure.

Polyvinylidene Fluoride

Polyvinylidene fluoride (Kynar 400) has shown higher radiation tolerance than other fluorocarbons such as Teflon and Kel-F. It has demonstrated an ability to withstand irradiation to a dose of 10^7 rads (C) in air or vacuum with no indication of degradation in physical properties except color change. An order-of-magnitude increase in the radiation dose to 10^8 rads (C) and above causes embrittlement and loss of flexibility and tensile strength. Low temperature, however, increases the radiation tolerance of polyvinylidene fluoride in that doses of this magnitude, 10^8 rads (C), at cryogenic temperatures do not reach damage threshold.

Changes in the electrical properties of polyvinylidene fluoride include decreases of between two and three orders of magnitude in volume resistivity during and after irradiation to doses up to 2.1×10^7 and 6.6×10^7 rads (C) in an air and a vacuum-cryotemperature environment, respectively.⁽³⁾ A decrease of approximately five orders of magnitude occurred with a dose of 2.1×10^8 rads (C) in the air atmosphere. Dissipation factor increased less than one decade, and the dielectric constant was essentially unaffected by the irradiation.

Polyimide

Polyimide (Kapton) has shown little or no change in either its physical or electrical properties to gamma doses (Co 60) of up to 10^9 rads (C).⁽¹⁵⁾ Tensile strength remained essentially constant when exposed to a total dose of this magnitude but decreased to approximately one-half its initial value between 1×10^9 and 6×10^9 rads (C). The electrical resistivity remained at 1×10^{19} ohm-cm or above and only decreased to 3×10^{18} ohm-cm at a total dose of 1×10^{10} rads (C). This same dose left the dielectric constant essentially unchanged and decreased the breakdown voltage to approximately 75 percent of its initial value.

Dielectric breakdown induced in polyimide (Kapton) by electron irradiation has been shown to be sensitive to both flux and temperature.⁽⁷⁾ A total of eight breakdowns on two samples were observed at room temperature for a flux of 10^{11} e/(cm²·s) and a fluence of 10^{13} e/cm² ($E_k = 30$ keV) - a factor of four greater than the number observed at a similar fluence and a flux of 10^{10} e/(cm²·s). The effect of temperature on the number of dielectric breakdowns is illustrated by the results at liquid nitrogen and room temperature. Fifteen and 35 breakdowns were observed, respectively, for the two specimens irradiated to a fluence of 2×10^{13} e/cm² ($E_k = 30$ keV) at room temperature while 75 and 120 breakdowns occurred with the specimens irradiated to a similar fluence at the temperature of liquid nitrogen.

No dielectric breakdowns were observed in polyimide (Kapton) that was subjected to proton irradiation that included fluences to 5×10^{14} p/cm² with a flux range of 10^9 to 2×10^{11} p/(cm²·s).⁽⁸⁾ The energy range of the protons was between 0.4 and 2.5 MeV and the test temperatures were -134 C and 27 C.

Polyimidazopyrrolone (Pyrrone)

Polyimidazopyrrolone polymers (Pyrrone) have been subjected to various radiation environments including electron, proton, and gamma (Co 60). Exposure to high doses of electron radiation, 1×10^{10} rads (C) ($E = 1$ MeV) and 5×10^9 rads (C) ($E = 2$ MeV) resulted in insignificant degradation in the mechanical and electrical properties of Pyrrone.^(16, 17) The yield strength of specimens irradiated to a fluence of 1×10^{10} rads (C) was approximately 70 percent greater than that of nonirradiated Pyrrone, the tensile strength was essentially unchanged, and elongation was reduced by two-thirds. Little or no difference was noted in the dielectric constant

and dissipation factors of nonirradiated specimens and those exposed to a fluence of 5×10^9 e/cm² (E = 2 MeV). However, this fluence caused an increase in dark current by a factor of 5 in Pyrrone made up of benzophenone tetracarboxylic acid dianhydride (BTDA) and diaminobenzidine (DAB) while the dark current of a Pyrrone composed of pyromellitic dianhydride (PMDA) and diaminobenzidine (DAB) increased approximately two orders of magnitude.

Dielectric breakdown induced in Pyrrone by electron irradiation to a given fluence is sensitive to both flux and temperature; the number of breakdowns that occur tends to increase with flux and decrease with temperature.⁽⁷⁾ An order of magnitude increase in electron flux, from 10^9 e/(cm². s) to 10^{10} e/(cm². s), resulted in twice as many breakdowns for similar fluences of 10^{13} e/cm² ($E_k = 30$ keV) at room temperature. Also, the number of breakdowns recorded at liquid nitrogen temperature was more than twice that observed at room temperature for a flux of either 10^{10} or 10^{11} e/(cm². s).

No dielectric breakdowns occurred in Pyrrone specimens irradiated to a proton fluence of 10^{13} p/cm² ($E_k = 1.0$ and 1.5 MeV) at temperatures of -134 C and 27 C.⁽⁸⁾ Dose rates were 10^9 and 10^{10} p/(cm². s) with specimens subjected to each rate for the total fluence.

The exposure of Pyrrone, both PMDA-DAB and BTDA-DAB, to a gamma dose rate of 10 to 1000 rads/min (Co 60) produced current densities of 1×10^{-11} to 6×10^{-11} ampere cm⁻² in the PMDA-DAB and 2×10^{-12} to 2×10^{-11} ampere cm⁻² in PTDA-DAB.⁽¹⁷⁾ The currents are attributed to the motion of free radiation-induced charge carriers migrating in the electric field.

Epoxy Laminates

Epoxy-glass laminates have shown little or no degradation in mechanical and/or electrical properties from reactor irradiation to 2×10^{13} n/cm² (E > 0.1 MeV) and 1×10^8 rads (C) or cobalt-60 gamma irradiation to 1×10^7 rads (C).^(3, 15) Variations in breakdown voltage have been observed at gamma doses below this level, however, with decreases of 15 to 30 percent from preirradiation values at 1×10^7 rads (C) and 50 to 70 percent at 1×10^9 rads (C). Other electrical properties such as resistivity, dielectric constant, and dissipation factor are not degraded significantly at this total dose.

The tensile strength of epoxy-glass laminates remains unchanged to a gamma dose of 1×10^7 rads (C) but decreases to less than 20 percent of the initial value at 1×10^9 rads (C). Compressive strength does not change significantly. A total gamma dose of 10^{10} rads (C) will cause an epoxy-glass laminate to become brittle and weak or to lose most of the resin binder.

Miscellaneous Organics

Radiation-effects information is available on organic bulk, sheet, and/or film materials other than those discussed on the preceding pages. The information, however, is limited to results from only one radiation-effects test of each material. Therefore, these results are limited to the tabular presentations of Tables 2 and 3. Table 2 is a listing of materials that were so seriously degraded by the indicated radiation dose that their physical and electrical properties could not be tested or measured. This is not to imply that these materials are all unsatisfactory in some radiation environments; it indicates only that they did not survive the indicated electron fluence. The listing in Table 3 consists of those materials that survived exposure to the radiation environment and includes some of the particulars concerning changes observed in their physical and electrical properties.

Ceramics

Ceramic insulating materials, such as silica, Steatite, Alsimag, Alox, and Pyroceram, in sheet and other basic physical configurations have shown virtually no change in a-c properties (dissipation factors and dielectric constant) with X-ray irradiation to doses up to 10^7 rads (C). Similar results have also been observed with reactor irradiation to doses as high as 10^{17} n/cm² ($E > 0.1$ MeV) and 10^9 rads (C). Permanent decreases of between one and two orders of magnitude will occur in the volume and surface resistivity of ceramic insulating materials at these doses. However, Steatite in combination with phosphate-bonded inorganic cements and chrome-plated copper conductors has shown little or no change in conductor-to-ground insulation resistance with neutron fluences of 2.2×10^{19} n/cm² ($E > 0.1$ MeV) and 9.0×10^{10} rads (C) gamma.⁽²⁰⁾ Also, Lucalox, a high-purity alumina, did not experience a change in resistivity when subjected to a neutron fluence of 1.6×10^{20} n/cm² ($E > \text{MeV}$) with temperatures of 800 to 1000 C.⁽²¹⁾

TABLE 2. MISCELLANEOUS ORGANIC BULK, SHEET, AND/OR FILM MATERIALS WHICH LIMITED INFORMATION INDICATE AS UNSATISFACTORY AT THE RADIATION EXPOSURE INDICATED⁽¹¹⁾

Material Identification	Total Electron Fluence at 60 C (E = 1.0 MeV)
Acetal resin	1.22×10^{16} e/cm ² (3.8×10^8 rads)
Acrylic plastic, molding grade (rubber modified)	5.80×10^{16} e/cm ² (1.8×10^9 rads)
Allyl carbonate plastic, cast	4.10×10^{16} e/cm ² (1.3×10^9 rads)
Cellulose acetate	5.80×10^{16} e/cm ² (1.8×10^9 rads)
Cellulose butyrate	4.10×10^{16} e/cm ² (1.3×10^9 rads)
Cellulose propionate	4.10×10^{16} e/cm ² (1.3×10^9 rads)
Chlorinated polyether	2.90×10^{16} e/cm ² (9×10^8 rads)
Polycarbonate	5.80×10^{16} e/cm ² (1.8×10^9 rads)
Polyfluoroethylenepropylene, Teflon FEP (copolymer)	3.67×10^{16} e/cm ² (1.1×10^9 rads)
Polymethyl methacrylate, cast	1.22×10^{16} e/cm ² (3.8×10^8 rads)
Polymethyl methacrylate, molding grade	4.10×10^{16} e/cm ² (1.3×10^9 rads)
Styrene acrylic copolymer	2.90×10^{16} e/cm ² (9×10^8 rads)
Polyvinyl chloride, DOP plasticized	3.67×10^{16} e/cm ² (1.1×10^9 rads)
Polyvinyl chloride, rigid	4.10×10^{16} e/cm ² (1.3×10^9 rads)

TABLE 3. RADIATION EFFECTS ON MISCELLANEOUS ORGANIC BULK, SHEET, AND/OR FILM MATERIALS WHERE ONLY LIMITED INFORMATION IS AVAILABLE

Material Identification	Total Integrated Exposure	Remarks
Acrylonitrile-butadiene-styrene	5.8×10^{16} e/cm ² (E = 1.0 MeV) at 60 C	Hardness increased 13 percent; flexibility, tensile strength, and ultimate elongation decreased 49, 58, and 93 percent, respectively. Dielectric constant increased <1.5 percent and DF decreased slightly. IR increased.(11)
Styrene-acrylonitrile copolymer	5.8×10^{16} e/cm ² (E = 1.0 MeV) at 60 C	Tensile strength and ultimate elongation decreased 34 and 47 percent, respectively. Hardness was unchanged and flexibility increased 5 percent. Dielectric constant increased 4 to 6 percent. DF increased to 0.01 at 1 KHz and 0.40 at 1 MHz. IR decreased one decade.(11)
Styrene-butadiene (high-impact styrene)	5.8×10^{16} e/cm ² (E = 1.0 MeV) at 60 C	Flexibility and ultimate elongation decreased more than 90 percent and tensile strength decreased 35 percent. Hardness increased. Dielectric constant increased slightly while DF increased ~50 percent. IR increased.(11)
Styrene-divinylbenzene	5.8×10^{16} e/cm ² (E = 1.0 MeV) at 60 C	Changes in physical properties were of no practical significance.(11)
Polyvinyl chloride acetate	5.8×10^{16} e/cm ² (E = 1.0 MeV) at 60 C	Insignificant changes in hardness, tensile strength, dielectric constant, and dissipation factor. Insulation resistance decrease two decades. Flexibility increased 30 percent.(11)
Polyvinylfluoride	5.8×10^{16} e/cm ² (E = 1.0 MeV) at 60 C	Serious degradation prevented measurement of physical degradation. Dielectric constant decreased 7 percent and dissipation factor increased one decade. Insulation resistance did not change.(11)
Polyester/glass laminate	2.5×10^6 rads (C)	Volume and surface resistivity decreased three decades. Dissipation factor increased from 0.003 and 0.006 to 0.019 and 0.010. No change in dielectric constant.(6)
91-LD Resin/181-Volan A laminates (copper clad)	2.5×10^{15} n/cm ² (E > 2.9 MeV) at 55 C	No degradation in physical properties.(18)
Silicone/glass laminate	5.0×10^{13} n/cm ² (E > 2.9 MeV) at 200 C 1.0×10^8 rads (C)	49 percent loss in flexure strength, slight change in color, thickness, and weight.(19)

A change or darkening in color is the only observable change in the ceramics' physical properties at the above doses. However, investigations of physical damage to doses of 10^{19} - 10^{20} n/cm² (E > 0.1 MeV) have shown dimensional and density changes. The latter varying from 1 to 17 percent depending upon the material tested.

Mica

Mica is the only inorganic insulating material other than ceramics on which there are radiation effects data for sheet or other basic physical forms of the material. These data include the evaluation of physical damage in a reactor environment for total doses up to 5×10^{13} n/cm² (E > 2.9 MeV) and 1×10^8 rads at 200 C and of changes in both physical and electrical properties in a cobalt-60 gamma environment to 1×10^{10} rads (C).^(15, 19) No significant effect has been observed other than color darkening for most forms of mica including flexible mica paper and flake and rigid-mica mat. A rigid, inorganic, bonded amber mica, however, experienced a 29 percent decrease in flexure strength at the above reactor environment.

A glass-bonded mica experienced no change in compressive strength to a total dose of 1×10^{10} rads (C) gamma; the tensile strength decreased approximately 50 percent with no decrease for doses up to 1×10^7 rads (C). The resistivity was unchanged and the dielectric constant increased less than 10 percent for the same total dose of 1×10^{10} rads (C) (Co 60). Variations in voltage breakdown ranged from 95 to 120 percent of the initial value to a gamma dose of 1×10^9 rads (C) and decreased to 70 percent at 1×10^{10} rads (C).

RADIATION EFFECTS ON SPECIFIC WIRE AND CABLE INSULATION

Both organic and inorganic wire insulations have been tested and evaluated as to their radiation resistance. A serious deterioration of physical properties as a result of irradiation has occurred with some organics, and others, demonstrating a high level of radiation tolerance, have survived doses of up to 1×10^8 rads (C). Special cables and wires insulated with inorganic materials have shown similar radiation resistance

to doses of 8.8×10^9 and 8.8×10^{11} rads (C). Changes in the electrical properties of wire having either organic or inorganic insulation are generally of little practical significance and include both temporary and permanent effects. The insulation resistance may decrease several orders of magnitude during irradiation and then completely recover or recover to within one order of magnitude of the initial value when the radiation exposure is terminated. Permanent decreases in dielectric strength have also been observed following exposure to radiation as have increases in dissipation factor and the attenuation of coaxial cables. Details concerning these and other effects of radiation are discussed in the following paragraphs as they pertain to specific wire and cable insulation.

Polytetrafluoroethylene (PTFE)

Polytetrafluoroethylene (Teflon) wire insulation has shown severe degradation in physical properties as a result of exposure to a radiation environment. The extent of the damage that occurs is sensitive to total dose and varies from a noticeable decrease in wire flexibility to the complete disintegration of the material.

The lowest total dose at which information on changes in physical characteristics is available is 10^3 rads (C) with a 5 psia oxygen atmosphere and ambient temperature of 90 C as other environmental conditions.^(22, 23) A decrease in flexibility was noted for a wire specimen having TFE Teflon insulation with an ML (polyimide resin) coating after exposure to these conditions. Wire insulated with the copolymer Teflon FEP and having this same outer coating, however, showed no loss in flexibility, nor did a Type-E TFE-insulated wire per MIL-W-1687D. Similar results also occurred for a dose of 6×10^4 rads (C) with a vacuum of 10^{-6} torr and a temperature of 150 C. These results indicate two possibilities: the TFE Teflon (polytetrafluoroethylene) insulated wire with the ML coating has a lower radiation tolerance and/or the 10^3 to 6×10^4 rads (C) total dose is the threshold area for damage to polytetrafluoroethylene-insulated wire and damage to the other wire insulations was not yet apparent.

The change in the physical properties of polytetrafluoroethylene-insulated wire and cable continues with increasing dose, and complete deterioration has been reported after total exposures of 10^7 and 10^8 rads (C). The damage is such that the inner core of a Teflon-insulated coaxial cable will appear sound, but will powder and crumble when stressed mechanically through handling or testing. Failure of this type in a coaxial cable could be expected to include shorting between conductors and/or between conductors

and the outer sheath or shield when radiation environments reach these dose levels. This should be of special concern in applications that include vibration or other mechanical stresses as a part of the intended environment.

The irradiation of polytetrafluoroethylene-insulated wire also results in the degradation of electrical properties. Insulation resistance measurements performed before and after irradiation have shown little or no significant change in this parameter. Breakdown voltage has decreased as much as 50 percent between twisted pairs of wire having initial breakdown at voltages as high as 15.8 to 28.2 kV.^(22, 23) The posttest range was 9.1 to 14.2 Kv. Several electrical characteristics of coaxial cables have shown the effects of degradation. The attenuation of a 10-foot length of RG-225/U at 400 MHz increased 0.20 db while the change for a similar sample of RG 142/U was so great it could not be measured after a total exposure of 3×10^{16} n/cm² ($E > 0.1$ MeV) and 2.3×10^8 rads (C).⁽²⁴⁾ The RG 142/U cable also experienced larger increases in other measured parameters including VSWR (1.19:1 to 2.4:1), apparent change in electrical length (0.224 wavelength), and phase shift (between 0 and +15 degrees).

Polyethylene

The physical and electrical properties of wire and cable that incorporate polyethylene as the insulating media have shown little or no degradation for total doses up to 10^7 and 10^8 rads (C) at temperatures of from 15 C to 100 C. This is a comparatively high radiation tolerance for plastic insulated wire. Some degradation is apparent in the physical properties after a dose of 9.6×10^7 rads (C) with the darkening of the polyethylene, but it still remains resilient with no indication of stiffness. It is estimated that threshold damage occurs at approximately 4.4×10^8 rads (C). Loss of flexibility has been observed, however, after cable insulated with polyethylene and having outer jackets of either Estane or Alathon received a total dose of 8.8×10^8 rads (C).⁽²⁵⁾ The polyethylene of both cables was brown and brittle and broken on the wire. The Estane jacket on the one cable was very pliable while the Alathon jacket on the other was very brittle. This embrittlement of the outer jacket material of a cable can offer a problem, particularly with a coaxial or shielded type, in that some materials used for this purpose become brittle at lower doses than the polyethylene. Therefore, the outer jacket can be the limiting factor in the application of a cable rather than the insulating material used on the wire the jacket encloses.

The electrical properties of polyethylene-insulated wire and cable have shown some degradation during and following exposure to a radiation environment. Insulation resistance is both rate and dose sensitive with changes of one to three orders of magnitude observed during exposure. Recovery is essentially complete following the termination of the irradiation. The characteristic impedance of coaxial cables has shown some variation as a result of radiation exposure but the extent of these variations is of little significance (0.5 to ~10 percent). Limited data on other coaxial-cable parameters indicate that little or no change occurs in attenuation, VSWR, or apparent electrical length when these cables are irradiated.

An induced current is also an electrical characteristic that has been observed in electrical cable of various insulations. The only steady-state-radiation data concerning this effect are limited to polyethylene-insulated coaxial cable.⁽²⁶⁾ Currents of the order of 10^{-8} amperes were observed during the cable's exposure to the radiation which included 1.2×10^{12} n/(cm²·s) ($E > 2.9$ MeV) and 6.6×10^7 rads (C) r/hr gamma at a reactor power of 1 megawatt.

Silicone Rubber

Silicone rubber wire insulation does not experience noticeable degradation of its physical properties at doses up to 8.8×10^5 rads (C). A slight change or lightening in color with a barely perceptible loss in resilience or flexibility has been observed in flat-ribbon multiconductor wire insulated with this material after an exposure of 8.8×10^6 rads (C).⁽²⁷⁾ Serious deterioration of the wire's mechanical qualities occurs with a total dose of 8.8×10^7 rads (C) and above. There is a definite loss in flexibility, and the silicone rubber insulation will crack and/or crumble when the wire is stressed mechanically.

The insulation resistance of wire insulated with silicon rubber decreases one or two orders of magnitude during irradiation with recovery to within one order of magnitude when the exposure is terminated. If the environmental conditions also include moisture and/or elevated temperature the combined effect can decrease the insulation resistance even further. The breakdown voltage of silicon wire insulation has shown some variation between pre- and postirradiation measurements after doses of 1×10^3 and 4×10^6 rads (C).^(22, 23) These changes in breakdown voltage, however, include both increases and decreases and are of little significance.

Polyimide

Polyimide resin film, ML, wire insulation has shown no indication of deterioration in physical or electrical properties up to a dose of 1.5×10^8 rads (C) and 4.4×10^{17} n/cm² ($E > 0.1$ MeV). Flexibility and stripping characteristics are unaffected with no visible difference between wire that has been irradiated and that which has not. Measurements of electrical parameters such as insulation resistance, capacitance, and dissipation factor have shown no significant difference between pre- and postirradiation values. Wires with a combination of glass braid and polyimide resin film insulation exhibited a breakdown voltage of approximately 1000 wires before and after receiving the total exposure indicated above. (27)

The absence of degradation at doses up to 1.5×10^8 rads (C) demonstrates a high level of radiation resistance for this wire insulation with a possibility of satisfactory performance at even higher doses.

Irradiation-Modified Polyolefin

Irradiation-modified polyolefin*-insulated wire has experienced no serious degradation in physical or electrical properties when irradiated to a total dose of 5×10^8 rads (C). The insulation may change somewhat in color, but it remains flexible and has some degree of compressibility. Wire specimens insulated with this polyolefin have successfully met standard military bend tests using a 10-D Mandrel following an electron dose of 5×10^8 rads (C) at 23 C. (28) A test to determine the corrosiveness of any gas evolved from the polyolefin on copper- and aluminum-surface mirrors was also included in this same study. No corrosive effect was observed.

Information on the effect of radiation on the electrical properties of irradiation-modified polyolefin-insulated wire is limited to comparisons of pre- and posttest measurements. However, as a precautionary procedure, the designer should allow for a decrease of one to three orders of magnitude in insulation resistance during irradiation. No significant changes of a permanent nature occurred in the only study that included measurements of insulation resistance and breakdown voltage on irradiation-modified polyolefin-insulated wire. (22, 23) The two environmental combinations

* Unidentified as to whether polyethylene or polypropylene.

used in this study were (1) an X-ray dose of 6×10^4 rads (C) with a vacuum of 10^{-6} torr and temperature of 150 C and (2) an X-ray dose of 1×10^3 rads (C) with a 5-psi oxygen atmosphere and a temperature of 90 C. The stability of the insulating qualities of this material when irradiated was also demonstrated in another study when wire insulated with this material completed a wet dielectric-strength test of 2.5 kV after a radiation dose of 5×10^8 rads (C). (28)

Coaxial cable insulated with irradiation-modified polyolefin (polyethylene) experienced an increase in attenuation of 0.30 and 0.40 db in a cable length of 10 feet when exposed to a total dose of 2.9×10^8 rads (C) and 3.0×10^{16} n/cm² ($E > 0.1$ MeV). (24) At the same time there was little change in VSWR and the apparent change in electrical length was 0.08 and 0.106 wavelength.

Irradiation-modified polyolefin-insulated wire and cable has demonstrated a high tolerance for radiation when compared to that of other organic insulations and should be suitable for many applications that include radiation as an environmental condition.

Miscellaneous Organics

Radiation-effects information is available on five organic wire insulations other than those discussed above. This information, however, is limited to results from only one radiation-effects test of each. Therefore, with one exception, this radiation effects information is confined to the tabular presentation of Table 4.

The single exception is the results of a study of electron irradiation of polyethylene terephthalate-insulated ribbon wire. (29) The purpose of the study was to determine the effects of shunt capacitance on temporary effects of the electron irradiation. Results of this study indicate that a voltage pulse observed during irradiation at 3.1×10^{10} e/(cm²·s) ($E > 60$ keV) at room temperature varied inversely with the total capacitance in the system. The average pulse height decreased from 5.1 volts at 1.1×10^{-9} farad to less than 0.01 volt at 1.0×10^{-7} farad. Increasing the load resistance from 3 kohms to 300 kohms increased the maximum pulse height to 35 volts and 0.2 volt, respectively, for the minimum and maximum capacitance values mentioned above. After irradiation to a total dose of 1.1×10^{14} e/cm² ($E > 60$ keV), electron-discharge patterns (Lichtenberg figures) were found in the insulation. Rough calculations indicated that

the power density along the discharge path is adequate to produce the physical damage observed. The actual pulse height of the discharges were possibly as high as 11,000 volts, and power densities of 3×10^{10} watts/cm² were indicated if a discharge time of 0.01 microsecond is acceptable. The data support a postulate that a portion of the incident electrons are stopped and stored within the dielectric. This charge increases with irradiation, and at some point in time it is released and transported to the conductor and is observed as a voltage pulse. A surface irregularity or pin prick initiates the release mechanism. Such pulses could be damaging to sensitive electronic circuits.

TABLE 4. RADIATION EFFECTS ON MISCELLANEOUS ORGANIC WIRE INSULATIONS

Material Identification	Total Integrated Exposure ^(a)	Remarks
Alkanex	4.6×10^7 rads (C), Co-60	Satisfactory performance, 150 C (encapsulated in rigid epoxy and semirigid silicone). ⁽³⁰⁾
Silicon-alkyd	4.6×10^7 rads (C), Co-60	Satisfactory performance, 150 C (encapsulated in rigid epoxy and semirigid silicone). ⁽³⁰⁾
Polypropylene	7.1×10^7 rads (C), Co-60	Unsatisfactory, becomes brittle and crumbles (15 C, 55 C, and 100 C). ⁽³¹⁾
XE-9003A	4.08×10^{16} n/cm ² (E > 0.5 MeV) Gamma dose unknown	Ambient temperature. Unsatisfactory, insulation too brittle and cracked for postirradiation testing. ⁽³²⁾
SE-975	4.08×10^{16} n/cm ² (E > 0.5 MeV) Gamma dose unknown	Ambient temperature. Unsatisfactory, insulation cracked and too brittle for postirradiation testing. ⁽³²⁾

(a) These exposures are not to be interpreted as indicating superiority in radiation tolerance of any material. They are the limits to which the wires or cables have been subjected and are not damage thresholds.

Ceramic

Magnet wire, insulated with ceramic enamel (Ceramicite and Ceram-1-temp), has demonstrated a high tolerance for radiation for total doses up to 1.5×10^8 rads (C) and 4.4×10^{17} n/cm² (E > 0.1 MeV) at room temperature. A tendency to powder during stripping tests is the only indication of deterioration of physical properties. The stability of electrical properties has also been satisfactory with some loss in dielectric strength and insulation resistance being observed. A decrease of approximately 16 percent occurred in breakdown voltage or dielectric strength between pre- and postirradiation measurements in one study.⁽²⁷⁾ Results of other studies

have shown a definite difference between the dielectric strength of irradiated and control specimens. These differences could be termed insignificant with one exception where the results of a study shows a breakdown voltage of 60 to 160 volts for irradiated specimens, and 140 to 500 volts for control specimens.⁽¹⁹⁾ Considerable difficulty due to the hygroscopic property of the ceramic insulation was encountered with these measurements and may have contributed to some of the difference. Changes in the insulation resistance as a result of exposure to a radiation environment have been insignificant.

Miscellaneous Inorganics

Radiation-effects information on seven inorganic wire insulations other than the ceramic discussed above is limited to single evaluations of the radiation resistance of each wire or cable. Of the seven wires and cables tested, four are standard products and three are special or non-production items. Because of the limited information available, information concerning the radiation resistance of these wires and cables are presented in the tabular format of Table 5.

RADIATION EFFECTS ON ENCAPSULATING COMPOUNDS

Encapsulating compounds that have been evaluated as to their radiation resistance include epoxy resins, silicone resins, polyurethane, and aninorganic, calcium aluminate. These materials, generally experienced insignificant changes in their physical and electrical characteristics from the radiation exposures to which they were subjected. An exceptions are discussed in the following paragraphs along with details concerning the effects experienced by all materials tested and the radiation environment to which they were exposed.

Silicone resin encapsulating materials, such as RTV-501 and Sylgard 192 and 183, have not been seriously degraded at radiation exposure doses of 2×10^{13} to 1.5×10^{15} n/cm² ($E > 0.1$ MeV) and 1.8×10^6 to 8.8×10^8 rads (C). Degradation of the physical properties has been limited to a slight but insignificant weight loss of less than 1 percent. Insulation resistance data show permanent decreases of 40 to 50 percent with the minimum resistance of approximately 1×10^{12} ohms after a total exposure

TABLE 5. RADIATION EFFECTS ON MISCELLANEOUS INORGANIC WIRE INSULATION

Material Identification	Total Integrated Exposure ^(a)	Remarks
Silica-glass (39001-1-16) double shielded coax	1.5 x 10 ⁸ rads (C) 4.4 x 10 ⁷ n/cm ² (E > 0.1 MeV)	Room temperature. No visible signs of degradation. No electrical tests. (27)
Quartz (39Q02-3-26) multiconductor coax	1.5 x 10 ⁸ rads (C) 4.4 x 10 ⁷ n/cm ² (E > 0.1 MeV)	Room temperature. No visible signs of degradation. No electrical tests. (27)
Asbestos and fiber (Phosroc III, RSS-5-203) lead wire	9.8 x 10 ⁷ rads (C) 4.1 x 10 ¹³ n/cm ² (E > 2.9 MeV)	200 C. No breaking, cracking, or spalling was evident when subjected to a bend test. Weight loss <0.2 percent. No electrical tests. Slightly darker in color. (19)
Mica paper-fiberglass (Mica-Temp, RSS- 5-304)	1.1 x 10 ⁸ rads (C) 4.5 x 10 ¹³ n/cm ² (E > 2.9 MeV)	200 C. No breaking, cracking, or spalling was evident when subjected to a bend test. Weight loss <0.15 percent. Slightly darker in color. (19)
S-994 Fiberglass	6.5 x 10 ¹⁰ rads (C) 1.5 x 10 ¹⁹ n/cm ² (E > 0.1 MeV)	Environment also included a temperature of 1200 F. In Duration of test 2300 hours. The in-pile insulation resistance was within 1/2 decade of nonnuclear results in almost all cases. Temperature was the overwhelming factor in determining level of insulation resistance (~10 ⁷ ohms). (33, 34)
Ceramic Kaowool and Refrasil (power cable)	8.8 x 10 ⁹ -8.8 x 10 ¹⁰ rads (C) (Estimated) 3 x 10 ¹⁹ n/cm ² (Energy unknown)	Cable met 1200 volt rms dielectric breakdown requirement. Also, withstood 2000 volt rms between conductor and ground for 5 minutes. (35)
Magnesium oxide (Rhodium conductor and platinum sheating)	5 x 10 ⁷ rads (C) 1.0 x 10 ¹⁵ n/cm ² (fission)	Met dielectric strength requirement of 1200 volts rms for 30 seconds. Insulation resistance decreased as much as four orders of magnitude between pre- and postirradiation measurements. (36)

(a) These exposures are not to be interpreted as indicating superiority in radiation tolerance of any material. They are the limits to which the wires or cables have been subjected and are not damage thresholds.

of 1.5×10^{15} n/cm² (E > 0.1 MeV) and 1.8×10^6 rads (C) gamma. In the only study where measurements were performed during irradiation, the insulation resistance decreased by something in excess of one order of magnitude ($> 2 \times 10^{12}$ ohms to 1×10^{11} ohms) when the reactor was at its maximum power level of 30 kW.⁽³⁷⁾ An estimate of the neutron and gamma rate at this level is 1.5×10^{11} n/cm².s (E > 0.1 MeV) and 6×10^4 rads (C)/hour, respectively.

Limited information on a polyurethane foam encapsulant indicates that this material may be more sensitive to radiation exposure than other encapsulating materials. Decreases in insulation resistance have approached three orders of magnitude during exposure to approximately 1.5×10^{11} n/cm².s (E > 0.1 MeV) and 6×10^4 rads (C) hour. Full recovery occurred, however, within 3 days after the irradiation was terminated with a total dose of 1.5×10^{15} n/cm² (E > 0.1 MeV) and 1.8×10^6 rads (C) gamma.⁽³⁸⁾

Several, but not necessarily all epoxy resin encapsulants have shown a radiation resistance that is above average for plastics. Polyfunctional epoxy resin and polyfunctional epoxy novolac resin with anhydride or aromatic amine hardeners appear to be the most resistant. Epoxies have withstood neutron and gamma doses up to 1.1×10^{16} n/cm² (E > 0.5 MeV) and 1×10^9 rads (C) from a reactor source without serious deterioration. Similarly, electron irradiation to a total exposure of 5.8×10^{16} e/cm² (E = 1.0 MeV) at 60 C and cobalt-60 irradiation to 1×10^8 rads (C) produced only limited degradation of an epoxy's physical and electrical properties. Epoxies that have shown a satisfactory radiation tolerance within the limits to which they were tested are listed in Table 6.

Information concerning the degradation of an epoxy encapsulant's physical properties indicate that a noticeable darkening in color and a slight loss in weight occurs when these materials are irradiated. Other changes that have also been reported for the radiation doses mentioned above include increases in hardness (2 percent), stiffness in flexure (4 percent), and tensile strength (8 percent), and decreases in ultimate elongation (6 percent). These changes in physical properties should not be of serious concern in the use of epoxies as encapsulants for electronic components and equipment. However, gamma doses from a cobalt-60 source in excess of 10^8 rads (C) may result in failure in some applications where the epoxy is under stress. The ultimate tensile strength of epoxies has decreased to between 43 and 24 percent of the initial value at 10^9 rads (C).⁽¹⁵⁾ Compressive strength was essentially unaffected to 10^{10} rads (C).

TABLE 6. EPOXIES EXHIBITING SATISFACTORY RADIATION TOLERANCE AT THE EXPOSURES INDICATED

Epoxy Identification	Total Integrated Exposure ^(a)
Bisphenol A	8.8 x 10 ⁷ rads (C) gamma 3.6 x 10 ¹³ n/cm ² (E > 0.1 MeV)
Eccobond 182	1 x 10 ⁸ rads (C) gamma 2 x 10 ¹³ n/cm ² (E > 0.1 MeV)
Epocast 17B	8.8 x 10 ⁷ rads (C) gamma 4.0 x 10 ¹³ n/cm ² (E > 0.1 MeV)
Epon 828	4.4 x 10 ⁶ rads (C) gamma 3.3 x 10 ¹⁵ n/cm ² (E > 0.1 MeV)
Maraset 622-E	1 x 10 ⁹ rads (C) gamma 1.1 x 10 ¹⁶ n/cm ² (E > 0.5 MeV)
Novalak	8.8 x 10 ⁷ rads (C) gamma 4.0 x 10 ¹³ n/cm ² (E > 0.1 MeV)
Scotchcast 5	1 x 10 ⁹ rads (C) gamma 1.1 x 10 ¹⁶ n/cm ² (E > 0.5 MeV)
Scotchcast 212	1 x 10 ⁹ rads (C) gamma 1.1 x 10 ¹⁶ n/cm ² (E > 0.5 MeV)
Stycast 1095	1 x 10 ⁸ rads (C) gamma 2 x 10 ¹³ n/cm ² (E > 0.1 MeV)
Stycast 2651 MM	4.4 x 10 ⁶ rads (C) gamma 3.3 x 10 ¹⁵ n/cm ² (E > 0.1 MeV)
12-007	1.8 x 10 ⁶ rads (C) gamma 1.5 x 10 ¹⁵ n/cm ² (E > 0.1 MeV)
412-M	1 x 10 ⁹ rads (C) gamma 1.1 x 10 ¹⁶ n/cm ² (E > 0.5 MeV)
420-A	1 x 10 ⁹ rads (C) gamma 1.1 x 10 ¹⁶ n/cm ² (E > 0.5 MeV)
1126A/B	1.8 x 10 ⁶ rads (C) gamma 1.5 x 10 ¹⁵ n/cm ² (E > 0.1 MeV)
CF-8793	9.4 x 10 ⁷ rads (C) gamma 3.8 x 10 ¹³ n/cm ² (E > 0.1 MeV)
CF-8794	1.0 x 10 ⁸ rads (C) gamma 4.0 x 10 ¹³ n/cm ² (E > 0.1 MeV)
Unidentified (Mineral filled)	5.8 x 10 ¹⁶ e/cm ² (E = 1.0 MeV)

(a) These exposures are not to be interpreted as indicating superiority in radiation tolerance of any material. They are the limits to which the materials have been subjected and are not damage thresholds.

The electrical properties of epoxy encapsulants show some variation in radiation tolerance but are generally of adequate stability for use in most electronic circuits. The insulation resistance has decreased by as much as two orders of magnitude during irradiation with a minimum of 1.7×10^{10} ohms being reported. Recovery to near initial value normally occurs within 2 to 4 hours after the irradiation is terminated. Changes in dielectric constant, capacitance, and dissipation factor are insignificant; the latter shows the greatest sensitivity to radiation by increasing approximately one order of magnitude. Polyfunctional epoxy resin and polyfunctional epoxy novolac resin with anhydride or aromatic amine hardeners have retained 90 percent of their initial dielectric strength at 1×10^9 rads (C).⁽³⁷⁾ Diglycidylethers of bisphenol A araldite epoxy with an aliphatic amine hardener retained 84 percent of its initial dielectric strength at 6.8×10^8 rads (C), but was severely damaged physically at 10^9 rads (C) so that the dielectric strength could not be measured.

The above information is representative of the radiation resistance of several epoxy encapsulants, but the reader should be cautioned that one type of epoxy (358-G) was considered as unsuitable following a test because it exhibited large variations in volume resistivity during exposure.⁽³²⁾ The extent of these variations is unknown and this information is included only as precautionary information.

Calcium aluminate, an inorganic encapsulant, was evaluated as part of one study where it was subjected to a total integrated exposure of 1×10^8 rads (C) gamma and 4.1×10^{13} n/cm² ($E > 2.9$ MeV) at 200 C.⁽¹⁹⁾ No significant changes occurred between pre- and postirradiation measurements of capacitance, dissipation factor, and insulation resistance. Dielectric strength of control and irradiated specimens was comparable following the radiation exposure.

RADIATION EFFECTS ON CONNECTORS AND TERMINALS

Connectors and terminals used in electronic circuits have experienced both permanent and temporary changes in their physical and/or electrical properties. These changes are associated with the insulating material rather than the metals used in these devices. The latter requires some consideration, however, since metals used in connector and terminal construction become radioactive when irradiated and, thus, offer a biological hazard to maintenance personnel.

The degradation of the insulating materials physical properties, which may ultimately lead to electrical failure, is a permanent effect and a major concern in selecting a connector or terminal for use in a radiation environment. This degradation of physical properties is manifested in the crumbling or disintegration of some organics that are employed as the insulating media. Thus, a connector or terminal that includes a material of this type will fail through structural collapse in a radiation environment of sufficient total exposure. Tetrafluoroethylene (Teflon) and similar fluorocarbon materials are well known for their lack of radiation resistance and this mode of failure.

Inorganic insulated connectors and terminals of the hermetic seal type, those having glass-to-metal seals, have also experienced physical damage when exposed to a radiation environment. This damage is in the form of cracking and chipping in the glass area immediately surrounding the metal pins used as conductors (an area of high stress under normal conditions). If this type of damage is more extensive than simple surface fractures, a loss in the sealing properties of the connector will result.

The changes in the electrical properties of connectors and terminals are generally temporary, with complete or what can essentially be termed complete recovery soon after the irradiation has been terminated. Changes in insulation resistance breakdown voltage and corona voltages have been reported by experimenters. The consensus is that these parameters are sensitive to the rate of irradiation during exposure. Data, however, lack sufficient consistency at this time to provide an estimate of how much change may be expected for a particular rate. Differences in environmental conditions other than radiation, such as humidity and/or minor differences in the same insulating material, may be responsible for these inconsistencies.

Reports indicate that connectors employing rubber compounds such as neoprene, silicone rubber, and Buna-N as the insulating material can withstand total exposures of as much as 10^{15} - 10^{16} n/cm² and ($E > 2.9$ MeV) and 8.8×10^6 rads (C) gamma at 55 C and still provide reasonable electrical performance. Decreases in insulation resistance of between one and two orders of magnitude have occurred during the irradiation of these connectors with recovery to within one order of magnitude of the preirradiation values within minutes after the irradiation was terminated. Neoprene-insulated connectors have shown a minimum insulation resistance of approximately 1×10^9 ohms during exposure to 1.5×10^{11} n/cm². s) ($E > 0.1$ MeV) and 6.1×10^4 rads (C)/hr. Buna-N-insulated connectors have exhibited minimums of less than 10 megohms for neutron fluxes and

gamma dose rates of 8.4×10^{10} n/cm². s) ($E > 0.9$ MeV) and 6.1×10^4 rads (C)/hr. Results from insulation-resistance measurements on the neoprene-insulated connectors are presented in Figure 10. Breakdown-voltage measurements on these connectors indicate values in excess of 500 volts during irradiation and greater than 1000 volts 3 weeks later.

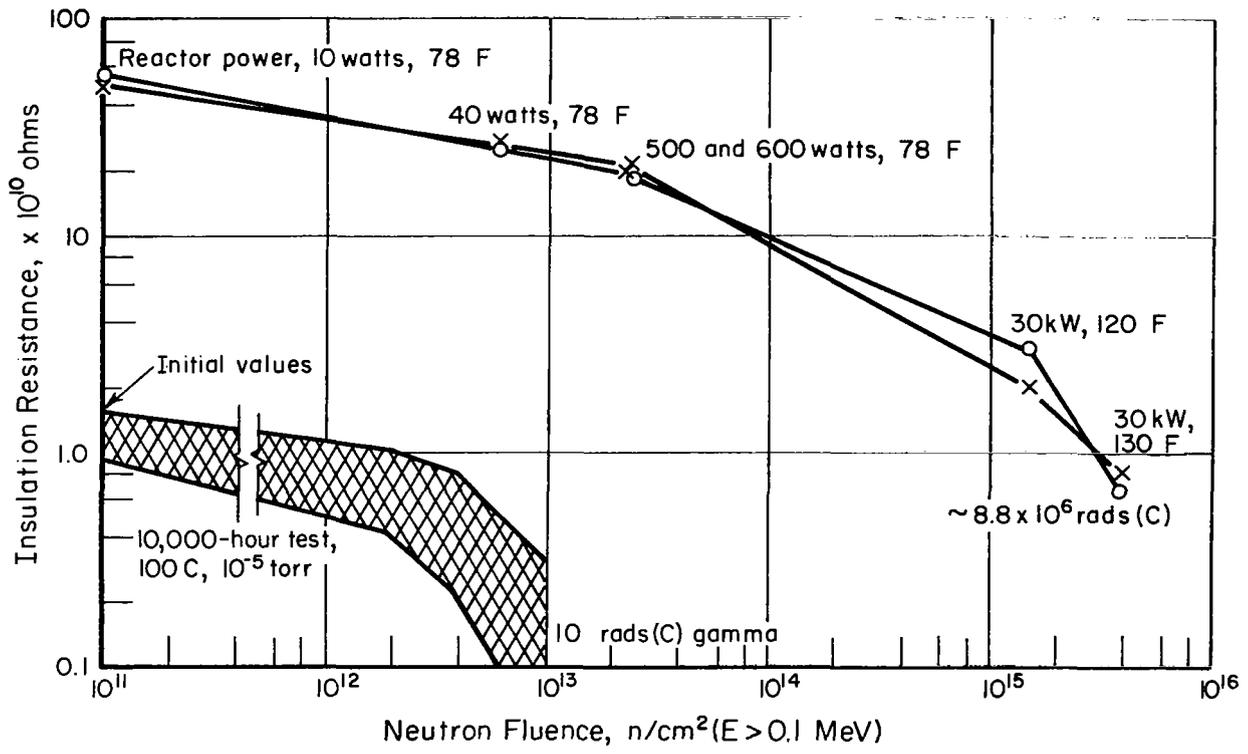


FIGURE 10. INSULATION RESISTANCE OF NEOPRENE-INSULATED CONNECTORS VERSUS TOTAL EXPOSURE^(38, 39)

Physical degradation has resulted in the recommendation that Buna-N-insulated connectors be replaced after a gamma exposure of 2×10^6 rads (C) at room temperature.

Plastic-insulated connectors that have been investigated as to their radiation resistance include units with phenol formaldehyde, melamine formaldehyde, and glass-fiber filled diallyl phthalate insulation. Connectors having a glass-insulated hermetic seal or glass-fiber filled diallyl phthalate insulation have shown superior resistance to radiation damage

when compared to silicon rubber-insulated units after a total exposure of 1.67×10^{16} n/cm² (E > 2.9 MeV) and $\sim 7 \times 10^8$ rads (C). Feedthrough terminals incorporating the latter for insulating purposes have also been tested in a radiation environment. Degradation in the insulation resistance of the connectors consisted of a decrease of between one and two orders of magnitude during irradiation. Combined effects of temperature (55 to 65 C) and radiation have resulted in decreases of four and five orders of magnitude.^(18,26) Minutes after radiation exposures of 10^{15} - 10^{16} n/cm² (E > 2.9 MeV) and 8.8×10^6 rads (C) gamma at 55 C, the insulation resistance recovered to within one order of magnitude of the preirradiation values. Breakdown-voltage information, which is limited to the diallyl phthalate-insulated connectors, indicate that no breakdown was observed at 500 volts or below during exposure to a radiation environment. Three weeks after exposure no breakdown occurred at 1000 volts. Of the three plastic insulators tested as connector insulation the diallyl phthalate was least subject to mechanical degradation.

Feedthrough terminals insulated with glass-fiber filled diallyl phthalate that survived a total exposure of 3.1×10^{16} n/cm² (E > 0.5 MeV) and 9.8×10^8 rads (C) gamma at room temperature experienced decreases of from 2000 to 3000 volts in corona ignition and extinction voltages during exposure at altitude equivalents of sea level to 70,000 feet. The insulation resistance remained fairly constant at $6-7 \times 10^7$ ohms during irradiation at a neutron fluence of 2.3×10^{10} n/(cm²·s) (E > 0.5 MeV) and a gamma rate of 2.6×10^5 rads (C)/hr. with a pretest resistance of $> 1 \times 10^{12}$ ohms. Capacitance and dissipation factor were fairly independent of the altitude and radiation conditions to which the terminals were subjected. Several of the terminals failed because of low corona voltages and insulation resistance: included were all of the smaller size and 50 percent of those classified as medium and large sizes.

Radiation-effects information on inorganic insulated connectors include the glass hermetic-seal type and a ceramic (alumina)-insulated AN type connector. Similar information is also available on ceramic-insulated feedthrough terminals. Insulation resistance data indicate that both types of connectors have a decrease of approximately two orders of magnitude during irradiation with recovery approaching preirradiation values after total exposures of $2-10 \times 10^{15}$ n/cm² (E > 0.1 MeV) and 8.8×10^6 rads (C) gamma at 55 C. Results of insulation resistance measurements on the ceramic-insulated connectors are presented in Figure 11. Combined effects of radiation and temperature (156 F) have produced decreases of up to five orders of magnitude in insulation resistance during irradiation at a neutron fluence of 1.2×10^{12} n/cm²·s (E > 2.9 MeV) and a gamma range of

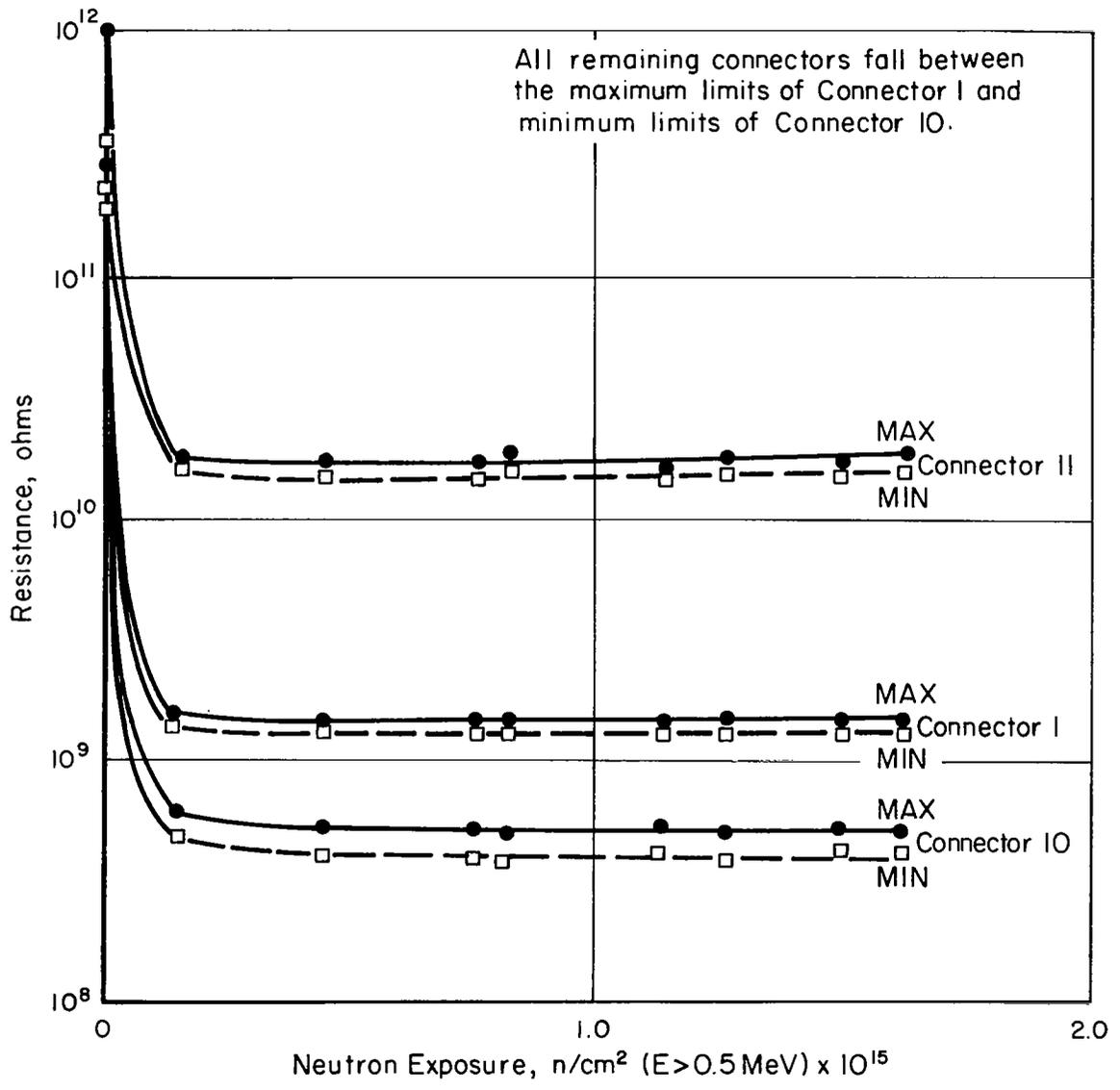


FIGURE 11. INSULATION RESISTANCE OF CERAMIC-INSULATED CONNECTORS(32)

6.6×10^7 rads (C)/hr. (26) Recovery following irradiation was within one or two orders of magnitude of the initial values. The glass hermetic-seal type connectors exhibited breakdown voltage characteristics in excess of 500 volts during irradiation and greater than 1000 volts 3 weeks after the radiation exposure was terminated. Corona voltage data on the ceramic-insulated AN connectors show a range of 1.2-1.8 kV for all but two connectors. One connector exhibited a distinct failure when the corona ignition voltage or a voltage breakdown of one pin was observed to occur at approximately 100 volts while a second connector experienced a decrease to between 600 and 800 volts in corona ignition voltage.

A radiation study of several types of ceramic-insulated feedthrough terminals indicate that these units experience insignificant degradation from a total exposure of 4.2×10^{13} n/cm² ($E > 0.1$ MeV) and 9.3×10^7 rads gamma at 200 C. The insulation resistance was 10^{14} - 10^{15} ohms before and after the irradiation.

It is recommended that the reader consult the section on sheet and bulk insulating materials for additional information on the connector insulations discussed above and others that may be of interest. In addition, the activation of metal parts provides a continuing source of radiation to the connector and surrounding electronic parts even after irradiation from the primary source has terminated. In glass to metal seals, with materials like Kovar or similar alloys, the interface between the metal and glass, a most sensitive area, is in an area of high radiation concentration and high physical stress and, thus, is more subject to damage. Therefore, the selection of a connector for use in a radiation environment must include consideration of both the insulating material and the metal parts.

CAPACITORS

INTRODUCTION

Dimensional change of the interelectrode (capacitor plate) spacing is the principal cause of capacitance changes during irradiation. This dimensional change is most pronounced when radiation-sensitive materials, generally organics, are used in one or more parts of the capacitor's construction. Pressure buildup from gas evolution and swelling causes physical distortion of capacitor elements and thus changes the interelectrode spacing. Radiation effects on the dielectric constant of capacitor dielectrics is limited as little or no change is shown in this property. Therefore, the effect on the dielectric constant is second-order effect, especially for inorganic dielectrics. Capacitor temperature changes by gamma heating, with resultant changes in physical dimensions and dielectric constant, is another second-order effect for the dose typically encountered.

Ionization of the air surrounding or within the capacitor structure, degradation of the dielectric and filler material, and radiation-induced temperature increases may cause decreases in the insulation resistance. The ionization effect is the main insulation effect observed during irradiation tests. Insulation resistance measurements of paper-dielectric capacitors exposed to intense radiation illustrate the effects of both ionization and insulation breakdowns within the capacitor. Upon irradiation, the insulation resistance immediately drops as a result of ionization, and then continues to decrease with the degradation of the dielectric and filler material after some given dose. Thermal-neutron contribution to insulation-resistance decrease must be considered in connection with electrolytic capacitors that use borates as the electrolyte, and fast neutrons must be considered for hydrogenous materials. Decreases in insulation resistance will occur with increasing temperatures; therefore, any rise in temperature associated with radiation will contribute to a decrease in the insulation resistance. Capacitors such as the mica, glass, and ceramic types exhibit high insulation resistances and low dissipation factors, while the electrolytic and some paper types exhibit low insulation resistances and high dissipation factors. The relative neutron-radiation sensitivity of capacitors according to dielectric material is shown in Figure 12.

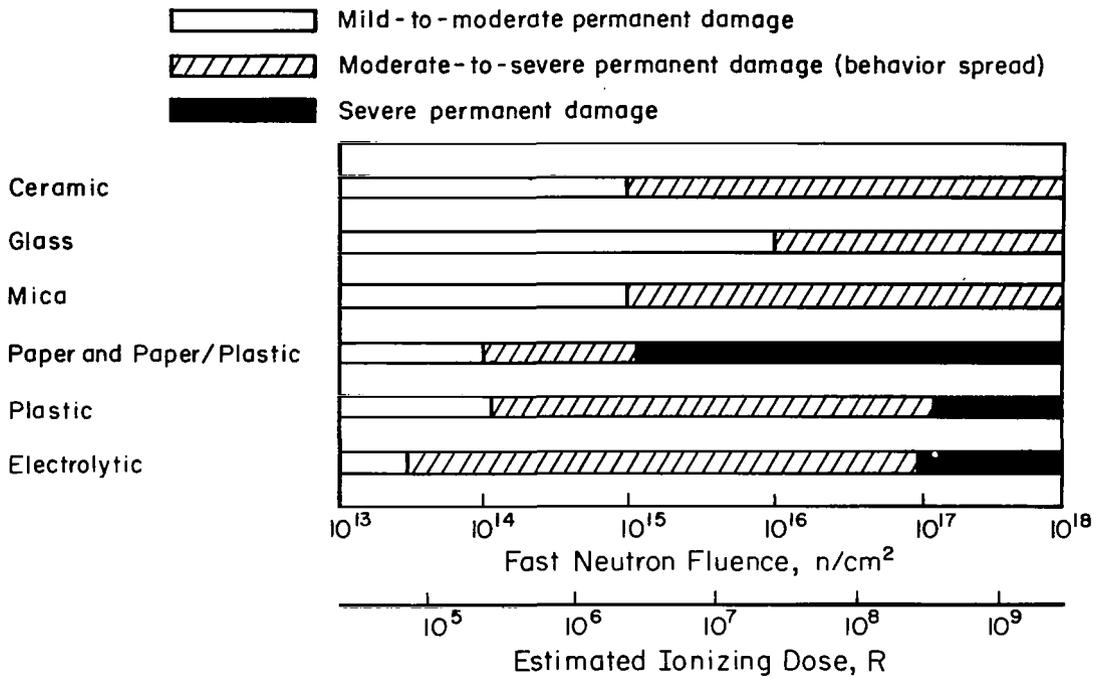


FIGURE 12. RELATIVE RADIATION SENSITIVITY OF CAPACITORS

If the capacitors are going to be used in a system that will operate in a nuclear or space environment, then temporary changes that occur during irradiation will be of interest. In general, the temporary capacitance change will be larger and more positive than the permanent change. This also seems to be the case for the dissipation factor, while the temporary leakage resistance may decrease by several orders of magnitude. It must be remembered, however, that the temporary effects are largely dependent on the flux rate, and the permanent effects are mainly the result of total exposure. More specific information concerning the various types of capacitors, as classified by dielectric material, is presented in the following sections.

Glass- and Porcelain-Dielectric Capacitors

The basic construction of glass-dielectric capacitors includes alternate layers of glass ribbon and electrode or plate (aluminum) material with an outer covering of glass. These layers are sealed together into a monolithic block by high temperature and pressure. Vitreous-enamel (porcelain-dielectric) capacitors are of similar construction, with alternate layers of ceramic glaze and silver that are fused into a monolithic block with an exterior of the same ceramic glaze. Applications for glass- and porcelain-dielectric capacitors include blocking, by-pass, coupling, high-stability beating oscillators and low-drift R-C oscillators. They are well suited for critical high R-F applications, within the limitations of their self-resonance frequency, and where a minimum of noise is required.

Capacitors having glass- or porcelain- (vitreous enamel) dielectrics compared to capacitors of other dielectric materials, have shown a relatively high resistance to damage from exposure to a neutron environment. The damage or effect of the radiation on the electrical properties of these capacitors includes both permanent damage and temporary effects. The temporary effects are attributed to ionization in the capacitor and in the immediate area surrounding the capacitor and its leads. Experimenters have attempted to reduce and/or eliminate part of the ionization problem in the near vicinity of the test specimen by potting the capacitor and its lead-connection area in wax or other insulating material and conducting the test in a vacuum. This encapsulation, however, sometimes presents more of an ionization problem in temporary effects because of charge equilibration.

Glass- and porcelain-dielectric capacitors have exhibited both temporary and permanent changes in capacitance as a result of irradiation. Changes in dissipation factor and insulation resistance are generally temporary effects with recovery to near preirradiation values within a few hours after the termination of the exposure. The dissipation factor of porcelain units, however, has sometimes experienced permanent changes after a neutron fluence of $\sim 10^{16}$ n/cm² ($E > 2.9$ MeV).

Capacitance measurements on glass-dielectric capacitors during irradiation have shown maximum temporary changes or variations between +4.0 percent and -2.5 percent. Permanent changes between +3.1 and -2.5 percent have also been recorded. The radiation environment for these changes included neutron fluences of 3.4×10^{18} and 5.7×10^{16} n/cm² ($E > 2.9$ MeV) and total gamma exposures of 7.7×10^8 to 3.0×10^9 rads (C). A maximum

change of only +0.1 percent, with an average increase of 0.05 percent has been observed, however, with a neutron flux and fluence of $\sim 4 \times 10^{12}$ n/(cm².s), E > 10 keV, and 8×10^{14} n/cm², respectively. (40) The gamma environment included a rate of 5.4×10^6 rads (C)/hr and a total dose of 3×10^6 rads (C). Several factors may be responsible for the differences in the results reported by various experiments, such as lack of close similarity in test specimens due to production changes and/or differences between production lots, instrumentation difficulties, and lead effects.

Maximum changes or variations in the capacitance of porcelain-dielectric capacitors during irradiation include a decrease of 3.5 percent and an increase of 2.1 percent. Permanent changes between -4.0 and +3.5 percent have also occurred. In many cases, however, the capacitance remains much more stable with temporary and permanent changes of less than 1.0 percent.

In general, the capacitance of glass- and porcelain-dielectric capacitors remains stable enough in a radiation environment that they are suitable for many of their intended applications, with the exception of circuits involving critical tuning where precision capacitors are a necessity. Applications in circuits of this type require shielding to protect the capacitors against the radiation environment.

The dissipation factor of glass- and porcelain-dielectric capacitors experiences temporary effects from exposure to a nuclear-radiation environment. Glass-dielectric capacitors have shown increases from initial dissipation factors of approximately 0.015 to values between 0.021 and 0.078 during irradiation with complete or nearly complete recovery when it was terminated at neutron fluences and total gamma exposures as high as 3.4×10^{18} n/cm² (E = unknown) and 7.7×10^8 rads (C), respectively. The dissipation factor of porcelain-dielectric capacitors has approached 0.05 during and after exposure to a nuclear-radiation environment. These devices have shown both complete recovery to preirradiation values and additional increases when the irradiation was terminated. The maximum, with the post-irradiation increase, has never exceeded 0.05, and in several tests the dissipation factor did not exceed 0.01 or 1.0 percent at the following neutron and gamma flux and total exposure levels: 4×10^9 n/(cm².s) (epicadmium), 2.1×10^{15} n/cm², 2.1×10^8 rads (C)/hr, and 3.2×10^{11} rads (C).

The insulation resistance of glass- and porcelain-dielectric capacitors decreases between two and three orders of magnitude when they are subjected

to a nuclear-radiation environment. This effect is temporary and the insulation resistance recovers when the irradiation is terminated.

Mica-Dielectric Capacitors

The internal construction of mica-dielectric capacitors includes alternate layers of mica-dielectric and metallic electrodes. The electrodes or capacitor plates may be of metal foil or deposited silver. The deposited silver units, because of the intimate contact between the electrode and dielectric, are used where high-stability capacitors are required, such as in timing and frequency-determining circuits and other applications where stability is of primary importance. They are not, however, recommended for applications that may include high-humidity, high-temperature, and constant d-c potentials. This is due to silver-ion migration, which is accentuated by these conditions. The foil types are less stable than the deposited silver (silver micas), and larger drifts are to be expected with these units, particularly at elevated temperature.

The capacitance and dissipation factor of mica capacitors are susceptible to permanent damage from irradiation, while changes in insulation resistance are generally temporary. The permanent changes in capacitance and dissipation factor are possibly due to changes in the physical structure of the capacitors, such as separation of the metal electrode and dielectric layers. Visual examination following exposure has shown severe damage in the form of casing fractures as a result of the irradiation.

Capacitance measurements on mica-dielectric capacitors have shown permanent changes of approximately 6.0 percent when capacitors of this type have been exposed to neutron fluences as high as 6×10^{15} n/cm² (E > 2.9 MeV) and 10^{16} n/cm² (E > 0.3 MeV) and total gamma exposures of 10^8 rads (C).

Changes in the dissipation factor of mica-dielectric capacitors vary from none, or no significant effect, to increases where the dissipation factor was as much as 0.10 after a neutron fluence of 1×10^{16} n/cm² (E > 0.3 MeV). The total gamma exposure is not known; however, the rate varies between 8.7×10^2 to 4.4×10^6 rads (C)/hr.⁽⁴¹⁾ A similar dissipation factor (0.10) was the result of a temporary increase during a dose-rate test, and decreased to 0.04 during a fluence or integrated exposure test that was a part of the same study.⁽⁴²⁾ No predominant or significant changes

were reported in tests at neutron fluences of 1×10^{14} and 1×10^{15} n/cm² (E > 2.9 MeV), and total gamma exposures of 1×10^7 and 1×10^8 rads (C). (32, 43)

The insulation resistance of mica-dielectric capacitors decreases to values in the range of 10^8 and 10^9 ohms during their exposure to a nuclear-radiation environment, 10^9 n/(cm²·s) (E 1 0.5 MeV) and 3×10^5 rads (C)/hr. Recovery to near preirradiation values, 10^{10} and 10^{11} ohms, occurs immediately following or soon after the irradiation is terminated. The decrease in insulation resistance is generally attributed to the ionization within the capacitor structure and in the near vicinity of the capacitor, as a result of the radiation environment.

Ceramic-Dielectric Capacitors

Basically, a ceramic-dielectric capacitor consists of a ceramic dielectric with a thin metallic film, such as silver, applied to either side and fired at high temperature. The fired metallic film serves as the electrodes or capacitor plates of the device. Ceramic capacitors are available as two basic types (general purpose and temperature compensating), with several body designs: disk, tabular, standoff, and feedthrough. The general-purpose units are used in applications where large capacitance changes and higher losses are not critical. Typical uses are for bypass, filter, and non-critical coupling circuits. The temperature-compensating units are used in more critical applications that make use of their temperature characteristics to compensate for parameter changes of other elements or components in the circuit. These applications include critical coupling and tuning circuits.

Ceramic capacitors have shown various degrees of sensitivity to steady-state nuclear-radiation environments. The capacitance and dissipation factor appear to be susceptible to both temporary and permanent effects, while the insulation resistance suffers from temporary effects due to ionization. The changes in capacitance for general-purpose ceramic capacitors are negligible when the extremely wide tolerances and temperature coefficients that are associated with these devices are considered. The capacitance changes that occur may be attributed, at least in part, to temperature effects and aging. The latter results in a gradual decrease in capacitance with time.

The capacitances of general-purpose ceramic capacitors have decreased during irradiation with but few exceptions, when increases were observed. These changes in capacitance vary from a minimum of 1 or 2 percent to a maximum of 20 percent. Typically, however, the maximum change is in the range of 10 to 15 percent. The permanent effect, i.e., change in capacitance, is normally less than the temporary effect that is observed during the actual exposure to the radiation environment. The difference between the temporary and permanent effect on capacitance may possibly be attributable to temperature change, and the permanent effect may be the result of aging. The possibility that the radiation environment accelerates the aging process, which is a decrease in dielectric constant, is a consideration.

Information on the effect of radiation on the dissipation factor of ceramic-dielectric capacitors is limited, and there are no clear trends indicated. The dissipation factor of these devices has increased during and after irradiation, remained rather stable, or even decreased.⁽⁴²⁾ The increases observed usually did not exceed 0.02.

The insulation resistance of ceramic-dielectric capacitors decreases as much as two to five orders of magnitude during irradiation at neutron fluxes and gamma dose rates of $\sim 4 \times 10^8$ n/hr ($\text{cm}^2 \cdot \text{s}$) ($E > 2.9$ MeV) and 2×10^8 rads (C), respectively. Recovery generally approaches the pre-irradiation values when the irradiation is terminated. Results from one reported experiment⁽⁴⁴⁾ show no indication of recovery within 2 days after the discontinuation of the exposure to a neutron flux and fluence of up to 7.54×10^9 n/($\text{cm}^2 \cdot \text{s}$) and 3.11×10^{15} n/ cm^2 ($E > 0.1$ MeV), respectively. The gamma environment included a dose rate of up to 4.1×10^5 rads (C)/hr and a total dose of 4.67×10^8 rads (C).

Paper- and Paper/Plastic-Dielectric Capacitors

The basic physical structure of paper-dielectric capacitors consists of two metal-foil strips or deposited metal films separated by two or more layers of paper dielectric. The paper is generally impregnated with wax, oil, or synthetic compounds to increase its voltage breakdown and to provide the desired characteristics. The paper/plastic-dielectric capacitors are similar in construction, with the addition of layers of plastic film in the paper layers. Paper and paper/plastic capacitors are used in general applications involving high voltages and currents at low frequencies, in

filters and networks of moderate precision at audio frequencies, and in bypass and coupling circuits.

Radiation-effects experiments on paper and paper/plastic capacitors, with and without impregnation, have shown them to be more sensitive to radiation than the inorganic types (ceramic, glass, and mica) by two and three orders of magnitude. Plain paper or paper/plastic is a more suitable dielectric for applications that include nuclear radiation as an environmental condition than the same or similar dielectric that has been oil impregnated. This is because the oil or other hydrocarbon used to impregnate the dielectric releases hydrogen or hydrocarbon gases when the device is placed in a radiation environment. The pressure buildup from the evolved gases subsequently causes the distortion of the capacitor element and a change in capacitance and dissipation factor. Hermetically sealed units have actually ruptured their enclosures and/or leaked at the terminal seals as a result of this pressure. The ionization within the capacitor structure and the immediate surrounding area that occurs during irradiation also contributes to changes in the electrical characteristics of paper and paper/plastic capacitors. These changes, however, are temporary and manifest themselves as a decrease in the capacitor's insulation resistance.

Measurements of capacitance on paper- and paper/plastic-dielectric capacitors have shown both increases and decreases during and after capacitor exposure to a radiation environment. The maximum changes observed in the capacitance of units of this construction are an increase of approximately 18 percent and a decrease of 50 percent. The 18 percent increase has been observed with a capacitor type that is molded in mineral-filled high-temperature plastic. If the results of two radiation studies in which these extremes occurred for a sample size of two is deleted from consideration, the range of capacitance degradation would be much less, +8.5 and -20 percent. It is readily understandable that the evolving of gas, with the associated distortion of the capacitor structure, could result in a decrease in capacitance by increasing the spacing between the capacitor plates or electrodes. The increase in capacitance is not as easy to explain unless the distortion may also in some instances increase the effective area of the capacitor plates.

The dissipation factor of paper- and paper/plastic-dielectric capacitors increases when the capacitors are subjected to a nuclear-radiation environment. These increases typically have been less than 1.0 percent in all of the referenced reports. The change in dissipation factor occurred with a neutron and gamma environment that included a neutron flux of $3.0 \times$

10^{11} n/(cm²·s)(epicadmium) for a fluence of 4×10^{17} n/cm² and a gamma rate and total dose of 8.7×10^5 rads (C)/hr and 3×10^8 rads (C), respectively.

The insulation resistance of paper- and paper/plastic-dielectric capacitors decreases as a result of irradiation. The temporary decrease that occurs is generally attributed to the ionization that is produced by the radiation environment. A permanent decrease in the insulation resistance may be the result of (1) a decrease in the volume resistivity of the substance used to impregnate the device and (2) the process that results in the embrittlement of the kraft-paper dielectric. Increases due to interelectrode distortion from pressure buildup is also a strong possibility.

Several programs have included sufficient quantities of paper- and/or paper/plastic-dielectric capacitors to provide statistical confidence in the results. The following discussions of individual test programs are presented for this reason.

One hundred CPO8A1KE105M paper-dielectric capacitors were subjected to combined environments of high temperature and nuclear radiation.⁽⁴⁵⁾ The ambient temperature was controlled at 85 C with the reactor power level limited to 1 megawatt during the first 24 hours. The reactor power level was then raised to 10 megawatts for the duration of the experiment while the temperature was still controlled at 85 C. The radiation environmental conditions for this study included a neutron fluence of 1.4×10^{16} n/cm² ($E > 2.9$ MeV) and a total gamma exposure of 9.0×10^8 rads (C).

Observations of capacitance during the combined environmental conditions indicated that the capacitors decreased in capacitance with increase in radiation intensity. Most of the capacitors exceeded their lower tolerance limit of -20 percent at approximately 8.4×10^{14} n/cm² ($E > 2.9$ MeV) and 3.41×10^7 rads (C). As the exposure increased further, there was a general trend for the capacitances to increase slightly, sometimes returning to within their specified tolerance. This behavior was followed by an almost exponential increase above the upper 20 percent tolerance level for several measurements when the capacitors failed catastrophically. Figure 13 is a graphic presentation of the reliability indices for these units based on the specified tolerance and the resulting catastrophic-failure occurrences. The reliability indices are the percent surviving the specified failure criteria at the indicated neutron fluence or gamma dose. Postirradiation examination of the capacitors revealed that 22 units were ruptured, 59 were short-circuit-type failures, 9, although not shorted, could not be charged, and only 10 capacitors were chargeable. The threshold of failure for the out-of-tolerance

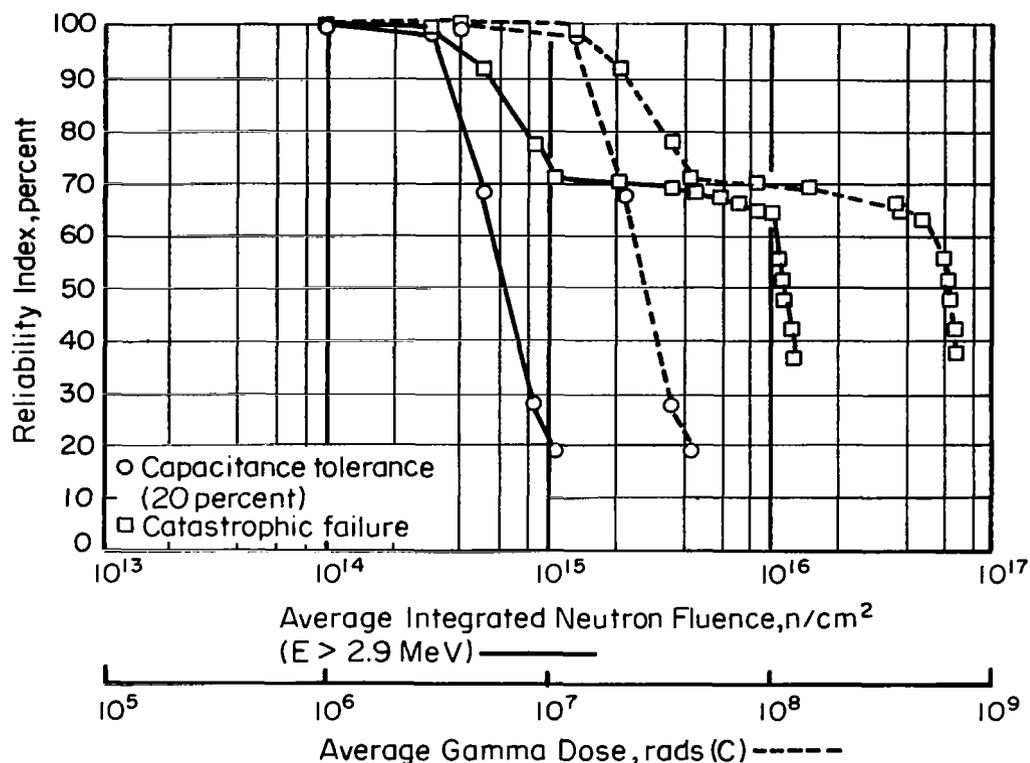
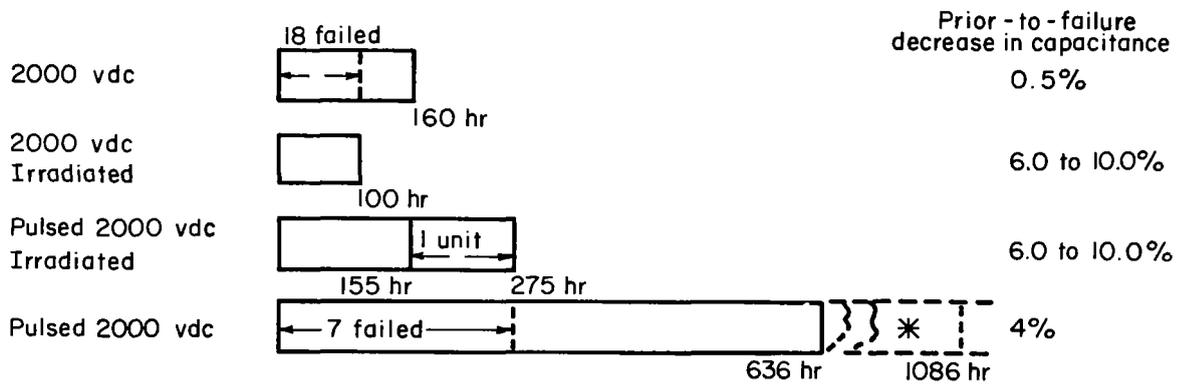


FIGURE 13. RELIABILITY INDEX FOR PAPER CAPACITORS FOR A 96 PERCENT CONFIDENCE LEVEL, BASED ON A SAMPLE SIZE OF 100 UNITS (CAPACITANCE AND CATASTROPHIC FAILURE)⁽⁴⁵⁾

and catastrophically failed units, as shown in Figure 13, was 1.04×10^{14} n/cm^2 ($E > 2.9$ MeV) and 3.92×10^6 rads (C).

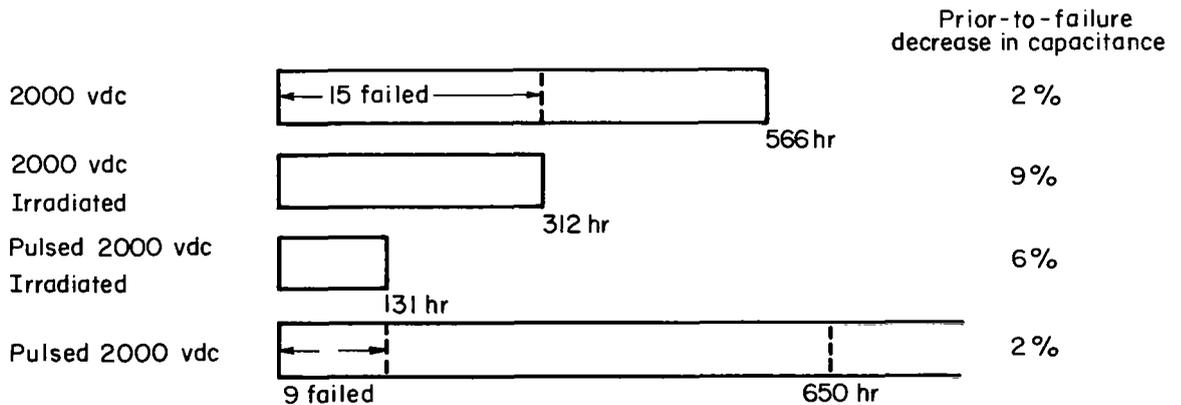
In another investigation⁽⁴⁶⁾ with a large sample size, a small group of units was initially stressed in order to obtain conditions for 75 percent failure in 1000 hours of operating-life time. It was determined that 2000 vdc and 135 C should be the stress conditions. The units being tested were paper/Mylar 0.1 μf , 600-volt, CPMO8 capacitors. The cobalt-60 source used provided a maximum gamma exposure of 8.77×10^4 rads (C)/hr.

Results of this investigation which included a constant-temperature environment and a temperature-cycled environment are given in Figure 14. The temperature-cycled group was subjected to room temperature and 135 C



a. Constant 135 C

*Because of equipment malfunction, the units failed at 636 hr. If there had been no trouble, 75 percent of the units should have failed by 1086 hr.



b. Temperature - Cycled Units

1. The pulsed 2000 vdc had a maximum surge current of 30 ma
2. In all cases the sample size equals 25 units, Type CPM08

FIGURE 14. EFFECTS OF GAMMA RADIATION ON PAPER/MYLAR CAPACITORS FOR 100 PERCENT SAMPLE-SIZE FAILURE⁽⁴⁶⁾

with 30 minutes to stabilize at each temperature. A total of 90 minutes was required at each temperature to make all necessary measurements. Measurements of dissipation factor and insulation resistance for both the constant-temperature group and the temperature-cycled group revealed no trend toward degradation before failure. All the failures that are indicated resulted from voltage breakdown. As a comparison, four units were passively irradiated in the gamma source for 1000 hours. These units showed the following results:

- (1) No case ruptures
- (2) 6 percent decreases in capacitance
- (3) A factor of two increase in dissipation factor
- (4) A factor of seven decrease in insulation resistance.

Twenty-four units were also operated at 840 vdc and 125 C (no radiation), and were found to be functioning normally after 5,331 hours.

A third study⁽³⁹⁾ included both paper- and paper/plastic-dielectric capacitors with deposited metal (metallized) plates or electrodes manufactured about 1965. Both types were subjected to five environmental conditions with d-c voltage applied. The paper-dielectric capacitors were also subjected to one of the environments with no voltage applied. The basic sample size at each test condition consisted of 20 units for a total of 100 paper/plastic capacitors and 120 paper capacitors. Each group of 20 specimens was subjected to one of the environmental conditions indicated in Table 7.

The sixth group of paper-dielectric capacitors (Test Group VI) was subjected to the same environmental conditions as Test Group III with no voltage applied.

Failure-rate computations at the 50, 60, and 90 percent confidence levels, as shown in Table 8 for the metallized-paper capacitors, indicate that temperature was the greatest contributor to their failure, since the capacitors in Test Group V (50 C) exhibited a much lower failure rate than that for any of the other test groups. The units subjected to normal atmospheric pressure, Test Group I, also experienced a failure rate approximately one-half that observed for units in the vacuum environments, with the exception of those in Test Group V. The no-load condition of Test Group VI resulted in a lower failure rate than that for Test Group III, which was subjected to identical environmental conditions, but included the application of a d-c voltage.

TABLE 7. TEST DESIGN, RATED VOLTAGE APPLIED

Test Group	Temperature, C	Pressure, torr	Neutron Fluence	Gamma Dose
I	100	760	None	None
II	100	10 ⁻⁵	None	None
III(a)	100	10 ⁻⁵	~10 ¹³ n/cm ² (E > 0.1 MeV)	~10 ⁷ rads (C)
IV(b)	100	10 ⁻⁵	~10 ¹³ n/cm ² (E > 0.1 MeV)	~10 ⁷ rads (C)
V(a)	50	10 ⁻⁵	~10 ¹³ n/cm ² (E > 0.1 MeV)	~10 ⁷ rads (C)

(a) 10,000 hours at 3 x 10⁵ n/(cm².s) and 1 x 10³ rads (C)/hr.

(b) 100 hours at 3 x 10⁷ n/(cm².s) and 1 x 10⁵ rads (C)/hr followed by 10,000 hours at 100 C and 10⁻⁵ torr without radiation.

TABLE 8. FAILURE RATE FOR P323ZN105K CAPACITOR, AT 50, 60, AND 90 PERCENT CONFIDENCE LEVELS⁽³⁹⁾

Test Group	Failure Rate at Indicated Confidence Level, percent/1000 hr			Percent Recorded as Failed
	50 Percent	60 Percent	90 Percent	
I	2.09	2.35	3.58	20
II	4.86	5.25	7.03	50
III	5.46	5.88	7.77	55
IV	4.26	4.67	6.41	40
V	0.30	0.39	0.98	0
VI	4.56	4.97	6.72	45
All test groups	3.19	3.32	3.87	35

The electrical characteristics of these capacitors experienced a greater degree of degradation from a 100 C ambient with a load voltage applied than from the radiation environment. Any radiation damage that occurred, however, may have been annealed by the elevated temperatures.

On the basis of the above results, it was concluded that the radiation levels involved in this study are of little concern compared to the catastrophic failures and degradation that resulted from the 100 C ambients. Therefore, the application or design engineer would need to be more concerned with normal degradation due to elevated temperature at 100 C than with the radiation environment of this program in the application of these capacitors.

No failures were observed among 100 metallized/Mylar (plastic) capacitors, also manufactured about 1965, that were subjected to the various test conditions in Table 7.

Failure-rate computations assuming one failure at the end of the test are shown in Table 9 for these capacitors. The minor difference between the failure rates for Test Group IV and those for the other test groups is due to the additional operating time associated with the 100 hours of high-flux radiation that these components received prior to the beginning of the 10,000-hour life test.

TABLE 9. FAILURE RATE FOR 118P10592S2 CAPACITOR AT 50, 60, AND 90 PERCENT CONFIDENCE LEVELS⁽³⁹⁾

Test Group	Failure Rate at Indicated Confidence Level, percent/1000 hr			Percent Recorded as Failed
	50 Percent	60 Percent	90 Percent	
I	0.30	0.39	0.98	0
II	0.30	0.39	0.98	0
III	0.30	0.39	0.98	0
IV	0.29	0.39	0.97	0
V	0.30	0.39	0.98	0
All test groups	0.06	0.08	0.20	0

Any degradation in capacitance that was observed with these capacitors would not be detrimental to their normal application. No significant amount of degradation was noted in the dissipation factor. The results from the insulation-leakage-current measurements indicated the greatest degradation in this parameter occurred in the 100 C vacuum environments of Test Groups II, III, and IV. The maximum leakage current approached 1.0 milliamperes in all three of these test groups.

It was concluded from the results obtained that a radiation environment of the level used in this study is not a significant factor in the application of these capacitors. The application engineer needs to be more concerned with the degradation associated with elevated temperature.

Plastic-Dielectric Capacitors

Most plastic-dielectric materials harden and eventually become brittle when irradiated. This results in flaking and crumbling especially under stress. The electrical properties of Mylar are stable to an absorbed dose of 10^8 rads. During irradiation, the dielectric constant and dielectric loss undergo significant changes, but they recover on removal from the radiation field.⁽⁴⁾ It takes about 12 days for a 2-mil specimen to approach a quiescent state after irradiation. Dielectric constant and dielectric loss show no permanent dose-rate effect. Some properties of Mylar do exhibit a dose-rate effect that is generally less at higher dose rates. For example, dielectric strength is considerably reduced at lower dose rates, but at higher dose rates the change is not nearly as great.

Plastic-dielectric capacitors are similar in construction to the paper and paper/plastic capacitors, with the exception that the dielectric is a thin plastic film rather than paper or paper and plastic. Materials commonly used as the dielectric film are polystyrene, polyethylene, polycarbonate, and Mylar (polyethylene terephthalate). In general, low-voltage units are manufactured without impregnation or liquid fill. However, for higher voltages, a liquid fill is required to reduce corona and increase voltage-flashover limits. Applications for plastic-dielectric capacitors are the same as those for the paper and paper/plastic capacitors.

Radiation-effects testing of plastic-dielectric capacitors has essentially been limited to devices employing Mylar as the dielectric film. Therefore, the following discussion of radiation effects on plastic-dielectric capacitors is concerned with or limited to Mylar capacitors.

Experiments to determine the effect of nuclear radiation on plastic-dielectric capacitors have shown that these organic dielectrics experience moderate-to-severe permanent damage at a radiation fluence an order of magnitude less than the inorganics, i. e., glass, ceramic, and mica. As in the case for paper- and paper/plastic-dielectric capacitors, plain plastic is a more suitable dielectric for nuclear-radiation environments than the same or similar dielectric impregnated with oil or wax. Impregnated hermetically sealed units may even experience a rupture of the exterior case or enclosure. This rupture may be the pushing out of the glass-to-metal end seals so that the material used to impregnate the capacitor leaks out, or, if there is a sufficient buildup of pressure, the end seal may even be blown completely free of the capacitor, with the capacitor element extending beyond the limits of its enclosure. Such a violent rupture occurring in an actual application, offers, in addition to electrical failure, a physical hazard to other component parts in the vicinity of the capacitor.

The capacitance of plastic-dielectric (Mylar) capacitors subjected to a radiation environment has both increased and decreased when pre- and post-irradiation measurements are compared. In general, these changes are within ± 4 percent of the preirradiation value at neutron fluences of 10^{15} n/cm² ($E > 2.9$ MeV) and 10^{16} n/cm² ($E > 0.3$ MeV). However, decreases of as much as 10 percent and as small as < 1 percent have also been recorded for similar capacitors and fluences. The differences in the sensitivity to a radiation environment may possibly be the result of differences in the Mylar and its treatment before or during the manufacture of the capacitors, or differences in the material used to impregnate them. The evolving of gas by the breakdown of the oil or wax used to impregnate the capacitors could be responsible for capacitance change. Bubbles forming between the layers of the capacitor could increase the spacing.

The dissipation factor of plastic-dielectric (Mylar) capacitors remains stable with a negligible amount of change. The change, if it occurs, is not detectable because of the measurement accuracy and/or the dissipation factor of the long leads required between the test capacitors in the radiation environment and the instrumentation used to measure their electrical characteristics. The maximum observed increase in dissipation factor is 60 percent of the initial value measured before the capacitors were inserted in the reactor. This increase occurred at a neutron fluence of 6×10^{17} n/cm² (epicadmium) and a total gamma dose of 4.4×10^8 rads (C).

The insulation resistance of plastic-dielectric capacitors decreases when they are exposed to nuclear radiation. Permanent changes in the insulation resistance may be due to the chemical breakdown process that occurs

in the oil or wax substances used to impregnate the capacitor or a change in the plastic-dielectric-materials characteristics. The insulation resistance of capacitors having a Mylar dielectric decreases as much as three and four orders of magnitude, with minimum values as low as 10 megohms. Recovery after the irradiation is terminated normally returns the insulation resistance to near preirradiation values, i. e., within an order of magnitude.

Two programs have included quantities or sample sizes of Mylar-dielectric capacitors to provide a higher than usual statistical confidence in the results. The following discussions of individual test programs are presented for this reason.

One hundred Hyrel Mylar capacitors, rated at 1.0 μf , were subjected to a combined environment of high temperature and nuclear radiation. (45) The ambient temperature was controlled at 85 C, with the reactor power limited to 1 megawatt during the first 24 hours. The reactor power was then increased to 10 megawatts for the duration of the experiment. The neutron

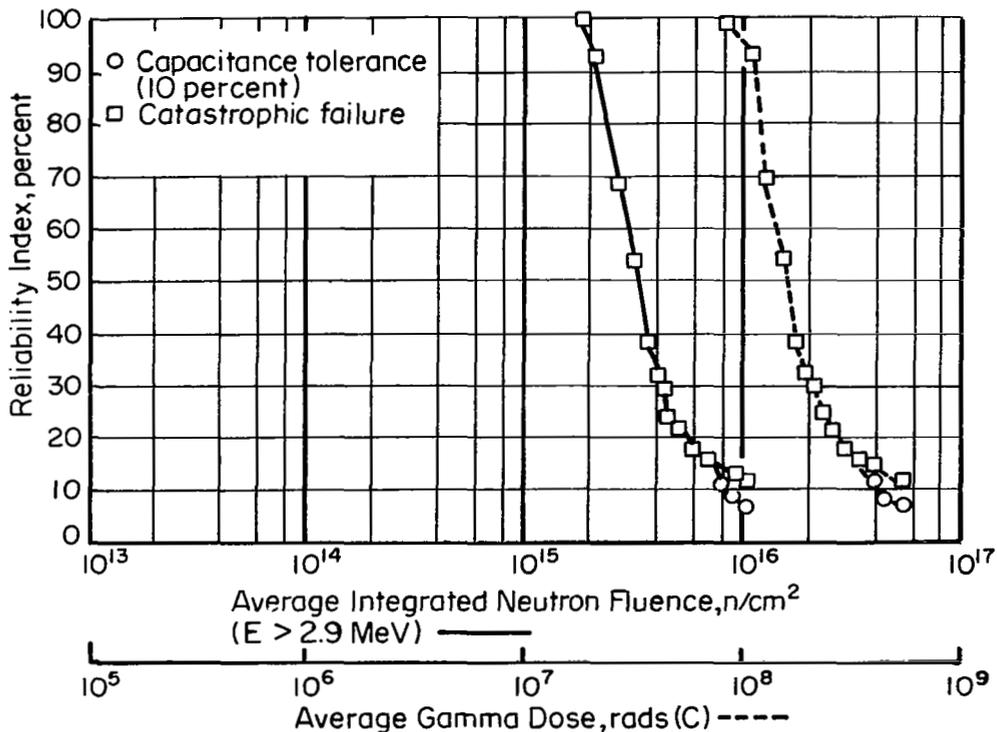


FIGURE 15. RELIABILITY INDEX FOR MYLAR CAPACITORS FOR A 95 PERCENT CONFIDENCE LEVEL, BASED ON A SAMPLE SIZE OF 98 UNITS (CAPACITANCE AND CATASTROPHIC FAILURE) (45)

fluence and total gamma exposures to which these Mylar capacitors were subjected were 1.32×10^{16} n/cm² (E > 2.9 MeV) and 8.5×10^8 rads (C), respectively. The capacitance values of the Mylar capacitors exhibited very little change for an extended period of radiation; a general increase was observed toward the end of the test. At the end of the test several units exceeded the 10 percent tolerance level specified for the capacitor. Prior to these failures, the mode of failure had been essentially limited to catastrophic-type damage. The reliability indices, shown in Figure 15, indicate this phenomenon by comparison of catastrophic failures with out-of-tolerance occurrence. Postirradiation examination of the Mylar capacitors revealed that 94 units had failed catastrophically and 81 had ruptured as a result of the test conditions. One capacitor that exhibited a nonshorted condition could not be charged, and 18 units of the entire test group were chargeable.

The second study that included a large sample size of Mylar capacitors consisted of subjecting them to the five environmental conditions listed in Table 7 with a d-c voltage applied. Nonenergized units were included in two of the environments (Test Groups VI and VII).⁽³⁹⁾ These additional test groups were subjected to the same environmental conditions as Groups I and III. The basic sample size at each test condition consisted of 20 units for a total sample size of 140 Mylar capacitors manufactured about 1965.

Failure-rate computations, Table 10, show that the combination of radiation exposure and 100 C temperature, Test Groups III and IV, resulted

TABLE 10. FAILURE RATE FOR 683G10592W2 CAPACITOR AT 50, 60, AND 90 PERCENT CONFIDENCE LEVELS⁽³⁹⁾

Test Group	Failure Rate at Indicated Confidence Level, percent/1000 hr			Percent Recorded as Failed
	50 Percent	60 Percent	90 Percent	
I	1.23	1.43	2.44	10
II	0.30	0.39	0.98	0
III	36.70	38.85	48.38	95
IV	18.76	20.02	25.53	75
V	0.30	0.39	0.98	0
VI	0.30	0.39	0.98	0
VII	0.30	0.39	0.98	0
All test groups	2.83	2.95	3.48	25.7

in exceptionally high failure rates. The results for the capacitors in Test Group V; radiation and 50 C, indicate that temperature was a definite factor in these failures, while results for Test Group II, 100 C without radiation, show a similar indication for the radiation environment. The results shown for Test Group VI, with environmental conditions identical to those for Test Group III but with no load applied, indicate that electrical load was also a factor in the failures. This concentration of failure in the radiation environments indicates that these capacitors are quite susceptible to radiation damage, even at the low levels used in this study, when in combination with a 100 C ambient temperature. Therefore, it was recommended that their application be limited to lower ambient temperatures, such as 50 C, when nuclear radiation is an environmental consideration.

Electrolytic Capacitors

Electrolytic capacitors offer a major advantage over other capacitor types for applications where space and weight requirements necessitate a high level of volumetric efficiency of the capacitors used in the circuits. The greatest capacitance-to-volume ratio (volumetric efficiency) is provided by electrolytic capacitors, and they are generally used in applications where this is of prime concern. A major disadvantage of electrolytic capacitors is that they are polar, and applications of nonpolar capacitors require two electrolytic capacitors connected back-to-back or a single unit having a foil that has been anodized on both sides. This reduces the capacitance by 50 percent, which in turn reduces the volumetric efficiency of the electrolytic capacitor, which as stated above is its major advantage.

The construction of an electrolytic capacitor includes an electrode or capacitor plate of some form that has been anodized on one side to form a dielectric film or insulating layer. A wet or dry electrolyte is provided between this anodized surface and the other terminal of the capacitor. Tantalum and aluminum are the commonly used metals for the anodized electrodes in electrolytic capacitors, and the capacitors are identified by which material is used. The tantalum electrolytics are generally considered more reliable than the aluminum electrolytics because the tantalum oxide layer in combination with the capacitor's electrolyte is more stable than the aluminum oxide layer and electrolyte combination. Both types, however, experience degradation in the form of increasing leakage currents and decreasing breakdown voltages during shelf life or operation at below-rated voltage. The aluminum units experience greater degradation because they

deform (the thickness of the oxide layer is reduced) at a more rapid rate than that for the tantalum. Applications for electrolytic capacitors include filtering and bypass circuits.

Information on the results of radiation-effects experiments with tantalum- and aluminum-electrolytic capacitors indicates that both types may be capable of surviving extended exposure to intense radiation. These results have also shown the tantalum units to be more radiation resistant; however, they offer a biological hazard where servicing of equipment may be required. This is due to the activation of the tantalum when subjected to thermal neutrons and the long half-life, 112 days, associated with the resulting radiation from the tantalum isotope Ta-182. This hazard is not associated with the aluminum units because of the very short half-life of 2.3 minutes for the aluminum isotope Al-28. The aluminum units also have the possibility of an isotopic reaction, $Al-27(n, \alpha) Na-24$, when exposed to a high level of fast neutrons. The sodium isotope has a half-life of 15 hours.

The electrical characteristics of electrolytic capacitors have experienced both temporary and permanent changes when exposed to nuclear radiation. The capacitance and dissipation factor suffer from both temporary and permanent effects. The leakage current, however, generally experiences a temporary increase with complete or nearly complete recovery to pre-irradiation values when the irradiation is terminated. Some of the electrolytic capacitors also experience physical damage because of their construction. These are the types that employ Teflon in the construction of the end seals of the capacitor case. Teflon is very sensitive to the nuclear-radiation environment, especially if oxygen is present in the atmosphere during the irradiation. It also suffers damage if exposed to oxygen after being irradiated in a vacuum or inert atmosphere. The Teflon end plugs of tantalum-electrolytic capacitors have popped out because of this sensitivity of Teflon to radiation, and the inner rubber seal protrudes.

The capacitance of tantalum- and aluminum- electrolytic capacitors has both increased and decreased during radiation-effects experiments. The changes in capacitance have varied between the maximums of -25 and +20 percent for tantalum types and between the maximums of -2 and +65 percent for aluminum. The changes are not necessarily permanent, and the capacitance in some studies has recovered to near the preirradiation value. Others, however, have shown additional degradation after the irradiation was terminated. Temporary increases in capacitance during irradiation may be due to temperature effects from gamma heating. The permanent changes or those that show recovery over an extended period of time would be indicative

of chemical changes in the oxide layer and/or electrolyte. Minor variations shown in some of the studies could very likely be due to variations in temperature.

The dissipation factor of tantalum and aluminum electrolytic capacitors has shown both temporary and permanent effects from exposure to a nuclear-radiation environment. The dissipation factor of high-capacity aluminum-electrolytic capacitors has increased by as much as 0.50, from preirradiation values, after a rather low neutron fluence and total gamma exposure of 4.8×10^{12} n/cm² (E > 0.5 MeV) and 7.1×10^5 rads (C), respectively.⁽⁴⁷⁾ Much smaller increases have occurred with some small-capacity units after a much higher neutron fluence and total gamma exposure, such as 2.5×10^{17} n/cm² (fast) and 6×10^8 rads (C). The difference in these results is very likely due to the large volumetric difference in the capacitors, and should be a consideration in what to expect in the application of similar devices.

The dissipation factor of tantalum-electrolytic capacitors may increase to where it exceeds 0.50 during irradiation. These high values or large increases occur when the Teflon end seals fail and there is a loss of electrolyte. Maximum increases in dissipation factor remain below 0.10 if there is no loss of electrolyte and may not exceed 0.05 with neutron and gamma flux and total exposure levels as high as 3×10^{11} n/(cm².s) and 6×10^{17} n/cm² (epicadmium), and 8.7×10^5 rads (C)/hr and 4.4×10^8 rads (C), respectively.

The leakage current of aluminum- and tantalum-electrolytic capacitors increases during irradiation by one or two orders of magnitude at neutron fluxes and gamma dose rates of 2.5×10^{10} n/(cm².s) E > 0.5 MeV and 3.6×10^5 rads (C), respectively. It has increased to values as high as 1000 microamperes for large capacitors such as 47 mfd and 100 Vdc. Smaller capacitors experience lower leakage currents since there is a direct proportionality between the product of capacitance, applied voltage and dose rate, and the leakage current. This increase is normally a temporary effect and the leakage current returns to near preirradiation values after the radiation exposure has been terminated. This recovery may not occur immediately but can require a period of several days.

Two programs on tantalum capacitors have included sufficient quantities of test specimens to provide a higher than usual statistical confidence in the results obtained. The following discussions of these individual test programs are presented for this reason.

One hundred Type TES-1M-25-20 solid-electrolytic-tantalum capacitors, nominal capacitance $1.0 \mu f$, were subjected to a combined environment of high temperature and nuclear radiation in one program.⁽⁴⁵⁾ The ambient temperature was controlled at 85 C with the reactor power limited to 1 megawatt during the first 24 hours. The reactor power was then increased to 10 megawatts for the duration of the experiment while the temperature continued to be controlled at 85 C. The neutron fluence and total gamma exposure to which these capacitors were subjected included $2.0 \times 10^{16} \text{ n/cm}^2$ ($E > 2.9 \text{ MeV}$) and $7.3 \times 10^8 \text{ rads (C)}$, respectively. The capacitance and dissipation factor of the tantalum capacitors increased very early in the test, with all units exceeding the 5 percent dissipation factor tolerance when the exposure reached $9.63 \times 10^{14} \text{ n/cm}^2$ ($E > 2.9 \text{ MeV}$) and $3.07 \times 10^7 \text{ rads (C)}$. This change can be observed in Figure 16, where the reliability indices

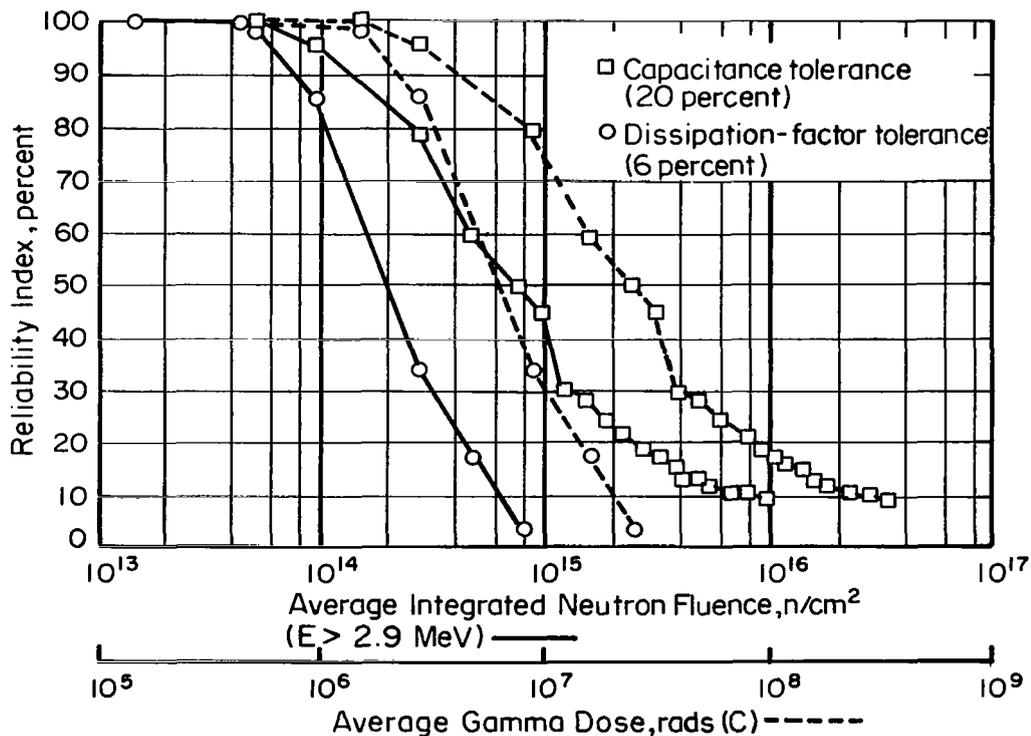


FIGURE 16. RELIABILITY INDEX FOR TANTALUM CAPACITORS FOR A 95 PERCENT CONFIDENCE LEVEL, BASED ON A SAMPLE SIZE OF 98 UNITS (CAPACITANCE AND DISSIPATION FACTOR)⁽⁴⁵⁾

are plotted on the basis of both capacitance and dissipation factor. No catastrophic failures occurred during the exposure, which, with the capacitance increases observed, would indicate that tantalum capacitors may be used in noncritical circuits to an integrated exposure of at least 1.6×10^{16} n/cm² (E > 2.9 MeV) and 5.1×10^8 rads (C). Postirradiation examination of the tantalum capacitors revealed no visual damage, and all capacitors were chargeable.

Two types of tantalum capacitors, manufactured about 1965, wet foil and wet slug, were included in the second study⁽³⁹⁾ that included statistically significant sample sizes. Both types were subjected to the five environmental conditions described in Table 7, with d-c voltage applied. The wet-foil tantalum capacitors were also subjected to one of the environments with no voltage applied. These additional capacitors, Test Group (VI), were subjected to the same environmental conditions as Test Group III, Table 7. The basic sample size of each test condition consisted of 20 units, for a total of 120 of the wet-foil-type and 100 of the wet-slug-type capacitor.

No failures were observed for 120 wet-foil tantalum capacitors, and no leakage or physical damage was detected during the final visual inspection.

Failure-rate computations are presented in Table 11 for these capacitors. The minor difference between the failure rates for Test Group IV and

TABLE 11. FAILURE RATE FOR 5K106AA6 CAPACITOR AT 50, 60, AND 90 PERCENT CONFIDENCE LEVELS⁽³⁹⁾

Test Group	Failure Rate at Indicated Confidence Level, percent/1000 hr			Percent Recorded as Failed
	50 Percent	60 Percent	90 Percent	
I	0.30	0.39	0.98	0
II	0.30	0.39	0.98	0
III	0.39	0.39	0.98	0
IV	0.29	0.39	0.97	0
V	0.30	0.39	0.98	0
VI	0.30	0.39	0.98	0
All test groups	0.05	0.06	0.16	0

those for the other test groups is due to the additional operating time associated with the 100 hours of high-flux radiation that these components received prior to the beginning of the 10,000-hour life test.

The range of capacitance remained well within the specified limit. A general increase was observed in the dissipation factor for all test groups, with the exception of Test Group V (50 C, vacuum, low-flux radiation environment). This would indicate that the 100 C ambient of the other test groups was responsible for the increase. No dissipation-factor degradation was apparent in the results from the radiation environments.

The results indicate that the various environmental conditions and combinations thereof that were included in this study offer no particular problem in the application of these capacitors.

Twenty-five failures were observed in a total sample of 100 of the wet-slug tantalum capacitors that were subjected to the five operating conditions of this study. Three of these failures were not confirmed by final measurements. Two of the remaining 22 indicated a high leakage-current condition (approaching short circuit), and 20 were open circuits during final measurements. The visual examination when the test was terminated revealed that the plastic covering on the capacitors in Test Group I (100 C, atmospheric pressure, no radiation exposure) had discolored to a dark brown and become hard, and the capacitors showed evidence of electrolyte leakage. In addition, all specimens in Test Group II (100 C, vacuum, no radiation exposure) also showed evidence of leakage, and the solder at one end of the case had melted on four capacitors.

Failure-rate computations for these units, Table 12, indicated a much higher failure rate for the capacitors in Test Groups I and II (nonradiation environments). The higher values for Test Group I were attributed, at least in part, to the fact that the plastic cover was left on the capacitors in this test group but was removed from all others as offering a possible outgassing problem in the vacuum environments. The plastic covers were considered as possibly having prevented or reduced the rate at which the heat due to internal losses could be dissipated. However, this did not explain the high failure rate for the capacitors in Test Group II (compared to that of Test Groups III and IV), which had their plastic covers removed.

A beneficial effect from the radiation was considered an unlikely possibility, but was given as one possible explanation of the catastrophic-failure distribution for these capacitors, i. e., high failure rates for the nonirradiated groups.

TABLE 12. FAILURE RATE FOR HP56C50D1 CAPACITOR AT 50, 60, AND 90 PERCENT CONFIDENCE LEVELS⁽³⁹⁾

Test Group	Failure Rate at Indicated Confidence Level, percent/1000 hr			Percent Recorded as Failed
	50 Percent	60 Percent	90 Percent	
I	11.82	12.56	15.80	85
II	7.31	7.81	10.05	30
III	0.30	0.39	0.98	0
IV	0.75	0.89	1.74	5
V	0.75	0.90	1.72	5
All test groups	3.25	3.39	4.02	25

The results obtained on these capacitors show that they can survive the radiation environment, but the results were somewhat inconclusive because of the excessive number of failures that occurred in the control environments.

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