THE EFFECT OF RADIATION ON ELECTRICAL INSULATING MATERIALS

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RADIATION EFFECTS INFORMATION CENTER
Battelle Memorial Institute
Columbus Laboratories
Columbus, Ohio 43201

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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REPORT

on

THE EFFECT OF RADIATION ON ELECTRICAL INSULATING MATERIALS

by

C. L. Hanks and D. J. Hamman

to

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Radiation Effects Information Center
Battelle Memorial Institute
Columbus Laboratories
Columbus, Ohio 43201

ABSTRACT

This report compiles and summarizes the information available in the Radiation Effects Information Center's technical files on the effects of steady-state radiation on electrical insulating materials. The insulating materials are classified as organic or inorganic with separate sections on bulk type specimens (film, sheet, etc.), wire and cable insulation, encapsulating compounds, and connectors and terminals. It is the intent of the report to provide information for "ballpark" or broad estimates of the effect of radiation on various insulating materials and is meant to be used as a guide in the early design stages. Detailed information as required in the terminal stages of a design should be requested from the REIC when details of all environmental conditions, radiation exposure rate, and total dose are known.

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REPORT

on

THE EFFECT OF RADIATION ON ELECTRICAL INSULATING MATERIALS

SUMMARY

Radiation damage to dielectric and insulating materials is a function of temperature and atmospheric conditions as well as the radiation environment. Many materials are more resistant to radiation in the absence of oxygen or moisture and at lower temperatures. Because of this influence of environmental conditions 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. The fabrication method used by the manufacturer can also be a factor in the amount of damage that occurs from radiation. For these reasons, it is the intent of this report to provide "ballpark" type information for use in the early design phase of a system. The more detailed information required as a design approaches finalization may be obtained, when available, by submitting a specific request to the REIC including details of radiation type, rate, and dose with other environmental conditions, i.e., space, vacuum, inert gas, temperature, etc.

Organic Materials

Both temporary and permanent changes occur in the characteristics of organic insulating and dielectric materials as a result of exposure to a radiation environment. Enhancement of the electrical conductivity is the most important of the temporary effects with increases of several orders of magnitude being observed. The conductivity increases exponentially in response to ionizing radiation until it reaches equilibrium at a value that is determined by the rate of exposure and ambient temperature for a specific material. Following the termination of the irradiation the induced conductivity gradually decreases. This decrease may include several discrete decay time constants. A generalized expression for conductivity in insulating materials utilizing the "unit-step function", U(t), combined with basic characterizations of the three intervals, i.e., exponential increase, equilibrium, and recovery yields the equation

$$\sigma(t,\dot{\gamma})\Big| = U(t)\sigma_o + U(t-a)\left\{\left[\sigma_o + A_\gamma\dot{\gamma}^\delta - A_\gamma\dot{\gamma}^\delta e^{-(t-a)/\tau_o(\dot{\gamma})}\right] - \sigma_o\right\}$$

$$+ U(t-b)\left\{\sigma_{eq}\sum_{i=1}^{n} k_i e^{-(t-b)/\tau_i} - \left[\sigma_o + A_\gamma\dot{\gamma}^\delta - A_\gamma\dot{\gamma}^\delta e^{-(t-a)/\tau_o(\dot{\gamma})}\right]\right\}$$

where:

σ_o = initial conductivity

A_γ = empirical constant

τ_o = time constant of response

δ = empirical constant

$\dot{\gamma}$ = gamma exposure rate

$\sigma_{eq} = \sigma_o + A_\gamma\dot{\gamma}^\delta$ = 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 ith τ.

Other temporary effects, in addition to the enhanced conductivity, are a reduction in breakdown and flashover voltages, increases in a-c loss characteristics, and variations in dielectric constants. These changes in electrical characteristics, however, are often not large enough to prevent the use of the insulators in a radiation environment, particularly, if allowances are made to minimize their effect on the circuits performance.

Permanent effects of radiation on organic insulating materials are normally associated with chemical changes, the most important of which are molecular scission and cross-linkage. The latter leads to hardening and embrittlement; increased strength, density, and melting point; and a decrease in solubility. Chain scission produces almost the opposite change in physical characteristics including decreases in hardness, tensile strength and melting point, and greater solubility. This physical degradation in the advanced stages is disastrous in that the insulating material br ks, crumbles, or powders thus losing structural integrity and causing failure. Changes in dissipation factor and insulation resistance have also occurred as permanent effects, but they are normally quite small and offer few problems except in the most uncommon applications.

A comparison of the relative radiation resistance of organic insulating materials to permanent effects is presented in Figure 1.

Gas evolution, a secondary reaction that occurs when organic insulators are irradiated, is also a problem because of pressure buildup in confined enclosures. Some of these gas species are corrosive and can be detrimental to electrical contacts, etc., especially in sealed parts such as miniature relays.

Inorganic Materials

In general, the inorganic insulating or dielectric materials are more resistant to radiation damage than the organics. Atomic displacement is responsible for permanent damage in the inorganic insulators and is manifested by changes in density, strength, and electrical properties. The density of crystalline insulators decreases while that of amorphous insulators increases from exposure to fast neutrons. The predominant effect on electrical properties is a change in resistivity. A comparison of the relative radiation resistance of inorganic insulators to permanent damage is presented in Figure 2.

Inorganics experience a strong photoconductive effect from the energy of incident radiation which is absorbed through ionization and electronic excitation. Transient changes of several orders of magnitude are normally tolerable, however, because of the high resistivity of inorganic insulators. The generalized equation presented in the summary of effects on organic materials is also applicable to radiation induced conductivity or photoconductivity in inorganics.

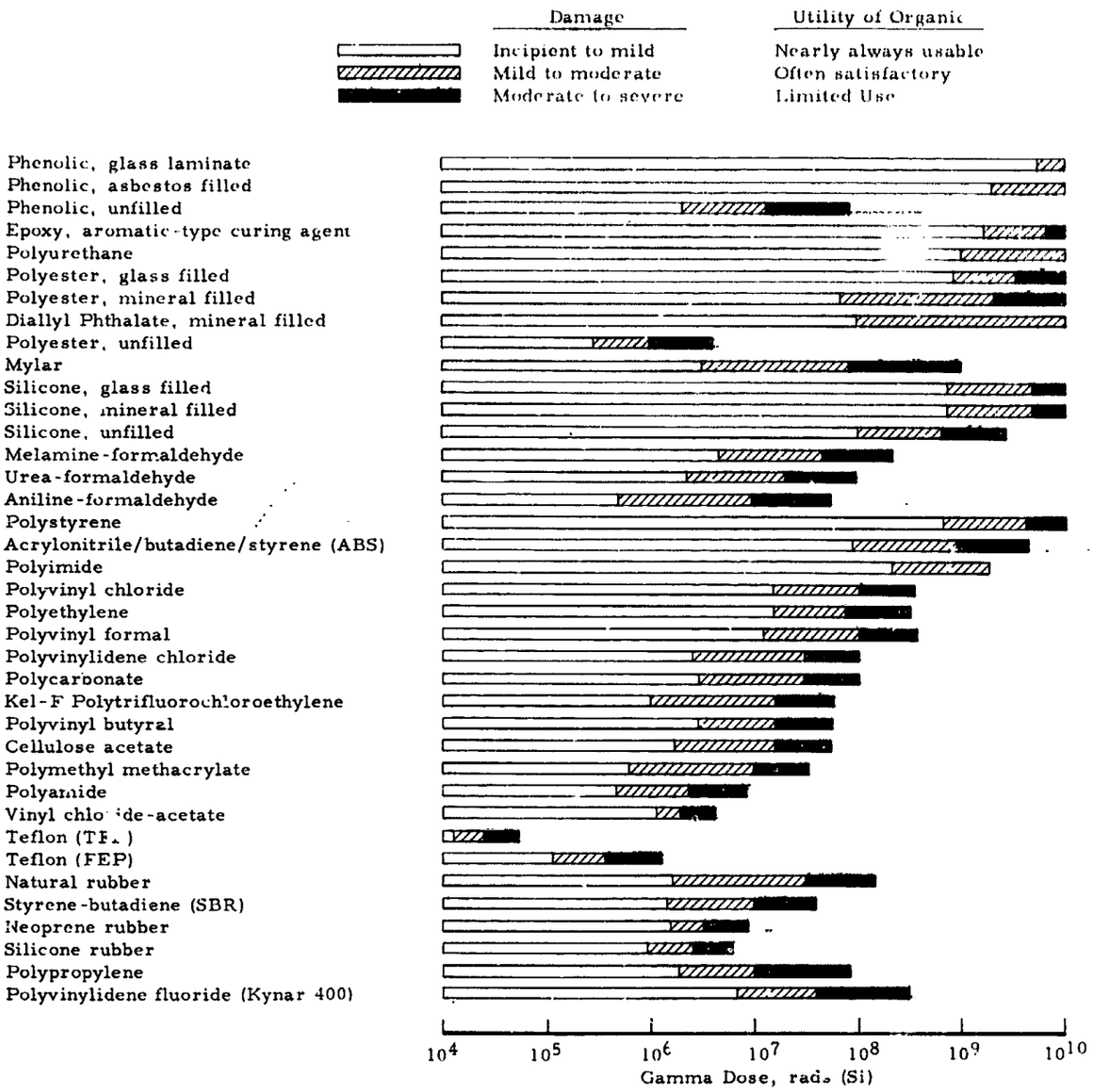


FIGURE 1. RELATIVE RADIATION RESISTANCE OF ORGANIC INSULATING MATERIALS

Based upon changes in physical properties.

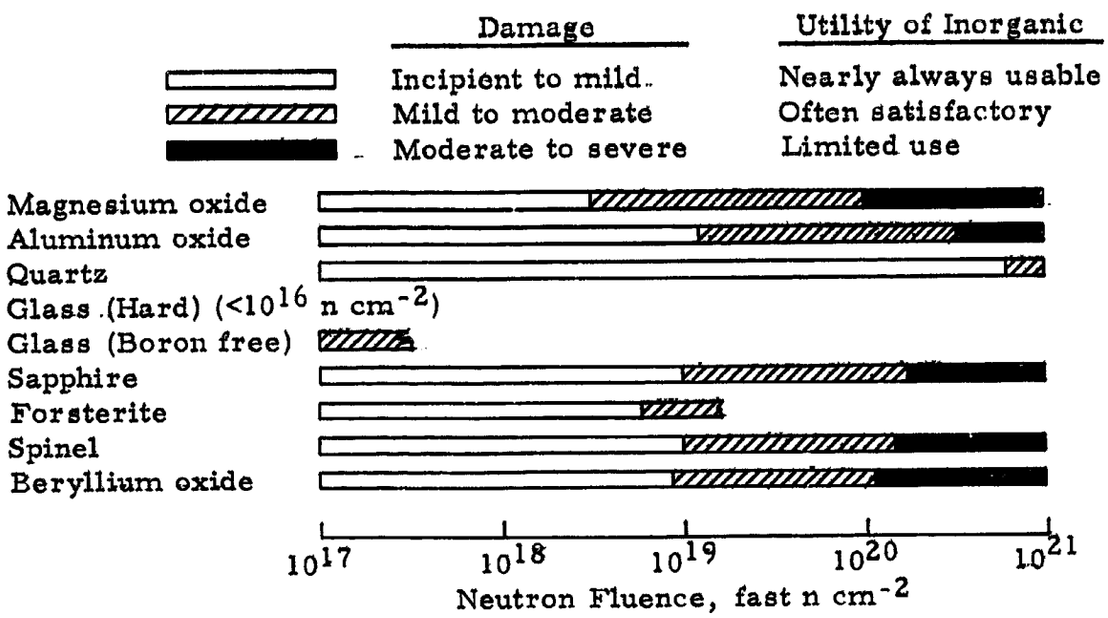


FIGURE 2. RELATIVE RADIATION RESISTANCE* OF INORGANIC INSULATING MATERIALS. BASED UPON CHANGES IN PHYSICAL PROPERTIES

*Varies greatly with temperature.

INTRODUCTION

Dielectric and insulating materials as applied to electronic circuitry are second only to semiconductor devices, such as integrated circuits, transistors, diodes, etc., 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 when 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 when used as other than a capacitor dielectric. Information on capacitors and their radiation tolerance is available in another report, "REIC Report No. 44, The Effect of Nuclear Radiation on Capacitors".

The degradation of an insulating material's electrical properties is the major concern of this report. Degradation of physical 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 the organic insulating materials, he is directed to REIC Reports Nos. 21 and 21 Addendum, "The Effect of Nuclear Radiation on Elastomeric and Plastic Components and Materials".

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. It is recommended that the more detailed information required in the later design phases be obtained through a request to the Radiation Effects Information Center for a file search in the area and conditions of specific interest.

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. Transient or pulse radiation effects are, therefore, not included in this document, and those readers requiring such information are referred to the TREE Handbook. *

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 and the field 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 with increases of several orders of magnitude being 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 3. The conductivity increases exponentially in response to a step increase in gamma dose rate, $\dot{\gamma}$, during interval A and is characterized by

$$(\sigma - \sigma_o) = A \left(1 - e^{-t/\tau_o}\right) \qquad (1)$$

where

σ_o = initial conductivity

σ = conductivity at time "t"

A = empirical constant

*Transient Radiation Effects on Electronics (TREE) Handbook, DASA 1420.

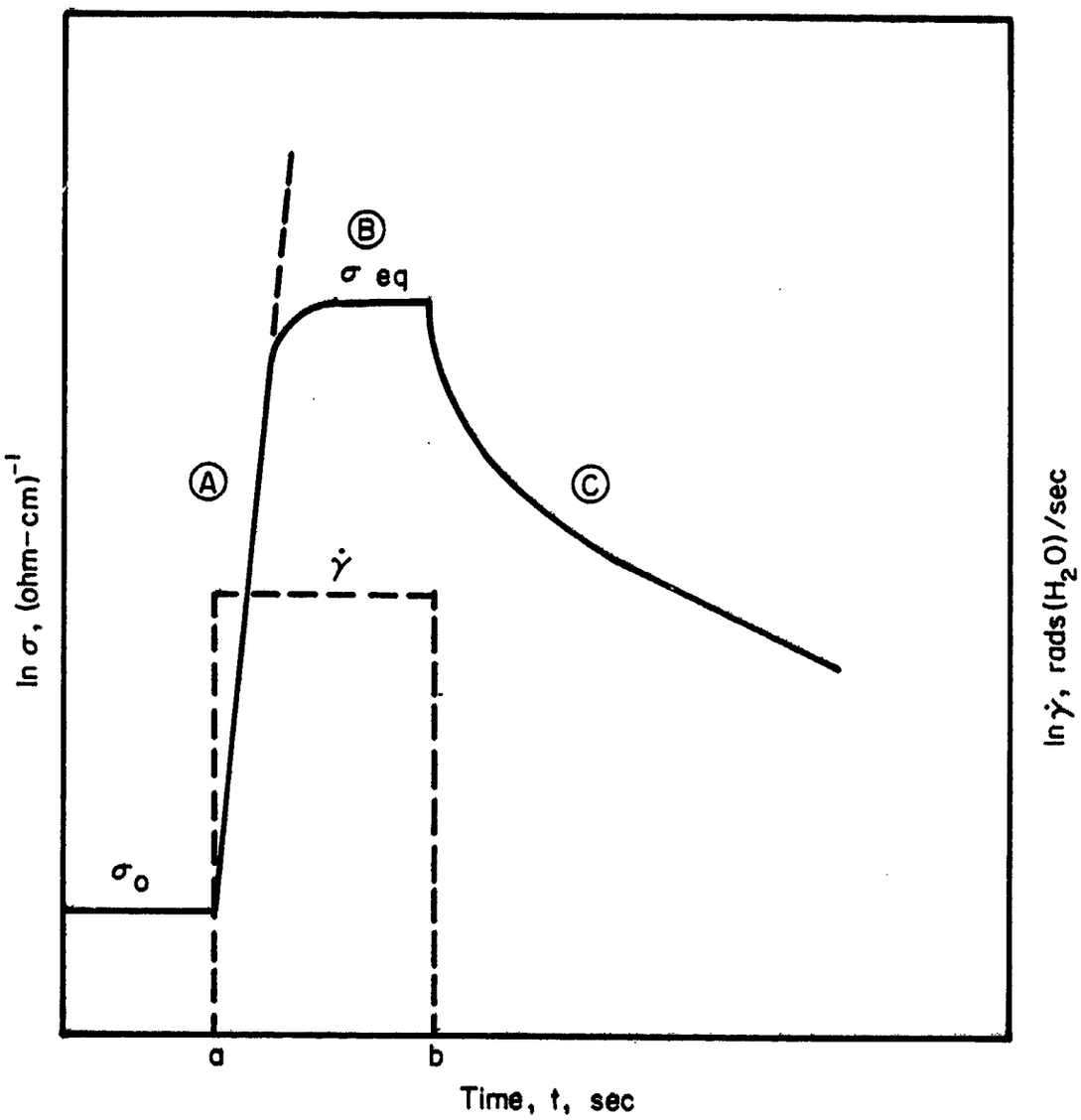


FIGURE 3. TYPICAL BEHAVIOR OF CONDUCTIVITY IN RESPONSE TO A RECTANGULAR PULSE OF GAMMA-RAY DOSE RATE[1]

$\tau_o = k_o \dot{\gamma}^{-\mu}$ = time constant of the response as a function of gamma dose, k_o and μ being empirical constants (see Figure 4).

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

$$(\sigma - \sigma_o) = A_\gamma \dot{\gamma}^{\delta} \tag{2}$$

where

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

$\dot{\gamma}$ = gamma 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

$$\sigma = \sigma_{eq} \sum_{i=1}^{n} k_i \, e^{-t/\tau_i} \tag{3}$$

where

$\sigma_{eq} = \sigma_o + A_\gamma \dot{\gamma}^{\delta}$ = 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 $i^{\underline{th}}$ τ_i.

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, to yield the equation

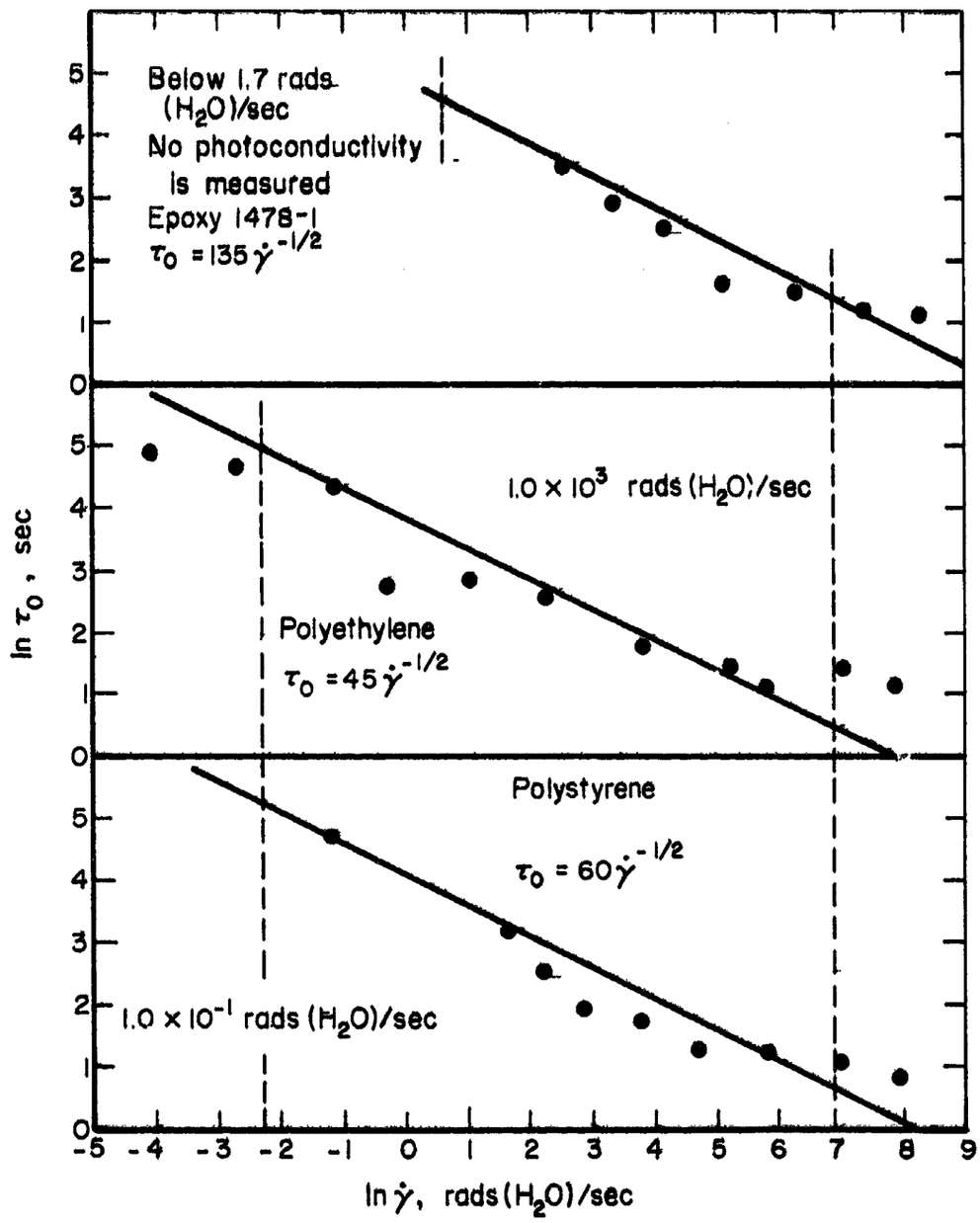


FIGURE 4. LOGARITHM OF TIME CONSTANT VERSUS LOGARITHM OF GAMMA-RAY DOSE RATE FOR POLYETHYLENE, POLYSTYRENE, AND EPOXY 1478-1 AT 38 C[1]

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

Material	Temperature, C	δ	A_γ	Range of $\dot{\gamma}$, rads (H_2O)/sec
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	3.3×10^{-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

Notes: (1) Data taken under steady state conditions after 1.8×10^3 seconds of electrification.

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

(3) Temperature is ± 1 C.

$$\sigma(t, \dot{\gamma}) \Big| = U(t)\sigma_o + U(t-a)\left\{ A_\gamma \dot{\gamma}^\delta \left[1 - e^{-(t-a)/\tau_o(\dot{\gamma})} \right] \right\}$$

$$+ U(t-b)\left\{ \sigma_{eq} \sum_{i=1}^{n} k_1 e^{-(t-b)/\tau_1} \right.$$

$$\left. - \left[\sigma_o + A_\gamma \dot{\gamma}^\delta \left(1 - e^{-(t-a)/\tau_o(\dot{\gamma})} \right) \right] \right\} . \qquad (4)$$

The cumulative results of the temporary effects as pertains 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. Where the designer is under severe space limitations or the application includes a high radiation exposure rate, however, it may be necessary to limit insulating material considerations to the inorganics.

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 cross-linkage. 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 could in turn 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 the more uncommon application where they would offer any problem.

A secondary reaction that may occur when an organic insulator or dielectric is irradiated is gas evolution. It is unlikely that the volume of gas would be of serious concern except in the case of organic fluids where sufficient pressure may be produced to distort or rupture a sealed enclosure. Gas evolution from the solid organic polymers is less than that for liquids because of a greater possibility of recombination and limited diffusion. 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. Failure from other causes, however, is likely to occur before the corrosion would become a problem, but some consideration in this area may be advisable when selecting sealed parts - like miniature relays - that contain electrical contacts.

Environmental conditions other than the radiation contribute to the degradation of organic insulators and dielectrics. Temperature and/or humidity may be important for some materials with the gaseous content of the ambient atmosphere being 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.

RADIATION EFFECTS ON INORGANIC MATERIALS

Inorganic insulating and dielectric materials are, in general, more resistant to radiation damage than 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 it is left unaltered chemically.

A large part of the energy of incident radiation is absorbed through electronic excitation and ionization producing 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. However, data are not available to provide the measured values of A_γ and δ. The high resistivity of inorganic insulators, however, permits transient changes of several orders of magnitude to be tolerated in most applications.

Atomic displacements lead to permanent changes in inorganic insulators which are manifested as changes in density, strength and electrical properties. The density of crystalline insulators decreases from exposure to fast neutrons while that of amorphous insulators, such as fused quartz and glass, increases. Changes in resistivity is the predominant effect on electrical properties with little or no change occurring in a-c characteristics.

The reader is cautioned in selecting an inorganic insulator for application in a strong thermal-neutron field and should be guided by the capture cross section of the material. High absorbers such as boron compounds may transmute and cause displacement damage to the point of serious deterioration of electrical 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 summarizes the results of these investigations.

Polytetrafluoroethylene (PTFE)

Polytetrafluoroethylene (commonly identified as Teflon TFE, but also including the trade names Halon TFE, Tetran, Fluon, Polyflon and Algoflon) has demonstrated a rather high susceptibility to radiation damage, which is quite apparent from its loss of physical properties when 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 this damage mechanism. The embrittlement becomes severe with extended irradiation (10^7 rads) and the polytetrafluoroethylene crumbles and/or powders. The approximate damage threshold and the 25 percent damage dose are 1.7×10^4 rads and 3.4×10^4 rads, 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 has 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.[2] 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 Figure 5, which also gives 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, i.e., similar deterioration occurs at a lower total dose. For example, in one study only negligible damage was observed at -65 F after a dose of 2.6×10^5 rads, while the tensile strength decreased 40 and 60 percent after similar doses at 73 and 350 F.[3]

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 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 of 5×10^{17} to 1×10^{18} ohm-cm or greater when irradiated under vacuum conditions to total doses of 10^6 rads 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 irradiated in air or vacuum to respective doses of 8×10^6 and 10^8 rads. Recovery is essentially complete within a day or two after the irradiation. Similar results have also been obtained under vacuum

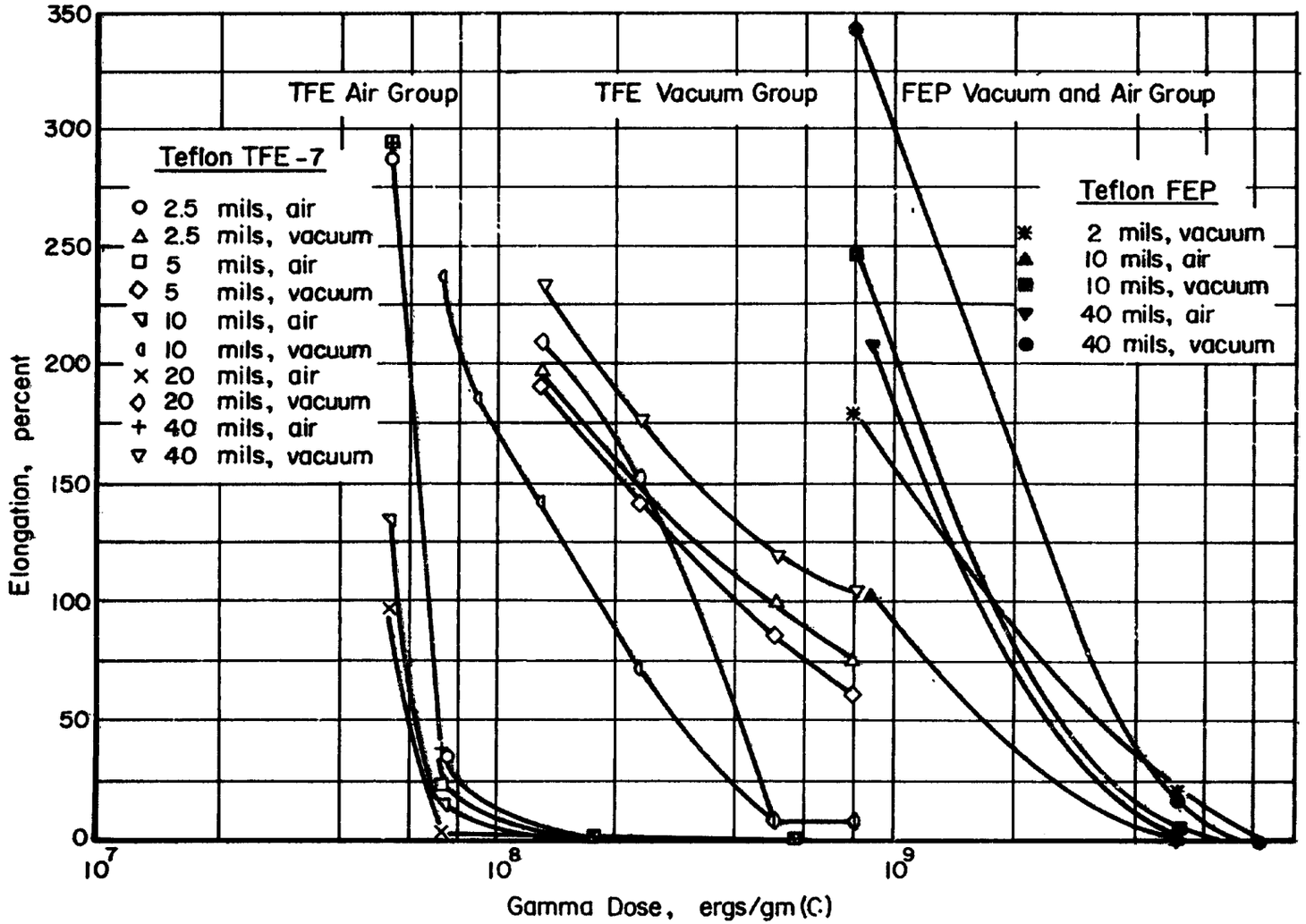


FIGURE 5. COMPARISON OF ULTIMATE ELONGATION VALUES OF VARIOUS THICKNESSES OF TEFLON TFE AND FEP IRRADIATED IN VACUUM AND AIR.(2)

conditions at cryogenic temperatures to a dose of 7×10^6 rads (C).[2] However, when this test was terminated at 9.5×10^7 rads (C), the final value for the dielectric constant during exposure was approximately 22 percent higher than the initial cryotemperature value.

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 6. 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 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 7 after the exposure shown in Figure 6.

Limited information on the effect of radiation on the dissipation factor of different Teflon types indicate a difference in sensitivity to 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.[5] Similar radiation exposure caused substantial increases to 0.408 and 0.169 for TFE-6 (extrusion resin) and TFE-7 (molding resin), respectively, in this same study.

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 1.3×10^6 rads (C) and a 25 percent damage dose of 2×10^7 rads.[3] The elongation of this material increased 47 percent and the impact strength

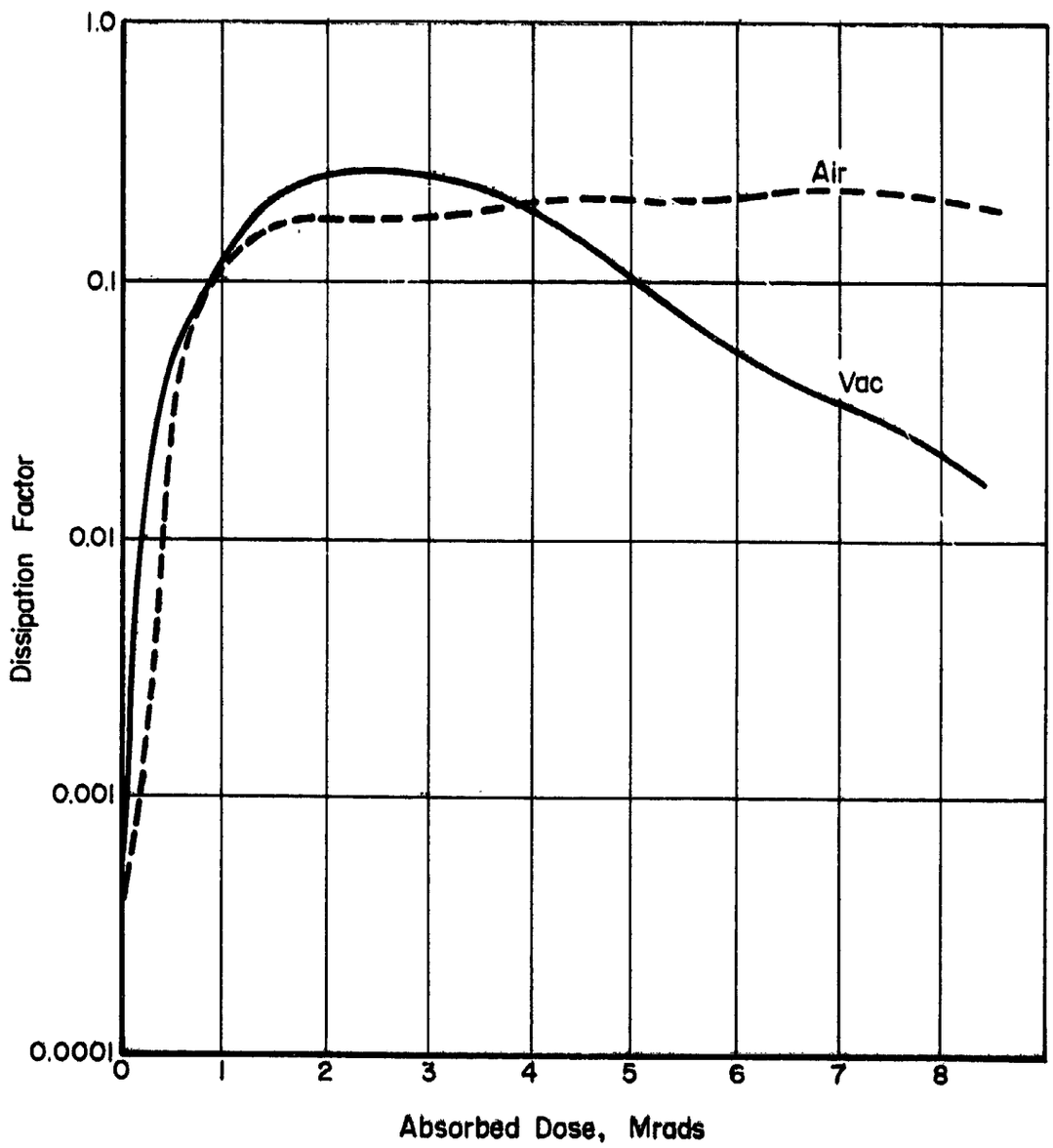


FIGURE 6. EFFECT OF X-RAY IRRADIATION ON TFE-6[4]

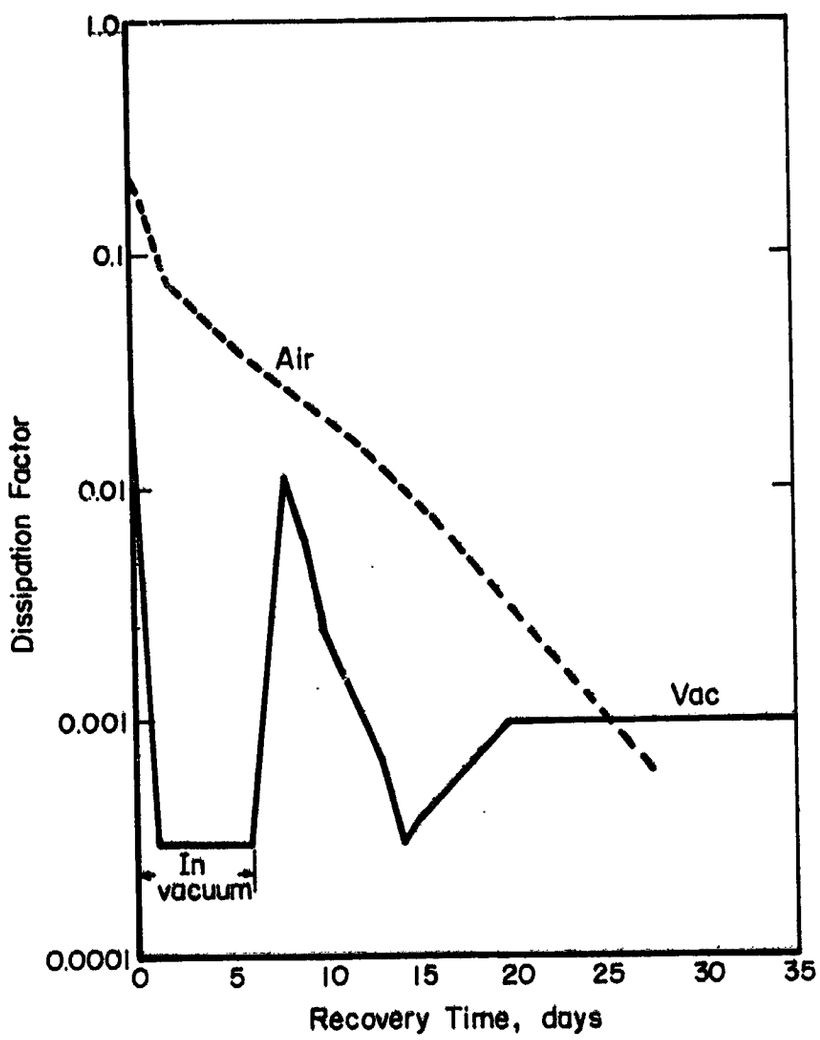


FIGURE 7. RECOVERY CHARACTERISTICS OF TFE-6 SPECIMENS AFTER X-RAY IRRADIATION AS SHOWN IN FIGURE 4[4]

decreased 16 percent when it was subjected to a total dose of approximately 2.4×10^7 rads (C).[6] The ultimate tensile strength was unaffected.

Electron irradiation with a total of 3.67×10^{16} e/cm^2 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 in a vacuum environment.[5] 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 charcateristic. Low values of 0.001 after 1920 hours of recovery in air were observed.[5]

A Russian study that included a total bremsstrahlung dose of 6×10^7 roentgens produced similar reductions in volume resistivity.[7]

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, after which it decreases and is 25 percent below the initial value at approximately 10^{10} rads (C).[3] The damage threshold is greater than 10^7 rads (C).

There are some differences in the results obtained from the irradiation of polyethylene with thinner films degrading 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/cm^2 at 60 C illustrates the differences these factors make.[8] The hardness and stiffness in flexure of the high-density material decreased as a result of the irradiation while the low-density and carbon filled 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 this material 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. 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.

Polystyrene

Irradiation studies of polystyrene have shown it to be one of the most radiation resistant 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 total dose of 5.8×10^{16} e/cm^2 at 60 C has resulted in decreases of approximately 50 percent in the tensile strength and ultimate elongation.[8] The hardness and the stiffness in flexure also decreased 1 percent and 13 percent, respectively, during this same study. These results indicate the 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 and as high as 10^8 rads. 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 and above causes severe embrittlement of polyethylene terephthalate to a degree that properties are unmeasurable.

Degradation of the electrical properties of polyethylene terephthalate within 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.

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/cm^2 at 60 C.[8] This same exposure improved the tensile strength by 49 to 107 percent. This agrees 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/cm^2 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 have been less than 6 percent while dissipation factor has recovered to below the initial value. Increases in insulation resistance during exposure are followed by complete recovery soon 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 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/cm^2 at 60 C resulted in decreases of 87 to 96 percent in ultimate elongation and tensile strength.[8] 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 when lower doses caused embrittlement of the material.[9] 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.

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.[10] A weight loss of 1 percent 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, however, with the exception of the results from an electron fluence of 5.8×10^{16} e/cm^2 at 60 C.[8] 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/cm^2 ($E > 0.5$ MeV) and gamma dose of 1.4×10^6 rads at 16 C to 29 C.[11] 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. This difference is unexplainable at this time; it may be from minor differences in the polyurethane or in the environmental conditions since the electron radiation study was conducted in a nitrogen atmosphere while the reactor study was under vacuum conditions.

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.[2] 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.

Miscellaneous Organics

Radiation effects information is available on organic bulk, sheet, and/or film materials other than those discussed on the preceding page. 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. 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.

Ceramic

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 factor and dielectric constant) with X-ray irradiation to doses up to 10^7 rads. Similar results have also been observed with reactor irradiation to doses as high as 10^{17} n/cm^2 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.

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/cm^2 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 are limited to the evaluation of physical damage at total doses up to 5×10^{13} n/cm^2 and 1×10^8 rads at 200 C.[13] 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,

TABLE 2. MISCELLANEOUS ORGANIC BULK, SHEET, AND/OR FILM MATERIALS WHICH LIMITED INFORMATION INDICATE AS UNSATISFACTORY AT THE RADIATION DOSE INDICATED[8]

Material Identification	Total Integrated Exposure
Acetal resin	1.22×10^{16} e/cm^2 at 60 C
Acrylic plastic, molding grade (rubber modified)	5.80×10^{16} e/cm^2 at 60 C
Allyl carbonate plastic, cast	4.10×10^{16} e/cm^2 at 60 C
Cellulose acetate	5.80×10^{16} e/cm^2 at 60 C
Cellulose butyrate	4.10×10^{16} e/cm^2 at 60 C
Cellulose propionate	4.10×10^{16} e/cm^2 at 60 C
Chlorinated polyether	2.90×10^{16} e/cm^2 at 60 C
Polycarbonate	5.80×10^{16} e/cm^2 at 60 C
Polyfluoroethylenepropylene, Teflon FEP (copolymer)	3.67×10^{16} e/cm^2 at 60 C
Polymethyl methacrylate, cast	1.22×10^{16} e/cm^2 at 60 C
Polymethyl methacrylate, molding grade	4.10×10^{16} e/cm^2 at 60 C
Styrene acrylic copolymer	2.90×10^{16} e/cm^2 at 60 C
Polyvinyl chloride, DOP plasticized	3.67×10^{16} e/cm^2 at 60 C
Polyvinyl chloride, rigid	4.10×10^{16} e/cm^2 at 60 C

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 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.[8]
Styrene-acrylonitrile copolymer	5.8×10^{16} e/cm^2 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.[8]
Styrene-butadiene (high-impact styrene)	5.8×10^{16} e/cm^2 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.[8]
Styrene-divinylbenzene	5.8×10^{16} e/cm^2 at 60 C	Changes in physical properties were of no practical significance.[8]
Polyvinyl chloride acetate	5.8×10^{16} e/cm^2 at 60 C	Insignificant changes in hardness, tensile strength, dielectric constant, and dissipation factor. Insulation resistance decrease two decades. Flexibility increased 30 percent.[8]
Polyvinylfluoride	5.8×10^{16} e/cm^2 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.[8]
Epoxy/glass laminate	2×10^{13} n/cm^2 (E >0.1 MEV) 1×10^8 rads(C)	Unaffected[2]
Epoxy/glass laminate (copper clad)	0.86×10^6 rads	No induced conductivity and no change in a-c loss properties.[5]
Polyester/glass laminate	2.5×10^6 rads	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.[5]
91-LD Resin/181-Volan A laminates (copper clad)	2.5×10^{15} n/cm^2 at 55 C	No degradation in physical properties.[12]
Silicone/glass laminate	5.0×10^{13} n/cm^2 at 200 C 1.0×10^8 rads	49 percent loss in flexure strength, slight change in color, thickness, and weight.[13]

inorganic, bonded amber mica, however, experienced a 29 percent decrease in flexure strength at the above dose.

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 while others have demonstrated a high level of radiation tolerance, surviving doses of up to 10^8 rads (C). Special cables and wires insulated with inorganic materials have shown similar radiation resistance to doses of 10^{10} and 10^{11} R. 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

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 with a 5 psia oxygen atmosphere and ambient temperature of 90 C as other environmental conditions.[14, 15] 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 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 total dose is the threshold area for damage to polytetrafluoroethylene insulated wire and damage to the other wire insulations was not yet apparent. The latter, i.e., approaching damage threshold, would compare to damage thresholds determined by other experimenters.

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 kilovolts.[14, 15] The post test range was 9.1 to 14.2 kilovolts. 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/cm^2 ($E > 0.1$ MeV) and 2.3×10^8 rads.[16] 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 1.1×10^8 R 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 5×10^8 R. 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 1×10^9 R.[17] 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 coax or shielded type, in that some materials used for this purpose become brittle at lower doses than the polyethylene. Therefore, it can be the limiting factor in the application of a cable rather than the insulating material used on the wire or wires 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 are of little significance (0.5 to ~10 percent). Data on other coaxial cable parameters is limited but indicate 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 is limited to polyethylene insulated coaxial cable.[18] Currents of the order of 10^{-8} amperes were observed during the cables exposure to the radiation which included 1.2×10^{12} $n/(cm^2 \cdot s)$ ($E > 2.9$ MeV) and 7.5×10^7 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 10^6 R. 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 10^7 R.[19] Serious deterioration of the wire's mechanical qualities occurs with a total dose of 10^8 R 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 10^3 and 4×10^6 rads.[14, 15] 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/cm^2 (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. Wire with a combination of glass braid and polyimide resin film insulation exhibited a breakdown voltage of approximately 1000 volts before and after receiving the total exposure indicated above.[19]

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. 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 at 23 C.[20] 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 post-test measurements. However, the designer should allow for a decrease of one to three orders of magnitude in insulation resistance during irradiation as a precautionary procedure. 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.[14, 15] The two environmental combinations used in this study were (1) an X-ray dose of 6×10^4 rads with a vacuum of 10^{-6} torr

*Unidentified as to whether polyethylene or polypropylene.

and temperature of 150 C and (2) an X-ray dose of 1×10^3 rads with a 5-psia 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 kilovolts after a radiation dose of 500 megarads.[20]

Coaxial cable insulated with irradiation-modified polyolefin (polyethylene) experienced an increase in attenuation of 0.30- and 0.40-db when exposed to a total dose of 2.9×10^8 rads (C) and 3.0×10^{16} n/cm^{-2} (E > 0.1 MeV).[16] 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 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.

TABLE 4. RADIATION EFFECTS ON MISCELLANEOUS ORGANIC WIRE INSULATIONS

Material Identification	Total Integrated Exposure[a]	Remarks
Alkanex	5.3×10^7 R, Co-60	Satisfactory performance, 150 C (encapsulated in rigid epoxy and semi-rigid silicone).[22]
Silicon-alkyd	5.3×10^7 R, Co-60	Satisfactory performance, 150 C (encapsulated in rigid epoxy and semi-rigid silicone).[22]
Polypropylene	7.1×10^7 rads(C), Co-60	Unsatisfactory, becomes brittle and crumbles (15 C, 55 C, and 100 C).[23]
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.[24]
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.[24]

(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.

The single exception is the results of a study of electron irradiation of polyethylene terephthalate insulated ribbon wire.[21] 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/(cm$^2 \cdot$ 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/cm^2, 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/cm^2 were indicated if a discharge time of 0.01 microsecond is acceptable. The data supports 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.

Ceramic

Magnet wire insulated with ceramic enamel (Ceramicite and Ceramitemp), has demonstrated a high tolerance for radiation for total doses up to 1.5×10^8 rads (C) and 4.4×10^{17} n/cm^2 (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.[19] 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.[13] 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 an inorganic, calcium aluminate. These materials, generally, experienced insignificant changes in their physical and electrical characteristics from the radiation exposures to which they were subjected. Any exceptions will be 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.

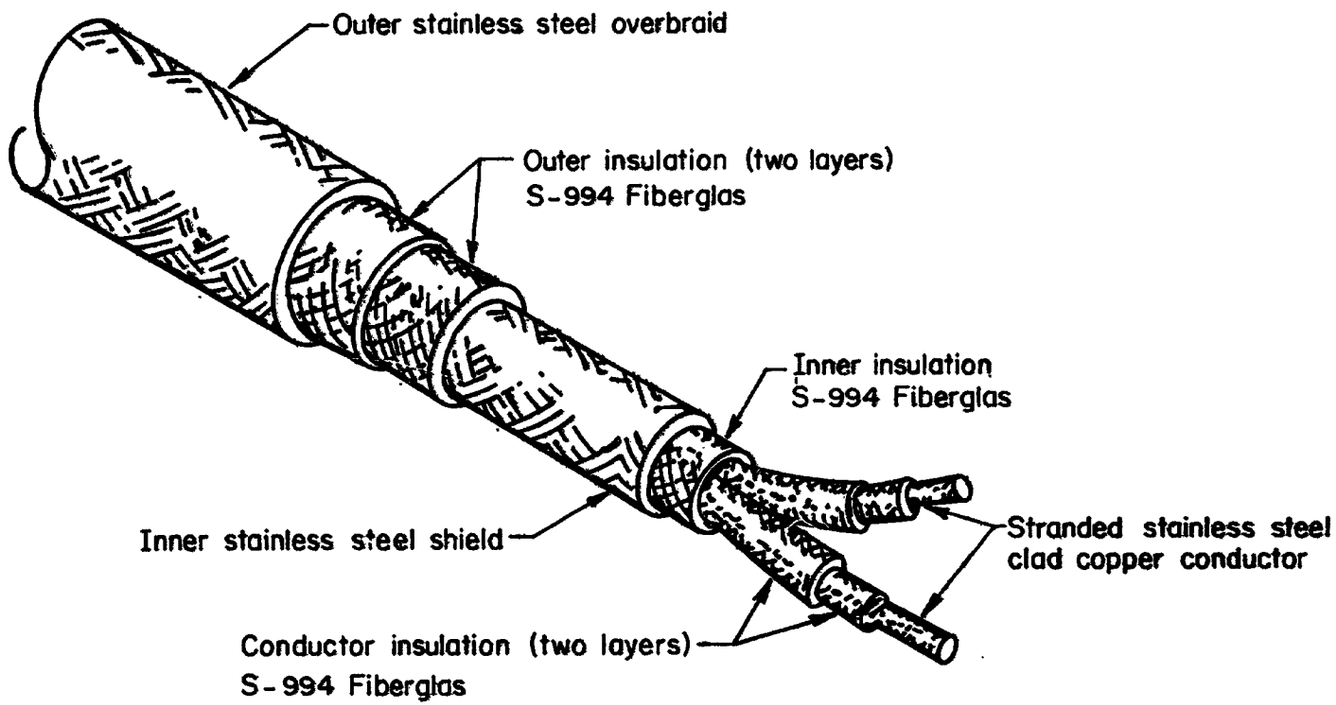
Silicone resin encapsulating materials, such as RTV-501 and Sylgard 182 and 183, have not been seriously degraded at radiation exposure doses of 2×10^{13} to 1.5×10^{15} n/cm^2 and 2×10^6 to 10^8 R gamma. Degradation of the physical properties has been limited to a slight but insignificant weight loss of less than 1 percent. Insulation resistance data show permanent decreases of 40 to 50 percent with the minimum resistance of approximately 10^{12} ohms after a total exposure of 1.5×10^{15} n/cm^2 and 2×10^6 R gamma. In the only study where measurements were performed during irradiation, the insulation resistance decreased by something in excess of one order of magnitude ($>10^{12}$ ohms to 1×10^{11} ohms) when the reactor was at its maximum power level of 30 kW.[29] An estimate of the neutron and gamma rate at this level is 10^{11} n/(cm^2·s), (E > 0.1 MeV) and 4×10^5 R/hr., 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 10^{11} n/(cm^2·s) (E > 0.1 MeV) and 4×10^5 R/hour. Full recovery occurred, however, within 3 days after the irradiation was terminated with a total dose of 1.5×10^{15} n/cm^2 and 2×10^6 R gamma.

TABLE 5. RADIATION EFFECTS ON MISCELLANEOUS INORGANIC WIRE INSULATION

Material Identification	Total Integrated Exposure	Remarks
Silica-glass (39001-1-16) double shielded coax	1.5×10^8 rads (C) 4.4×10^7 n/cm^2 (E >0.1 MeV)	Room temperature. No visible signs of degradation. No electrical tests.[19]
Quartz (39002-3-26) multiconductor coax	1.5×10^8 rads (C) 4.4×10^{17} n/cm^2 (E >0.1 MeV)	Room temperature. No visible signs of degradation. No electrical tests.[19]
Asbestos and fiber (Phosroc III, RSS-5-203) lead wire	9.8×10^7 rads 4.1×10^{13} n/cm^2	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.[13]
Mica paper-fiberglass (Mica-Temp, RSS-5-304	1.1×10^8 rads 4.5×10^{13} n/cm^2	200 C. No breaking, cracking, or spalling was evident when subjected to a bend test. Weight loss <0.15 percent. Slightly darker in color.[13]
S-994 Fiberglass (Stainless steel overbraid and inner shield, see Figure 8)	7.4×10^{10} R 1.5×10^{19} n/cm^2 (E >0.1 MeV)	Environment also included a temperature of 1200 F. Duration of test 2300 hours. The in-pile insulation resistance was within 1/2 decade of non-nuclear results in almost all cases. Temperature was the overwhelming factor in determining level of insulation resistance (~10^7 ohms).[25,26]
Ceramic Kaowool and Refrasil (Power cable)	10^{10} - 10^{11} R (Estimated) 3×10^{19} n/cm^2	Cable met 1200 volt rms dielectric breakdown requirement. Also, withstood 2000 volt rms between conductor and ground for 5 m[illegible]s.[27]
Magnesium oxide (Rhodium conductor and platinum sheating)	5×10^7 rads (C) 1.0×10^{15} n/cm^2	Met dielectric strength requireme[illegible] 1200 volts rms for 30 seconds. Insulation resistance decreased as much as four orders of magnitude between pre- and postirradiation measurements.[28]

(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.



High-Temperature Cable Harness Material

FIGURE 8. HIGH-TEMPERATURE CABLE-HARNESS CONSTRUCTION[26]

Several, but not necessarily all epoxy resin encapsulants have shown a radiation resistance that is above average for plastics. They have withstood neutron and gamma doses up to 1.1×10^{16} n/cm^2 (E > 0.5 MeV) and 10^9 rads (C) from a reactor source without serious deterioration. Similarly, electron irradiation to a total exposure of 5.8×10^{16} e/cm^2 (E = 1.0 MeV) at 60 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 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.

The electrical properties of epoxy encapsulants show some variation from exposure to a radiation environment, 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 soon after the irradiation is terminated. Changes in dielectric constant, capacitance, and dissipation factor are insignificant with the latter of the three showing the greatest sensitivity to radiation by increasing approximately one order of magnitude.

The above information is representative of the radiation resistance of several epoxy encapsulants, but the reader should be cautioned that one epoxy (358-G) was considered as unsuitable following a test because it exhibited large variations in volume resistivity during exposure.[24] 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 gamma and 4.1×10^{13} n/cm^2 at 200 C.[13] No significant changes occurred between pre- and postirradiation measurements of capacitance, dissipation factor, and insulation resistance. Dielectric strength was comparable between control and irradiated specimens following the radiation exposure.

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

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

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 some 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 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. 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 of a temporary nature 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. 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/cm^2 and 10^7 R 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

[illegible]

[illegible] connector insulated connectors are presented in Figure [illegible]. Breakdown voltage measurements on these connectors indicate values in excess of [illegible] volts during irradiation and greater than 1000 volts 3 weeks later.

Physical degradation resulted in a recommendation that the [illegible] insulated connector be replaced after a gamma exposure of 2 x 10^{6} rads (C) at room temperature. The silicone rubber insulated units were rated second best to connectors having glass fiber filled diallyl phthalate insulation and a glass insulated hermetic seal type for the same reason after a total exposure of 1.07 x 10^{16} n/cm^2 (E > 2.9 MeV) and 7 x 10^8 rads (C).

Plastic insulated connectors that have been investigated as to their radiation resistance include units with phenol formaldehyde, melamine formaldehyde, and fiber glass filled diallyl phthalate insulation. 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.[12,18] Minutes after radiation exposures of 10^{15} - 10^{16} n/cm^2 and 10^7 R 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 less subject to mechanical degradation.

Feedthrough terminals insulated with fiber glass filled diallyl phthalate that survived a total exposure of 3.1 x 10^{16} n/cm^2 (E > 0.5 MeV) and 9.8 x 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 x 10^7 ohms during irradiation with a pretest resistance of >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, including all of the smaller size and 50 percent of the ones classified as the medium and large sizes.

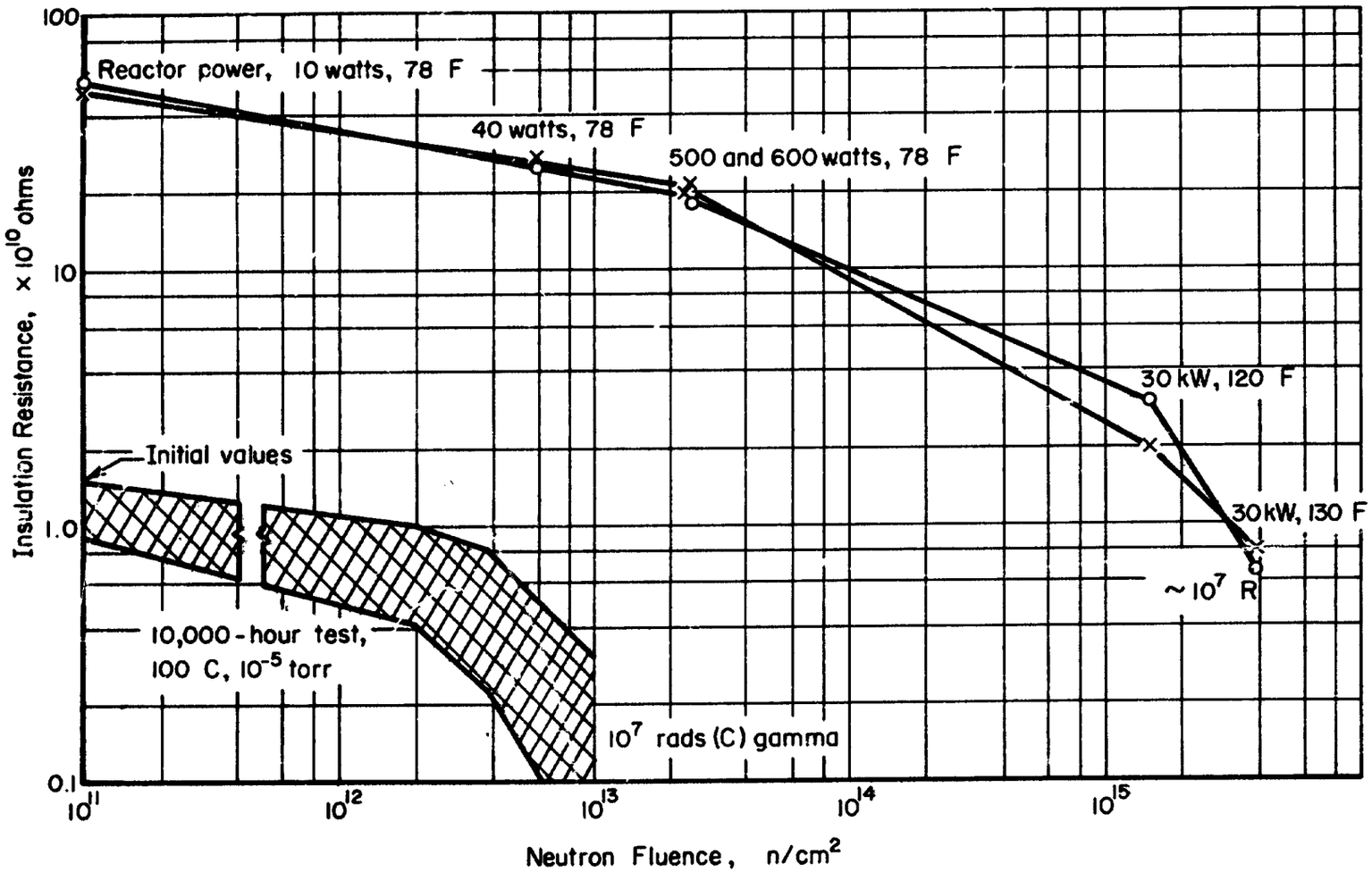


FIGURE 9. INSULATION RESISTANCE OF NEOPRENE INSULATED CONNECTORS VERSUS TOTAL EXPOSURE[29, 30]

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 feed through 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 $2\text{-}10 \times 10^{15}$ n/cm^2 and 10^7 R gamma at 55 C. Results of insulation resistance measurements on the ceramic insulated connectors are presented in Figure 10. Combined effects of radiation and temperature (156 F) have produced decreases of up to five orders of magnitude in insulation resistance.[18] 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 kilovolts 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/cm^2 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 the case of 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 thus 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.

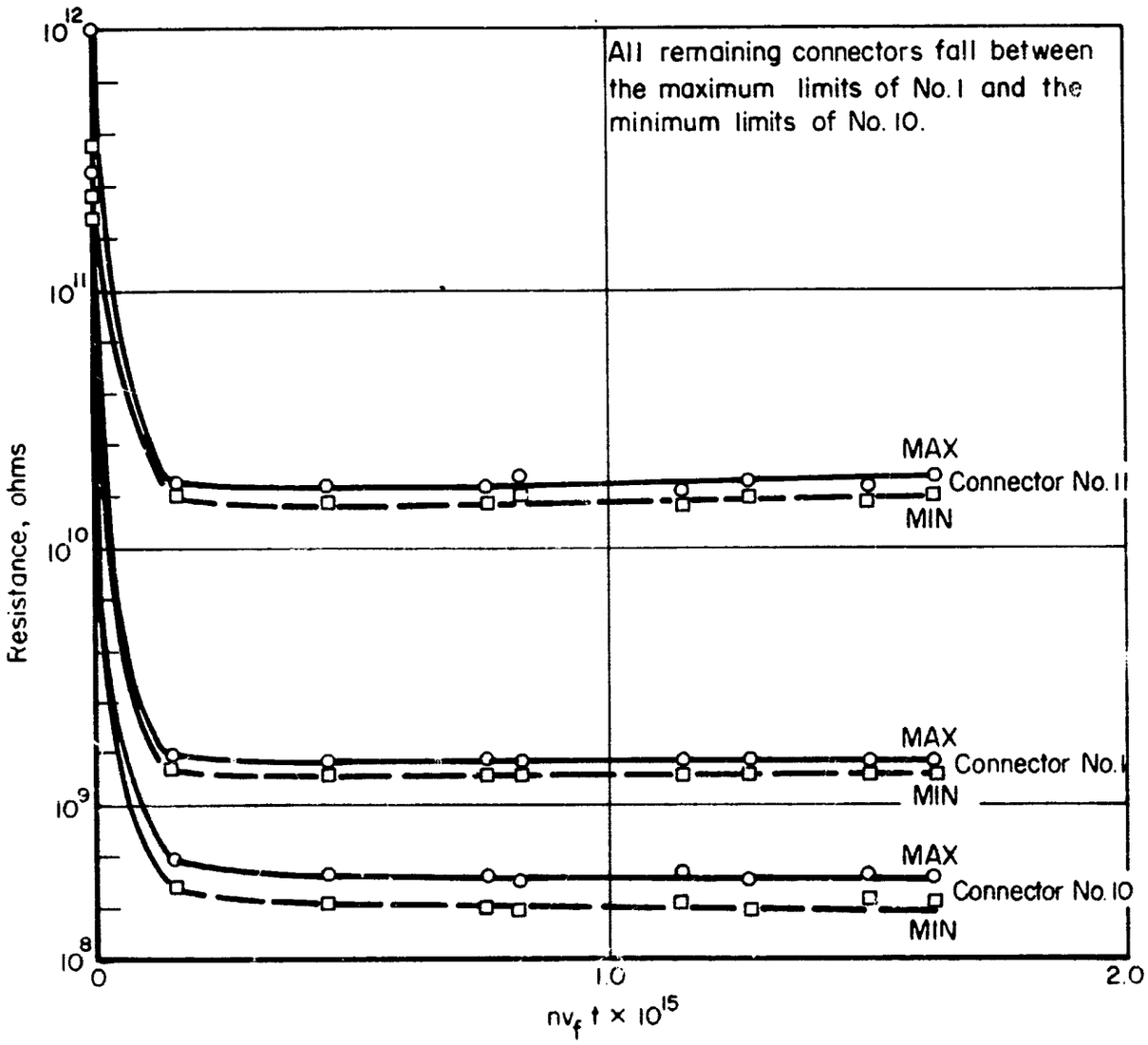


FIGURE 10. INSULATION RESISTANCE OF CERAMIC INSULATED CONNECTORS[24]

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