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RADIATION EFFECTS DESIGN HANDBOOK SECTION 3 ELECTRICAL INSULATING MATERIALS AND CAPACITORS

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RADIATION EFFECTS DESIGN HANDBOOK

Section 3. Electrical Insulating Materials and Capacitors

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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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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 toher 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 fron nonconducting to conducting states, and the return of these carriers fron 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, γ, during Interval A and is characterized by

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

where

σ_o = initial conductivity

σ = conductivity at time t

A = empirical constant

$\tau_o = k_o\dot{\gamma}^{-\mu}$ = time constant of the response as a function of gamma dose, gamma equivalent ionizing dose, or dose rate k_o 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

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

where

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

γ = 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

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

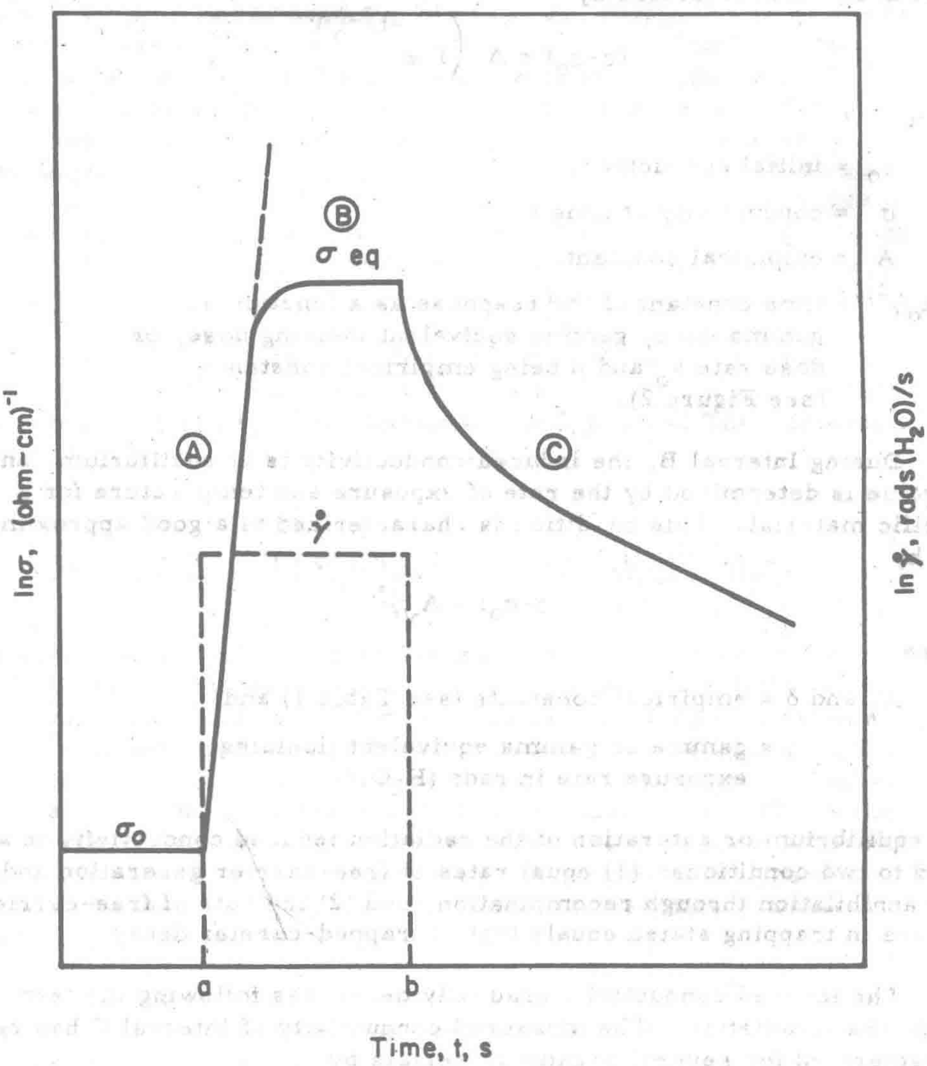


FIGURE 1. TYPICAL BEHAVIOR OF CONDUCTIVITY IN RESPONSE TO A RECTANGULAR PULSE OF GAMMA-RAY DOSE RATE[1]

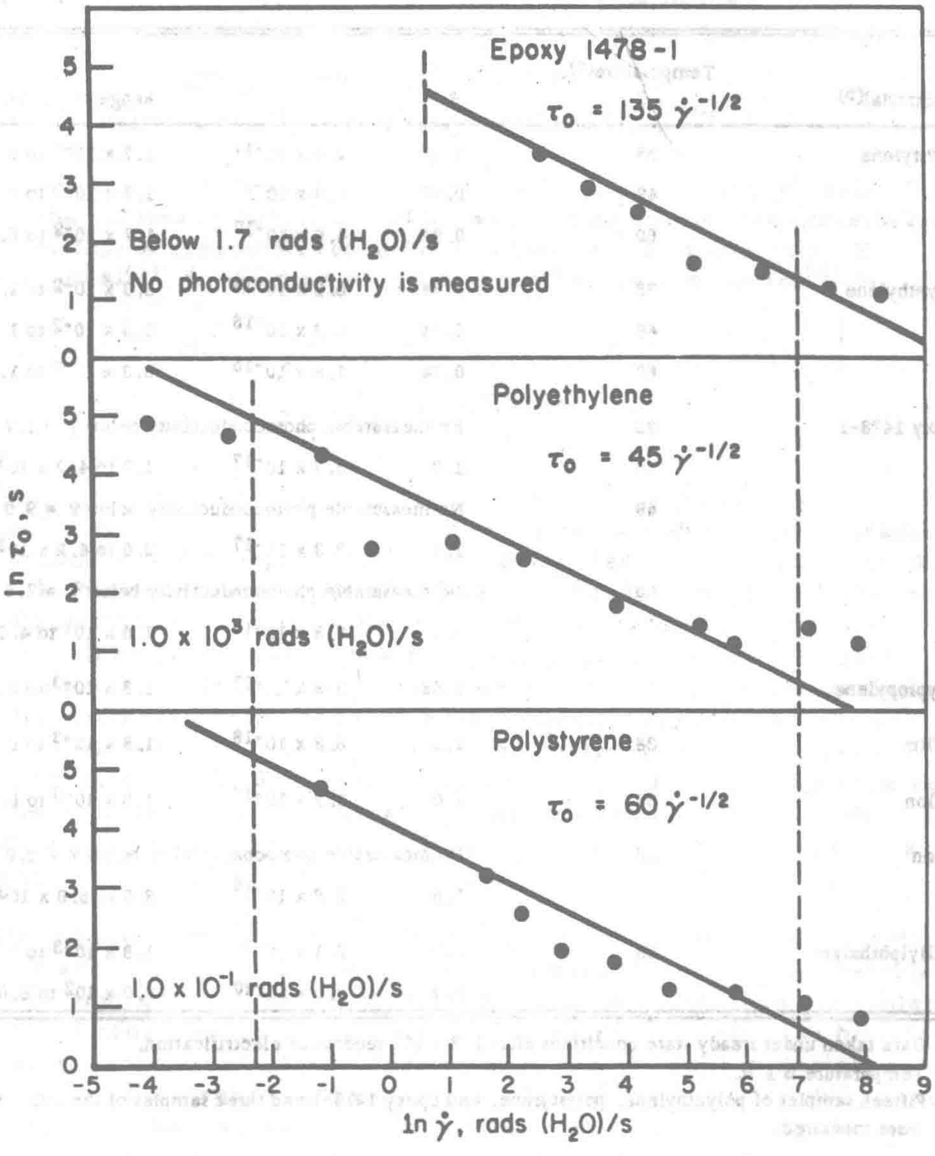


FIGURE 2. LOGARITHM OF TIME CONSTANT VERSUS LOGARITHM OF GAMMA-RAY DOSE RATE FOR POLYETHYLENE, POLYSTYRENE, AND EPOXY 1478-1 AT 38 C(1)

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

Material[b]	Temperature[c], C	δ	A_γ	Range of $\dot{\gamma}$, rads (H_2O)/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 ± 1C.

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

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^{th} τ_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

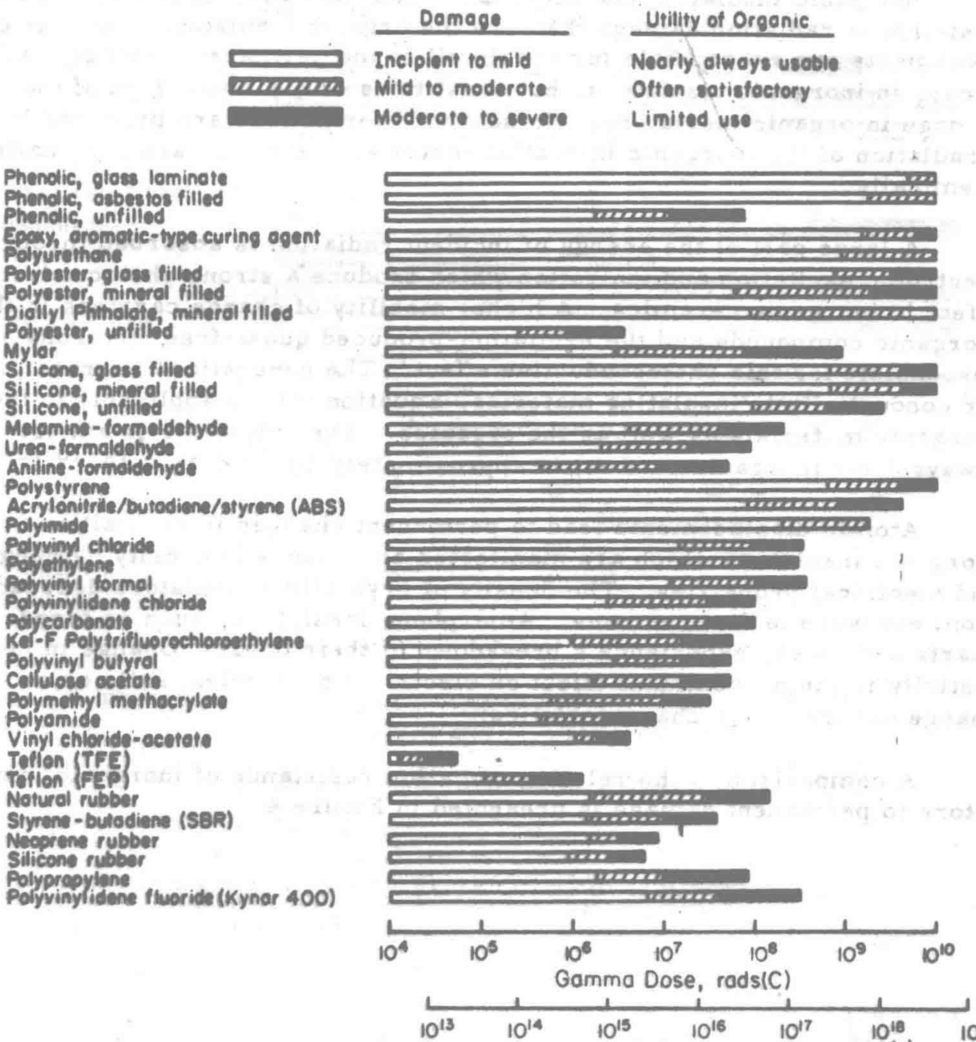
$$\sigma(t,\dot{\gamma}) = \Big[U(t) - U(t-b)\sigma(t-b) \Big] \; \sigma_o + \Big[U(t-a) + U(t-b)\sigma(t-b) \Big] A_\gamma \dot{\gamma}^{\delta} \left(1 - e^{-(t-a)/\tau o} \right) . \quad (4)$$

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. Howver, 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 tney 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) = 4×10^{8} n/cm^{2})

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 materias, 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.