NASA
SPACE VEHICLE
DESIGN CRITERIA
(STRUCTURES)

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NUCLEAR AND SPACE RADIATION EFFECTS ON MATERIALS

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

FOREWORD

NASA experience has indicated a need for uniform criteria for the design of space vehicles. Accordingly, criteria are being developed in the following areas of technology:

Environment
Structures
Guidance and Control
Chemical Propulsion

Individual components of this work will be issued as separate monographs as soon as they are completed. A list of all previously issued monographs in this series can be found at the end of this document.

These monographs are to be regarded as guides to design and not as NASA requirements, except as may be specified in formal project specifications. It is expected, however, that the criteria sections of these documents, revised as experience may indicate to be desirable, eventually will become uniform design requirements for NASA space vehicles.

This monograph was prepared under the cognizance of the Langley Research Center. The Task Manager was T. L. Coleman. The authors were H. Shulman of Teledyne Isotopes and W. S. Ginell of McDonnell Douglas Corporation. A number of other individuals assisted in developing the material and reviewing the drafts. In particular, the significant contributions made by J. W. Allen of General Dynamics Corporation, C. P. Berry of McDonnell Douglas Corporation, C. E. Dixon of Aerojet-General Corporation, J. E. Drennan and D. J. Hamman of Battelle Memorial Institute, W. R. Ekern of Lockheed Missiles & Space Company, J. W. Haffner of North American Rockwell Corporation, J. J. Lombardo of NASA Lewis Research Center, J. L. Modisette of NASA Manned Spacecraft Center, J. Moteff of General Electric Company, A. Reetz, Jr., of the NASA Office of Advanced Research and Technology, and G. D. Sands of NASA Langley Research Center are hereby acknowledged.

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NUCLEAR AND SPACE RADIATION EFFECTS ON MATERIALS

1. INTRODUCTION

Space vehicles are subject to bombardment by nuclear particles and electromagnetic radiations from both external and onboard sources. During some missions, radiation exposure may be sufficient to degrade the critical properties of structural materials and jeopardize flightworthiness of the spacecraft.

This monograph is concerned with the identification of the significant property changes induced in structural materials by radiation from the nuclear reactor, the isotope power source, and from space, and the exposure levels at which these effects become important. Structural materials are defined as those that provide fundamental load-carrying capability or protection against the natural space environment while satisfying a functional requirement (e.g., viewing port for astronaut). Material properties affected by radiation are discussed in three categories in this monograph. These are:

1. Mechanical: Tensile strength, elasticity, elongation, impact properties, fatigue strength, hardness, shear strength, and dimensional stability.

2. Thermal: Thermal conductivity and stored energy.

3. Optical: Emissivity, absorptance, and reflectance.

This monograph does not include coverage of radiation effects produced during exposure of structural materials to the high-fluence, high-temperature environment characteristic of the interior of a space-qualified nuclear reactor.

Sources of external radiation include geomagnetically trapped radiation belts, solar flares, solar wind, solar electromagnetic radiation, galactic cosmic radiation, and auroral radiation. Types of external radiation that can constitute a threat to the integrity of spacecraft include energetic electrons, alpha particles, protons, and photons. Typical onboard sources of radiation include nuclear reactors for propulsion and electrical power, and radioisotope-fueled power sources. Reactor radiations of importance to design are neutrons, gamma rays, and beta particles, depending upon the

isotope. Bremsstrahlung radiation (X-radiation), which is more penetrating than the electrons that produce it, is emitted when energetic charged particles interact with spacecraft materials and are decelerated.

Parameters that determine the severity of the effects of radiation on spacecraft structural materials include mission profile (which defines the radiation environment), the presence of an onboard radiation source, the local conditions of pressure and temperature, and the sensitivity of critical material properties to radiation.

To assess the radiation problem for a specific spacecraft, several steps are followed:

1. The external radiation environment to which the vehicle will be subjected is predicted for each mission. This includes type and energy spectrum of each radiation, dose rate, and fluence as functions of time into the mission and location of the vehicle. The internal radiation environment is defined by the nature of the internal source (nuclear reactor or isotope), and the materials and geometry of internal radiation absorbers and scatterers. Components of the external radiation penetrating the vehicle skin also will contribute to the internal environment definition. In both cases, emission of secondary radiation must be accounted for.

2. Representative materials for each structural application are checked to determine the effect of the predicted radiation environment on their critical properties; materials that will perform their function when exposed to the anticipated radiation environment are then tabulated with the radiation effect of concern shown for each material.

3. After the best material for each function has been selected, the complete design is analyzed to determine that all subsystems perform as required in the predicted environment. Testing to supply required information may be necessary at any of these steps.

The structure often acts as the primary radiation shield for more sensitive components of the spacecraft system, such as electronic systems and man. Where appropriate, the optimum procedure is to use materials that will provide both the desired structural properties and the required radiation protection.

Protection against space radiation is the subject of another monograph (NASA SP-8054). Models of the external radiation environment are presented in other monographs in the Environment series (see page 43).

2. STATE OF THE ART

Predictions of the flux and energy spectrum of those components of the space-radiation environment that are relatively constant and independent of time can be made with confidence. However, estimating the magnitudes of other components is subject to some uncertainty because large fluctuations (factor of 10 or more) over short time intervals (minutes to days) have been observed.

Radiation attenuation by the spacecraft structure and local variations of the internal radiation environment resulting from absorption, scattering, and secondary radiation generation can be estimated adequately by the use of existing shielding-calculation techniques.

Interactions between radiation and matter can be grouped into two broad classes: (1) those concerning radiochemistry (i.e., ionization and free radical production) and (2) atomic displacement collisions in ordered solids. Theoretical calculations of the magnitudes of these interactions are somewhat imperfect; uncertainties arise from the inability of investigators to determine accurately the damage mechanism and the influence of material impurities and environmental conditions on the radiation effects.

Literature on engineering tests of radiation effects on the properties of structural materials is extensive, but these tests seldom duplicate the exact materials used in spacecraft or the actual conditions of the space environment. In some circumstances, these differences can be critical.

In general, the mechanical properties of structural metals or ceramics will not be significantly degraded following exposure to fluences of $<10^{17}/cm^2$ protons ($E > 1$ MeV)*, $< 10^{17}/cm^2$ neutrons ($E > 1$ keV), or $< 10^{18}/cm^2$ electrons ($E > 1$ MeV). It is expected, therefore, that space radiation will not constitute a significant hazard because such fluences can be accumulated only on extremely long missions (hundreds of years).

Polymeric substances, however, are considerably more sensitive to radiation and significant effects are to be expected. In the case of all three categories of materials (metals, ceramics, and polymers), nuclear-reactor and radioisotope-power radiations are of more immediate concern than space radiation because of the high radiation-dose rates associated with these internal sources.

*E = energy; eV = 1.6×10^{-19} J

2.1 Spacecraft Radiation Environments

2.1.1 External Sources

The major components and general characteristics of the space-radiation environment are listed in table I in the Appendix. Of those listed, only the trapped radiation in the inner Van Allen belt can be considered constant, and then only in the absence of high-altitude nuclear-weapon bursts. The intensity and spectral characteristics of the remaining sources are functions of the solar activity and the location in the solar system.

For space vehicles within the magnetic field of a planet, the radiation environment will be a function of orbital parameters such as altitude and inclination. For example, the NIMBUS weather satellite, with an altitude of 600 nmi (nmi = 1.852 km) and an inclination of 80 deg, was exposed to an annual fluence of 2×10^{11} electrons/cm^2 ($E > 1$ MeV) and 7×10^9 protons/cm^2 ($E > 4$ MeV).

2.1.2 Internal Sources

The most significant onboard source of radiation is a nuclear reactor designed for propulsion or for auxiliary power. The intensities and energy spectra of neutrons and gamma rays emitted by a reactor depend on design of both the reactor and its shield (ref 1). For specific designs, the radiation field emitted by these sources can usually be calculated to within a factor of 10.

The radiation environment adjacent to radioisotope-fueled power generators has been carefully studied for several usable isotopes. Graphical data for determining dose levels outside of typical shields used for enclosures of radioisotope heat sources are given in reference 2.

Table II in the Appendix lists examples of the type and magnitude of the radiation environment which can be expected at specific positions surrounding two typical internal nuclear-powered sources: (1) the SNAP-8 power reactor and (2) the SNAP-19 radioisotope thermoelectric generator. The radiation-intensity levels at the stated positions are approximate values indicating the magnitude of the hazard.

The fast neutron flux and calculated gamma dose rates in the vicinity of a propulsion-type nuclear reactor are shown in figures 1 and 2 as functions of polar angle (ref. 3). It can be seen that the calculated dose rates depend upon the assumptions made in the derivation of the computational program.

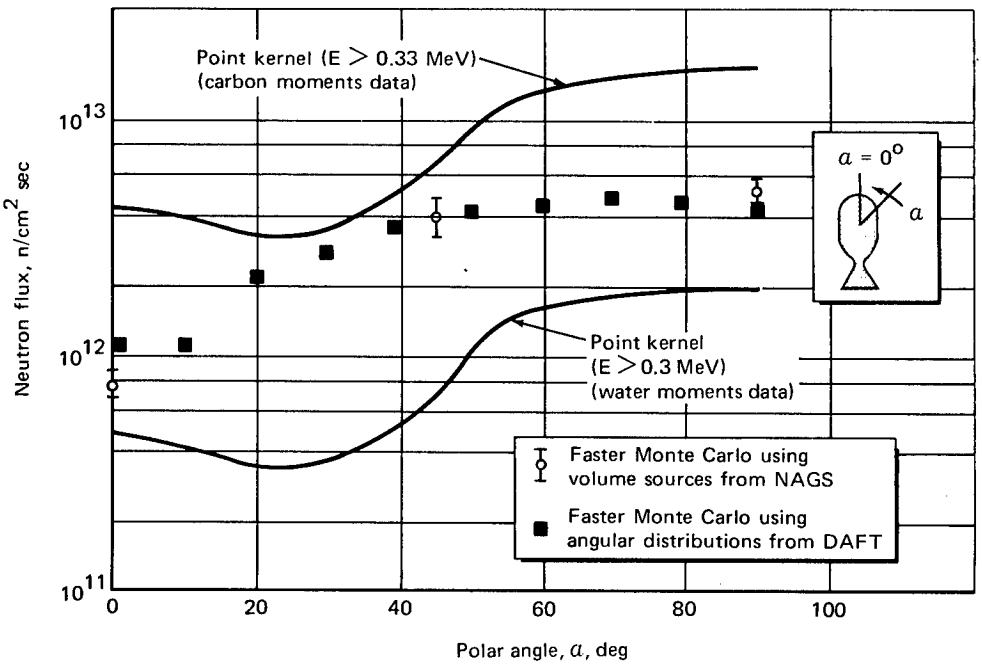


Figure 1. – Fast neutron flux (E > 0.3 MeV) at 10 ft (3.05 m) from center of flight-type nuclear reactor as a function of polar angle, α (point kernel and Monte Carlo).

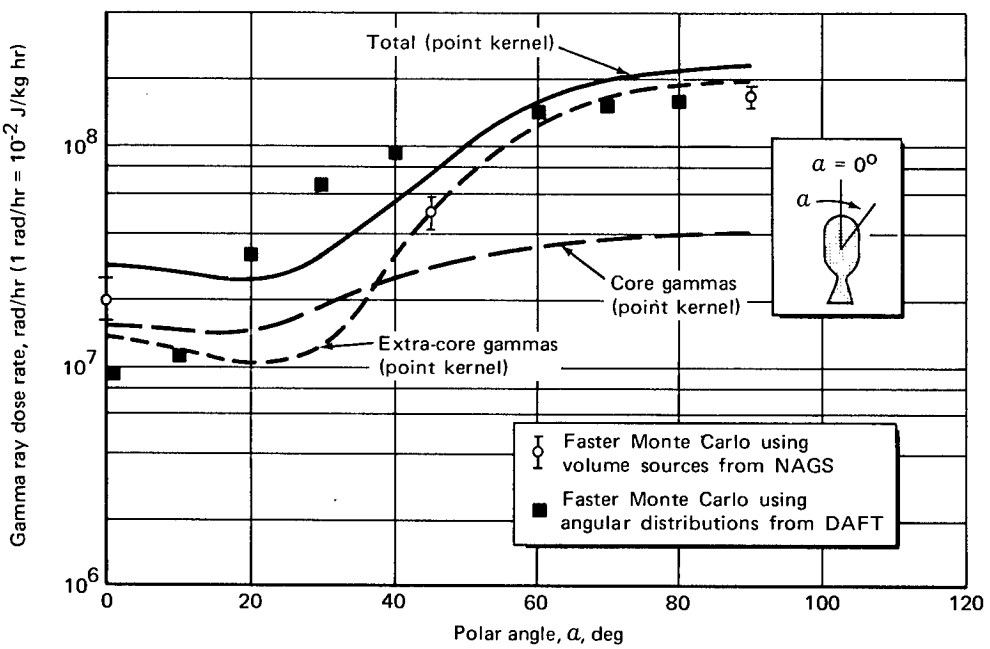


Figure 2. – Gamma-ray dose rate at 10 ft (3.05 m) from center of flight-type nuclear reactor as a function of polar angle (point kernel and Monte Carlo).

2.2 Effects of Radiation on Materials

Energetic particles and photons can interact with solids to produce atomic displacements, electronic excitations, or both. Atomic displacements result from the elastic scattering of an energetic particle by an atomic nucleus so that the kinetic energy transferred to the nucleus in the collision is sufficient to break the chemical bonds to neighboring atoms (ref. 4). The moving atom may then serve as a projectile to produce secondary displacements or, if sufficiently energetic, will ionize or otherwise excite other atoms adjacent to its path.

Electron-induced displacement damage in materials is qualitatively and quantitatively unlike that caused by protons or alpha particles, and neutrons produce macroscopic modifications in the properties of solids that are dissimilar to those caused by the other particles. A crucial point in this regard is the effectiveness of thermal annealing in restoring the preirradiation mechanical properties of metals. Neutron-irradiated metals generally tend to retain some remnants of radiation damage, even after thermal treatment at elevated temperatures (875°K), but electron-induced damage is observed to anneal usually well below 300°K (ref. 5).

Electronic excitation is produced directly by electron, gamma, proton, or ion irradiations; however, fast neutron irradiations can also produce electronic excitation. When a neutron-produced displaced atom is accelerated to a speed exceeding that of an electron in its outermost shell, the atom will tend to lose electrons and appear as a rapidly moving ion. In hydrogenous substances and other materials having low atomic numbers, electronic excitation by neutrons is quite significant.

Radiation Units. The terminology and units used to describe radiation exposure depend strongly on the type of interaction responsible for property degradation in the irradiated material. If displacement damage is the principal effect, then exposure rate is expressed in terms of a particle current density (i.e., particles/cm^2 sec^1). When exposure rate is integrated over time, the result is expressed as particle fluence (i.e., total particles/cm^2). In all cases, the particle energy spectrum or energy limits should be specified (ref. 6).

In the case of electronic-excitation effects, the quantity of importance is the total energy absorbed per unit mass of material. A radiation dose unit called the rad has been adopted to express this quantity and is defined as the absorption of 100 ergs per gram of material [1 rad (material) = 10^{-2}J/kg (material)]. The rad is a meaningful description of the absorbed radiation intensity (dose) only when related to a specific material because different materials absorb energy from the same beam in varying degrees. Doses are commonly reported in terms of rads (carbon) for organic polymers. When considering the effects of ionizing radiation on materials, it is often important to

specify the rate of linear energy transfer (LET). The LET, which is expressed in units of keV absorbed per micron of track, is a measure of the local intensity of ionization along the track of an ionizing particle. The value increases with the square of the charge on the particle and decreases as its velocity increases.

Radiation Transport. Determination of the radiation energy at a particular point in the spacecraft requires consideration of secondary sources, as well as the processes of attenuation and scattering by intervening and adjacent materials. Common secondary sources include (1) bremsstrahlung, which are high-energy X-rays, emitted as a result of the deceleration of energetic-charged particles; (2) the gamma rays and X-rays emitted during neutron capture and inelastic scattering of neutrons; and (3) massive particles (e.g., alphas) which result from some nuclear reactions in materials. Transport of gamma rays and neutrons through absorbers can be described by the product of an attenuation factor (absorption and scattering out of the beam) and a buildup factor (scattering from the surrounding medium into the point of observation) (ref. 1). Buildup factors are complex functions of radiation energy, materials, and geometrical configuration. Exact, hand-calculated solutions to the problem of radiation transport through complex geometries are not generally attempted because of the availability of rapid, more precise techniques involving Monte Carlo computerized calculations.

2.2.1 Metals, Alloys, and Metal-to-Metal Bonds

The principal effect of radiation on metals and alloys is the creation of lattice vacancies and interstitial atoms in an otherwise perfect crystal. This results in an overall dilation that decreases the density of the material. In metals that were neutron-irradiated at ambient temperature, the measured decrease in density was much smaller than that predicted by theory (ref. 7). However, in specimens irradiated and measured at cryogenic temperatures (below 30°K), closer agreement between experiment and theory was obtained. Contrary to theoretical analyses that predicted large modifications to elastic properties, tests have shown that the elastic moduli of metals are not appreciably affected by neutrons below a fluence of 10^{17} n/cm^2.

Plastic properties of metals are markedly affected by radiation. The properties affected include yield strength, ultimate tensile strength, elongation, reduction in area, creep, rupture stress, fatigue stress, hardness, impact strength, and ductile-to-brittle transition temperature. In general, metals exhibit reduced plasticity and ductility and increased hardness following irradiation.

As a possible explanation of the foregoing observations, it has been suggested that because plasticity is associated largely with the motion of dislocations, any mechanism that impedes this motion can produce the class of effects observed in irradiated metals.

The means by which displacements interact with dislocations is not clearly understood, but several plausible models have been proposed. In pure metals, the most likely mechanism appears to be the formation of clusters of interstitials or vacancies which impede the motion and slip of dislocations. This is analogous to the action of clusters of impurity atoms in alloys. Vacancies also enhance the diffusion of minor component atoms in alloys and promote a form of precipitation hardening.

Tests conducted to determine the effects of neutron irradiation on the mechanical properties of metals and alloys have shown that temperature of exposure, time at temperature, fluence, energy spectrum, and material properties (i.e., composition, degree of cold work, prior heat treatment and quenching, and grain size) are important variables. Engineering data on property changes of reactor-irradiated structural metals are presented in references 8 to 11.

The principal effects of neutron irradiation on the mechanical properties of metals are summarized in table III in the Appendix; table IV shows some typical test results for tensile and elongation properties; and table V lists results of tests which show the effects of neutron irradiation on fatigue, hardness, and reduction in area.

The transition from brittle-to-ductile fracture occurs at higher temperatures as a result of neutron irradiation. For example, the transition temperature was increased by 25°K for A212B steel irradiated at 353°K with 5×10^{18} neutrons/cm^2 ($E > 1$ keV); after a fluence of 5×10^{19} n/cm^2, the transition temperature was increased by 56°K (ref. 12).

The creep-rate and stress-rupture properties are generally affected by neutron irradiation. The direction and magnitude of changes in these properties depend on the particular metal and such factors as fluence, test and irradiation time, and temperature (refs. 13 and 14).

Neutron irradiation produces significant quantities of helium and hydrogen in beryllium, with the result that the metal decreases in density. After exposure in a reactor to 10^{21} n/cm^2 at 973°K, the density decrease amounted to about 1 percent.

The slight decrease in the thermal conductivity of beryllium, which was irradiated and measured at cryogenic temperatures and at a fluence of 10^{19} n/cm^2, was observed to anneal out at a temperature of approximately 250°K (ref. 15).

Relatively little information is available on the effects of radiation on metal-to-metal welded bonds. For welds irradiated at cryogenic temperatures, inconsistent results have been obtained. For example, irradiation increases the weld-joint tensile strength of Type 301 stainless steel from 255 to 266 ksi (1 ksi $\approx$ 6.895 MN/m^2); however, after

Type 2014 T6 aluminum had been irradiated at 63°K, followed by testing at 37°K, a slight decrease in tensile strength of the weld was observed. Both of these tests were conducted after exposure to a neutron fluence of 2×10^{17} n/cm^2 ($E > 0.33$ MeV) (ref. 16).

The degree to which changes in mechanical properties of neutron-irradiated metals can be predicted is summarized in table VI in the Appendix. The wide uncertainties reflect the general state of the art with respect to the entire class of materials under this heading. The changes in some properties of many specific metals and alloys are predictable to much greater accuracies (often within a factor of 2 to 3).

2.2.2 Polymers

Polymeric substances exhibit a wide variety of radiation effects. The formation of new chemical bonds after irradiation usually results in irreversible effects. Generally, these are manifested as changes in appearance, chemical and physical states, and mechanical, electrical, and thermal properties. However, not all properties of a polymer are affected to the same degree by radiation.

The radiation stability of a polymer is dependent upon the chemical structure of the material because radiation-induced excitation is not coupled to the entire chemical system, but is often localized at a specific bond. The addition of energy-absorbing aromatic rings to the chemical structure significantly increases the radiation stability of some polymers by aiding in the redistribution of the excitation energy throughout the material. Conversely, those polymers with highly aliphatic structures (e.g., ethers and alcohols) are the least resistant to radiation.

Irradiated polymers generally undergo two types of reactions: cross linking and chain scission. The cross-linking process results in formation of chemical bonds between two adjacent polymer molecules. This reaction increases the molecular weight of the polymer until the material is eventually bound into an insoluble three-dimensional network. Chain scission, or fracture of polymer molecules, decreases the molecular weight and increases solubility. Both reactions can significantly alter the physical properties of a polymer. However, the degree and direction of change are not the same for all polymers.

In general, chain scission results in a decrease in Young's modulus, reduced yield stress for plastic flow, increased elongation, decreased hardness, and decreased elasticity. It sometimes causes embrittlement and release of gas. Release of hydrogen gas can cause a large increase in the thermal conductivity of low-density thermal insulators such as organic foams and corkboards. An exposure of 5×10^7 rad (carbon) (C) could double

the thermal conductivity of corkboard (ref. 17). Pressure buildup caused by hydrogen (several psi) could be sufficient to cause rupture of insulation bonding or the vapor barrier in an organic cryogenic insulator. Cross linking generally increases Young's modulus, impedes viscous flow, decreases elongation, increases hardness, and leads to embrittlement.

The presence of oxygen during irradiation usually plays a prominent role in determining the degree to which any polymer will be permanently modified. Although details of the "oxygen mechanisms" have not been completely elucidated, it is clear that oxygen enters into the reactions that take place after the initial production of free radicals. Thus, the thickness of the sample and the radiation dose rate are important factors affecting the course of oxygen-sensitive reactions.

Inorganic filler-additives, such as asbestos or silica, can have two ameliorative effects on irradiated polymers. These materials may act as efficient excitation-energy sinks and may also serve to add structural strength to the degraded polymeric matrix materials.

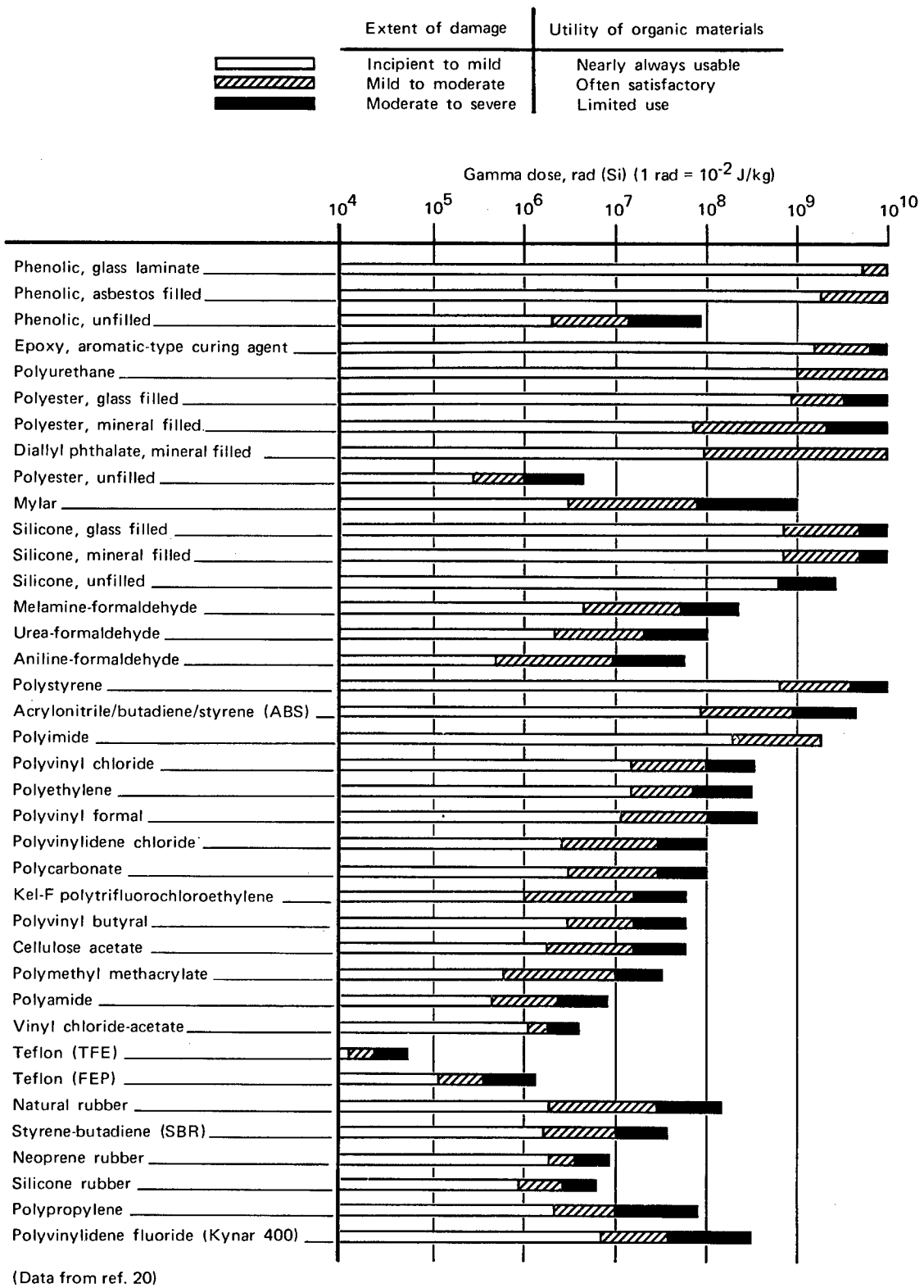
The quantity of existing engineering data on mechanical properties of irradiated polymers is vast. Fundamental and comprehensive reviews of available data are contained in references 18 to 20; the relative radiation resistance of some organic materials is given in figure 3.

2.2.2.1 Thermosetting Plastics

"Thermosets" are polymeric materials which have been cross linked into essentially infinite three-dimensional networks by the application of heat. These network polymers are insoluble and infusible. They are used primarily as molding powders and as binders for laminates. Table VII in the Appendix lists representative samplings of the effects of ionizing radiation on this class of materials.

2.2.2.2 Thermoplastics

Thermoplastic materials are polymers that can be softened by heat. This class includes hydrocarbon thermoplastics (e.g., polyethylene), polyamides (e.g., nylon), oxygen-containing thermoplastics (e.g., Mylar, polymethyl methacrylate, cellulosics), and the halogen-containing thermoplastics (e.g., polyvinyl chloride, Kel-F, Teflon). A summary of typical effects in representative materials and doses for significant alterations of properties, is presented in table VIII in the Appendix.



(Data from ref. 20)

Figure 3. – Relative radiation resistance of organic materials based upon changes in physical properties.

2.2.2.3 Adhesives

Because of their organic base, adhesives are fairly susceptible to radiation damage. Neutron, gamma, and beta radiation cause similar damage for equivalent absorbed doses. The effects of radiation on adhesives have been determined by measurement of changes in lap shear strength, tensile strength, and by peel and fatigue tests following irradiation. Unfortunately, most tests have not been conducted under dynamic load conditions.

Generally, adhesives developed for high-temperature applications are the most radiation resistant (refs. 19 and 21). These include the epoxy-, nylon-, and vinyl-phenolics, all of which retain as much as 60 percent of initial bond strengths to 10^9 rad (C). However, there are apparently no published data on the simultaneous effects of radiation and high temperatures on adhesives.

The addition of fillers to adhesives usually improves their overall radiation stability. In some cases, however, this is done at a sacrifice of shear strength. In a study to determine the comparative effectiveness of various additives on the radiation resistance of an epoxy adhesive, it was shown that antirads (substances having a capacity for absorbing and dissipating excitation energy) or scintillators gave little improvement (ref. 22).

2.2.2.4 Elastomers

Of the polymeric materials, elastomers are among the most sensitive to radiation damage. Their properties in tension or compression depend strongly on the configuration of long-chain molecules. Therefore, polymer cross-linking and chain-scission reactions induced by radiation have a profound effect on these mechanical properties. Studies have shown that damage to elastomers is caused by chain scission, cross linking, and chemical reaction with environmental agents, especially oxygen. The radiation damage is temperature-dependent and greater in air than in vacuum. Moreover, the type and degree of damage is often sensitive to the application of either static or dynamic loading during irradiation. Variations in the compounding and curing of a particular elastomer can change significantly its resistance to radiation.

Organic chemical additives (antirads) are effective in inhibiting radiation damage in elastomers. Phenyl compounds are the most widely used antirads because energy dissipation is more efficient in aromatic groups than in other chemical species.

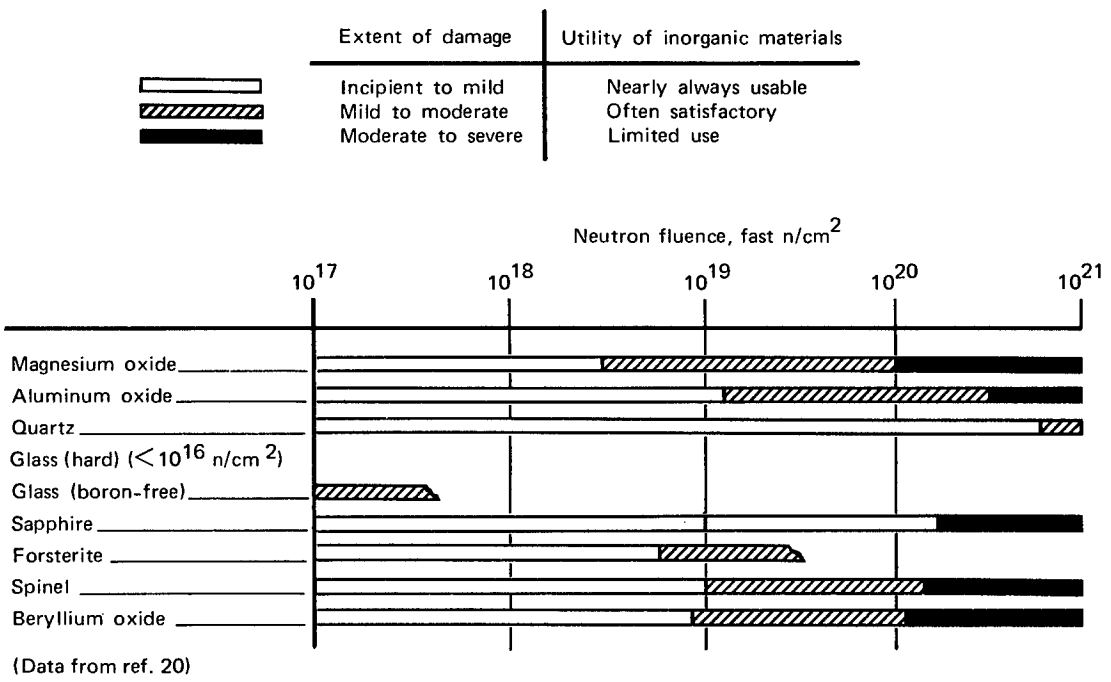
A compilation of representative studies of the effects of radiation on elastomers is shown in table IX in the Appendix. The materials are listed in the table in ascending

order of resistance to radiation. This ordering is qualitative and specific for a particular property (degradation of tensile strength under gamma radiation).

Ultraviolet (uv) irradiation of elastomers in air generally results in chain scission and subsequent evaporation of volatile, low molecular-weight byproducts. The resistance of elastomers to degradation by uv in air is roughly comparable to their resistance to the effects of gamma radiation (ref. 23).

2.2.3 Ceramics, Graphite, and Glasses

In general, the mechanical properties of ceramics are not appreciably changed by exposure to ionizing radiation doses of less than 10^9 rad (ceramic) or by neutron fluences of less than 10^{19} n/cm^2. The relative radiation resistance of some inorganic materials is given in figure 4 (ref. 20). At higher exposure levels, effects resulting from lattice displacement and gas formation become important. The latter effect is particularly important in boron- or beryllium-containing ceramics owing to the formation of gaseous helium following exposure to thermal neutrons. Large changes in the thermal conductivity of ceramics have been observed at neutron fluences of 10^{18} to 10^{19} n/cm^2.



(Data from ref. 20)

Figure 4. – Relative radiation resistance of inorganic materials, based upon changes in physical properties.

Radiation effects in ceramics are comprehensively reviewed in references 20 and 24. Table X in the Appendix contains a summary of the salient effects in four technologically important materials.

Graphite has been studied extensively with respect to neutron radiation effects because this material finds extensive use as a moderator in nuclear-reactor systems. The following table shows how certain properties of graphite are affected by neutron irradiation.

Property	How affected
Mechanical strength	Increases
Mechanical hardness	Increases
Thermal conductivity	Decreases substantially
Stored energy, or enthalpy	Increases
Chemical (particularly oxygen) reactivity	Increases
Dimensional stability	Anisotropic expansion

The irradiation tests demonstrated that effects become significant at high neutron fluence levels $>10^{19}$ n/cm^2 ($E>1$ keV). Experimental results and theoretical discussions are reported in references 24 to 29.

In the area of glasses, various allotropes of the silica system and fused silica have been extensively investigated. At a fluence of about 1.5×10^{20} n/cm^2 ($E>1$ keV) it has been found that quartz, cristobalite, tridymite, and fused silica all approach a limiting density of 2.20 g/cm^3. This common phase is completely disordered and optically isotropic (refs. 30 to 32).

The low-temperature thermal conductivity of neutron-irradiated fused silica increases as the density increases and reaches a limiting value of about twice the initial value after exposure to 6×10^{19} n/cm^2 (ref 33). Changes in mechanical properties (such as Young's modulus, shear modulus, and compressibility) of neutron and gamma-irradiated glasses are generally negligible to slight (less than 5 percent) (refs. 34 and 35). In the case of thermal-neutron irradiated borosilicate glass, the production of helium gas results in cracking and, ultimately, in the disintegration of the glass (ref. 36).

The darkening and loss of transparency of glass following exposure to ionizing radiation is a well-documented phenomenon (refs. 7 and 24). The addition of small amounts (~2 percent) of CeO_2 to glass substantially suppresses the discoloration processes (ref. 37).

2.2.4 Thermal-Control Coatings

The optical properties (emittance, absorptance, reflectance) of the exposed surface of a spacecraft are critical to proper temperature control of the entire system. The effects of radiation on the surface optical properties are hence of concern in all aspects of spacecraft reliability.

The effect of ion bombardment on the optical properties of metals (Ti, Cu, Al) is negligible (ref. 38). Results have indicated that a proton fluence of $10^{21}/cm^2$ (E = 1 keV) in aluminum can increase the spectral absorptance/total-hemispherical-emittance ratio (a/ϵ) by a factor of 2 in the visible portion of the spectrum. This fluence is equivalent to approximately 30 years in space, assuming continuous maximum solar activity.

Radiation stability of coatings is determined by the chemical and mechanical stability of the matrix, and is influenced by additives such as pigments and plasticizers, and by the type of surface on which the coating is applied. A class of heteraromatic polymers (pyrones) has been shown to retain its original tensile properties after a 10^{10}-rad (C) irradiation with 2 MeV electrons (ref. 39), and this material has been suggested for use as a coating-material matrix. Highly pigmented coatings are generally more radiation resistant than those containing lesser amounts of pigments.

Extensive work has been done to determine the synergistic effects of uv radiation, particulate radiation, and vacuum environment on the physical properties of both organic and inorganic thermal-control coatings (ref. 40). Tests performed on ZnO pigments indicate that they are quite stable under uv exposure and have a low solar absorptance (ref. 41). Specially prepared organic coatings have also been tested under uv radiation and vacuum conditions (ref. 42). A comprehensive compilation of the types of coatings and their response to the space environment can be found in references 19 and 42.

2.3 Tests

Specialized facilities are required to determine the effects of both the primary (external and internal) and secondary radiation environment components on spacecraft structural materials.

Accelerated neutron testing can be performed at one of several operational test reactors; for example, the NASA Plum Brook Reactor (ref. 43). Control of such environmental conditions as temperature and pressure during testing can be provided at most reactor facilities (ref. 44).

In mechanical-properties testing, the postirradiation measurements on radioactive samples include remote handling and measurements in hot cells, a procedure which requires good planning and careful experimental design. In all cases of accelerated testing, fluence and dose-rate effects must be taken into consideration.

Ionization effects can be studied by exposing materials to gamma-ray sources (cobalt-60 or cesium-137) or by exposure to a charged-particle accelerator beam (ref. 45). In most of the radioisotope facilities, it is a reasonably simple matter to control atmosphere, pressure, and temperature in the vicinity of specimens. On the other hand, ingenuity is required to achieve cryogenic temperatures for samples exposed to the output of low-energy (1 MeV or less) particle accelerators. For low-energy protons, a common vacuum is used for the accelerator drift tube and the cryostat, and samples are placed in intimate thermal contact with the cryostat coldfinger.

Reference 45 describes the capabilities of the available particle accelerators which include betatrons, fixed-frequency cyclotrons, frequency-modulated cyclotrons, linear accelerators, potential-drop machines, and synchrotrons. Accelerated testing can be performed at these facilities.

Gamma-radiation dosimetry is generally accurate and repeatable to better than 20 percent. A reactor's neutron fluence can be estimated with comparable precision, and for the practical purposes of materials testing, the accuracies (20 percent) provided by foil- or pellet-activation techniques are quite adequate.

Gamma spectra can be determined quite accurately for an uncharacterized source by means of germanium (Li-drifted) PIN detectors. The actual neutron-energy spectrum of a given nuclear reactor is difficult to determine. Most sources have been characterized but the accuracy with which the spectrum is known will vary, depending upon the time history of the reactor, the experiment geometry, and the measurement techniques used.

In particle accelerators, the total beam current and energy can be measured with a satisfactorily high degree of accuracy (less than 1 percent error), but determination of the beam profile may be somewhat less accurate.

3. CRITERIA

Space vehicles shall be designed to limit the degradation of the pertinent properties of structural materials by radiation to a value consistent with the overall reliability requirements. The total radiation environment shall be defined for the anticipated space-vehicle mission. The effects of the radiation environment on mechanical and thermophysical properties shall be determined for each class of materials considered for use in structural elements of the space vehicle or for use in space-vehicle components intended to serve a structural function. It shall be shown by analysis or test, or by a suitable combination of both, that the radiation environment expected to be encountered by the space vehicle will not sufficiently degrade the mechanical and/or thermophysical properties of materials to cause or precipitate a failure of any structural element or structural function.

3.1 Spacecraft Radiation Environments

The radiation environment shall be identified from reliable and current information. Both natural and onboard sources of radiation shall be considered. All radiation shall be defined in terms of type, intensity, energy spectrum, temporal variation, and spatial distribution. Radiations to be included are neutrons, protons and heavier ions, electrons, and photons (gamma rays, X-rays, and ultraviolet rays). Definition of the space vehicle's radiation environment shall include the ambient temperature, and the composition and pressure of the local atmosphere. All pertinent mission phases shall be investigated, taking into consideration uncertainties resulting from limited knowledge of the environments.

3.2 Effects of Radiation on Materials

Materials for which the effects of radiation shall be determined shall include, but not be limited to, all metals, alloys, polymers, ceramics, graphite, glasses, and thermal-control coatings considered for use in the space vehicle.

3.2.1 Mechanical Properties

Analysis of structural parts shall, as a minimum, account for radiation-induced modifications to tensile-yield strength, ultimate tensile strength, shear strength, ductility, ductile-to-brittle transition temperature, fatigue strength, fracture toughness, hardness, creep, stress rupture, burst strength, impact resistance, and compressive strength, as applicable. The analysis shall be based on data showing the nature and magnitude of modifications to these properties for materials either identical or similar to those being analyzed. The radiations and other environmental conditions such as

temperature and the pressure and composition of ambient gases shall be as nearly identical to those expected to be encountered as is practicable. Degradation of these properties beyond levels which would impair the structural or functional integrity of the spacecraft shall not be permitted.

3.2.2 Thermophysical Properties

Analysis of insulating materials shall, as a minimum, account for radiation-induced modifications to thermal conductivity. Analysis of heat-shield and ablative materials shall, as a minimum, account for radiation-induced modifications to specific heat, thermal conductivity, stored energy, heat of fusion, and heat of sublimation. Analysis of thermal-control surfaces and coatings shall, as a minimum, account for changes in optical absorptance, reflectance, and emittance resulting from exposure to radiation. The analyses shall be based on data showing the nature and magnitude of modifications to these properties for materials either identical or similar to those being analyzed, under radiations as nearly identical to those expected to be encountered as is practicable, and under identical or similar environmental conditions such as temperature and the pressure and composition of ambient gases. Degradation of these properties beyond levels which would impair the functional integrity of the spacecraft shall not be permitted.

3.3 Tests

When available test results do not allow the degradation of material properties to be determined analytically (i.e., by analogy, comparison, or interpolation), tests of the material or materials being considered shall be performed in radiation facilities that simulate, as nearly as practical, the conditions of the projected environment. Changes in appropriate material properties shall be measured, and an analysis of these changes shall be made to determine the suitability of the material or materials for use in the spacecraft.

4. RECOMMENDED PRACTICES

Three basic steps that should be followed to assess the effects of radiation on the properties of candidate structural materials are as follows:

1. Predict an external and internal radiation environment for each mission, taking uncertainties into consideration.

2. Examine each material function and identify materials that possess the required design properties when exposed to the anticipated radiation environment.

3. Analyze the complete design to determine that each subsystem will perform its required function when exposed to the predicted environment.

It is essential that the first two steps be taken in the early stages of any program.

4.1 Spacecraft Radiation Environments

The type, fluence, dose rate, energy spectrum, temporal variation, and spatial distribution of nuclear radiation at points of interest inside and outside the spacecraft should be determined for the duration of the mission. Uncertainties in these predictions (e.g., frequency and intensity of solar flares) should be explicitly detailed and conservatively estimated for worst-case conditions.

For onboard sources, such as nuclear auxiliary power generators or propulsion reactors, the environment should be defined when the fueled generator is mated with the spacecraft structure. For external sources, the definition of the environment should include all radiations striking the space vehicle after liftoff.

Definition of the environment consists of two parts: (1) identification of external and internal radiation sources and (2) determination of the environment in the vicinity of the part or material. External and internal radiation should be defined from a knowledge of the mission trajectory. The most current information available on temporal and spatial variations in magnetically trapped radiations and solar corpuscular radiations should be used in the definition of the external-source environment. (Space radiation is the subject of a planned NASA monograph.) Reference 46 provides several exercises in the calculation of external-source radiation for extended space missions. Internal-source information (including data on spectrum and flux) should be obtained from the manufacturers of the nuclear-propulsion and nuclear-power-supply systems.

The radiation environment in the vicinity of a structural component is a function of the space-vehicle configuration. When computing the local environment, the role of other parts and materials in attenuation of radiation and as secondary sources of gamma and X-radiation should be assessed. For many purposes (e.g., determining whether external charged particles will penetrate the skin of the spacecraft), hand computations should be used to estimate the magnitude of the problem. For protons and heavier ions, attenuation should be computed by the Bethe-Bloch formula and by using range-energy tables such as those given in reference 47; electron ranges in several materials have been computed (refs. 48 and 49) for energies up to 10 MeV. For an

analytical treatment of more complicated calculations, such as scattering in complex geometries, machine computation may be necessary. (Radiation protection is the subject of another planned NASA monograph.)

Secondary photons (bremsstrahlung) produced during interaction of electrons with materials can be an important process. The ratio of radiation loss to ionization loss increases with electron energy and with the atomic number of the material. An estimate of the magnitude of the effect can be made with some degree of reliability (ref. 50).

As a zero-order approximation, mass-absorption coefficient tables should be used to compute gamma-ray and X-ray attenuation in simple geometries. When estimating dose at a point of interest in an environment that includes neutrons, consideration should be given to inelastic fast-neutron scattering in the surrounding media and to capture of thermal neutrons. Both of these processes generate X-ray's and gamma rays (ref. 1).

4.2 Effects of Radiation on Materials

Candidate materials for each structural function should be rated for relative radiation hardness. The preliminary evaluation should include:

1. Tabulation of the minimum acceptable engineering properties of interest for each part.

2. Enumeration of the available materials whose initial (i.e., unirradiated) properties meet the minimum acceptable engineering requirements for that part.

3. Review of the existing compilations of radiation effects in various materials and a determination of the radiation level at which the engineering properties fall below minimum acceptable values.

4. Elimination from consideration those materials for which there is clear evidence of failure at the predicted level of exposure.

If the material does not meet the required radiation-hardness level, alternate designs should be considered. The use of local shielding should be avoided but may be justified only in circumstances where other considerations require the use of a particular material and design. When there is doubt because existing data are inadequate, appropriate tests should be conducted. Experimental testing is at present the only really adequate recommended practice.

4.2.1 Metals, Alloys, and Metal-to-Metal Bonds

When assessing radiation damage to the mechanical properties of metals used in space vehicles, it is usually unnecessary to consider the effects of space radiation for the reason that, in a one-year mission, a spacecraft might be exposed to a fluence of only about 10^{12} protons/cm^2 ($E > 1$ MeV); 10^{17} protons/cm^2 are required for detectable damage. Although energetic electrons can also cause displacement damage, the fluence for most trajectories is well below 10^{18} electrons/cm^2 ($E > 1$ MeV), the level at which changes in mechanical properties are detectable.

An onboard nuclear reactor is the one radiation source most hazardous to spacecraft structural materials. Property changes should be considered for any structural member that will be subjected to a fast-neutron ($E > 1$ keV) fluence greater than 10^{17} n/cm^2. Properties of concern may include, but are not limited to, tensile-yield strength, ultimate tensile strength, ductile-to-brittle transition temperature, shear strength, ductility, dimensional stability, creep-rupture, fracture toughness, fatigue strength, and hardness.

Because absorption of neutron and gamma radiation can cause temperature increases in structural members, heating effects should be computed (ref. 1). Realistic heat-loss mechanisms for the various components of the system should be assumed. Boron-rich alloys or other materials with high thermal-neutron absorption cross sections should receive special attention and consideration. Reference 8, a fairly recent compilation, should be consulted as a starting point for a literature search on the properties of irradiated metals. It is recommended that the original documentation, rather than secondary sources, be consulted if possible. The files of the Radiation Effects Information Center (REIC), Battelle Memorial Institute, Columbus, Ohio, should be reviewed as a source of comprehensive information.

In a survey of the literature for applicable data, it is important to note any differences between the referenced materials or test conditions and those of concern. Unless the effects of these differences on the radiation susceptibility can be demonstrated analytically or by reference to previous experimental data, tests should be conducted. Such differences might include, but not be limited to, degree of cold work, grain size, and impurity content. The effects of temperature and pressure should always be taken into consideration.

4.2.2 Polymers

Polymers are the structural materials most seriously affected by nuclear radiation. The role of temperature, pressure, and composition of the projected environment should be taken into account when acceptability of polymers in a radiation environment of more

than 10^5 rad (material) has been determined by analysis (i.e., through use of published data). When the predicted dose is within a factor of 10 of the failure dose for a polymeric material, and the linear energy transfer of the radiation used to generate test data is different from that anticipated, acceptability of the material must be well substantiated. This guideline should also be observed with respect to extrapolations between diverse dose rates. Relevant material parameters can include density, viscosity, tensile strength, elongation, Young's modulus, Poisson's ratio, compressibility, adhesive strength, impact strength, and thermal conductivity.

References 18 and 51 are complementary sources of information on radiation effects in polymers. Reference 18 encompasses a fundamental treatment of the radiochemistry of these materials; reference 51 consists of a later comprehensive compilation of test results and references.

4.2.2.1 Thermosetting Plastics

Published literature should be used to verify acceptability of thermosetting plastics for doses up to 10^7 rad (C). For anticipated doses in excess of 10^7 rad (C), the use of plastics containing mineral fillers should be considered.

4.2.2.2 Thermoplastics

The effects of radiation on the properties of fluorine-containing thermoplastic polymers vary considerably, depending upon pressure, temperature, and atmospheric composition. Generally, these thermoplastics should be regarded as unacceptable for use at doses in excess of 5×10^4 rad (C); other thermoplastic materials should be regarded as safe for use to 10^6 rad (C). When demonstrating their acceptability to levels above 10^6 rad (C), the relevance of fillers, ambient atmosphere, and temperature should be assessed in the contexts of cited tests and intended use.

4.2.2.3 Adhesives

Preference should be given to adhesives designed for high-temperature application if they have suitable properties under the design conditions. Adhesives may be verified as acceptable to doses of less than 5×10^7 rad (C) by reference to published test results.

4.2.2.4 Elastomers

Since the range of radiation resistance within the class of elastomers is wide, from 10^5 to 5×10^8 rad (C), caution should be exercised in the selection of a material to perform satisfactorily at anticipated exposures equal to those indicated. Improvement

in the radiation resistance of an elastomer by the addition of antirads should be accepted only when there are test data for the specific elastomer (with antirads), and test conditions are sufficiently similar to anticipated conditions to generate no serious question of the validity of extrapolation.

4.2.3 Ceramics, Graphite, and Glasses

References 24 and 25 contain fairly complete tabulations of radiation effects in ceramics, graphite, and glasses. More comprehensive references to original data on specific materials can be obtained from the REIC.

Ceramic properties appreciably affected by neutron irradiation include density, elastic modulus, compressive strength, mechanical integrity, and thermal conductivity. Fast-neutron ($E > 1$ keV) effects are significant at levels near 5×10^{18} n/cm^2. Compounds containing beryllium or boron can be adversely affected by thermal-neutron fluences as low as 10^{17} n/cm^2. The effects of gamma rays or charged particles should always be taken into consideration when the dose exceeds 10^6 rad (material).

The principal structural properties of graphite that may be significantly modified by radiation include density, thermal conductivity, and stored energy. Changes in these properties should be accounted for when fast-neutron ($E > 1$ keV) fluences are in excess of 10^{19} n/cm^2.

Structural properties of glass are usually unaffected by fast-neutron ($E > 1$ keV) fluences less than 10^{19} n/cm^2. When the glass is to be used as a viewing port, darkening of the glass by ionizing radiation usually limits its usefulness. Under such circumstances, it is advisable to specify radiation-resistant glass (e.g., cerium-doped) (ref. 37). For anticipated dose levels in excess of 10^7 rad (glass), experimental qualification procedures should be required.

4.2.4 Thermal-Control Coatings

When thermal-control coatings are exposed to ultraviolet radiation, as well as to the more energetic electromagnetic and particulate radiations, it is necessary to verify their acceptability. Attention should be directed toward the combined effects of electron irradiation, proton irradiation, hard vacuum, temperature, and electromagnetic irradiation. To determine the qualification of a specific coating for any spacecraft mission, effects of the environment on the cohesive and adhesive properties (to a given substrate) of the coating should be considered, along with the effects on optical reflectance, absorptance, and emittance. Some specialized information is available in

references 19 and 38 to 40. For more complete and more recent data, the files of the REIC should be consulted.

4.3 Tests

When no reliable information on the effects of radiation on the structural materials of interest exists in the published literature, tests simulating the radiation environment should be conducted to obtain the necessary information. In such cases, the relevance of environmental and material factors that might contribute to changes in important properties must be carefully assessed before the testing is initiated. A careful theoretical estimate of the nature of anticipated results should be part of the test planning. The relationship between observed changes and total radiation exposure over a broad range of values (at least one order of magnitude) about the point of interest should be determined.

When accelerated tests are conducted, it is good practice to assess rate effects by subjecting specimens to a range of dose rates at constant fluence. In general, the simulation of ionizing effects of protons by electrons or gamma rays, or vice versa, should not be practiced. Simulation of electron-ionization effects by an equivalent absorbed dose from gamma rays is usually acceptable, providing the average quantum energies are comparable. Attention should be given to possible synergistic effects, especially during accelerated tests. Effects resulting from simultaneous exposure to two or more components of the radiation environment (e.g., protons and electrons, ultraviolet radiation and protons) should be evaluated. Unless the effects of electronic excitation are clearly negligible (e.g., in metals), when testing in a nuclear reactor it is good practice to separate the effects of gamma rays from those due to neutrons. This is accomplished by preferential shielding of one or the other components (lead for gamma rays and hydrogenous substances for neutrons).

Although dosimetry services are usually provided by test facilities, it should be ascertained that the method of recording the absorbed dose, fluence, and spectrum is sufficiently detailed to permit expression of the results as functions of these parameters.

Sample mounting during exposure should simulate the conditions of temperature, ambient atmospheric conditions, and mechanical loading, under which the part under investigation will function in the spacecraft. Whenever feasible, measurement of properties of interest should be performed during irradiation or at least within minutes following its cessation.

APPENDIX

TABLES CITED IN TEXT

TABLE I. – EXTERNAL RADIATION SOURCES

Radiation source	Type of radiation	Energy (E)	Flux (particles/cm^{2}sec)	Peculiar characteristics	Reference
Galactic cosmic rays	Protons (~90%) Alpha (~10%)	10^{-2} GeV - 10^{10} GeV	2	Least significant	52
Solar wind	Protons (~95%)	~1 keV	2×10^8 at 1 AU[b]	Low energy restricts hazard to surface effects	53
Solar cosmic ray events (solar flares)	Protons (95%)	Spectrum is very steep above 30 MeV ($\sim E^{-5}$); below 10 MeV, spectrum $\sim E^{-1.2}$	See footnote[c]	Energy and number of particles released per event varies; 10^8 particles/cm^2 for medium flare	54
Solar electromagnetic	Infrared, visible, ultraviolet, soft X-rays	6000°K black body radiator, erratic below 1200 Å[a]		Spectrum below 1200 Å[a] depends strongly on solar cycle	55, 56
Trapped radiations					
1. Inner belt (1.2 to 3.2 earth radii)	Protons and electrons	Energy of protons (E_p) $<$30 MeV (90%) Energy of electrons (E_e) $<$5 MeV (90%)	Protons: 5×10^5 ($E > 1$ MeV); Electrons: 2×10^7 ($E > 0.5$ MeV)	Flux varies with magnetic latitude; electron populations of both belts subject to perturbations due to high-altitude nuclear bursts; outer-belt protons are nonpenetrating	57, 58
2. Outer belt (3 to 7 earth radii)	Protons and electrons	Virtually all protons less than 1 MeV	Protons: ($E > 10$ keV): 10^9 Electrons: $5.2 \times 10^7 e^{-5E}$ (E in MeV)		
Aurora	Electrons and protons	E_e between 2 and 20 keV; E_p between 80 and 800 keV	10^{10} (electrons) during auroral storms; $<10^7$ protons	Observed between 65° and 70° north and south magnetic latitudes at altitudes between 100 and 1000 km	59

[a] Å = 0.1 nm

[b] AU ≈ 149.6 Gm

[c] Precise prediction of solar-flare activity cannot now be made.

APPENDIX

TABLE II. – TYPICAL INTERNAL RADIATION SOURCES

Source	Type of radiation	Energy spectrum	Radiation intensity	Measurement position
SNAP-8 (reactor)	Neutrons	Modified fission	1.5×10^5 n/cm^2-sec ($E > 0.1$ MeV)	At power-conversion system (10 ft below reactor)
	Gammas	Fission	1.5 rad (C)/sec	
SNAP-19 (isotope) Pu-238	Neutrons	Degraded spontaneous fission (9%) (α,n) reaction (91%)	1.5×10^3 n/cm^2-sec ($E > 10$ keV)	At converter package
	Gammas	Monoenergetic, 0.75 MeV	5×10^{-6} rad (C)/sec	

TABLE III. – QUALITATIVE EFFECTS OF NEUTRON IRRADIATION ON MECHANICAL PROPERTIES OF METALS

Mechanical property	How affected
Yield strength	Increases
Ultimate tensile strength	Increases
Percent elongation	Decreases
Brittle-to-ductile fracture-transition temperature	Increases
Weld-joint tensile strength	Varies; temperature important
Creep rate	Varies
Stress-rupture life	Decreases, then increases, with neutron fluence
Fatigue	For constant strain, cycles-to-failure decreases
Hardness	Increases
Necking-down failure during tensile test	Decreases

TABLE IV. – TYPICAL EFFECTS OF NEUTRON IRRADIATION ON TENSILE PROPERTIES OF METALS

Material	Condition	Environmental conditions		Test temperature, °K	Yield strength 1000 psi[a]		Ultimate tensile strength 1000 psi[a]		Total elongation percent		Reference
		n/cm^2 (E> 1 MeV)	Exposure temperature, °K		Unirradiated	Irradiated	Unirradiated	Irradiated	Unirradiated	Irradiated	
Al-1099	Annealed	8×10^{20}	373	RT[b]	2	2	7	12	46	30	60
	H-14	7.5×10^{16}	16	16	7	43	34	49	61	46	61
Al-2024	T-6	2×10^{19}	323	RT[b]	45	49	72	71	26	25	62
Al-6061	T-6	5×10^{20}	323	RT[b]	40	44	47	50	21	22	62
410SS	Annealed	5×10^{19}	538	RT[b]	38	57	60	78	33	26	63
Inconel 718		4.5×10^{19}	553	RT[b]	158-162	178	190-200	196	12 to 21	9	64
Inconel 718		6×10^{17}	77	77	196	212	206	212	1	1	
Hastelloy C		9×10^{19}	1013	293	80	89	146	158	10	9	64
Hastelloy C			16	16	111	112	186	185	39	50	65
Ti pure	Annealed	1×10^{17}	17	17	130	132	185	183	31	34	12
Ti pure		1×10^{18}	17	17	130	170	185	217	31	26	12
Ti-6Al-4V	Annealed	1×10^{17}	17	17	243	254	260	274	7.6	5.7	12
Ti-6Al-4V		1×10^{18}	17	17	243	300	260	221	7.6	4.7	12

[a] 1000 psi $\approx$ 7 MN/m^2

[b] Room temperature

TABLE V. – ILLUSTRATIVE TEST RESULTS, NEUTRON-RADIATION EFFECTS ON MECHANICAL PROPERTIES OF METALS

Material	Test	Neutron fluence ($E > 10$ Kev)	Exposure temperature, °K	Results	Reference
Magnesium	Cycles-to-failure under fatigue stress of 5000 psi[a]	10^{19} n/cm^2	353	Unirradiated sample failed after 9×10^7 cycles; irradiated samples failed after 5×10^7 cycles	66
AISI type 304 stainless steel	Fatigue life: alternate expansion and contraction of thin-walled specimens between rigid concentric mandrels; total strain was 4%	7×10^{19}	922	Unirradiated samples failed after about 20 cycles; irradiated samples failed after 8 cycles	67
Pure nickel (99.95%)	Hardness	1.7×10^{20}		When measured at 273°K, hardness increased from 100 kg/m^2 to 175 kg/m^2; damage completely annealed at 973°K	68
Zircaloy-2	Reduction in area	1.1×10^{20}	333	Unirradiated samples: 51% Irradiated sample: 49%	69
		2.9×10^{20}	333	Irradiated sample: 42.6%	69

[a]5000 psi $\approx$ 34 MN/m^2

APPENDIX

TABLE VI. – ESTIMATE OF PREDICTION PRECISION OF MECHANICAL PROPERTY CHANGES IN METALS AND ALLOYS FOLLOWING NEUTRON IRRADIATION

	Threshold for detectable damage[a] (n/cm^2) ($E > 1$ keV)	
Temperature	Pure metals	Engineering materials
$\geqslant 300°K$	One order of magnitude (typically 10^{18} to 10^{19})	Two orders of magnitude (typically 10^{17} to 10^{19})
Cryogenic temperatures $< 100°K$	One order of magnitude (typically 10^{16} to 10^{17})	Insufficient data (estimate 10^{16} to 10^{18})

[a]Changes $\geqslant 1\%$

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TABLE VII. - TYPICAL EFFECTS OF IONIZING RADIATION ON THE THERMOSETTING PLASTICS

Material	Parameter	Dose, rad (C)	Effects	Reference
Unfilled phenolic	Tensile and impact strength	5×10^7	Slight reduction	70
		3×10^8	50% reduction	70
Epoxy	Flexural strength	10^8	$\geqslant$80% of original when cured with aromatic agents; 50% to 80% of original when cured with aliphatic curing agents	18 71 72
		10^9	50% to 80% of original when cured with aromatic agents; $<$10% of original, when cured with aliphatics	18 71 72
Phenol-formaldehyde with asbestos filler	Tensile strength	3.9×10^9	25% reduction	18
Polyurethane foam sandwich construction	Ultimate flexural strength; flatwise compressive strength	10^9	No changes observed	73

TABLE VIII. – TYPICAL EFFECTS OF IONIZING RADIATION ON THERMOPLASTICS

Material	Parameter	Dose, rad (C)	Effects, comments	Reference
Polyethylene	Tensile properties	2×10^7	In normal polyethylene, this dose constitutes threshold for detectable changes in tensile properties; high-density polyethylene (more crystalline than ordinary polyethylene) suffers damage after about 4×10^6 rad (C)	74 75
	Tensile properties	9×10^7	About 50% degradation; material becomes rubberlike and then very brittle; carbon black filler enhances resistance to radiation damage	75 74
Polyvinyl formal	Tensile strength	2×10^7	Onset of loss of strength	76 (also ref. 15, ch. 6)
		1×10^8	25% degradation	
Telflon (TFE)	Tensile strength	2×10^4	Damage "threshold" in air	76 (also ref. 15, ch. 6)
		4×10^4	25% reduction in ultimate tensile strength; absence of oxygen in atmosphere enhances stability to about a factor-of-10 larger dose; low temperature also improves stability (by two orders of magnitude)	
Polyvinylchloride	Tensile strength	5×10^6	Decreases about 25%	77
	Elongation	5×10^6	Decreases about 10%, very sensitive to air, presence of plasticisers tends to cause more rapid degradation	76 (also ref. 15, ch. 6)

TABLE VIII. – TYPICAL EFFECTS OF IONIZING RADIATION OF THERMOPLASTICS – Concluded

Material	Parameter	Dose, rad (C)	Effects, comments	Reference
Polystyrene	Tensile strength and elongation	5×10^9	Decrease by only 5% to 10%; high-impact polystyrene, which contains modifiers, is far more susceptible to damage; marked losses in elongation and impact strength after 10^7 rad (C); little difference between air and vacuum exposures	78 18
Nylon sheet	Elongation and notch-impact strength	8.6×10^5	"Threshold" of damage	78
		4.7×10^6	25% reduction	
Polypropylene	Impact strength	6×10^6	Reduced by 7%	79
		10^7	Less than 50% of original; material becomes progressively more weak and brittle	
Cellulose acetate	Impact strength	2×10^7	25% reduction; cellulosics are among the least stable polymers in a radiation environment	51
Polymethyl methacrylate	Notch-impact strength	10^6	"Threshold" for detectable decrease	76 (also ref. 15, ch. 6)
		10^7	25% reduction	

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TABLE IX. – TYPICAL IONIZING RADIATION EFFECTS ON ELASTOMERS

Elastomer	25% Damage dose, rad (C)	Predominant effect
Fluorocarbon	10^6	Chain scission; gas evolution
Butyl	4×10^6	Cis-tran isomerization; chain scission
Silicone	4×10^6	Usually cross linking
Neoprene	6×10^6	Cross linking
Nitrile	7×10^6	Cross linking
Styrene	1×10^7	Cross linking
Natural rubber	2.5×10^7	Cross linking
Urethane	4.3×10^7	Chain scission

APPENDIX

TABLE X. – TYPICAL TEST RESULTS OF RADIATION EFFECTS ON CERAMICS

Material	Property	Fluence for appreciable change	Effects	Reference
BeO	Density	10^{19} n/cm^2 (E > 1 keV)	Decreases 10^{-2}% to 10^{-1}%	80
	Thermal conductivity	10^{19} n/cm^2 (E > 1 keV)	Large decrease; to ½ initial value by 10^{20} n/cm^2	81, 82
	Modulus of elasticity	5×10^{19} n/cm^2 (E > 1 keV)	Decreases by as much as 50%	83
	Compressive strength	10^{19} n/cm^2 (E > 1 keV)	Substantial decrease with increasing dose	84
	Mechanical integrity	10^{20} n/cm^2 (E > 1 keV)	Cracking; powdering by 10^{21} n/cm^2	84
Al_2O_3	Density	10^{19} n/cm^2 (E > 1 keV)	Decreases about 1% by 6×10^{20} n/cm^2	85
	Thermal conductivity	10^{19} n/cm^2 (E > 1 keV)	Decreases to less than ½ initial value	86
	Thermal conductivity	Co-60 gammas; 10^6 rad (Al_2O_3)	Decreases to 50% of initial value by 3×10^6 n/cm^2	86
MgO	Thermal conductivity	3×10^{19} n/cm^2 (E > 1 keV)	Decreases 40%	87
B_4C	Mechanical integrity	10^{20} thermal n/cm^2	Cracking and eventual disintegration	24

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