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Designing Equipment for Use in Gamma Radiation Environments

K. U. Vandergriff

CONSOLIDATED FUEL REPROCESSING PROGRAM

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DESIGNING EQUIPMENT FOR USE IN GAMMA RADIATION ENVIRONMENTS

K. U. Vandergriff
Fuel Recycle Division

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ABSTRACT

High levels of gamma radiation are known to cause degradation in a variety of materials and components. When designing systems to operate in a high radiation environment, special precautions and procedures should be followed. This report (1) outlines steps that should be followed in designing equipment and (2) explains the general effects of radiation on various engineering materials and components. Much information exists in the literature on radiation effects upon materials. However, very little information is available to give the designer a step-by-step process for designing systems that will be subject to high levels of gamma radiation, such as those found in a nuclear fuel reprocessing facility. In this report, many radiation effect references are relied upon to aid in the design of components and systems.

1. INTRODUCTION

It is known that high levels of radiation can cause significant damage by altering the properties of materials. A practical understanding of the effects of radiation is required to design equipment to operate reliably in a gamma radiation environment. Information in this report has been collected from many different sources to assist with this understanding. The major emphasis is on how radiation affects various types of materials and components and how to incorporate these effects into the equipment design. The report is intended as a reference to aid designers and does not address the technical aspects of the physics involved in radiation effects. The material will acquaint the designer with pertinent information that can be applied to specific design situations. The report primarily contains basic information useful to a designer with limited experience in designing for a radiation environment. Ample references are provided, however, to accommodate the designer who has the desire and need to become technically proficient in the details of radiation effects.

Note that the extent and effect of radiation damage is dependent on the type of material, the magnitude of radiation dose received, and many other environmental factors. There is no "cook book" approach to designing for a radiation environment. In actual operation, the conditions will vary for each component and should be addressed accordingly. Where material data are referenced, this report makes an effort to identify the conditions under which the data were collected and what specific properties were measured; however, in some cases, this information is not available from the references. The degree of conservatism to be applied in the use of the data should be determined by the system designer.

2. SCOPE

Some general principles should be followed in the design of equipment that will operate in a gamma radiation environment. These principles, or steps, which are delineated in Sect. 3 establish the format for the rest of this report. Each step listed in Sect. 3 is described in detail in the subsequent sections.

Section 4 gives a brief description of the radiation environment to help familiarize the designer with new or unusual terminology. It includes radiation-related definitions and units of radiation measurement. Sections 5, 6, and 7 are brief descriptions of the necessary design steps, including information on establishing acceptable lifetimes, laying out and simplifying the systems, and determining both the failure modes and the failure criteria.

Section 8 contains information on various components and their behavior in a radiation environment. Data in this section come from testing and from the experience of many different laboratories, vendors, and irradiation facilities. Section 9 explains some of the possible design solutions which help to reduce the impact of radiation. These solutions include: unit and source shielding, strategic location of components, making use of available radiation-hardened equipment, and analyzing components to determine their radiation resistance. Section 10 describes actions necessary for designing remotely maintainable equipment and establishing a preventive maintenance program. Section 11 summarizes how to design equipment for use in radiation environments.

Appendix A is provided to give a brief overview of gamma radiation, and Appendix B and Appendix C contain detailed information on radiation effects on specific inorganic and organic materials. Appendixes B and C are compilations of material test results from many irradiation tests and experiments. These appendixes can help a designer determine (based on a materials evaluation) if a component will have an adequate lifetime in a radiation environment. Although some of the information referenced herein is either for electromagnetic pulse radiation from nuclear explosions or for total accumulated dose levels below those needed, the basic guidelines, procedures, and information may be of help to designers. Where available, information concerning both chemical trade names and generic names has also been included.

3. SYSTEM DESIGN PROCEDURES TO MINIMIZE RADIATION EFFECTS

The job of the designer is to design equipment or systems to perform a particular function. This must be done at a reasonable cost and provide an acceptable availability. When designing equipment to operate in a high gamma radiation environment, such as will be present in a nuclear fuel reprocessing facility, several important steps should be followed as outlined in the flow diagram in Fig. 3.1. These procedures for designing equipment for a radiation environment are as follows:

Step 1: Define the radiation environment.

Step 2: Identify and simplify the components.

Step 3: Establish an acceptable design-life for each component.

Step 4: Determine failure criteria and failure modes.

Step 5: Evaluate the effects of radiation on components and use appropriate design margins.

Step 6: Establish design solutions by reducing the environmental and operational stresses with shielding, use of hardened components, etc.

Step 7: Design for remote maintainability and develop a preventive maintenance program.

As illustrated in Fig. 3.1, the design process involving radiation effects is complex and involves many tradeoffs. The better the understanding of all areas influencing the design, the better the judicious choices of components, parts, and materials. If radiation effects are considered in every aspect of the design process, the probability for a system to operate successfully in a radiation environment is greatly improved.

A thorough characterization and understanding of the radiation environment is the first and most important step. As in all designs, the system should be established in Step 2 to meet the operating requirements. At this step, the task of designing equipment for a radiation environment can be vastly simplified if the system components are selected with respect to radiation (e.g., radiation-sensitive components replaced with traditionally more radiation-hardened technology, etc.). The job of designing a system to operate in a high radiation environment is also additionally simplified if radiation-sensitive components are moved out of cell or are moved into areas of lower radiation wherever possible.

Step 3 involves establishing an acceptable design-life for each component. This is often done when establishing the design criteria and is especially important when working with radiation-sensitive components. At Step 4, the failure criteria and failure modes should be determined so as to help define when and how the components will fail. At Step 5, each component should be analyzed for radiation effects. This is an important step and may take a significant amount of time to accomplish, because each component must be carefully examined (i.e., every potentially radiation-sensitive material identified, etc.). After each component has been evaluated for radiation effects, the designer will be ready to establish design solutions to the radiation problems (Step 6). This work is often complex and involves many tradeoffs (e.g., cost, time, materials availability, etc.). And finally, in Step 7, the components should be designed for remote maintainability to allow for easy changeout of failed components, and a preventive maintenance program should be developed based on the results and findings of the other steps. Elements of these steps are detailed in the next sections.

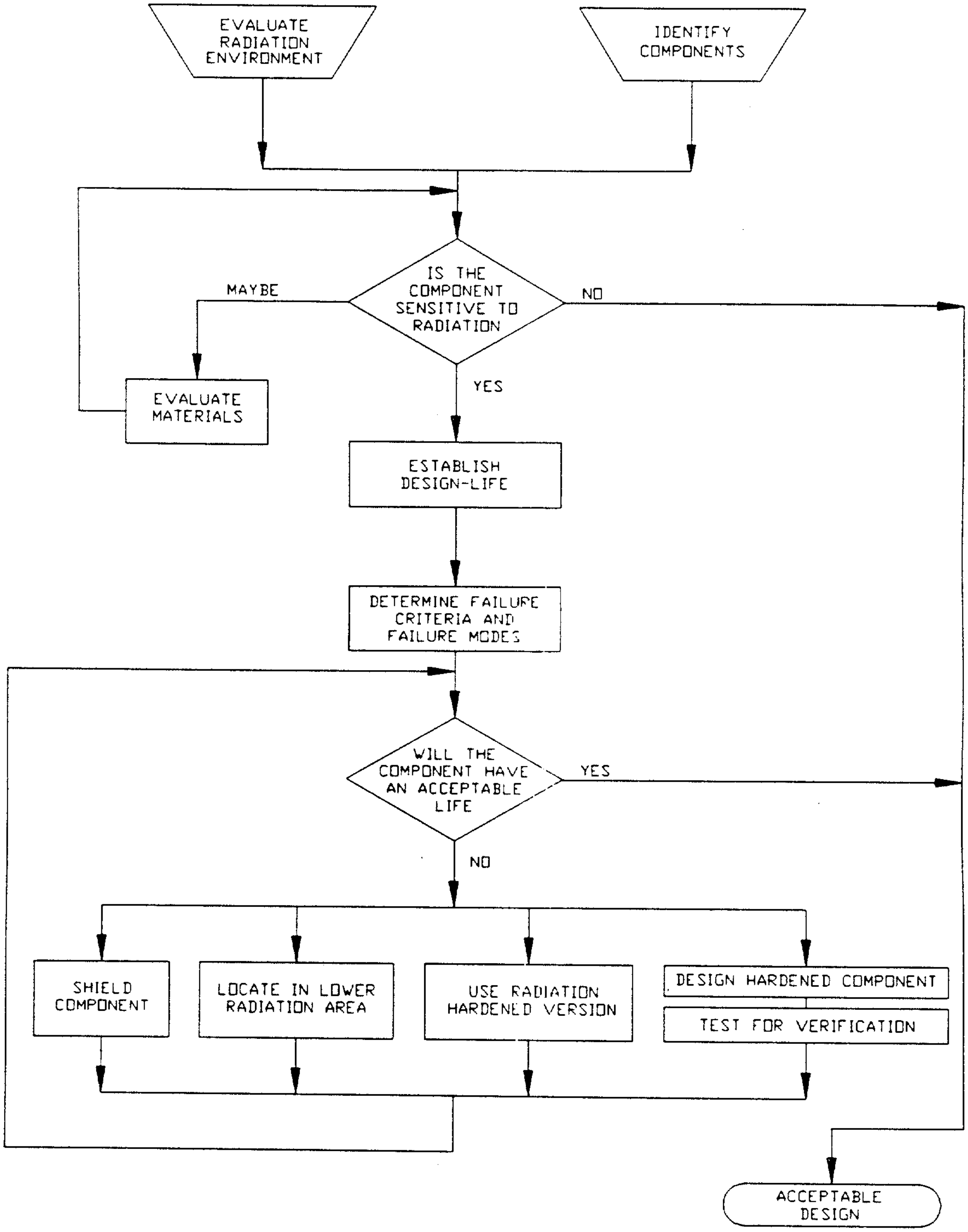

Fig. 3.1. System design process to minimize radiation effects.

4. RADIATION ENVIRONMENT

To effectively design systems that will be exposed to radiation, the designer must fully characterize and understand the radiation environment. The type and magnitude of radiation that will be present in the environment are the most important variables to be determined. The type and magnitude of radiation are established by determining the background and local radiation with a radiation map of the facility. The magnitude and duration of the transient sources must also be considered in order to determine the total exposure of the system to radiation.

A study of the radiation levels in fuel reprocessing cells showed that gamma radiation is the major type of radiation that affects equipment operation and will be the dominant damaging radiation considered in this report.[3] Calculations performed for spent nuclear fuel show that neutron damage from spent fuel (worst case) is more than a factor of 10^7 lower than the corresponding damage due to gamma radiation. Also, the source of secondary gamma rays produced from neutron-induced reactions within plant equipment and structural components is negligible compared to the direct gamma source. If a device is extremely sensitive to neutrons, a separate, detailed analysis to estimate neutron interference or damage will be required; since the neutron energy spectrum may be modified because of the effects of nearby objects.[3]

In reviewing the literature focused on the radiation environment and its effect on components, the designer often encounters terminology unique to the subject. Basic definitions necessary for a working understanding of radiation and its effects are included in the subsection that follows. In addition, a description of radiation dose units is provided.

4.1 RADIATION-RELATED DEFINITIONS

Absorbed dose: The amount of energy imparted by nuclear (or ionizing) radiation to unit mass of absorbing material. The commonly used unit is the rad (see also the definition for curie).

Curie: A measure of the disintegration rate of a source. Originally equal to the disintegrations per second in 1 g of radium, it is now defined as 3.70×10^{10} disintegrations/s. The curie is useful for comparing the strengths of various sources of the same isotope.[2]

Dose: A measure of energy (in ergs, joules, or calories) deposited per unit mass (g). The absorbed dose of energy is usually given in terms of rads commonly referred to as accumulated or total exposure to radiation. It is a quantity of ionizing (or nuclear) radiation. The term dose is often used in the sense of the "exposure dose," expressed in roentgens, which is a measure of the total amount of ionization that the quantity of radiation could produce in air.

Electromagnetic radiation: A traveling wave motion resulting from oscillating magnetic and electric fields. Familiar electromagnetic radiation ranges from X rays (and gamma rays) of short wavelength, through the ultraviolet, visible, and infrared regions, to radio waves of relatively long wavelength. All electromagnetic radiations travel in a vacuum with the velocity of light.

Electron volt (eV): The kinetic energy of an electron accelerated from rest through a potential difference of 1 V. It is equivalent to $1.6 \times 10^{(-12)}$ erg.

Fluence: The transfer of energy (in ergs, joules, or calories) across a unit of area (cm^2).

Flux: The transfer of energy or particles per unit time across a unit of area (e.g., neutrons · cm^2/s).

Gamma ray (γ): Nuclear radiation of high energy originating in atomic nuclei. Gamma rays are highly penetrating. Physically, gamma rays are identical to high-energy X rays; the only essential difference is that the X rays do not originate from atomic nuclei but from the electron cloud around the nucleus.

Radioactive half-life: The time required for the activity of a given radioactive species to decrease to half of its initial value because of radioactive decay. The half-life is a characteristic property of each radioactive species and is independent of its amount or condition.

Ionization: The process of producing ions or changing an uncharged atom to a charged atom by either adding or removing an electron. The separation of an atom or molecule that normally is electrically neutral into its electrically charged components.

Radiation hardening: The concept of making anything (e.g., components, circuits, systems) less susceptible to damage from nuclear radiation. Radiation hardening is the process by which a vulnerable part (or system) is modified to make it less vulnerable to a specified radiation environment, or the design process aimed at improving the radiation tolerance of the part.

Roentgen absorbed dose (rad): Absorption dose of 100 erg/g (C). The rad is a measure of radiated energy absorption of any form (particle or electromagnetic) in any material:

1 rad = 3.0E7 electrons/cm^2 at 1 MeV (electrons)
1 rad = 1.0E6 protons/cm^2 at 1 MeV (protons)
1 rad = 3.0E6 neutrons/cm^2 at 1 MeV (neutrons)
1 rad = 2.2E9 photons/cm^2 at 1 MeV (photons)

It is important to specify the material when this term is used. Because carbon is a common reference material, its symbol, C, is often found in parentheses. Silicon is used in many applications involving electronic materials.

Roentgen (R): Exposure dose of 87.8 erg/g (C) to air; the amount of radiation that produces ionization, 1 electrostatic unit (esu) of charge of either positive or negative sign in 1 cm^3 of air at normal temperature and pressure. This term specifies the amount of ionizing radiation released in standard temperature and air pressure. It is the quantity of radiation that produces 2.083×10^9 ion pairs/cm^3 of air at standard pressure, 760 mm, and standard temperature 25°C (77°F) at sea level.

Tenth-value thickness: The thickness of a given material which will decrease the amount (or dose) of gamma radiation to one-tenth of the amount incident upon it. Two tenth-value thicknesses will reduce the dose received by a factor of 10×10 (i.e., 100), and so on. For radiation of a particular energy, the tenth-value thickness of various materials is roughly inversely proportional to the density of the material (see Sect. 9.1). The radiation attenuation of gamma rays is dependent upon the electron density (i.e., the density of the material).

4.2 RADIATION DOSE UNITS

When dealing with radiation, two different kinds of radiation dose units are frequently encountered:

1. Exposure dose (usually measured in roentgens) is a measure of the radiation field defined so as to be independent of the material being exposed.

2. Absorbed dose (usually measured in rads) is defined in units of energy absorbed by a unit mass of the exposed material and depends upon the material being exposed.[6] The rad is defined as "the deposition of 100 erg of absorbed energy per gram of exposed material." The MKS unit for absorbed dose is called the gray (GY). One GY is defined as "the deposition of 1 joule per kilogram of energy." The equivalence between the gray and the rad is 1 GY = 100 rads.[7]

The fundamental differences between exposure and absorbed dose should be noted, and appropriate caution should be used when making calculations. For many materials, exposure to a 1 R radiation field produces an absorbed dose of ~1 rad. Note that the rad is defined in terms of the exposed material. Thus, two different materials exposed to the same radiation field can absorb different numbers of rads. However, the numerical errors resulting from treating rads, rads (material), and roentgens as equivalent will generally be relatively small, ~10 or 20%.[6]

Information on the ability of a material to withstand degradation, or "radiation hardness," is usually described in terms of the absorbed dose, which corresponds to some specified critical amount of damage in a specific engineering property. Material properties typically evaluated include compression set, elasticity, hardness, and conductivity. Radiation damage does not always decrease the material property; in some select cases, the property is actually improved with increased radiation.

When determining radiation effects, two general dose levels are of interest:

- The threshold dose, which is the lowest dose at which radiation effects are identifiable, often depends on the sensitivity of the equipment with which measurements of a particular property are made and, as a result, has limited reproducibility and appreciable uncertainty. It is not surprising to find wide variations in the values reported for threshold levels.
- The percent-change dose corresponds to an arbitrarily fixed amount of degradation (e.g., 25% dose, which is the dose at which the material property has degraded by 25% of its original value).

When determining the effects of radiation on the component, the threshold dose is not necessarily an indicator of component failure. Components often continue to perform their desired function after material degradation begins. A large portion of the data contained in this report is for the threshold dose; therefore, it is left to the designer to determine the amount of conservatism desired in the system designs. Even if specific component test data are available, it is often difficult to determine the actual component behavior from radiation-effects data alone. The individual operating environment will be a unique combination of conditions (e.g., movement, vibration, atmosphere, etc.) that are often difficult to model. Therefore, each item should be addressed on an individual basis.

5. IDENTIFYING AND SIMPLIFYING THE SYSTEMS

Once the system criteria have been established and the conceptual design has been laid out, the next step is to locate the equipment within the process cell. Identify what equipment will be essential to the system and where it will be stationed within the cell. This will help to determine the surroundings of each component (i.e., to aid with shielding analysis, etc.). Shielding and other special requirements may significantly impact the placement of cell walls and equipment; and may, in fact, limit the feasibility of certain access and maintenance procedures. In a remotely maintained facility, it is necessary to know anticipated radiation levels in the process cells to estimate the equipment lifetimes. This is especially important when considering radiation damage to materials and components.[3]

Once the equipment has been identified and located in the cell, the design should be simplified to eliminate unnecessary components within the cell walls where the radiation field is the strongest. When it comes to designing systems to operate in high radiation environments, the old adage holds true: "If in doubt, leave it out." The fewer components located in cell, the better. Remote maintenance makes changeout of failed components more time consuming. The greater the number of components in cell, the greater chance of failed components—and the greater the amount of time spent on repairs. Radiation-sensitive components should receive special attention in the simplification process. Attempts should be made to locate them out of cell or in areas less exposed to the high levels of radiation.

6. ACCEPTABLE DESIGN-LIFE

As the system design progresses, an acceptable design-life should be established for each component as part of the design criteria. It should be determined whether the component needs to last the life of the facility, or whether shorter lifetimes are acceptable. Once the required design-life has been established, the effects of radiation on the component lifetime should be addressed to determine if the component will meet the desired requirement.

A rough estimate of a component life in a radiation environment can be made by simply dividing the radiation hardness of the component by the estimated dose rate in the cell:

$$\text{Lifetime (h)} = \frac{\text{Radiation Hardness (rad)}}{\text{Radiation Dose Rate (rad/h)}}$$

Several possible actions can be taken to increase component lifetime:

- the component hardness can be increased,
- the radiation dose rate can be decreased, or
- increasing the hardness and decreasing the dose rate can be combined.

The radiation hardness can be increased through the use of components comprised of radiation-resistant materials, which may often be very expensive. Material information for determining the hardness of a component is contained in Appendix B and Appendix C. Information on making use of radiation-hardened components and conducting a radiation hardening program is contained in Sect. 9.3 and Sect. 9.4.

The dose rate can be decreased through (1) unit shielding, which lowers the dose received by the component; (2) source shielding, which lowers the overall dose rate in the facility; or (3) strategic siting of equipment in areas of less intense dose rates (i.e., moving equipment farther away from the source, etc.). If the estimated component lifetime is inadequate for operation, solutions should be considered as detailed in Sect. 9.1 and Sect. 9.2.

7. FAILURE CRITERIA AND FAILURE MODES

Failure criteria and possible failure modes should be established for each component. Failure criteria help define the conditions for component failure. Radiation will cause some components to slowly degrade, resulting in a change in the component performance. The failure criteria help to define how much degradation a component is permitted to withstand before failing to perform its intended function. The failure modes should be identified to better understand how the component will fail. When exposed to a radiation environment, components will have certain susceptible areas that will be affected by radiation and that will cause failure. Identifying the areas where the component may fail (e.g., a leaky seal or a short) will help pinpoint areas where actions are required to make the component more radiation-resistant. Some typical equipment failure modes are shown in Table 7.1. The required level of confidence that the component will meet its required life expectancy must be evaluated. Higher levels of confidence are necessary for components with greater "consequences of failure," and a higher "degree of difficulty for recovery," for each of the predicted failure modes.

Table 7.1. Typical modes of failure for components

Component	Failure mode	Contained in
Seals	Generally, elastomeric seals become hard and brittle, causing the seals to begin to leak.	Bearings Gear boxes Motors Solenoid valves Valves
Insulation	Insulation becomes brittle and falls off the wires. This results in short circuits and/or a failure to hold pins and wires in place. For most components, degradation of dielectric properties is secondary.	Accelerometers Battery packs Cables Circuit boards Connectors Electrical heaters Motor windings Potentiometers Relays Resolver windings Thermocouples
Lubricants	Radiation changes lubricity, usually by thickening, which prevents proper lubrication.	Bearings Gear boxes Motors Resolvers Other moving parts

8. RADIATION EFFECTS ON COMPONENTS

The effects of radiation on an individual component depend mainly upon the materials from which the component is made. In general, the engineering property of concern in a given case will depend upon the function to be fulfilled by the component. Further, the design of the particular equipment in which a component is used will determine, in part, the amount of degradation of a given engineering property that can be tolerated. It is important to determine the amount of degradation that the equipment can tolerate while retaining a sufficiently high probability for performing its assigned function. In the literature, "threshold" values are generally reported; the threshold values are normally the dose required to begin degradation in a particular material property. In other cases, a "percent-change dose" is reported; this dose is the dose required to cause a certain percentage of change (i.e., 25%, 50%, etc.) in the material property. In some applications, degradation levels may be quite high, yet the equipment may still be able to function as intended.

Many electrical and mechanical components are required for operation of the total system or nuclear fuel reprocessing facility. Some examples of the necessary components (revised from ref. 5) are shown in Table 8.1.

Table 8.1. Examples of components in a system

Electronic components	Amplifiers, controllers, indicators, inverters/chargers, logic devices, meters, power supplies, recorders, and signal conditioners
Electrical components	Batteries, cables, connectors, heaters, insulation/tape, penetrations, terminal blocks, and transformers
Electromechanical components	Circuit breakers, fuses, monitors, motors, relays, switches, transmitters, and valve operators
Electrostructural	Battery racks, motor control centers, instrument racks, and panels
Mechanical equipment	Air locks, cranes, ducting, filters, handling equipment, heaters, motors, piping, pumps, tanks, and valves

To aid in understanding the effects of radiation on system design, information has been compiled on various individual components. The following subsections describe some general components and the effects of radiation on their performance. It should be noted that a large majority of radiation-effects data that is available on components come from nuclear plant experience and equipment qualification testing. The radiation scenario is slightly different in a fuel reprocessing facility, which has relatively constant high levels of gamma dose, than in a nuclear reactor, which considers both an operational period (with relatively lower dose levels) and an accident period (with a short-lived, high dose level and a steam exposure).

To assist with component selection, a list of suggested vendors for radiation-hardened equipment is included in Table 8.2. It shows some typically-used equipment and possible vendors of radiation-hardened versions.

Table 8.2. Possible radiation-resistant component vendors

Item	Sources	Radiation Resistance	Comments
AC motor class H, type RH	Reliance Electric	2×10^8	0-600 V
Resolvers	Northern Precision Laboratories	1×10^9	
LVDT	Schoeritz	1×10^{12}	
Electrical connectors	Lemo	1×10^9	
	VEAM	1×10^{10}	
Electric wire cable	Kyle Technologies	6×10^{14}	Power and instrument cable
	Boston Insulated Wire (BIW)	2×10^8	
Proximity detectors	Capacitek	6×10^{14}	Depends on cable

8.1 ELECTRICAL AND ELECTRONIC COMPONENTS

Electrical and electronic components are often highly sensitive to radiation damage. A brief description of some of the effects of radiation on certain components is contained in the following subsections.

8.1.1 Capacitors

Capacitors of glass, mica, or paper are generally radiation resistant to dose levels of 10^7 rad. Their capacitance varies only slightly with radiation dosages; however, prolonged exposure makes their performance vary in random patterns. Oil and impregnated capacitors suffer considerable gas evolution. This gas evolution swells the capacitor and leads to leakage. Electrolytic capacitors fail in ~1/10 the exposure time required to damage other types of capacitors.

A list of common capacitor materials and their threshold dose levels (as summarized from ref. 8) follows:

Capacitors (materials)	Threshold levels (rad)
Glass	1×10^7
Paper	1×10^7
Mica	1×10^6
Ceramic	1×10^6
Virteous enamel	1×10^6
Tantalum	1×10^5
Electrolyte	1×10^4

8.1.2 Circuit Boards

The insulating resistance of foil-clad laminates is reduced and warping, blistering, and physical distortion occur due to exposure in radiation fields. A coating of the boards improves radiation resistance, and special ceramic boards are a feasible alternative to the normal laminates.

8.1.3 Electrical Cables

In general, cables include almost any system of conductors separated by an insulating medium. (See Table 8.2 for some possible vendors of radiation-resistant cable.) For most insulators, the life in a radiation field depends on its resistance to mechanical damage (i.e., brittleness, peeling, etc.), rather than its electrical properties. Permanent changes in electrical properties with irradiation are often minor. The dielectric constant, as being a property that is determined jointly by all of the molecules in the material, will not change significantly until a substantial percentage of those molecules have been altered. Because of this characteristic, the dielectric constant usually changes only slightly up to dose levels where other engineering properties, such as integrity (cracking), have undergone appreciable changes.[5]

Note that the insulation resistance of organic materials may be susceptible to dose-rate effects. The insulation resistance of certain materials may decrease by a factor of 10^3 to 10^4 during gamma ray irradiation at 10^4 to 10^6 rad/h. The temporary decrease in resistance can cause problems in high-impedance circuits; however, postirradiation recovery is generally a problem only for very large total doses. A list of insulators (reported in ref. 5 to display some dose-rate sensitivity) may indicate synergistic or multistress interference effects:

- Chloroprene
- Chlorosulfonated polyethylene
- Crosslinked polyolefin
- Ethylene propylene
- Mylar
- Teflon (normally avoided in any radiation environment)
- Polyethylene
- Polyvinyl chloride

Most plastics used for insulators harden and eventually become brittle in a radiation field. This characteristic results in chipping and peeling of the insulation, especially if flexing occurs. Inorganic insulators (e.g., ceramics, glass, and mica) and organic-inorganic combinations (mica and glass used with silicone or phenolic varnishes) can normally be used successfully in high-radiation and high-temperature environments.[9] If high flexibility is desired, coiling the wires, as in an ordinary telephone cord, may be useful in reducing stress in irradiated cables.

8.1.4 Electrical Connectors

Irradiation of electrical connectors causes shrinking, cracking, and degradation of dielectric properties of the insulators. The use of ceramic inserts in the connectors will provide much better radiation resistance.

For information on insulating materials, see the electric cable information in Sect. 8.1.3 and see also Table 8.2 for possible vendors of radiation-resistant connectors.

8.1.5 Resistors

Resistors of higher values are more susceptible to damage from radiation than those of lower values. Failures and damage result from a lowered resistance, which becomes variable with changes in the radiation levels. Wire-wound resistors are generally less affected than any other type. Some typical resistors and their radiation resistance levels, as summarized from ref. 8, are as follows:

Resistors	Threshold levels (rad)
Precision wire-wound ceramic bobbin	1×10^8
Metal film	1×10^7
Precision wire-wound epoxy bobbin	1×10^6
Carbon film	1×10^6
Other film	1×10^5
Composition	1×10^4
Oxide film	1×10^3

8.1.6 Transformers

Physical damage is most evident in transformers because of the expansion of potting compounds and the degradation of insulating material.[1] This expansion can lead to "shorts" and/or the rupture of seals and cases. At high radiation levels, the permeability and coercive forces are reduced.[8]

8.2 MECHANICAL AND ELECTROMECHANICAL COMPONENTS

Radiation often damages the organic materials in mechanical equipment (e.g., seals, lubricants, winding insulation, etc.). A brief explanation of some of the damage to components caused by radiation is included in the following subsections.

8.2.1 Hoses, Flexible Tubing, and Diaphragms

Soft plastics (e.g., polyethylene, fluorocarbons, polyvinyl chloride, etc.) and elastomeric materials are widely used for flexible tubing, diaphragms, and hoses. The choice of material is generally influenced by the fluid, the atmosphere, and the temperature.[9] It is generally required that the hose retain strength but not necessarily flexibility. Fortunately, radiation will usually damage the flexibility much sooner than it will the tensile strength.

To add strength or to add resistance to damage, many hoses incorporate a filler with the polymeric material. Inorganic fillers such as fiberglass, asbestos, and carbon will increase the resistance to radiation and may greatly increase the useful life of the hose.[9]

8.2.2 Magnets

Hard magnetic materials (e.g., Alnico, chromium steel) are highly resistant to radiation. Soft magnetic materials (such as those used for cores in various magnetic devices) are more susceptible. When properly controlled, however, irradiation can actually be used to improve magnetic properties.[1] Although not significant in a fuel reprocessing environment, large doses of radiation from neutrons (and charged particles) can adversely affect the magnetic properties of permanent magnets.

8.2.3 Motors

In a motor, the most likely general areas for radiation damage are the insulation, lubrication, and seals. Of environmental conditions to be considered, temperature is the most important when selecting insulating materials for magnet wire used in motor and brake construction. Elevated temperatures caused by Joule heating in energized motor and brake coils may cause failure by exceeding the insulating material's maximum allowable operating temperature. Elevated temperatures may also accelerate damage by the radiation. Degradation of physical properties will affect the dielectric strength of insulators and the resistance of electrical conductors.

In a motor's lubrication system, the organic seal is often 2 to 10 times more sensitive to radiation than the lubricant itself. Information concerning radiation damage to lubricants and elastomers as well as information concerning how to select a lubricant and elastomer for a motor is contained in the materials information in Appendix C. See also Table 8.2 for a possible vendor of radiation-hardened motors.

8.2.4 Potting or Encapsulating Compounds

Many polymeric systems can be formulated to provide the electrical resistance, moisture resistance, and mechanical properties required for coating electrical components; however, since compounds that cure at moderate temperatures are desirable, methods of application restrict bulk potting to a few compounds of relatively few polymers.[9] Consequently, epoxy resins and silicone elastomers and resins are the most commonly used.

Silicone potting materials have the greatest flexibility and moisture resistance and should not show great sensitivity to radiation, as strength is more than adequate. However, radiation-generated gas may be an important consideration.[9] For high-frequency use, the service lifetime is likely to be limited by dielectric breakdown strength.[9]

8.2.5 Seals, O Rings, and Gaskets

Plastics and elastomerics are the most popular materials for seals, gaskets, and O rings. Rubbers and some of the softer plastics are used when soft, resilient materials are required. A wide range of materials and fillers can be used to give the desired properties. The properties most important to seals, O rings, and gaskets are hardness, tensile strength, elongation, compression set, and plastic flow.[9]

From available radiation data on elastomers, the tensile strength, set-at-break, and compression-set values decrease at first for some elastomers but increase for others. The changes that occur are due to the curing state. The curing state, in turn, is dependent upon the processes used in fabrication. Special O rings, for example, can withstand 10^9 rad without major changes. Two examples are butadiene acrylonitrile and ethylene propylene.[5] Elastomers, which have shown promise when irradiated to $\sim 10^8$ rad at room temperature, include natural, SBR, nitrile, neoprene (if not immersed in water), and some polyurethane rubbers. For temperatures above 300°F, consider the use of Viton-A, Kel-F, nitrile rubber, and silicone elastomers. The performance of a static seal may be adequate well beyond the reported material life if the seal is not disturbed.[5]

Seals and gaskets have been found to be more radiation-resistant when immersed in oil. Seals of Viton-A and silicone rubber immersed in oil may be capable of service to a dose of $\sim 10^8$ rad, two orders of magnitude greater than the maximum service in air. Ingredients can be added to the material to help defend against radiation damage. These ingredients are commonly known as "antirads" and can somewhat improve the radiation stability of nitrile, neoprene, SBR, and natural rubbers. The antirads, which are material-specific, may increase the service life by about one order of magnitude.[5]

8.2.6 Thermal Insulation

Irradiation of polymeric insulation may slightly increase the evolution of gas, and thus the thermal conductivity, which is the essential property of thermal insulation. Thermal insulation generally used is an efficient, low-density foam. Polyurethanes, polystyrene, natural and synthetic rubbers, and polyvinyl chlorides are common materials, but almost any plastic or elastomer can be formulated with foaming or blowing agents at some stage of its production. Often, radiation will alter the compressive and tensile strength of the foam; in fact, where operation of a device depends upon support by a foamed component, some polymers can severely limit the radiation tolerance.[9]

9. DESIGN SOLUTIONS TO THE RADIATION PROBLEM

Potential radiation problems should be identified and addressed early in the design process. Possible solutions to reduce the impact of radiation include (1) adding unit and source shielding, (2) siting components in strategic locations, (3) making use of commercially available, radiation-hardened components, and (4) conducting individual component hardening programs. Each of these solutions are described in detail in the following subsections.

9.1 UNIT AND SOURCE SHIELDING

Shielding can be effectively accomplished in two ways: (1) by shielding the radiation source and, as a result, lowering the total dose that all equipment receives, and (2) by using local-unit shielding, which shields specific items especially susceptible to radiation damage.

Source shielding can be obtained by several methods, including adding removable plates surrounding a radiation source and placing radioactivity inventories in separate cells. Whenever radionuclide sources cannot be shielded, unit shielding can help to lower the radiation dose received by individual components or systems. For example, system electronics can often be isolated and effectively enclosed in shielding, motors can be surrounded by lead housings to lower the dose received by the windings and lubricants, and movable remote equipment can be kept in shielded "parking garages" when not in use.

Shielding is effective because gamma rays are attenuated when they pass through matter. This results in a decrease in their intensity as a function of distance of penetration into the material. Because incident photons lose energy by ionization, the losses-per-unit distance of photon path are proportional to the average concentration of electrons in the material.[7] Usually, the attenuation properties of a material are proportional to the atomic number and density.[10] Effective gamma shielding uses materials with as high an atomic number as practical, considering other requirements. Relatively thin shields of dense materials can provide significant attenuation of gamma rays, while thicker shields are required for less dense materials.

Generally, uranium shields gamma rays better than lead, lead shields better than iron, and so on. Lead is a common gamma-ray shield, but in many cases larger thicknesses of structural materials (e.g., steel and concrete) can be more cost-effective and still do an adequate job of shielding.[10] Often in shielding, a tenth-value thickness (the amount of material thickness needed to attenuate to 10%) is used. Table 9.1 shows approximate tenth-value attenuation thickness for shielding construction materials for fission product gamma rays.[7,10]

The shielding design can be a complex analytical process. The data in Table 9.1 can be used for rough, "ball-park" estimates, but actual shielding requirements are based on many factors, including the radiation source, energy levels, material density, and desired attenuation. If shielding is critical to the survival of a component, a complete shielding analysis is recommended. Reference 2 is good reference for the attenuation coefficients of the elements.

Figure 9.1 (from ref. 11) gives approximate tenth-value thicknesses for shielding materials for various energy levels. A typical, conservative, energy value for use in estimating the necessary shielding is 1 MeV.

Table 9.1. Approximate tenth-value attenuation thickness for shielding materials for fission product gamma rays

Material	Density (lb/ft^3)	Tenth-value (in.)
Uranium	1172.0	0.54
Tungsten	1227.0	0.7
Lead	709.0	1.1
Iron	486.0	2.7
Steel	490.0	3.7
Concrete	144.0	12.0
Water	62.4	26.0

9.2 STRATEGIC SITING OF EQUIPMENT

In the system design, a strategic siting of components can aid in reducing the effects of radiation on certain components. Components known to be sensitive to radiation can be moved away from the major sources of radiation. For some designs, certain areas are inherently self-shielded and could be possible locations for the more radiation-sensitive components.

Another action to be considered is to move radiation-sensitive components outside the radiation environment. This relocation can be accomplished by siting items in an adjacent room having lower radiation levels. This approach, however, generally involves design tradeoffs in the complexity of the system (e.g., if the motor control is moved outside the high-radiation environment, a pair of wires, which are also susceptible to radiation damage, must then penetrate the cell walls).

9.3 RADIATION-HARDENED EQUIPMENT

Some traditionally radiation-sensitive components have been modified and are commercially available in radiation-hardened versions. Manufacturers and vendors are often the best sources for component-hardness information. (See Table 8.2, which lists some of the commercially available, radiation-resistant equipment.) As a rule, the radiation-resistant components tend to be more expensive due to their special design and limited marketability.

If radiation-hardness information for a component is not available, the approximate hardness can often be determined with a materials analysis; however, the effects of radiation on materials are both transient and permanent and may vary widely according to the composition and type of material. A conservative approach should be used in predicting the useful life of a radiation-sensitive component. In practice, it is advisable to determine the acceptable dose of the most sensitive material in the component as the acceptable dose for the component. The acceptable dose represents the amount of radiation a material can absorb before radiation effects deteriorate the operation of the component past the established failure criteria.

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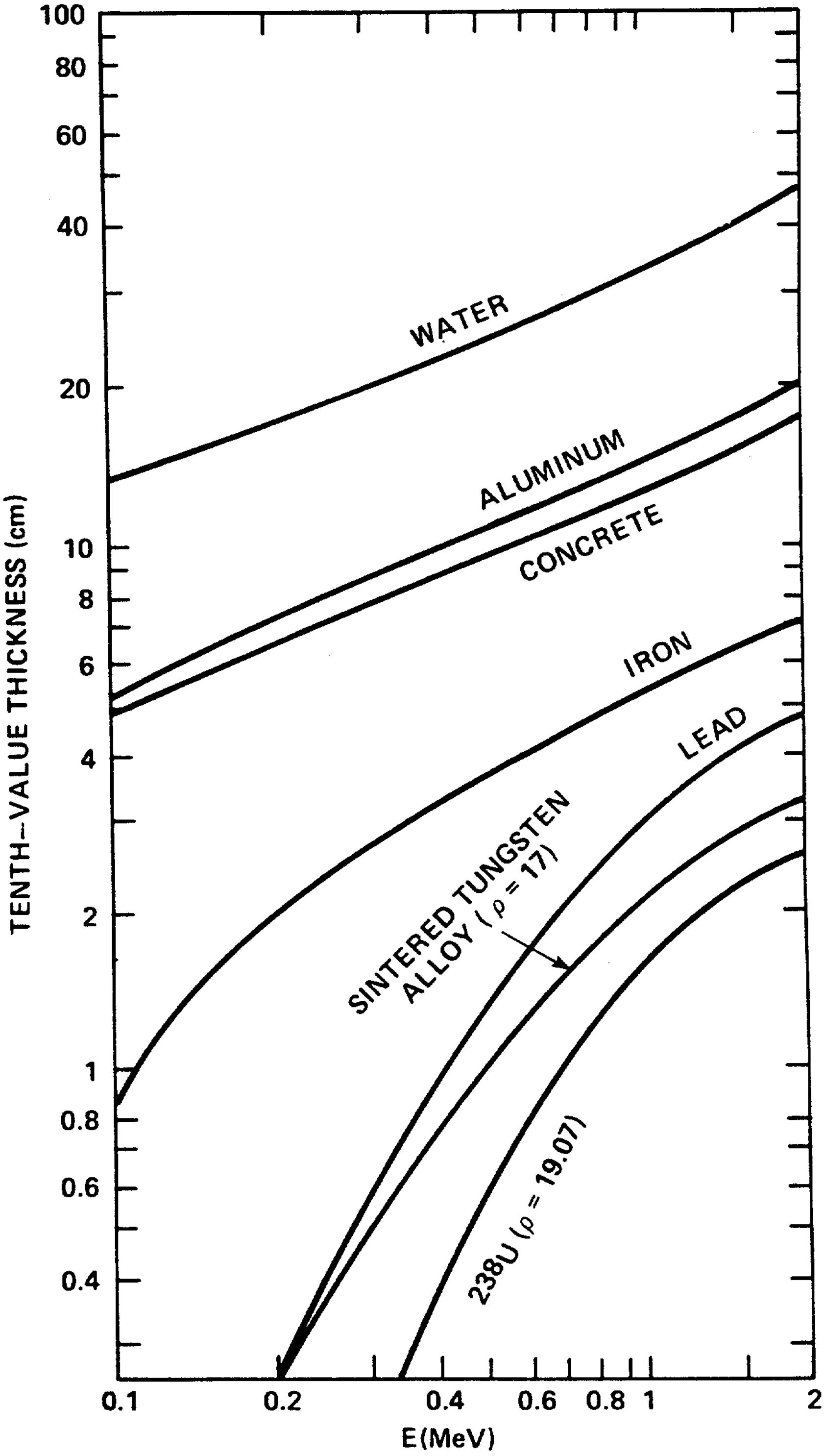

Fig. 9.1. Tenth-value attenuation thickness for shielding materials.

To aid in materials analysis, detailed information on radiation effects to specific materials is contained in Appendix B and Appendix C. Note that dose rate, total exposure, and varied environmental factors all play a role when examining the effects of radiation. Environmental factors such as temperature, pressure, and humidity may influence the magnitude of the property change; moreover, these factors are interdependent and the resulting effects can be extremely complex. Elevated temperature, the presence of oxygen, and increases in stress can lower radiation resistance. These effects are not well known for many materials, however, and may sometimes be the opposite of those normally expected.

9.4 COMPONENT HARDENING PROGRAM

Selective hardening of components can be expensive and is usually done only when significant quantities are to be produced.[7] For example, to make an electric servomotor more radiation-resistant, a heavier and highly radiation-resistant insulation for the windings may be necessary. This need, in turn, may require both a somewhat larger coil and housing assembly and a complete redesign of the motor (to match the performance characteristics of the smaller, conventional motor), possibly resulting in a prototype development program. Following fabrication of a special design, proof testing to verify the component hardness should be conducted which, again, adds to both the cost and schedule. To be cost effective, a special design should probably increase the useful life of a component by more than one order of magnitude.

As noted, special designs or extensive modifications of commercial designs can often be expensive. If a special hardening program is deemed worthwhile, the program can be accomplished by following the steps for hardening a component. These steps (as summarized from ref. 1) are as follows:

Step 1: Develop a realistic performance requirement for the system.

Step 2: Provide failure criteria.

Step 3: Determine the radiation tolerance specifications for the system.

Step 4: Select parts and materials for the component.

Step 5: Perform an assessment of the materials, based on available data, to establish the upper bounds of radiation that an item can tolerate and still function.

Step 6: Conduct radiation tests for verification.

10. DESIGNING FOR SYSTEM MAINTENANCE

A designer is normally attempting to meet availability requirements imposed on the component or system. The previous sections have covered approaches to increasing availability by increasing the reliability of equipment in the high-radiation environment. There are times, however, where these approaches are not feasible because of other constraints (e.g., cost, schedule, size, etc.). An alternative method of increasing availability of a component is to minimize the repair (i.e., replacement) time for a failed component. Although somewhat outside the scope of this report it is perhaps appropriate to identify some of the general principles that can be applied to designing equipment to facilitate remote replacement. A more complete description of remote maintenance design guidelines is contained in ref. 10. These design principles are to

1. design equipment with individually replaceable modules,
2. group (to the extent possible) items of similar radiation resistance together in these modules,
3. provide diagnostic capabilities sufficient to identify the cause of failure,
4. locate (if possible) the diagnostic equipment out of the high-radiation environment, and
5. design the equipment by using remote maintenance design principles.

In addition to designing components and systems for remote maintenance, the designer should assist with the development of a preventive maintenance (i.e., replacement) program. The use of radiation effects on materials information; test data; and reliability, availability, and maintainability (RAM) analysis enables estimation of the lifetimes of the components in the system. Based on these lifetimes, a spare parts and preventive maintenance program can be established to reduce the actual system downtime due to failures. Components can be replaced on a regular basis before failure actually occurs. A scheduled preventive maintenance program will not actually reduce the effects of radiation; however, it will have a considerable impact on the mean-time-to-repair and, therefore, will increase the overall system availability by eliminating the time required for detection and diagnosis of failures. With preventive maintenance, repairs are made during regularly scheduled downtimes rather than on an emergency basis during operation.

For a preventive maintenance program to be most effective, typically a cost analysis should be performed to confirm the absolute benefits. However, it is known that certain equipment have a finite lifetime in irradiation fields. It is apparent that replacement of these items during scheduled downtimes will increase the system reliability and provide confidence that the system will operate with fewer failures.

Some actions that should be taken to establish a preventive maintenance program include the following:

1. Establishing the lifetimes of all equipment by using hardness ratings, dose rate, etc.
2. Monitoring equipment, where possible, (especially the radiation-sensitive equipment) for incipient failures.
3. Establishing the spare parts inventory based on the replacement component availability requirements (Will the replacement have to be custom-made? What will be the procurement time? What is the impact of the failure on facility operation?, etc.).
4. Establishing the plant operation scenario (to help identify planned downtimes, loads on equipment, etc.).

11. CONCLUSIONS

When designing systems to operate in a high-radiation environment, the deisgner must carefully plan every step in the design process. An understanding of radiation and its effects is essential. High levels of radiation will degrade some material properties and shorten component lifetimes. The system designer should remove as many radiation-sensitive items out of the radiation environment as possible and still provide for the intended function.

Acceptable design lives should be established for each component based on its intended function. Failure criteria and probable modes of failure should be identified. Each component should be examined for possible radiation sensitivity, and design solutions should be established based on individual requirements. Some possible design solutions include (1) unit and source shielding, (2) specially locating the components, (3) making use of radiation-hardened components, (4) examining materials to determine their hardness, and (5) conducting component hardening programs to develop radiation-hardened equipment. Cost and availability are two of the major factors to be considered when determining design solutions. Basic principles for designing equipment to be remotely maintainable should be applied. Finally, a preventive maintenance program should be developed prior to startup of the system or facility to lessen the impact of radiation by replacing components before they actually fail. A preventive maintenance program will reduce system failures and improve facility operations.

Designing systems for use in a high-gamma radiation environment can be accomplished with success if the effects of radiation are understood and if careful planning and good design practices are used. The radiation environment and its effects on component operation should be evaluated and taken into consideration throughout the design process; and each system, component, and material should be closely examined.

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APPENDIX A
GAMMA RADIATION - WHAT IS IT?

Gamma rays are members of the family of photons that include X rays as well as ultraviolet, visible, infrared, and other rays across the energy spectrum, to include radio waves. High-energy gamma rays have the shortest wavelengths, on the order of fractions of an angstrom (10^{-8} cm), to a few angstroms for X rays. Gamma rays, like all photons, have zero rest mass. This means that their existence ceases by annihilation if and when they are brought to rest. All photons travel with the speed of light; they are uncharged and they interact mainly with free electrons or electrons bound to an atomic system.[1]

Gamma radiation has various effects on materials. The selection of materials which can withstand exposure to ionizing radiation is a relatively new field (less than 50 years old). When selecting materials, it should be known that synthetic organic materials are among the most radiation-sensitive materials, with some showing signs of degradation around 10^4 or 10^5 rads. Ceramics are more radiation resistant and metals are often the most radiation-resistant.

For comparison with engineering materials, a total dose of from 450 to 500 rad will produce a 50% mortality effect in humans.[2] A total dose of 5×10^3 rad will cause sure and sudden death.[3] The interaction of gamma rays with matter generally occurs through three mechanisms: the photoelectric effect, Compton scattering, and pair production.

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APPENDIX B
GUIDELINES FOR RADIATION EFFECTS ON INORGANIC MATERIALS

This section contains general radiation effects information on inorganic materials from a variety of references. When available, data for specific materials are furnished. Radiation affects different materials in different ways. Generally, organic materials tend to be the most sensitive to radiation effects; ceramics and metals are more radiation-resistant. In this section, optic materials are distinct from ceramics due to the different properties that are needed to carry out the intended function of the material. Information on the radiation sensitivity for the different materials is contained in the following subsections.

B.1 RADIATION EFFECTS ON METALS

In general, most properties of metals are not significantly directly affected by gamma irradiation. The major effect of high cumulative radiation doses is that the tensile strength and yield strength are increased, with a corresponding decrease in ductility.[1] For radiation resistance, metals are the preferred material, followed by inorganic materials and organic materials, respectively.[2]

Of the metals commonly used, aluminum and aluminum alloys are the most radiation-resistant, followed closely by stainless steels. Some commonly used metals and their damage thresholds are given in Table B.1, which was summarized from ref. 1 in this appendix.

Table B.1. Damage thresholds of commonly-used metals

Rank	Metals	Threshold level (rad)
1	Aluminum and its alloys	5×10^{13}
2	300 Series stainless steel	1×10^{13}
3	400 Series stainless steel	5×10^{12}
4	Iron	3×10^{12}
5	Copper	2×10^{12}
6	Brass and bronze	1×10^{12}
7	Nickel and its alloys	1×10^{12}
8	Beryllium copper	6×10^{11}

In most metals, radiation effects can be removed by annealing. Most radiation effects are compensated for by an abundance of free electrons, which allow metallic atoms to be quickly restored to their electronic equilibrium; therefore, the radiation effects on metals can basically be ignored in reprocessing plant designs.[2]

B.2 RADIATION EFFECTS ON CERAMICS

Ceramics are fairly resistant to radiation damage. They are considerably more radiation-resistant than plastics or other organic materials but not quite as resistant as metals. The general effect of radiation on ceramics is an increase in dimensional swelling and a corresponding decrease in density. These effects can often be removed or reduced by annealing the ceramic. Table B.2, derived from ref. 1 in Appendix B (see B.1), lists some commonly used ceramics and their radiation damage thresholds.

Table B.2. Damage thresholds for common ceramics

Rank	Ceramics	Threshold level (rad)
1	Alumina	5.0×10^{12}
2	Silicon carbide	6.0×10^{10}
3	Mica	5.0×10^{9}
4	Quartz	2.0×10^{9}
5	Glass, flint	2.5×10^{7}
6	Glass, borosilicate	1.0×10^{7}
7	"Vycor" glass	5.0×10^{6}

Information on fiber optic materials is listed under Optic Materials because of the different properties needed.

B.3 RADIATION EFFECTS ON OPTIC MATERIALS

Many optic materials are severely degraded by gamma radiation. Gamma radiation reduces light transmission by darkening the optic material. Some optic materials transmit light poorly after submission to gamma radiation, as shown in Table B.3 (summarized from ref. 3 in this appendix). There are a few materials, however, that are fairly resistant to radiation. For example, the light transmission characteristics indicate that the purified fused silica (Corning 7940) shows only an 11% degradation for various wavelengths after a dose of 5×10^9 rad.

Table B.3. Light transmission in optical materials subjected to gamma radiation

Material	Radiation dose ($\times 10^9$ R)	Average light transmission before dose (%)	Light transmission after dose (%) at various wavelengths			
			4×10^3	5×10^3	6×10^3	7×10^{3a}
Borosilicate crown-2 (517:645)	1.0	98	0	3	25	46
Borosilicate crown-2, protected (517:645P)	1.0	98	60	86	88	89
Dense flint-2 (617:366)	5.0	94	0	1	11	21
Dense flint-2, protected (617:366P)	1.0	91	45	83	85	86
Purified fused silica (Corning 7940)	5.0	100	89	89	89	89
Quartz	1.0	99	35	30	31	56
Styron 690, 1/8-in. thick	1.0	65	0	11	47	62
Styron 690, 1/2-in. thick	1.0	75	0	2	28	56
Type 1723, electron-tube, envelope glass	0.1	83	7	23	39	63
Vycor	0.02	99	0	0	0	1
Vycor, protected	0.5	99	24	24	36	61

[a] Wavelengths are measured in Angstroms.

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APPENDIX C

GUIDELINES FOR RADIATION EFFECTS ON ORGANIC MATERIALS

Radiation data of organic materials frequently exhibit complex effects. In some cases, the amount of degradation at a given absorbed dose depends on the dose rate. In other cases, the degradation increases with time after the irradiation ends, for times as long as several months.[1] In still other cases, the amount of degradation depends upon either the presence or absence of oxygen surrounding the materials.[1] Additionally, organic materials can vary widely between manufacturers. Properties—such as density, pigmentation, and molecular weight, along with the specific manufacturing process—may differ between materials and can affect the radiation resistance.

Organic materials such as polymers, insulator materials, and elastomers may experience considerable property changes when exposed to a large gamma dose (e.g., from 10^6 to 10^{10} rad). These property changes are caused by scattering or absorption of the gamma rays in the electronic shells of the material being irradiated, which produces ionization or excitation. Electrons and atoms recombine to produce excited molecules, which may undergo bond breakage. The charged atoms and free radicals produced by bond rupture are highly reactive, causing a variety of complex reactions before production of the final products.

The rupture of chemical bonds in organic materials, such as polymers, yields fragments of the large molecules as well as hydrogen atoms. The molecule may undergo scission (a breakup into small molecules) or cross-linking (a recombination into a network structure). Cross-linking and scission are competing mechanisms. Cross-linking tends to harden the material, while molecular scission tends to soften the material.

Important side reactions are the production of fragments of low molecular weight. Many of these fragments are gases (e.g., hydrogen). Gas evolution can rupture the cases of hermetically sealed equipment. Higher molecular weight gases may be retained in a solid polymer and may eventually cause swelling, cracking, and even foaming at high temperatures. In general, the properties of soft, flexible organic materials are altered more rapidly than are the properties of hard, rigid organics. Many organic materials experience considerable property degradation by a dose of 10^8 rad.

Radiation resistance of organics may sometimes be improved by adding compounds called antirads, by using fillers, and by adding radiation-resistant resins. The use of these materials must be evaluated on a case-by-case basis.

Information in these appendixes on organic materials is divided into five categories, based on the similarity of properties or applications: (1) adhesives, (2) coatings, (3) elastomers, (4) lubricants, and (5) plastics. Where applicable, the lowest threshold dose is identified beneath the material name, along with that property first affected by the radiation. The data furnished in the various appendixes are generally listed by the chemical name of the material; however, in some cases materials may be more widely known by their trade names. To assist in finding the material, a listing of some of the materials by trade names and chemical names, where available, is contained at the end of the sections.

C.1 RADIATION EFFECTS ON ADHESIVES

Adhesives are subject to attack by penetrating radiation. When under load, the exposed surface of the adhesive is generally the most highly stressed portion of the joint and is susceptible to crack initiation. The use of fillers can increase the radiation tolerance of a given adhesive system. It should also be noted that if the better adhesives are used, considerable bond degradation (i.e., 50% or more) can occur without jeopardizing system integrity.[1] Some common adhesives and their trade names are shown in Table C.1.

Table C.1. Generic designation and trade names of adhesives

Generic designation	Trade names
Epoxy	A-1 EC-1386 Epon VIII Epon 901 FM-100
Epoxy nylon	Metlbond 408
Epoxy phenolic	Aerobond 422 Epon 422 HT-424 Metlbond 302
Epoxy polyamid	BC-1648 Metlbond 406
Nitrile phenolic	Scotchweld AF-6
Silicone	Q3-0079
Vinyl phenolic	FM-47

Reference 3 provides a summary of data on the radiation stability of many adhesives. Most of the information is based on static tests at room temperature.

1. Adhesives, in general, can be classified according to the dose ranges shown in Table C.2.
2. The use of neoprene-nylon-phenolics and cellulosics generally should be avoided.
3. Oxidation is an important factor in the degradation of adhesives at elevated temperatures. Most adhesives show better thermal resistance in a vacuum or in an inert atmosphere; however, one epoxy-phenolic adhesive, Hexell 422-J, retained better shear strength after exposure to 10^9 rad at 350°F in air than after exposure to the ambient temperature-air environment alone.[3]

Table C.2. Dose ranges for adhesives

Dose range	Comments
5×10^7 rad	Neoprene-nylon-phenolic adhesives have been shown to maintain useful properties
10^8 rad	Neoprene-phenolics exhibited useful properties
5×10^8 rad	Epoxy, epoxy-Thiokol, nitrile-phenolic, and nitrile-phenolic adhesives retained useful properties
1×10^9 rad	Epoxy phenolic, vinyl phenolic, and modified nylon phenolic adhesives are choices judged most useful

C.2 RADIATION EFFECTS ON COATINGS

Coatings are used on a wide range of equipment and components. The primary functions of coatings are protection against corrosion, electrical conductivity, fire, humidity, as well as oxygen, ozone, and other contaminants.[1] Radiation tends to affect coating materials in several different ways. Some examples of radiation damage to synthetic organic coatings, which are derived from ref. 1 in this appendix, follow:

- Blistering
- Cracking
- Color change
- Debonding
- Embrittlement
- Loss of plasticizer and/or fillers
- Loss of tensile, shear, and peel strengths
- Surface flaking

A main consideration in selecting coatings for equipment in a high-radiation area is the ease of contaminant removal. Other considerations include temperature performance, humidity performance, quality control aspects, and cleaning methods.

The radiation resistance of protective coatings varies for a number of factors, including pigments, additives, plasticizers, solvents, catalysts, and curing agents. Damage thresholds are difficult to establish. However, some general guidelines for the selection of coatings that are to be subjected to radiation (as revised from ref. 2) are as follows.

1. Pigmented coatings are more highly radiation-resistant than are those coatings containing little or no pigment. Carbon black inhibits damage, but some grades of titanium dioxide accelerate damage.
2. The choice of a primer is important when a coating is to be applied to metal substrates.
3. The degree of cure for any specific system can influence radiation resistance.
4. Residual solvents can influence radiation resistance.
5. Gamma radiation and heat initially improve the physical properties of many organic coatings. However, exposure to radiation beyond a given dose tends to excessively crosslink and/or degrade organic coatings. For epoxies applied to steel, failure usually occurs at the metal-coating interface.[2]

Many coating systems are not overly affected by radiation exposures below 1×10^8 rad. Phenolic alkyd enamels, silicone alkyd enamels, and alkyd-epoxy formulations may all be useful above 10^9 rad. Reference 2 indicates that three coating systems (two epoxy-based and one modified phenolic-based) did not fail after being tested to 5×10^9 R in demineralized water. The reference also sites evidence of greater radiation resistance in air.[2]

The surface to which the coating is applied often has a significant influence on radiation resistance. For example, Amercoat 33 is a vinyl coating that failed on an aluminum panel after 2×10^8 rad, but lasted to 1×10^9 rad on a concrete panel. In general, coatings on concrete tend to be more stable. Additional data on coatings that have been applied and tested on specific surfaces are furnished in Table C.3 (summarized from ref. 2).

Table C.3. Radiation resistance of mounted protective coatings

Polymer base	Trade name[a]	Surface	10^9 rad	Appearance[b]
Epoxy	Epon-395	Steel	0.67	No failure
Furan	Alkaloy-550	Concrete	0.94	No failure
		Steel rod	0.84	No failure
Modified phenolic	Amphesive-801	Concrete	0.94	No failure
		Steel rod	0.87	Severely embrittled
Silicone alkyd	Solar silicone	Concrete	0.67	No failure
	Alkyd	Steel	0.67	No failure
Styrene	Prufcoat	Concrete	0.87	Failed blistered
		Steel	0.87	Failed cracked
		Steel (wet)	0.08	Failed cracked
Vinyl	Corrosite-22	Aluminum	0.21	Failed blistered
		Concrete	1.10	Borderline failure
Vinyl chloride	Amercoat-33	Aluminum	0.21	Failed blistered
		Concrete	1.05	Failed blistered
		Steel	0.87	Failed blistered

[a] Manufacturers of Epon-395: The Glidden Company; Alkaloy-550 and Amphesive-801: Atlas Mineral Products Company; Solar Silicone Alkyd: Solar Division, Gamble Skogmo, Inc.; Prufcoat: Prufcoat Laboratories, Inc.; Corrosite-22: Corrosite Corporation; Amercoat-33: Amercoat Corporation

[b] Appearance was examined for blisters, cracking, hardening, tackiness, etc.

C.3 RADIATION EFFECTS ON ELASTOMERS

Radiation generally affects elastomers by altering tensile strength, elongation, and compression set properties. Elastomers are thermoplastic polymers whose service temperature is above their glass transition temperature.[1] Though the base polymers are often similar, elastomers are generally less radiation-resistant than are most thermoplastics and thermosetting resins. The radiation resistance of elastomers often depends on the use of curing agents, fillers, and other additives.

Typical elastomers have many and varied uses in facility equipment. Some typical uses are as follows:

- Diaphrams
- Filler material
- Gaskets and seals
- Hoses
- Insulation
- Jackets
- O Rings
- Supports

In general, elastomers can be grouped by radiation resistance. These groups are summarized and listed in Table C.4.

Table C.4. Radiation resistance of elastomeric materials

Highest radiation-resistant elastomers	polyurethane rubbers natural rubber adduct rubber ethylene propylene rubber (EPR) styrene-butadiene rubber (SBR) Viton-A (in oil)
Moderate radiation-resistant elastomers	Poly FBA Cyanosilicone rubber vinyl pyride elastomer acrylonitrile rubber nitrile rubber neoprene rubber Hypalon Kel-F
Poor radiation-resistant elastomers	silicone rubber polyacrylic rubber butyl rubber polysulfide rubber (Thiokol)

Note that particular compounds may be exceptions to these generalizations and that conflicting data exist for some classes of compounds. In addition, compounds with high radiation resistance may be unsuitable for a particular application because of other properties. Some test information on the degradation of elastomer properties is shown in Table C.5 (summarized from ref. 7).

The radiation resistance of elastomers depends upon the type of curing agent, antioxidants, fillers, and other additives, as well as the processing and curing conditions. Filler-loaded elastomers are more resistant to radiation than to pure gum stock. Carbon black appears to be the best filler for improving radiation resistance. Indications are that slightly under-cured compounds have better radiation stability.[2] Presently available rubber materials for use above 149°C (300°F) do not have good radiation resistance. Silicones and fluorine-based polymers, the best temperature-resistant rubbers, are below average in radiation resistance. Nitrile and neoprene rubbers have been used at elevated temperatures below 149°F (300°F).[2]

Improvements in radiation stability by a factor of 2 to 10 can be realized through the use of protective agents such as amines and phenols, which are commonly called antirads. These materials often have antioxidant properties. Antirads are material-specific, however, and vendor data should be consulted.[2] Immersion in oil can increase the radiation-resistance of some materials. Viton-A and some silicon rubbers, for example, show highly improved radiation stability when immersed in oil. It has been suggested that petroleum may act as a scavenger for free radicals, or provide an effective medium for energy transfer.

Elastomeric materials are often designated by their trade name or popular name. A list of some elastomers and these names (summarized from ref. 2) is provided as Table C.6.

C.3.1 SPECIFIC ELASTOMERIC MATERIAL RADIATION INFORMATION

Information and test results for individual elastomeric materials are provided in this subsection. The majority of the following information is summarized from ref. 2, unless otherwise indicated.

Adduct Rubbers

(Threshold - 4×10^6 rad for tensile strength and elongation)

Adduct rubbers are made by reacting diene rubbers, such as polybutadiene, isoprene, and others, with alkyl mercaptans to remove unsaturations. Adduct rubbers have been found to show better radiation resistance than natural rubbers or neoprene rubbers. The radiation resistance apparently increases as saturation increases. When tested to a dose of 4.4×10^6 rad, samples of 86 and 92% saturated adducts of polybutadiene showed small change (<10%) in tensile strength and elongation. At a dose of 1.9×10^7 rad, the elongation had decreased ~20%. Tensile strength increased for both samples.

Butadiene (BR)

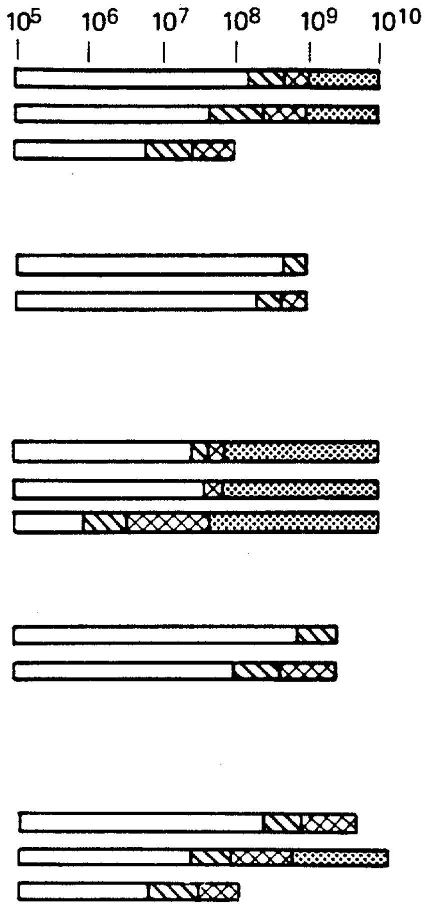
(Threshold - 10^6 rad for compression set)

A sample of polymerized polybutadiene retained 70% of the original tensile strength and 31% of its initial elongation after 1.7×10^8 rad. General resistance to compression set during irradiation is less than that of natural rubber.

Table C.5. Radiation resistance of elastomers

Material	Initial value
Hydrocarbon rubbers	
Natural rubber	
Tensile strength, psi	2600
Elongation at break, %	420
Compression set, recovery, %	93
Ethylene-propylene rubber (EPR)	
Tensile strength, psi	1320
Elongation at break, %	275
Butyl rubber GR-150	
Tensile strength, psi	1100
Elongation at break, %	525
Compression set, recovery, %	91
Butadiene rubber	
Tensile strength, psi	2380
Elongation at break, %	525
Styrene-butadiene rubber (SBR) (GRS-50)	
Tensile strength, psi	1700
Elongation at break, %	270
Compression set, recovery, %	90

Percent of initial value lost at given dose (rads)[a]

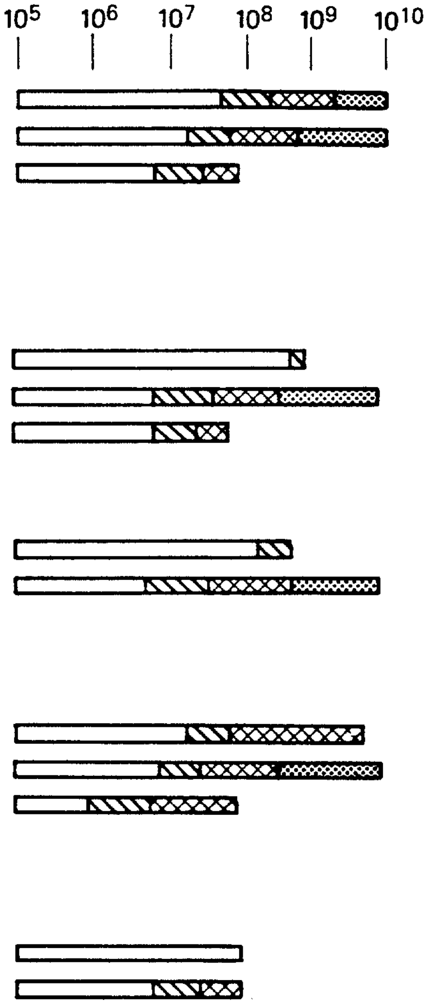


[a]Key for radiation effects:

□	0-20% decrease of initial value
▧	20-50% decrease of initial value
▦	50-90% decrease of initial value
▒	90-100% decrease of initial value

Table C.5. (continued)

Material	Initial value	Percent of initial value lost at given dose (rads)[a]
Oxygen-containing rubbers		
Polyacrylic rubber		
Hycar PA-21		
Tensile strength, psi	2000	
Elongation at break, %	230	
Compression set, recovery, %	92	
Nitrogen-containing rubbers		
Nitrile rubber		
Hycar OR-15		
Tensile strength, psi	1900	
Elongation at break, %	250	
Compression set, recovery, %	92	
Vinyl pyridine		
(Philprene VP-15-1)		
Tensile strength, psi	2790	
Elongation at break, %	405	
Polychloroprene rubber		
Neoprene W		
Tensile strength, psi	2900	
Elongation at break, %	450	
Compression set, recovery, %	62	
Fluororubber		
Viton A		
Tensile strength, psi	1875	
Elongation at break, %	160	

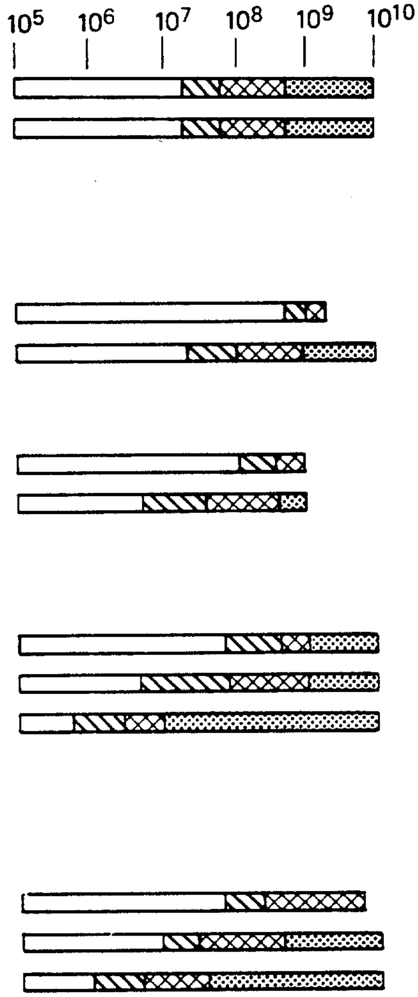


[a]Key for radiation effects:

▭	0-20% decrease of initial value
▧	20-50% decrease of initial value
▦	50-90% decrease of initial value
▒	90-100% decrease of initial value

Table C.5. (continued)

Material	Initial value	Percent of initial value lost at given dose (rads)[a]
Polyurethane rubber (Genthane)		
Tensile strength, psi	4040	
Elongation at break, %	500	
Sulfur-containing rubbers		
Adduct rubber (92% saturation)		
Tensile strength, psi	2660	
Elongation at break, %	490	
Chlorosulfonated polyethylene Rubber (Hypalon)		
Tensile strength, psi	1980	
Elongation at break, %	350	
Polysulfide rubber Thiokol ST		
Tensile strength, psi	800	
Elongation at break, %	162	
Compression set, recovery, %	90	
Miscellaneous rubbers		
Silicone rubber Silastic 7-170		
Tensile strength, psi	525	
Elongation at break, %	95	
Compression set, recovery, %	97	



[a] Key for radiation effects:

☐	0-20% decrease of initial value
▧	20-50% decrease of initial value
▩	50-90% decrease of initial value
░	90-100% decrease of initial value

Table C.6. Popular, generic, and trade names of elastomers (summarized from ref. 1)

Popular name	Generic designation	Trade name
Acrylics	Polyacrylate	Acrylon
		Angus HR, SH
		Hycar
		Lactoprene
		Paracil OHT
		Precision acrylics
		Thiacril
		Vyram
Butyl GRI	Isobutylene-isoprene	Bucar butyl
		Enjay butyl
		I.I. rubber
		Oppanol B
		Petro-Tex butyl
		Polysar butyl
		Precision butyl
		Vistanex MM
EPR	Ethylene propylene	Angus KR
		APK
		C 23
		Dutral N
		Enjay EPR
		Nordel
		Olethene
Floroelastomers	Vinylidene fluoride hexafluoropropylene	Angus VA, SC
		Fluorel
		Precision fluoro
		Viton
	Fluorosilicone	Precision fluorosilicone
	Trifluorochloro-ethylene-vinylidene-fluoride	Silastic LS 53
Hypalon	Chlorosulfonated polyethylene	Angus HN
		Hypalon
		Precision hypalon
Natural rubber	Natural polyisoprene	Coral
		DPR
		Natsyn
		Okolite
		Shell isoprene
		Trans P.R.

Table C.6. (continued)

Popular name	Generic designation	Trade name
Neoprene GRM	Chloroprene	Angus G
		Neoprene
		Okoprene
		Perbunan C
		Precision neoprene
		Sovprene
		U.S. rubber neoprene
Nitrile; Buna-N; G.R.A.; N.B.R.	Acrylonitrile butadiene	Angus DS, WR, FR, LR, E, P
		Butacril
		Chemigum
		Chemivic
		FR-N
		Herecrol
		Hycar OR
		Parker Nitrile
		Perbunan
		Polysar Krynao
		Precision Nitrile
		Royalite
		Tylac
Polybutadiene; Buna; S.K.A.	Butadiene	Ameripol CB
		BR rubber
		Budene
		Cisdene
		Diene
		Duradene
		Duragen
		Polysay tacktene
		S.K.B.
		Texus synpol EBR
		Trans 4 or cis 4
Polyisoprene synthetic	Synthetic polyisoprene	Ameripol SN
		Coral
		DPR
		Natsyn
		Philprene
		Shell IR
		Trans PIP Cariflex

Table C.6. (continued)

Popular name	Generic designation	Trade name
Polyurethane	Diisocyanate-polyester or polyether	Adiprene
		Chemigum XSL
		Conathene
		Contilan
		Cyanoprene
		Desmodur
		Desmolin
		Disogrim
		Elastocast
		Elastolan
		Elastothane
		Estane
		Genthane
		Guidfoam
		Lamigom
		Mearthane
		Microvon
		Multrathane
		Pagulan
		Phoenolan
		Polyvon
		Precision urethane
		Solithane
		Texin
		Vorylen
		Vulcarprene
		Vulkollan
SBR; Buna-S; GRS; SKB	Styrene-butadiene	Ameripol
		Angus R.G.
		ASRC polymers
		Butaprene S
		Carbonix
		Cariflex
		Chemigum IV
		Copo
		Darex
		Duradene
		Flowbrene
		FR-S
		Gen-flow
		Gentro
		Hycar OS, E, TT

Table C.6. (continued)

Popular name	Generic designation	Trade name
		Krylene Kryflex Nagapol Naugatex Philprene Plioflex Phiolite S Pliotuf Polysar S S polymers Solprene Synpol Tylac
Silicone	Polysiloxane	Angus SIL, SIS Acrosil Cohrlastic Fairprene General Electric SE Parker Silicone Rhodorsils RTV Silastic Union Carbide KY
Thiokol: GRP	Organic polysulfide	Alkylene polysulfide rubber F.A. polysulfide rubber Perduren Precision Thiokol S.T. polysulfide rubber Thioplasts Vulcaplas
Vinylpyridine	Butadiene-2-methyl 5-vinyl pyridine	Philprene

Butyl Rubber

(Threshold - <7 × 10^5 rad for tensile strength)

Butyls are the least radiation-resistant rubbers known. For the tensile strength, the threshold for butyl rubber is reported to be <7 × 10^5 rad; 25% damage occurs at 7 × 10^5 rad and 50% loss occurs at 3 × 10^6 rad. One reference recommends a use limit of ~4 × 10^6 rad for butyl gaskets and seals; another reference suggests a use limit of 5 × 10^6 rad for butyl-based insulation, and still another reference suggests that butyl rubber not be used because of the rapid decrease in mechanical properties with radiation exposure.[1]

Ethylene Propylene

(Threshol - 1 × 10^6 rad for compression set)

Some experimental formulations showed poor radiation resistance; however, a number of commercial materials demonstrated radiation resistance comparable to crosslinked polyethylene. As with other polyolefins, radiation resistance will depend on the effectiveness of antioxidant systems. Dose-rate effects have been identified. No changes in oxidation resistance were found up to 1 × 10^8 rad. Elongation was not significantly changed after an irradiation dose of 5 × 10^6 rad but was degraded by 52% after 5 × 10^7 rad and by 63% after 1 × 10^8 rad.

Fluoroelastomers

(Threshold - 10^5 to 10^6 rad for compression set)

In radiation environments, outgassing of corrosive acids and high compression set can occur for fluoroelastomer O rings, sealants, and gaskets. Thresholds have been reported to be 10^5 and 10^6 rad. It is suggested that fluoroelastomers not be used as dynamic seals beyond 10^6 rad. Changes in mechanical properties have been reported at doses of 10^7 and 10^8 rad in air at room temperature. Of the fluoroelastomers, Kel-F and fluorosilicones (methyl silicone base) are probably the least radiation-resistant. Common names which have been tested include Viton A, Poly FBA, Viton B, Fluorocarbon V747-75, Fluorosilicone L 677-70, HA-1, and HA-2.

Hypalon (CSM)

(Threshold - 5 × 10^5 rad for elongation)

A recommended service limit was set at 5 × 10^7 rad, but it appears that a slightly higher limit could be acceptable. Hydroquinone has been found effective in increasing radiation resistance.

Natural Rubber (NR)

(Threshold - 2 × 10^6 rad for compression set)

The resistance of natural polyisoprene to radiation alone is relatively good. Antiox 4010 (*N*-cyclohexyl-*N*-phenyl-*p*-phenylenediamine) was found to be effective in increasing the radiation resistance. Threshold changes in compression set were noted after 2 × 10^6 rad. Threshold values for elongation and tensile strength are 5.5 × 10^6 rad and 2.4 × 10^7 rad, respectively.

Neoprene (CR)

(Threshold - 8 × 10^5 rad for compression set)

Above 5 × 10^6 rad, a decrease in oxidation resistance has been reported. After a dose of 5 × 10^6 rad, the ultimate elongation was 93% of its original value and only 46% after a dose of

5×10^7 rad. Irradiation in air and vacuum to a dose of 1.9×10^7 rad resulted in a 50% decrease in elongation. One test indicated that two of three commercial neoprene compounds examined exhibited postirradiation degradation after storage in air. One reference noted only minor changes in mechanical properties of an aromatic plasticizer neoprene after a dose of 8.7×10^7 rad. Excessive compression set and loss of flexibility may occur at radiation doses above a few megarads.

Nitrile

(Threshold - 10^6 rad for compression set)

Various copolymers of acrylonitrile and butadiene are commercially available. Polymers with a higher acrylonitrile content tend to show better retention of tensile strength. Elongation of high-acrylo polymers is initially high but may decrease more rapidly than low-acrylo compounds at moderate radiation exposures. This trend in elongation may reverse at higher doses. The stability of high- and medium-percentage acrylo compounds to air irradiation is not greatly affected by carbon black fillers, although better flexibility seems to be retained with minimum carbon black. A large number of antirads have been found to improve overall radiation stability and compression set characteristics.

Polyacrylate

(Threshold - $\sim 10^6$ rad for set-at-break)

The elastomer showed initial changes at $\sim 10^6$ rad and a 25% damage level at 3×10^6 rad. One test on Hycar PA for set-at-break showed a threshold change after 10^6 rad and a 25% increase after 3×10^6 rad. Another study reported threshold change in compression set at 1.5×10^6 rad and 25% increase at $\sim 10^7$ rad. Elongation decreased initially at 3×10^6 rad, 25% at 1.5×10^7 rad, and 50% at 3×10^7 rad. Tensile strength also decreased with a threshold dose at 4×10^6 rad and 25% damage at 6×10^7 rad. Reduction of compression set by the addition of antirads was better than with most other rubbers. Hycar PA-21 showed ~50% compression set at 8.4×10^6 rad; however, with anitrad UOP-88, it exhibited ~50% compression set at 3.7×10^7 rad. Unirradiated controls took on only ~13% compression set. Alpha-naphthyl amine and FLX (*N*-phenyl-*N'O*-tolyethylene diammine) are also recommended antirads.

Polyurethane

(Threshold - $\sim 10^6$ rad for compression set)

Polyurethane has similar radiation resistance to natural rubber. Tensile strength apparently degrades equally at ambient or elevated temperatures. Compression set is greatly increased by elevated temperatures, whether irradiated or not. Irradiation in the presence of moisture may lead to more rapid degradation due to the moisture sensitivity of the material. Polyester-based urethanes are more resistant than are polyether-based materials. Estane VC cured with dicumyl peroxide has shown a 50% compression set after 5.5×10^7 rad. Adiprene C, sulfur cured with carbon black reinforcement, showed poor radiation resistance. Effective antirads include *p*-phenylene diisocyanate and diphenyl methene-4-4′-diisocyanate.

Information from several references indicate different radiation resistances of different materials:

1. After 6×10^7 rad, one VC Estane retained 80% of its initial tensile strength and 50% of its tensile strength after 2×10^8 rad. A 20% decrease in elongation occurred after 1×10^8 rad and a 50% decrease after 3×10^8 rad.

2. A threshold damage for one polyurethane was reported at 8.7×10^6 rad and a 25% damage was found after 4.3×10^7 rad.
3. Polyurethane P642-70 O rings were tested and the hardness was found to be unaffected by 10^8 rad. The tensile strength was not affected at 10^7 rad but had decreased by 60% after a dose of 10^8 rad. The compression set was 55.5% after 10^7 rad and was greater than 90% after 10^8 rad.
4. A urethane cable insulation had lost 50% of its tensile strength after 1×10^7 rad. After 10^8 rad, the tensile strength had decreased by 75%. After 10^7 rad, the elongation was decreased by 10% and by 50% after 2×10^8 rad. The hardness was slightly increased after 10^7 rad and was ~125% of the initial value after irradiation to 10^8 rad.

Silicones

(Threshold - 5×10^5 rad for oxidation resistance)

The silicone rubbers are more resistant to radiation than the butyls and polysulfides; however, a broad range of radiation resistances occurs, depending on the silicone molecule structure, the presence of additives (e.g., fillers and antirads), and the vulcanizing system. The radiation resistance can also be affected by environmental conditions (e.g., elevated temperature, oxidizing conditions, mechanical stress, etc.). For many formulations, the compression set becomes excessive when irradiated; outgassing, however, is less than with hydrocarbon rubbers. Note that peroxide curing agents may leave residues, which make silicone rubber more susceptible to oxidation.

The following information on various silicone rubber materials and components is of considerable interest:

1. A dimethyl silicone cable insulation retained 100% of its tensile strength after a dose of 5×10^7 rad. After 5×10^6 rad, the elongation was reduced by 10% and by 66% after 5×10^7 rad. The oxidation resistance was apparently greatly reduced when irradiated. The cable was suggested usable up to 5×10^7 rad.
2. Connectors that use silicone rubber insulations can withstand exposures to as much as 10^7 R and still provide reasonable electrical performance. Transient decreases in the insulation resistance occur during irradiation with minimums of $<10^7\,\Omega$. Dow Corning R-7521 maintained good electrical and physical properties after 5×10^8 rad. Encapsulating compounds RTV-501 and Sylgard 182 and 183 were reported to not be seriously degraded after exposure to 2×10^6 to 10^8 R gamma.

Styrene-Butadiene (SBR)

(Threshold - 2×10^6 rad for compression set and elongation)

SBR rubbers with the highest styrene content are generally the most radiation resistant. Information on different material test results follows:

1. Threshold changes in the compression set, elongation, and set-at-break were reported after 2×10^6 rad. At 10^7 rad, a 25% change in these properties was noted. Stress cracking has been noted after doses as low as 4.3×10^7 rad.
2. Buna-S indicates no change in hardness below 10^7 rad. For elongation, set-at-break, and compression set, a 50% damage level was reached at 6×10^7 rad. Also, the tensile strength reached threshold at 6×10^7 rad and hardness was 125% of the original value.
3. Synpol 1500 increased its radiation resistance when antirads such as acridine, pyrene, or fluoranthene plasticizers were used. The best antirads recommended for Synpol 1500 were derivatives of *p*-phenylene diamine or phenyl naphthyl amine.

4. A commercial SBR O ring was tested and found that the hardness was not affected below 1×10^7 rad. The stress/strain effects were minor below 3.6×10^7 rad and tensile properties were retained after 1.2×10^8 rad. After 1.6×10^9 rad, elongation was 20%. The compression set was found to be the most sensitive property, with a 50% damage level after a dose of 3×10^7 rad.

Thiokol (PTR)
(Threshold - 3×10^5 rad for hardness)

Thiokol rubbers show better retention of ultimate elongation than do neoprene and polyacrylate elastomers, although the tensile strength degrades rapidly. The radiation resistances of Thiokol ST and Thiokol FA polysulfide rubbers are similar to that of butyl rubber. One Thiokol ST formulation showed a 50% decrease in tensile strength and elongation after 1×10^6 rad. Another Thiokol ST, tested at a different facility, exhibited threshold changes in elongation and set-at-break after 5×10^5 rad and a 25% decrease in those properties after a dose of 4×10^6 rad. Threshold changes in compression set were noted after 6×10^5 rad and in hardness after 3×10^5 rad.

Vinylpyridines
(Threshold - $>10^6$ rad)

The radiation resistance of vinylpyridines is believed to be approximately equal to that of natural rubber. Below 4×10^7 rad, carbon black-filled stock showed little change in tensile strength.

C.4 RADIATION EFFECTS ON LUBRICANTS

Lubricants are used in moving mechanical devices so as to reduce surface friction, to cool, or to prevent corrosion. In general, lubricants are found in four general forms:

- liquid lubricants (e.g., oils),
- greases and lubricants with dissolved solids,
- solid lubricants containing synthetic organic polymers, and
- dry lubricants.[3]

Organic lubricants generally consist of base oils and additives. Base oils are the largest constituent, and additives provide the desired lubricant properties. A base oil can be a blend of several components. The most frequently used commercial lubricants are derived from mineral oils; however, products with synthetic bases, such as esters, ethers, silicones, or polyalkenes (polyolefins), are also encountered.[3] Two types of lubricants (hydrocarbons and aromatic hydrocarbons) are listed in Table C.7 (summarized from ref. 1).

Radiation exposure accelerates the oxidation of lubricants and can degrade their physical and performance properties. Radiation attacks all of the components of lubricants, including the base oils and additives. Irradiation may affect some of the important properties of a lubricant, such as the viscosity, consistency, acidity, or oxidation stability. Continued exposure to radiation eventually turns almost all liquid organic lubricants into hard, brittle solids.[3]

The radiation effects on lubricants depend upon the amount of absorbed energy; the exact composition of the specified material; and environmental conditions such as pressure, temperature, and gaseous composition of the atmosphere. The general effects of radiation on lubricants (from ref. 1) are:

Table C.7. Categories of lubricants

Hydrocarbons	Aromatic hydrocarbons
Heptane	*n*-Butylbenzene
Dodecane	Alkylbenzene 250
Hexadecane	Alkylbenzene 350
Polybutene	Octadecylbenzene
Glycerin	Phenylcyclohexane
n-Butylethyl ether	*m*-Diphenylbenzene
Amyl ether	Dowtherm A
Isoamyl ether	*n*-Butyl phenyl ether
Dimethoxytetraglycol	*n*-Butyl Benzoate
Polypropene oxide	Diethyl-*o*-phthalate
Polybutoxyethene	phenyl *n*-propyl ketone
Butyl hexanoate	Dichloroblphenyl
	Naphthalene
	Phenylnaphthalene
	Pentalene 95
	Pentalene 290
	Dimethyl silicone (DC-200)
	Dimethyl silicone (DC-500)

1. Physical properties are changed, materials of higher and lower molecular weights are formed, and the olefin content is increased.
2. Viscosity increases.
3. Liquid products (fuels and oils) darken and acquire an acrid odor.
4. Hydrogen content decreases and density increases.
5. Gases evolve (e.g., hydrogen and light hydrocarbons).
6. Polymerization to a solid state may occur.

Lubricants may be selected in a given component, primarily for one or more of the following properties:

- Chemical stability
- Compatibility with seals and other materials
- Corrosiveness
- Heat capacity (specific heat)
- Temperature stability
- Thermal or heat conductivity
- Viscosity[1]

When selecting components to be used in a radiation environment, the lubricant that typically comes with gear boxes, bearings, and so on, may have to be removed and replaced with a more radiation-resistant lubricant. If possible, some components are best operated unlubricated in a high radiation environment. If machinery in a nuclear radiation environment must be lubricated, the following guidelines from ref. 4 may be helpful:

1. The organic base fluid of a lubricant is the most important item governing radiation resistance. Base materials vary 1000-fold in ability to withstand radiolysis. The stability of the base materials is listed below, descending in order from the most radiation-resistant to the least radiation resistant.

    polyphenyls
    poly (phenyl ethers)
    alkylaromatics
    aliphatic ethers
    mineral oils
    aromatic esters
    aliphatic esters
    silicones
    aromatic phosphates

2. Oil lubricants, in general, can be classified according to dose ranges as shown in Table C.8.

Table C.8. Dose ranges for oil lubricants

Dose rate	Comments
10^6 rad or below	No unusual problems noted from radiation
10^6 to 10^7 rad	Methyl silicones, aliphatic diesters, and phosphate esters become affected. Polymers in solution degrade. For most other cases, environmental factors other than radiation are controlling
10^7 to 10^8 rad	Radiation effects on physical properties render diesters and certain mineral oils marginal in performance. Oxidation stability and thermal stability are adversely affected for all fluids in this range
10^8 to 10^9 rad	Oxidation and thermal stabilities of most lubricants are seriously changed. Major effects occur in most physical properties. Aliphatic ethers, aromatic esters, and certain mineral oils (carefully selected) may be used
10^9 to 10^{10} rad	Polyphenyls, poly (phenyl ethers), or alkylaromatics are needed
10^{10} rad and above	Radiolysis causes extreme effects. Lubrication with even the best organic fluids is highly restricted, and laminar solids should be considered for use

3. Radiation damage in base oils can be reduced by selected additives. They are most effective in the least stable fluids. However, greater gains in resistance can be made from judicious choices of base stocks than from attempts to improve radiation-sensitive fluids with additives.
4. Additives normally used in lubricants (e.g., antioxidants, antiwear agents, and antifoam agents) can themselves suffer radiation damage. Their depletion during irradiation or their radiolysis products can cause complications at radiation levels below which the base oil itself degrades.
5. Oxidation drastically reduces the life of a lubricant; radiation accelerates oxidation.
6. The role of temperature is interrelated with those of oxygen, additives, and radiation dose. Below about 140°C (284°F), radiation damage is not a function of temperature in the absence of oxygen.
7. Under irradiation, greases first soften because of damage to the gel structure, then harden because of a cross-linking of the oil. Conventional greases are usable to ~10^7 rad. Special products are available for higher doses; a few are usable in the range of 10^9 to 5×10^9 rad. For example, Mobil 28, a polyalpha olefin, is reported to withstand gamma radiation to 3×10^9 rad.[1]
8. Typical elastomers used in seals, which are in contact with lubricants, are 2 to 10 times more sensitive to radiolysis than are lubricants. Elastomer stability is the limiting factor in many lubrication systems. (See Appendix C.3 for a discussion concerning elastomers.)
9. Many machine elements have some tolerance for degraded lubricants. In some cases, a system will function for a higher radiation dose than would be predicted from the static radiation changes in a critical physical property.

Radiation degradation for some lubricating base oils is contained in Table C.9 (summarized from ref. 8). Data on specific nuclear radiation-resistant greases are shown in Table C.10. For more detailed information on lubricants and the effects of radiation, see ref. 4.

Table C.9. Radiation effects on lubricants

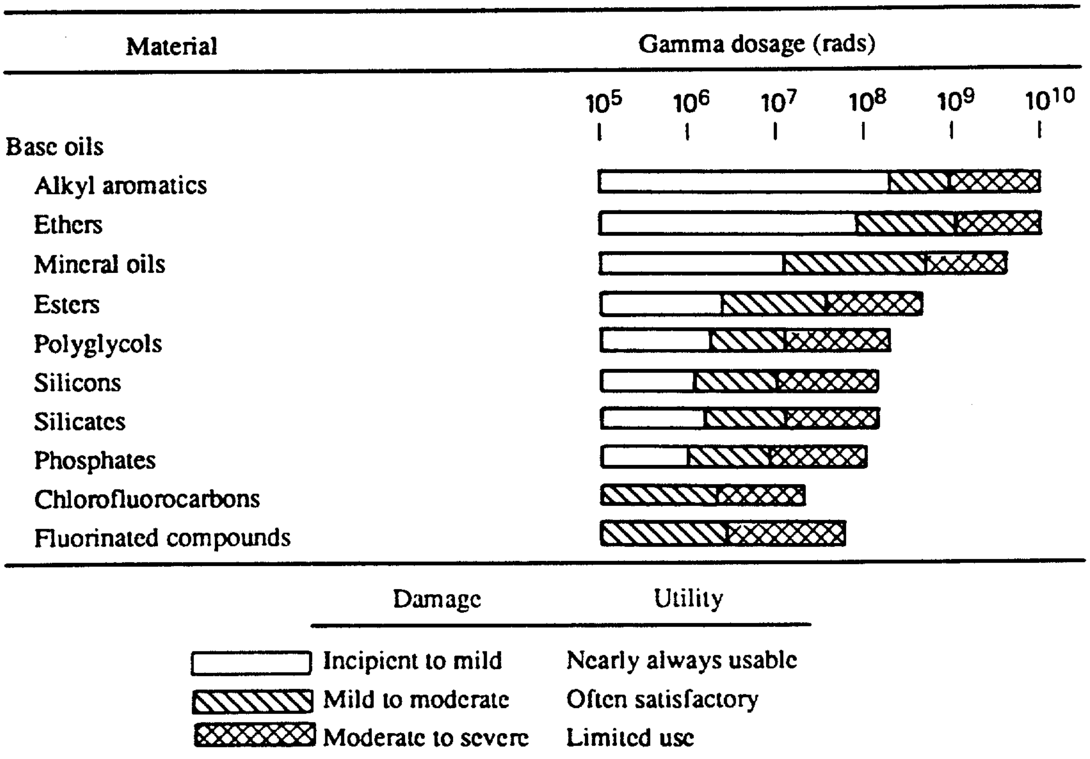


Table C.10. Summary of nuclear radiation-resistant lubricants

Product	Operating range °F (°C)[a]	Radiation dose limit (10^8 rad)	Product description	Recommended use
NRRG-159 (NLGI Grade 2-1/2)	-10 to 325 (-23 to 163)	30	Special synthetic aromatic oil; sodium amate thickener; selenide oxidation inhibitor	Antifriction bearings; motors; pumps; accessories
NRRG-235 (NLGI Grade 2)	0 to 200 (-19 to 93)	50	Synthetic aromatic oil, silica thickener; selenide oxidation inhibitor. Contains graphite and molybdenum disulfide as "residual lubricants"	Low-speed, high-load sliding surfaces, screw mechanisms; Provides residual lubrication in remote machinery, such as remote valves
NRRG-335 (NLGI Grade 2)	0 to 250 (-18 to 121)	50	Synthetic aromatic oil, sodium amate thickener; selenide oxidation inhibitor	Antifriction bearings, valve actuating and screw mechanisms
NRRG-509 (NLGI Grade 0)	0 to 200 (-19 to 93)	50	A soft (ASTM worked penetration 360 to 380) version of NRRG-335 containing molybdenum disulfide	Special product for enclosed gear trains or any services including a semifluid lubricant
Chevron Industrial Grease Medium (NLGI Grade 1-1/2)[b]	-10 to 325 (-23 to 163)	10	Mineral oil; sodium amate thickener, oxidation and rust-inhibited; excellent worked stability	Antifriction bearings; motors; pumps; accessories
Chevron SRI Grease 2 (NLGI Grade 2)[b]	-10 to 325 (-23 to 163)	5	One medium grade; mineral oil; polyurea thickener, oxidation and rust inhibited	Antifriction bearings; motors; pumps; accessories

Table C.10. (continued)

Product	Operating range °F (°C)[a]	Radiation dose limit (10^8 rad)	Product description	Recommended use
NRRO-358	+20 to 225 (-7 to 107)	50	Low viscosity aromatic base oil plus selected polymers (some split and some crosslink) to provide a "constant viscosity" effect; selenide-inhibited	Hydraulic pumps and accessory equipment; gear trains; control mechanisms
NRRO-360	+20 to 225 (-7 to 107)	50		
Chevron OC Turbine Oil[b]	+20 to 225 (-7 to 107)	0.5	Various viscosity grades; blends of solvent refined paraffinic mineral oils; oxidation-inhibited	Industrial steam turbines and related uses; general purpose oil lubrication

[a] In air, can be extended in inert atmosphere.

[b] Conventional lubricant which provides satisfactory lubrication under low dosage radiation.

Source: Chevron Technical Bulletin No. 10, Chevron U.S.A., Inc., 1978.

C.5 RADIATION EFFECTS ON PLASTICS

Plastics are generally equal or superior to elastomers in radiation resistance. The rigid plastics are more radiation-resistant than the softer plastics. The two general types of plastics are thermoplastics and thermosetting plastics. Thermoplastics soften when heated but return to their original properties when cooled, and these are the most versatile plastics. Crosslinking can transform them into thermosetting materials.[3] Thermosetting plastics harden permanently during heating or curing, forming rigid plastics. Many of these are quite radiation-resistant, but also are less versatile than thermoplastics.[3] Detailed radiation effects information on thermoplastics and thermosetting plastics is contained in the remainder of this appendix. Also included is a listing of plastic materials and their chemical and trade names in Table C.11.

Table C.11. Ranking of radiation resistance of plastics

Highest radiation-resistant plastics	glass-fiber phenolics
	asbestos-filled phenolics
	certain epoxy systems
	polyurethane
	polystyrene
	mineral-filled polyester
	mineral-filled silicones
	furane-type resins
	polyvinyl carbazole
Moderate radiation-resistant plastics	polyethylene
	melamine-formaldehyde resins
	urea-formaldehyde resins
	aniline-formaldehyde resins
	urfilled phenolic resins
	silicone resins
Poor radiation-resistant plastics	methyl methacrylate
	unfilled polyesters
	cellulosic
	polyamides
	Teflon

Some plastics are more radiation-resistant than are others. Plastics can be categorized in general groups according to radiation resistance and are shown in Table C.11.

Gassing (the giving off of gas) of most plastics is a problem in enclosed or poorly ventilated systems. Fluorine-containing materials, such as Teflon, Kel-F, or PVC, experience degradation of physical properties due to irradiation and will liberate halogen or halogen acid, which can have corrosive effects on adjacent components at ~10^4 rad for Teflon, 10^6 rad for Kel-F, and 10^7 rad for PVC.

Many thermosetting plastics and thermoplastics are more easily recognized by their trade or family name. To aid with materials analysis, information on the family, trade, and general names for thermoplastics and thermosetting plastics are furnished in Tables C.12, C.13, and C.14.

Table C.12. Trade names and chemical names for thermoplastics and thermosetting plastic materials

Trade name	Chemical name
ABCOLITE	Polystyrene (PST)
ABSON	Acrylonitrile butadiene styrene (ABS)
ACETOPHANE	Cellulose acetate
ACROLITE	Urea formaldehyde
ACRONAL	Acrylic resin
ACRYLOID	Polyacrylester
ACRYSOL	Polyacrylester
ACRYTEX	Polyacrylacid
AFCOLENE	Polystyrene
AGILENE	Polyethylene
AGILIDE	Polyfinylchloride
AKULON	Polyamide
ALATHON	High-pressure polyethylene
ALBAMIT	Melamine formaldehyde
ALEOTHEX	Polyvinylalcohol (PVA)
ALGOFLON	Polytetrafluorethylene (PTFE)
ALKATHENE	Polyethylene
ALKON	Polyacetal
ALKYLDALE	Polyaster
ALPHALUX 400	Polyphenylene oxide (PPO)
ALTUGLAS	Acrylic resin
AMEROID	Casein resin
AMPACET	Polystyrene
ARALDITE	Epoxy resin
ARNITE	Polyethylene terephthalate
AROPOL	Polyester
ASTRALIT	Polyvinylchloride (PVC)
ATLAC	Polyester
BAKELITE	Polyvinylchloride, polyethylene, polypropylene, polystyrene, phenoxy, and polysulfone
BENVIC	Polyvinylchloride
BEXOID	Cellulose acetate
BECTRENE	Polystyrene
BLENDEX	Arylonitrile butadiene styrene (ABS)

Table C.12. (continued)

Trade name	Chemical name
BONOPLEX	Polymethacrylester
BUTACITE	Polyvinylbutyral
BUTOFAN	Copolymer butadiene styrene
CALADENE	Phenolic
CAMPCO C119	Polycarbonate
CAPRAN (film)	Polyamide 6
CARDURA	Epoxy resin
CARINA	Polyvinylchloride
CARINEX	Polystyrene
CARLONA	Polyethylene
CARLONA P	Polypropylene
CASCO RESINS	Urea formaldehyde, phenolic
CATABOND	Polyester
CATALIN	Phenolic
CEAPREN	Polyester
CELLIDOR	Cellulosics
CELLIT	Cellulosics
CELLOFOAM	Polystyrene
CELSON	Polyoxymethylene
CIBANITE	Aniline formaldehyde
COVISIL	Silicone
CR 39	Diallyl-polycarbonate
CRYSTIC	Polyester
CYCOLAC	Acrylonitrile butadiene styrene (ABS)
CYMEL	Melamine formaldehyde
DACRON	Polyethylene terephthalate
DAPLEN	Polypropylene
DAPON	Polyester
DARVIC	Polyvinylchloride
D. C. RESINS	Silicone
DEDERON	Polyamide
DELRIN	Acetal

Table C.12. (continued)

Trade name	Chemical name
DESMODENE	Polyester
DESMODUR	Polyurethane
DESMOPHEN	Polyurethane
DEVCON	Epoxy resin
DIAFLON	Polytetrafluorethylene (PTFE)
DIORIT	Polymethylmethacrylate
DOLAN	Polyacrylonitrile
DOW CORNING	Silicones
DOWEXSO	Polystyrene (sulfonated)
DRALON	Polyacrylonitrile
DURALON	Furan resin
DURATHON	Polyacetal
DURETHANE	Polyurethane
DUREZ	Phenolic
DURITE	Phenolic
DYLAN	Polyethylene
DYLENE	Polystyrene
DYNAPOL	Polyester
DYXYL	Polyamide
EKAVYL	Polyvinylchloride
ELVANOL	Polyvinylalcohol
ELVAZET	Polyvinylacetate
EMULTEX	Polyvinylacetate
EPIALL	Epoxy resin
EPIKOTE	Epoxy resin
EPON	Epoxy resin
EPOPHEN	Epoxy resin
EPOXYLITE	Epoxy resin
ERINOLD	Casein resin
ERTACETAK	Polyacetal
ERTAKIB	Polyamide
ERTALYTE	Polythylene teraphthalate
ERTAPHENYL	Polypheylene oxide
ERVALKYD	Alkyd resin
ESTANE	Polyurethane

Table C.12. (continued)

Trade name	Chemical name
ETHOCEL	Ethyl cellulose
EXON	Polyvinylchloride
FLEXON	Polyvinylchloride
FLUON	Polytetrafluoroethylene (PTFE)
FLUORLON	Polytetrafluoroethylene (PTFE)
FLUOROTHENE	Polychlorotrifluoroethylene (PCTFE)
FORMICA	Melamine-formaldehyde
FORMVAR	Polyvinylformal
FORTICEL	Cellulosics
GABRASTER	Polyester
GABRITE	Urea formaldehyde
GANSOLITE	Casein resin
GEDEX	Polystyrene
GELVA	Polyvinylacetate
GELVATOL	Polyvinylalcohol
GEON	Polyvinylchloride
GLIDPOL	Polyester
GRILON	Polyamide
H Film and HT film	Polyamide
HALON	Polytetrafluoroethylene (PTFE)
HAVEG	Phenolic
HERCULON	Polypropylene
HETRON	Polyester
HIFAX	Polyethylene
HOSTAFLON	Polychlorotrifluoroethylene (PCTFE)
HOSTAFLON TF	Polytetrafluoroethylene
HOSTAFORM C	Polyoxymethylene
HOSTALEN G	Polyethylene
HOSTALEN PPH	Polyprophlene
HOSTALIT	Polyvinylchloride
HOSTYREN	Polystyrene
HYDEFLON	Polytetrafluoroethylene (PTFE)

Table C.12. (continued)

Trade name	Chemical name
IGAMID U	Polyurethane
IGELIT	Polyvinylchloride
IXAN	Polyvinylidene chloride
KAPTON (film)	Poly~~a~~mide Polyimide
KARBATE	Phenolic
KEL F	Polychlorotrifluoroethylene (PCTFE)
KOROSEAL	Modified polyvinylchloride
KRALASTIC	Acrylonitrile butadiene styrene (ABS)
KYNAR	Polyvinylidene fluoride
LACQRENE	Polystyrene
LACTOPHANE	Cellulosics
LAMINAC	Polyester
LAROMIN	Polyamine
LEGUVAL	Polyester
LEKUTHERM	Epoxy resin
LEXAN	Polycarbonate
LORKALENE	Polystyrene
LUCITE	Polymethyl methacrylate
LUCOVYL	Polyvinylchloride
LUPOLEN	Polyethylene
LURAN	Styrene acrylonitrile (SAN)
LUSTRAN	Acrylonitrile butadiene styrene (ABS)
LUSTREX	Polystyrene
LUVICAN	Polyvinylcarbazole
MAKROLON	Polycarbonate
MARBLETTE	Phenolic
MARCO MR	Polyester
MARFOAM	Polyurethane
MARLEX	Polyethylene
MARVINOL	Polyvinylchloride
MELINEX	Polyethylene terephthalate
MELMAC	Melamine formaldehyde
MELOX	Melamine formaldehyde
MERAKLON	Polypropylene

Table C.12. (continued)

Trade name	Chemical name
MERLON	Polycarbonate
MICARTA	Phenolic
MONDUR	Isocyanates
MONSANTO	Polystyrene
MOPLEN	Polyvinylacetate
MOWILITH	Polyvinylacetate
MOWIOL	Polyvinylalcohol
MYLAR	Polyethylene terephthalate
3M	Epoxy resin
NAILONPLAST	Polyamide
NOMEX YARN	Polyamide (aromatic)
NORSOLENE	Coumarone resin
NORYL	Polyphenylene oxide
NOVODUR	Acrylonitrile butadiene styrene (ABS)
NYLON	Polyamide
OPALON	Polyvinylchloride
ORGAMID	Polyamide
ORIZON	Polyethylene
ORLON	Polyacrylonitrile
OROGLAS	Polymethacrylester
OXIDWACHS	Polyethyleneglycol
PARAPLEX	Polyester
PARYLENE N,C,D	Parylene
PENTON	Chlorinated polyether
PERLON	Polyurethane
PERLON L	Polyamide
PERSPEX	Polymethyl methacrylate
PHENOLITE	Phenolic
PHOTEX	Polyacrylacid
PLASKON ALKYD	Polyester
PLASTACELE	Cellulose acetate

Table C.12. (continued)

Trade name	Chemical name
PLEOGEN	Polyester
PLEXIDUR	Polymethyl methacrylate
PLEXIGLAS	Polymethyl methacrylate
PLEXILEIM	Polyacrylacid
PLIOVIC	Polyvinylchloride
PLYOPHEN	Phenolic
POLECTRON	Polyvinylcarbazole
POLYDUR	Polyethylene
POLYFLON	Polytetrafluoroethylene
POLYOX	Polyethylene
POLYSTYROL	Polystyrene
POLYTHENE	Polyethylene
POLYTHERM	Polyvinylchloride
POLYVIOL	Polyvinylalcohol
PPO	Polyphenylene oxide
PROFAX	Polypropylene
PROPATHENE	Polypropylene
PROPIOFAN	Polyvinylacetate
PRYALINE	Cellulose nitrate
RAYOLIN	Polyolefin
RESIMENE	Melamine formaldehyde
RESINOL	Phenolic
RESINOX	Phenolic
RESOCEL	Phenolic
RESOFIL	Phenolic
RHODANITE	Cellulose acetate
RHODOPAS	Polyvinylacetate
RHODORSIL	Styrene acrylonitrile (SAN)
RHODOVIOL	Polyvinylalcohol
RILSAN	Polyamide
ROSITE 2000	Phenolic
ROYALITE	Acrylonitrile butadiene styrene (ABS)
SAFLEX	Polyvinylbutyral
SARAN	Polyvinylidiene chloride

Table C.12. (continued)

Trade name	Chemical name
SARAN F	Polyvinylchloride
SELECTRON	Polyester
SICRON	Polyvinylchloride
SILMAR	Polyester
SODETHANE	Polyurethane
SOLITHANE	Polyurethane
SOLVIC	Polyvinylchloride
SOMOPLAS	Polyvinylchloride
SOREFLON	Polytetrafluoroethylene
STYREX	Polystyrene
STYROFOAM	Polystyrene
STYRON	Polystyrene
STYROPOR	Polystyrene
SURLYN	Ionomer resin
SUSTONAT	Polycarbonate
SYLGAND	Silicone
SYNVAREN	Phenolic
SYNVARITE	Phenolic
SYNVAROL	Urea formaldehyde
TEDLAR	Polyvinylfluoride
TEFLON	Polytetrafluoroethylene
TEFLON FEP	Copolymer of hexafluoropropene and tetrafluoroethylene
TENITE	Polypropylene
TENITE BUTYRATE	Cellulose acetate butyrate
TERLURAN	Styrol polymer
TERPLEX	Polymethacrylester
TERYLENE	Polyethylene terephthalate
TETRAN	Polytetrafluoroethylene
TEXIN	Polyurethane
TORTULEN P	Polypropylene
TREVIRA	Polyethylene terephthalate
TRIACEL	Cellulose acetate
TRITHENE	Polychlorotrifluoroethylene

Table C.12. (continued)

Trade name	Chemical name
TROGAMID	Polyamide
TROLEN P	Polypropylene
TROLITUL	Polystyrene
TRULON	Polyvinylchloride
TUFNOL	Phenolic
TYBRENE	Acrylonitrile butadiene styrene (ABS)
TYGON	Polyvinylchloride
ULTRAMID	Polyamid
ULTRON	Polyvinylchloride
UNION CARBIDE	Silicone resin
UROX	Urea formaldehyde
VARCUM	Phenolic
VELON	Polyvinylidene chloride
VESPEL	Polyimide
VESTAMID	Polyamide
VESTAN	Polyvinylidene chloride
VESTOLEN	Polyethylene
VESTOLITE	Polyvinylchloride
VESTYRON	Polystyrene
VIBRATHANE	Polyester
VIBRIN	Polyester
VINAROL	Polyvinylalcohol
VINAVIL	Polyvinylacetate
VINAVINOL	Polyvinylalcohol
VINIDUR	Polyvinylchloride
VINNAPAS	Polyvinylacetate
VINNOL	Polyvinylchloride
VINOFLEX PC	Polyvinylchloride
VINYLITE A	Polyvinylacetate
VINYLITE	Polyvinylchloride
VINYLON	Polyvinylalcohol

Table C.12. (continued)

Trade name	Chemical name
VIPLA	Polyvinylchloride
VISCOSE	Cellulosics
VYBAK	Polyvinylchloride
WELVIC	Polyvinylchloride
XYLONITE	Cellulostics
ZETAFIN	Polyethylacrylate
ZYTEL	Polyamide

C.5.1 THERMOPLASTICS RADIATION INFORMATION

Table C.15 gives test data for radiation effects on thermoplastics (summarized from ref. 8) and the remainder of this section contains detailed radiation information on various thermoplastic materials. The major source for this section of the appendix is ref. 2, with additional information from other sources as indicated.

Acetal Resins

(Threshold - 6×10^5 rad for tensile strength and elongation)

Acetal resins are often used as gears, bearings, or other molded plastic parts. The acetal copolymer is sold as Celcon. Some other copolymers are Alkon, Durathon, Ertacetal, and Hostaform C. The only test data found are for the homopolymer, Delrin. Reference 3 delineates several other sources for which the threshold dose ranges from 1×10^5 rad, 20% decrease of tensile strength at 3×10^6 rad, to a 20% loss of elongation at 1×10^6 rad, to a 50% decrease of tensile strength at 8×10^6 rad, and to a 50% loss of elongation at 2×10^6 rad. For tests done on a 0.02-in. specimen, a 90% loss of elongation was demonstrated at 3×10^6 rad.[2]

Acrylic Resin

(Threshold - 7×10^5 rad for tensile strength and elongation)

Acrylic resin is generally 90% (or more) polymethyl methacrylate. The test data cited in ref. 2 indicate that Lucite and Plexiglass have fairly equal radiation resistances. Lucite shows a threshold dose of ~7.5×10^5 rad, a 25% loss in elongation and tensile strength at 10^7 rad, and a 50% loss at 2×10^7 rad. Loss in light transmission was ~50% at 5.5×10^6 rad. The shear strength and impact strength were first affected at 10^7 rad; they were reduced by 25% at 4×10^7 and decreased by 50% at 6.2×10^7 rad.[2]

Increased oxidation has been noted following irradiation. Gases are often trapped in the polymer, and heating during irradiation causes foaming and expansion of the material to 5 to 10 times the original volume by trapped gases.[2]

Table C.13. Family, chemical, and trade names of thermoplastic materials

Family name	Chemical name	Trade name
Acetals	Polyacetal	Alkon
		Celson
		Delrin
		Curathon
		Ertacctal
		Hostaform C
Acrylics	Acrylic resin	Acnyloid
		Acronal
		Acrysol
		Altuglas
		Bonoplex
		Diakon
		Lucite
		Oroglas
		Perspex
		Plexidur
		Plexiglas
		Terplex
		Zetafin
	Polyacrylonitrile	Dolan
		Dralon
		Orlon
Cellulosics	Cellulose esters	Acetophane
		Bexoid
		Cellidor
		Cellit
		Cellophane
		Forticel
		Lactophane
		Plasticele
		Pyraline
		Rhodanite
		Tenite butyrate
		Triacel
		Xylonite
	Ethyl cellulose	Ethocel

Table C.13. (continued)

Family name	Chemical name	Trade name
Halogenated polymers (Polyvinylchloride)	Agilide	Astralit
		Bakelite
		Benvic
		Carina
		Darvic
		Ekavyl
		Exon
		Flexon
		Geon
		Hostalit
		Igelit
		Koroseal
		Lucovyl
		Marvinol
		Opalon
		Pliovic
		Polytherm
		Saran F
		Sicron
		Solvic
		Somoplas
		Trulon
		Tygon
		Ultron
		Vestolite
		Vinidur
		Vinnal
		Vinoflex
		Vinylite
		Vipla
		Vybac
		Welvic
	Polyvinylfluoride	Tedlar
	Polytetrafluoroethylene (PTFE)	Algoflon
		Diaflon
		Fluon
		Fluorlon
		Halon
		Hostaflon TF
		Hydeflon

Table C.13. (continued)

Family name	Chemical name	Trade name
		Polyflon Soreflon Teflon Tetran
	Polychlorotrifluoro- Fluorothene ethylene (PCTFE)	Hostaflon Kel F Trithene
	Polyvinylidene chloride	Diorit Ixan Saran Velon Vestan
	Polyvinylidene fluoride	Kynar
Phenoxy resins	Phenoxy	Bakelite
Polyamides	Polyamide	Akulon Capran (film) Dederon Drxyl Ertalon Grilon Nailonplast Nomex (aromatic) Nylon Orgamid Perlon L Rislan Trogamid Ultramid Vestamid Zytel
Polycarbonates	Polycarbonate	Campco C119 Lexan Makrolon Merlon Sustonat

Table C.13. (continued)

Family name	Chemical name	Trade name
Polyolefines	Polyethylene	Agilene
		Alathon (high pressure)
		Bakelite
		Carlona
		Dylan
		Hifax
		Hostalen G
		Lupolen
		Marlex
		Orizon
		Polydur
		Polythene
		Rayolin
		Vestolen
	Polypropylene	Bakelite
		Carolina P
		Daplen
		Herculon
		Hostalen PPH
		Meraklon
		Moplen
		Pro-fax
		Propathene
		Tenite
		Tortulen P
		Trolen P
	Ionomer resin	Surlyn
Polyethylene terephthalate	Arnite	
same		Dacron
		Ertalyte
		Melinex
		Mylar
		Terylene
		Trevira
Polyphenylene oxide		Alphalux 400
Polyphenylene oxide		Ertaphenyl
		Noryl
		PPO

Table C.13. (continued)

Family name	Chemical name	Trade name
Polysulfones	Polysulfone	Bakelite
Styrene polymers	Polystyrene	Abcolite Afolene Ampacet Bakelite Bextrene Carinex Cellofoam Dowexso Dylene Gedex Hostyren Lacqrene Lorkalene Lustrex Monsanto Polystyrol Styrex Styron Styropor Terluran Trolitul Vestyron
	Acrylonitrile-butadiene-styrene copolymer	Abson Blendex Cycolac Kralastic Lustran Novodur Royalite Tybrene
	Styrene-acrylonitrile copolymer	Luran Rhodorsil

Table C.13. (continued)

Family name	Chemical name	Trade name
Vinyl polymers	Polyvinylacetate	Elvazet Emultex Gelva Movolith Propiofan Rhodopas Vinavil Vinnapas Vinylite A
	Polyvinylalcohol	Aleothex Elvanol Gelvatol Mowiol Polyviol Rhodoviol Vinarol Vinavinol Vinylon
	Polyvinylbutyral	Butacite Saflex
	Polyvinylformal	Formvar
	Polyvinylcarbazole	Luvican Polectron

Acrylonitrile-Butadiene-Styrene (ABS)
(Threshold - ~10^7 rad for tensile strength)

After a threshold dose of 10^7 rad, the tensile strength increases slightly and then decreases after ~2×10^8 rad. After 10^9 rad, slightly more than 50% of the original value is retained. Other styrene copolymers also exhibit radiation resistances less than commercial polystyrene (threshold of 2×10^7 rad). The radiation resistance depends upon the relative proportions of the polymer components. Styrene-acrylonitrile and styrene-butadiene survive electron irradiation to 1.8×10^9 rad; however, the electrical properties are degraded. Styrene-divinyl benzene is little affected under the same conditions. Poly-alpha-methyl styrene also shows radiation resistance somewhat less than does polystyrene. Since polystyrene shows postirradiation oxidation effects, copolymers probably will also. ABS and SAN are common commercial names for these materials.

Table C.14. Chemical and trade names of thermosetting materials

Chemical name	Trade name
Aminoplast	Acrolite Albamite Casco resins Cibanite Cymel Formica Gabrite Melmac Melox Resimene Synvarol Urox
Casein resin	Ameroid Erinoid Gansolite
Epoxy resin	Araldite Cardura Devcon Epiall Epikote Epon Epophen Epoxylite Lekuthem 3M
Furan resin	Duralon
Phenolic	Caladene Catalin Durez Durite Haveg Karbate Marblette Micarta Phenolite Resinol Resinox Resocel Rosite 2000 Synvaren

Table C.14. (continued)

Chemical name	Trade name
	Synvarite
	Tufnol
	Varcum
Polyester	Alkyldale
	Aropol
	Atlac
	Catabond
	Ceapren
	Crystic
	Dacron
	Dapon
	Desmodene
	Dynapol
	Ervalkyd
	Gabraster
	Glidpol
	Hetron
	Laminac
	Leguval
	Marco MR
	Paraplex
	Plaskon
	Pleogen
	Selectron
	Silmar
	Vibrathane
	Vibrin
	Vulcaprene
~~Polymide~~ Polyimide	Kapton (film)
	Vespel
Polyurethane	Desmodur, Desmophen
	Durethane
	Estane
	Igamid U
	Perlon
	Sodethane
	Solithane
	Texin

Table C.14. (continued)

Chemical name	Trade name
Silicone resin	Covisil D.C. resins Dow Corning Silopren Sylgand Union Carbide

Aliphatic Polyamide (Nylon Fiber)
(Threshold - 8.7 × 10^4 rad for flex life)

Nylon cords that are irradiated show signs of degradation at 8.7 × 10^4 rad. After a dose of 1.7 × 10^7 rad, nylon fiber with an age resistor and phenothiazine show little change in tensile strength and was 1.5 higher than the original elongation.

Aramid
(Threshold - 7 × 10^6 rad for elongation)

Nomex yarns (an aramid) have been tested to 3.3 × 10^8 rad and still show no effects. Aromatic polyamides show considerably better radiation resistance than do aliphatic polyamides and are less sensitive to oxidation. Nomex yarn and Kevlar are some commercial names for these materials.

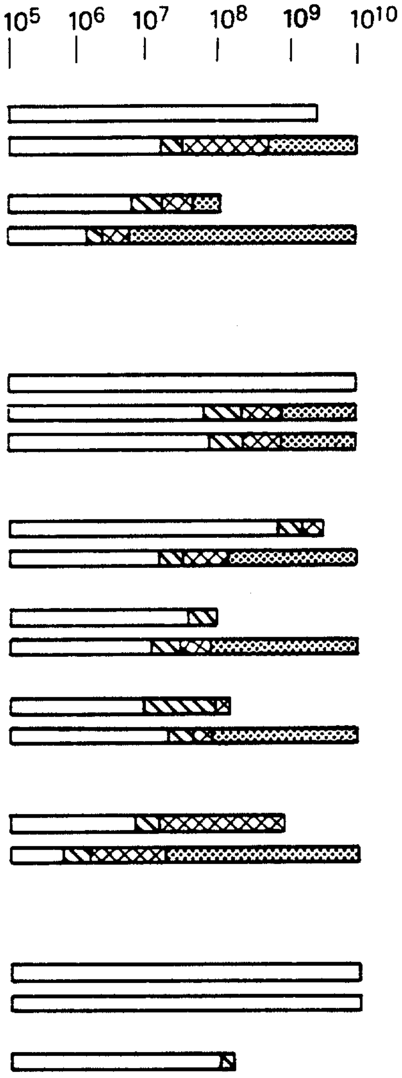
Cellulose
(Threshold - 1 × 10^5 rad for tensile strength)

Cellulose is the basic component of electrical insulating papers. The threshold dose for cotton fibers irradiated in air is ~10^5 rads. A 23% loss in tensile strength was observed at 4.4. × 10^6 rad. The breaking strength was reported to decrease from 5 to 7% for 1 × 10^6 rad. Postirradiation degradation occurs only if the moisture content of the irradiated samples is quite low. Rapid degradation occurs at high doses. The crystallinity was reportedly decreased and the hydrolysis rate was increased.[2]

Cellulose Acetate
(Threshold - 8 × 10^5 rad for tensile strength)

Reference 2 cites the threshold dose for rayon fibers as 8 × 10^5 and the suggested use limit as 2 × 10^7 rad. Some reduction in thermal resistance was noted. The effect was the same in air or nitrogen at various dose rates. Initial changes in shear strength of Plasticele were noted at 2 × 10^6 rad, a 25% decrease at 2 × 10^6 rad, and a 50% loss at 3 × 10^7 rad. The elongation and impact resistance degraded at approximately the same rate. The tensile strength was 50% of the original value at 6 × 10^7 rad. The dielectric properties of cellulose acetate are reported to be stable to higher radiation doses than are physical properties.[2]

Table C.15. Effects of radiation on mechanical properties of thermoplastics

Material	Initial value	Dose Rate Mrads/h	Thickness, (in.)	Percent of initial value decreased at given dose (rads)[a]
A. Hydrocarbon polymers				
1. High-density (linear) polyethylene				
a. Super dylan:				
Tensile strength, psi	3000	2	0.12	
Elongation at break, %	170			
b. Marlex-50:				
Tensile strength, psi	4280	1	0.002	
Elongation at break, %	600			
2. Low-density (branched) polyethylene				
a. Alathon:				
Tensile strength, psi	1400	2	0.19	
Elongation at break, %	250			
Notch impact strength, ft-lb/in.	11.2			
b. Alathon 10:				
Tensile strength, psi	1820	2	0.13	
Elongation at break, %	450			
c. Alathon 3:				
Tensile strength, psi	1915	1	0.003	
Elongation at break, %	380			
d. Irrathene 101:				
Tensile strength, psi	2390	1	0.010	
Elongation at break, %	525			
3. Polypropylene (Profax)				
Tensile strength, psi	4660			
Elongation at break, %	70			
4. Polystyrene				
a. Clear polystyrene:				
Tensile strength, psi	1800	2	0.12	
Elongation at break, %	0.32			
b. Polyflex:				
Tensile strength, psi	11300	1	0.002	

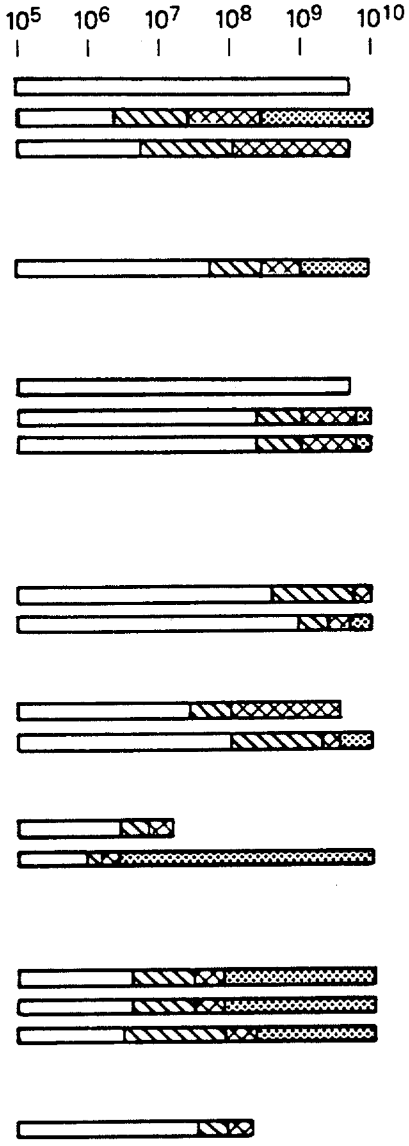
[a] Key for radiation effects:

▭	0-20% decrease of initial value
▧	20-50% decrease of initial value
▦	50-90% decrease of initial value
▒	90-100% decrease of initial value

Table C.15. (continued)

Material	Initial value	Dose Rate Mrads/h	Thickness, (in.)
c. High-impact polystyrene:			
Tensile strength, psi	3100	2	0.10
Elongation at break, %	20		
Notch impact strength, ft-lb/in.	0.67		
5. Polyalpha-methyl styrene			
Shear strength, psi	6000	2	0.17
6. Butadiene-styrene copolymer Rubber blend (Pliotuf)			
Tensile strength, psi	4300	2	0.08
Elongation at break, %	3.8		
Notch impact strength, ft-lb/in.	0.8		
B. Oxygen-containing polymers			
1. Polyvinyl formal			
Tensile strength, psi	7400	2	0.005
Elongation at break, %	2		
2. Polyvinyl butyral			
Tensile strength, psi	2200	2	0.016
Elongation at break, %	220		
3. Polyformaldehyde (Delrin)			
Tensile strength, psi	10450		0.02
Elongation at break, %	70		
4. Polymethyl methacrylate			
a. Lucite			
Tensile strength, psi	10700	2	0.13
Elongation at break, %	4.5		
Notch impact strength, ft-lb/in.	0.37		
b. Plexiglass II			
Notch impact strength, ft-lb/in.	1.0	0.5	0.25

Percent of initial value decreased at given dose (rads)[a]



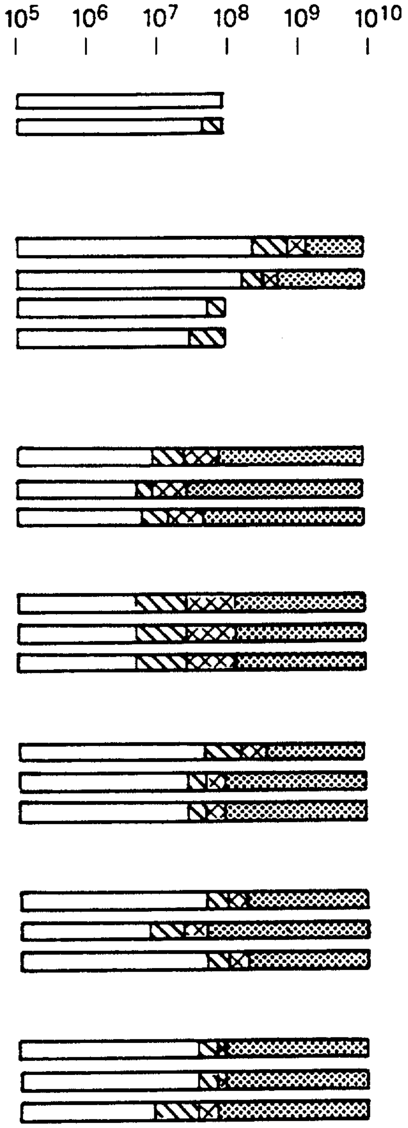
[a]Key for radiation effects:

- □ 0-20% decrease of initial value
- ▧ 20-50% decrease of initial value
- ▩ 50-90% decrease of initial value
- ▒ 90-100% decrease of initial value

Table C.15. (continued)

Material	Initial value	Dose Rate Mrads/h	Thickness, (in.)
5. Polycarbonate (Macrofol):			
Tensile strength, psi	6800	1	0.003
Elongation at break, %	75		
6. Polyethylene terephthalate Mylar "A"			
Tensile strength, psi	25000	2	0.002
Elongation at break, %	50		
Tensile strength, psi	20300	1	
Elongation at break, %	150		
7. Cellulosics:			
a. Ethyl cellulose			
Tensile strength, psi	6000	2	0.125
Elongation at break, %	40		
Notch impact strength, ft-lb/in.	2.0		
b. Cellulose propianate			
Tensile strength, psi	2600	2	0.62
Elongation at break, %	1.6		
Notch impact strength, ft-lb/in.	1.1		
c. Cellulose acetate			
Tensile strength, psi	5300	2	0.125
Elongation at break, %	20		
Notch impact strength ft-lb/in.	1.37		
d. Cellulose nitrate			
Tensile strength, psi	7600	2	0.125
Elongation at break, %	30		
Notch impact strength, ft-lb/in.	2.75		
e. Cellulose acetate-butyrate			
Tensile strength, psi	4200	2	0.180
Elongation at break, %	60		
Notch impact strength, ft-lb/in.	3.3		

Percent of initial value decreased at given dose (rads)*



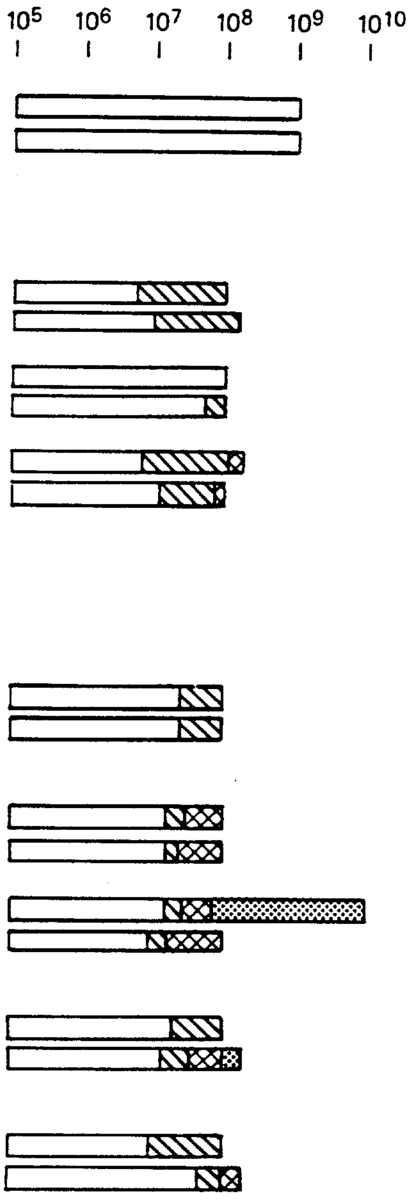
*Key for radiation effects:

☐ 0-20% decrease of initial value
▨ 20-50% decrease of initial value
▩ 50-90% decrease of initial value
░ 90-100% decrease of initial value

Table C.15. (continued)

Material	Initial value	Dose Rate Mrads/h	Thickness, (in.)
C. Halogen-containing polymers			
1. Rigid polyvinyl chloride			
Tensile strength, psi	8100	0.2	0.17
Notch impact strength, ft-lb/in.	0.5		
2. Plasticized polyvinyl chloride			
a. (Ceon 8630)			
Tensile strength, psi	2555	1	0.004
Elongation at break, %	245		
b. (Ceon 8630)			
Tensile strength, psi	2735	1	0.02
Elongation at break, %	300		
c. (Ceon 8640)			
Tensile strength, psi	3150	1	0.004
Elongation at break, %	225		
3. Polyvinyl chloride with special plasticizers (70 parts plasticizer per 100 parts polymer):			
a. Tritoyl phosphate			
Tensile strength, psi	2100	0.2	0.06
Elongation at break, %	318		
b. Di-2-ethylhexyl phthalate			
Tensile strength, psi	1900	0.2	0.06
Elongation at break, %	364		
c. Di-2-ethylhexyl sebacate			
Tensile strength, psi	1300	0.2	0.06
Elongation at break, %	318		
d. Polypropylenyl sebacate (Reoplex 100)			
Tensile strength, psi	2000	0.2	0.06
Elongation at break, %	342		
e. Polypropylenyl sebacate modified (Reoplex 110)			
Tensile strength, psi	2000	0.2	0.06
Elongation at break, %	234		

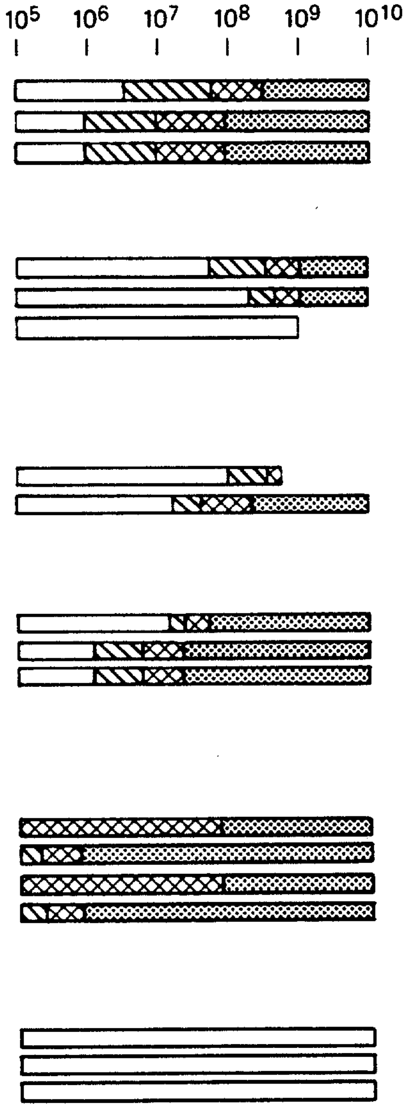
Percent of initial value decreased at given dose (rads)[a]



[a]Key for radiation effects:
□ 0-20% decrease of initial value
▨ 20-50% decrease of initial value
▩ 50-90% decrease of initial value
▒ 90-100% decrease of initial value

Table C.15. (continued)

Material	Initial value	Dose Rate Mrads/h	Thickness, (in.)	Percent of initial value decreased at given dose (rads)[a]
4. Vinyl chloride-vinylidene chloride copolymer				
Tensile strength, psi	3700	2	0.13	
Elongation at break, %	200			
Notch impact strength, ft-lb/in.	1.6			
5. Polyvinyl chloride acetate				
Tensile strength, psi	9000	2	0.13	
Elongation at break, %	3.1			
Notch impact strength, ft-lb/in.	0.5			
6. Polyvinyl fluoride (du Pont R-20)				
Tensile strength, psi	8830			
Elongation at break, %	160			
7. Polychlorotrifluoroethylene (Kel-F)				
Tensile strength, psi	4900	1	0.12	
Elongation at break, %	50			
Notch impact strength, ft-lb/in.	1.9			
8. Polytetrafluoroethylene (Teflon)				
Tensile strength, psi	4800	1	0.06	
Elongation at break, %	400			
Tensile strength, psi	3900	1	0.03	
Elongation at break, %	400			
D. Nitrogen-containing polymers				
1. Polyvinyl carbazole				
Tensile strength, psi	1800	2	0.15	
Elongation at break, %	0.32			
Notch impact strength, ft-lb/in.	0.27			

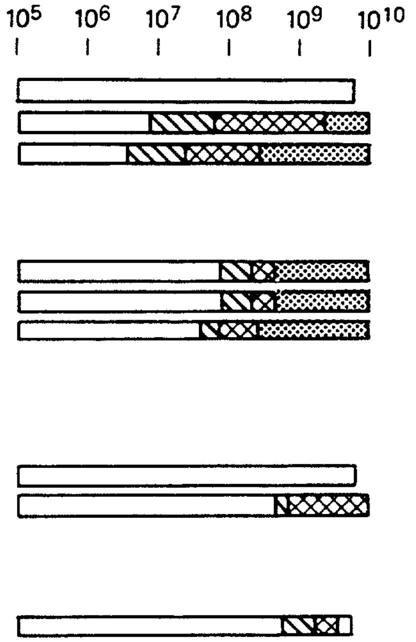


[a] Key for radiation effects:

▭	0-20% decrease of initial value
▧	20-50% decrease of initial value
▦	50-90% decrease of initial value
▒	90-100% decrease of initial value

Table C.15. (continued)

Material	Initial value	Dose Rate Mrads/h	Thickness, (in.)	Percent of initial value decreased at given dose (rads)[a]
2. Nylon				
Tensile strength, psi	7600	2	0.10	
Elongation at break, %	62			
Notch impact strength, ft-lb/in.	2.8			
3. Casein resin				
Tensile strength, psi	8500	2	0.24	
Elongation at break, %	20			
Notch impact strength, ft-lb/in.	0.5			
4. Styrene-acrylonitrile Copolymer (Royalite)				
Tensile strength, psi	4000	2	0.06	
Elongation at break, %	10			
E. Miscellaneous polymers				
1. Silicone-glass cloth laminate				
Shear strength, psi	13500	1	0.07	



[a] Key for radiation effects:

□	0-20% decrease of initial value
▧	20-50% decrease of initial value
▩	50-90% decrease of initial value
▒	90-100% decrease of initial value

NOTE: Irradiated in air at 25°C unless otherwise noted.

Cellulose Acetate Butyrate

(Threshold - 3.4 x 10^5 rad for elastic modulus)

The elastic modulus is the first property affected. Tenite II has been tested in thin film and fiber forms. The reported thresholds are 3.4 x 10^5 to 5 x 10^5 rad with an increase of ~20% at 3.2 x 10^7 rad. The impact resistance is affected above doses from 6.8 to 8 x 10^5 rad. The impact resistance decreases 25% at 6.6 x 10^6 rad or more, and decreases 50% at 3 x 10^7 rad. Elongation as well as shear and tensile strength are affected at 1.6 x 10^6 rad, are reduced 25% at 2.3 x 10^7 rad, and are further reduced 50% at 3.3 x 10^7 rad. Oxidation effects occur. Radiation resistance is reported to be better at high doses for tests done on 0.125-in.-thick samples.[2]

Cellulose Nitrate

(Threshold - 5 x 10^5 rad for elongation)

Large quantities of gas are evolved when this material is irradiated. A Pyralin sample was tested and the elongation was found to be affected at a threshold dose of 5 x 10^5 rad. The 25% damage dose is 3.5 x 10^6 rad and the 50% dose is 1 x 10^7 rad. The impact resistance has a threshold of 1 x 10^6 rad and degrades rapidly past that dose. The 50% damage dose was found to be 3 x 10^6 rad. Shear and tensile strength were affected at 1 x 10^6 rad but did not degrade as rapidly as the elongation property.[2]

Cellulose Propionate

(Threshold - 3×10^5 rad for impact resistance)

Samples of Forticel were tested for their radiation resistance. Impact resistance is the property found to be the most sensitive to radiation with a threshold dose of 3×10^5 rad; a 25% decrease occurred after 4.4×10^6 rad, and a 50% decrease occurred after 1.5×10^7 rad. Elongation reduces by 25% at 3.5×10^6 rad and 50% at 1.5×10^7 rad. The tensile strength reduces 25% at 5×10^6 rad and 50% at 1.5×10^7 rad. The threshold dose of shear strength is 4×10^5 rad, and the 50% degradation dose is 3×10^6 rad. Gas evolves during irradiation.[2]

Ethyl Cellulose

(Threshold - 1.5×10^6 rad for impact resistance)

Irradiation tests show that for impact resistance, Ethocel R-2 has a threshold dose of 1.5×10^6 rad, a 25% reduction dose of 5×10^6 rad, and a 50% loss at 1×10^7 rad. The tensile strength is affected above 3×10^6 rad and reduces to 50% at 2×10^7 rad. The elongation and shear strength are affected at 2×10^6 rad; elongation is reduced by 25% at 4×10^6 rad and 50% at 4×10^7 rad. Test results show that at 10^9 rad, 105 mL/g of gas evolved.[2]

Ionomer Resins

(Threshold - 2×10^6 rad for elongation and tensile strength)

If oxidation effects are maximized, a lower threshold would probably be present. At 9×10^8 rad, <50% of the tensile strength was lost. The radiation resistance is dependent upon the effectiveness of antioxidants, which can be added to the resin.

Parylene

(Threshold - unknown)

The radiation-resistant properties are reported to be less than those of Mylar, which has a threshold dose of 4×10^7 rad for tensile strength.

Polyacrylonitrile

(Threshold - ~1×10^6 rad for tensile strength)

The threshold for tensile strength for polyacrylonitrile fibers is given as 1×10^6 rad in ref. 2. Significant loss in tensile strength for Orlon fibers after 8×10^6 rad suggests a maximum-use-level of 5×10^7 rad. Dolan and Dynel are other commercial names for polyacrylonitrile fibers.[2]

Polycarbonate

(Threshold - 7×10^5 rad for elongation)

Polycarbonate film showed initial changes in elongation at a dose of 7×10^5 rad. This property increased, then decreased to ~50% of original at a dose of 7×10^7 rad. At 3×10^6 rad, the tensile strength showed changes; it first increased, then decreased gradually to 50% of original at 1×10^8 rad. A Macrofol film irradiated to a dose of 1×10^8 rad showed an ~20% loss in elongation and tensile strength. Lexan was too brittle to test after 2.6×10^8 rad.

Polychlorotrifluoroethylene

(Threshold - 1.2×10^6 rad for shear strength and elastic modulus)

After an irradiation of 1×10^7 rad, a 0.3-cm sample of Kel-F had approximately a 50% loss of elongation and impact strength, with negligible change in tensile strength. Fluorothene showed threshold values of 1.2×10^6 rad for shear strength and elastic modulus, 3.6×10^6 rad for elongation and impact strength, and 3.6×10^7 rad for tensile strength. Oxidation effects are not as dramatic as with Teflon. Hostaflon and Trithene are other commercial names for polychlorotrifluoroethylene.

Polyethylene (PE)
(Threshold - 3.8×10^5 rad for elongation under stress. Note the threshold dose actually does not indicate damage but rather shows an improvement of the original properties.)

At a total dose of 4.4×10^6 rad, a 2-mil Marlex sample lost ~90% of its original elongation and <15% of the original tensile strength. A 0.003-in. sample of Alathon lost ~10% of its elongation and tensile strength at 8.7×10^6 rad. At a total dose of 4.4×10^7 rad, the sample had lost ~33% of the tensile strength and 87% of the elongation. Antioxidants may greatly improve radiation resistance but are not frequently used in commercial formulations. Many antioxidants are relatively insoluble in polyethylene and may migrate from the polymer, making it more susceptible to oxidation.

A service limit of 1×10^8 rad is recommended for HDPE (high-density polyethylene), NF-CLPE, and CB-CLPE (nonfilled and carbon black-filled chemically crosslinked polyethylene) cable insulations.

Polyethylene Terephthalate (PET)
(Threshold - 4.4×10^6 rad for tensile strength and elongation)

At 2.5×10^7 rad, Dacron fibers are not significantly degraded. Quinone and quinhydrone are effective antirads. Mylar (oriented PET film) appears to be more radiation-resistant than nonoriented fibers. At a dose of 4×10^7 rad, the tensile strength begins to show initial effects. A 50% reduction in elongation is observed at 3×10^8 rad and, after 6×10^8 rad, there is a 50% decrease in tensile strength. Mylar film capacitors have been found serviceable after 10^8 rad. Outgassing during irradiation is minimal and is mostly hydrogen.

Polymethyl Alpha-Chloroacrylate
(Threshold - ~7×10^5 rad)

A damage threshold of 8.2×10^5 rad was reported in ref. 3, along with a 25% damage at 1.1×10^6 rad, but the properties measured were not indicated. Polymethyl Alpha-Chloroacrylate has a reported radiation resistance similar to polymethyl methacrylate, and the threshold is assumed to be similar to that of PMMA.[2]

Polyphenylene Oxide
(Threshold - ~10^5 rad for tensile strength)

There is a slight increase in tensile strength at 10^5 rad. The material retains slightly greater than original strength, to ~10^9 rad. Noryl, PPO, and Alphalux 400 are commercial names for polyphenylene oxide.

Polypropylene
(Threshold - <4×10^5 rad)

The threshold dose listed was determined on the basis of the susceptible chemical structure of polypropylene and its general similarity to polyethylene (with a threshold of 3.8×10^5 rad). The damage threshold in air may appear to be as high as 10^7 rad; however, several references report extensive postirradiation oxidation. This sensitization to oxidative degradation can be totally blocked by beta-activated thioether additives.

Polystyrene
(Threshold - 2×10^7 rad for tensile strength)

For unstabilized polystyrene sheets irradiated in air, the tensile and flexural strengths were reduced by ~50% at a dose of 1×10^8 gamma and by 75% at 2×10^8 rad. Some commercial products that contain various antioxidants and stabilizers show thresholds ranging from 10^8 to $>10^9$ rad. One reference notes postirradiation oxidation for some commercial materials. Permanent decreases in volume resistivity and insulation resistance of one or two orders of magnitude occur after doses as low as 4×10^6 rad. Styrene is approximately three times more sensitive to neutron irradiation than to gamma irradiation.

Polysulfone
(Threshold - ~5×10^7 rad for flexural strength)

The flexural strength for polysulfone began to show initial effects at a dose of 5×10^7 rad. At 1.7×10^8 rad, the tensile and flexural strengths were reduced to 50% of the original values. At elevated temperatures, an increased sensitivity to radiation is noted. Sulfur dioxide is evolved during irradiation.

Polytetrafluorethylene
(Threshold - 1.5×10^4 rad for elongation)

The threshold change of elongation for Teflon-TFE is reported to be at 1.5×10^4 rad; for tensile strength it is 2.1×10^4. The shear and impact strength threshold dose is 1.8×10^5 rad. Oxidation effects are quite large. Teflon-FEP (a copolymer of fluoroethylene and perfluoropropylene) is more resistant than is Teflon-TFE. Teflon-FEP shows 10 times greater radiation resistance. Electrical properties are affected differently for irradiation in air than for irradiation in a vacuum. Tetran, Fluorlon, and Hostaflon FT are some of the other commercial names for polytetrafluoroethylene.

Polyvinyl Butyral
(Threshold - ~3×10^6 rad for elastic modulus)

The elastic modulus of polyvinyl butyral increases during radiation due to cross-linking. The elongation at break decreases. At 1.9×10^7 rad, there is an estimated 25% damage level. At 1×10^8 rad, there is a 50% change in the tensile strength and at 3×10^8 there is a 50% change in elongation. Butacite and Saflex are common commercial names for polyvinyl butyral.

Polyvinyl Carbazole
(Threshold - 8.8×10^7 rad for impact strength)

All physical properties appear to be relatively insensitive to radiation and are reported unchanged at 2×10^9 rad. Grinlan F showed a 25% damage level after a dose of 4.4×10^9 rad. Other trade names for polyvinyl carbazole are Luvican and Polectron. The threshold value cited here is for Polectron.

Polyvinyl Chloride Acetate
(Threshold - 1.4×10^6 rad for elongation)

This material shows signs of softening and darkening and an evolution of hydrogen chloride (HCL) when irradiated. Vinylite showed a threshold dose of 1.4×10^6 rad for elongation, which increased rapidly with a 50% increase at 3×10^7 rad. The shear strength was affected initially at

5×10^7 rad, tensile strength at 5×10^8 rad, and impact strength at 4×10^9 rad. One reference reports a 200% increase in elongation at 5×10^6 rad, followed by a gradual softening and weakening of a polyvinyl chloride acetate plastic.

Polyvinyl Chloride, Plasticized

(Threshold - 5×10^5 rad for temperature at break)

Reference 2 collected data from several tests on plasticized PVC. The results of the tests are as follows:

1. One test reports that dc resistivity of one PVC cable insulation was affected after 5×10^6 rad, and sensitivity to water and steam was increased above this value. Large decreases in oxidation resistance were noted above 5×10^6 rad.
2. Another test reports results for 4-mil and 20-mil samples of Geon 8630 that were irradiated in air at room temperature. The 4-mil sample lost ~20% of its original tensile strength after 7×10^6 rad but retained <50% tensile strength after 1×10^8 rad. The 0.020-in. sample lost <20% of its original tensile strength at 1×10^8 rad. The elongation of the 0.004-in. sample was reduced by 20% at 1×10^7 rad. The elongation of the 20-mil sample was reduced by 20% at 7×10^7 rad. There were indications of extensive oxidation effects with the 4-mil samples of Geon 8640 irradiated in air and in a vacuum.
3. There are marked differences in the thermal properties of irradiated PVC. A reduction in the melting temperature of the polymer was noted in air but not in a vacuum.

Polyvinyl Chloride - Rigid

(Threshold - $>10^6$ rad)

A 0.17-in.-thick sample was irradiated in air at 2×10^5 rad/h at ambient temperature to a total dose of $\sim 10^9$ rad. The sample showed an 80% or better retention of tensile and notch impact strength. However, another test cited in ref. 3 indicates that a rigid PVC sample irradiated to 1.3×10^9 rad at 60°C with 1 MeV electrons showed very serious degradation. The radiation resistance is undoubtedly dependent upon the thermal and oxidizing conditions, as is the resistance of plasticized PVC.[2]

Polyvinyl Fluoride

(Threshold - 10^7 rad for elongation)

Polyvinyl fluoride is sometimes marketed as Tedlar. Tests conducted on DuPont R-20 exhibits ~20% loss of elongation at 2×10^7 rad and a 50% loss at 5×10^7 rad. The tensile strength was not significantly affected below 1×10^8 rad. The radiation resistance of polyvinyl fluoride is less at elevated temperatures. A sample irradiated at 60°C to 1.8×10^9 rad resulted in severe physical degradation; however, the insulation resistance was unchanged and the dielectric constant was decreased by only 7%.

Polyvinyl Formal

(Threshold - $\sim 1.6 \times 10^7$ rad for tensile strength and elastic modulus)

Formvar showed a decrease in tensile strength and elastic modulus when irradiated. A 25% damage level was reported for 1.2×10^8 rad and a 50% damage level was reported for 1×10^9 rad.

Polyvinylidene Chloride

(Threshold - 3.7 × 10^6 rad for elongation)

Initial changes in elongation and impact strength begin at 3.7 × 10^6 rad. The tensile strength and elastic modulus are affected at 6.4 × 10^6 rad and the shear strength begins to decrease at 4.1 × 10^7 rad. A 25% loss occurs at 4.1 × 10^7 for elongation and impact strength, at 1.6 × 10^8 rad for tensile strength, and at 5.5 × 10^8 for shear strength. Irradiation causes darkening and an evolution of HCL. Saran, Vestan, Velon, and Diorit are some of the commercial names for polyvinylidene chloride.

Polyvinylidene Fluoride

(Threshold - 8 × 10^6 rad - property not specified)

Kynar 400 showed only color change after 10^7 rad but was brittle and lost flexural and tensile strength at 10^8 rad. Volume resistivity was reduced by ~10^5 after 2 × 10^8 rad. The dielectric constant was unchanged.

Propylene-Ethylene Polyallomer

(Threshold - 1 × 10^6 rad for tensile strength and elongation)

This material has a "polyallomer" suffix, which indicates a unique bonding mechanism. This means that this material is neither a physical mixture nor a true copolymer. At 4 × 10^7 rad, the tensile strength was reduced by 50%; at a dose of 7 × 10^6 rad, elongation was reduced by 50%.

Tefzel Fluoropolymer (copolymer of Ethylene and Tetrafluoroethylene)

(Threshold - unknown)

At 2 × 10^7 rad, Tefzel insulation had a decrease in elongation of ~25%. Dose rate effects have been noted, showing that the higher dose rates lead to less damage for a given total dose. Oxidative effects are greater at lower dose rates. Electrical properties are reported to be stable at much higher radiation doses.

C.5.2 THERMOSETTING PLASTICS RADIATION INFORMATION

Table C.16 provides radiation effects data for thermosetting plastics (summarized from ref. 7). The remainder of this section of the appendix contains detailed radiation effects information for individual thermosetting plastic materials. The major sources of detailed test information for this section are ref. 2 and ref. 5. Other sources are as indicated.

Aminoplast Resins

(Threshold - unknown)

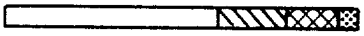
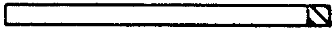
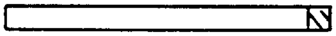
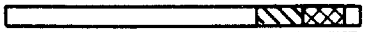
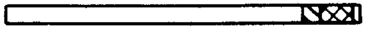
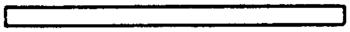
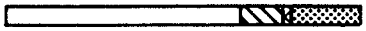
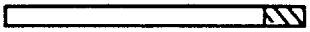
These are reaction products of aldehydes and certain amine compounds. They are most often used as molding materials; however, they are also occasionally used in adhesives and coatings.[2]

Aniline Formaldehyde

(Threshold - 6.7 × 10^5 rad for impact strength)

The impact strength of Cibanite increased above the threshold dose with a 25% increase at 1.3 × 10^7 rad, but showed a 50% loss at 1.2 × 10^8 rad. Shear and tensile strength and elongation decreased at approximately the same rate with threshold, 25% decrease, and 50% decrease occurring at 9.1 × 10^7, 2.4 × 10^9, and 3.6 × 10^9 rad, respectively. The elastic modulus was unchanged at the highest dose.[5]

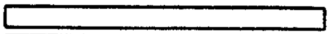
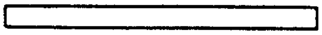
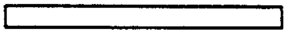
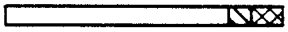
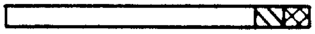
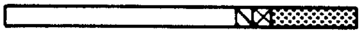
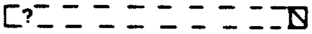
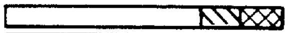
Table C.16. Effects of radiation on mechanical properties of thermosetting plastics

Material	Initial value	Dose Rate Mrads/h	Thickness, (in.)	Percent of initial value decreased at given dose (rads)[a]
A. Oxygen-containing polymers				10^5 10^6 10^7 10^8 10^9 10^{10}
1. Cast polyester (Selectron 5038)				
Tensile strength, psi	2000	2	0.26	
Elongation at break, %	20			
Notch impact strength, ft-lb/in.	0.7			
2. Mineral-filled polyester (Plaskon Alkyd)				
Tensile strength, psi	4700	1	0.13	
Elongation at break, %	6.2			
Notch impact strength, ft-lb/in.	0.4			
3. Allyl diglycol carbonate resin				
Tensile strength, psi	6700	2	0.12	
Elongation at break, %	2.4			
Notch impact strength, ft-lb/in.	0.35			
4. Triallyl cyanurate resin				
Shear strength, psi	2000	2	0.25	
5. Cast phenolic				
Tensile strength, psi	11000	2	0.18	
Elongation at break, %	2			
Notch impact strength, ft-lb/in.	0.5			
6. Asbestos fabric-filled phenolic				
Tensile strength, psi	11000	1	0.12	
Elongation at break, %	1.3			
Notch impact strength, ft-lb/in.	3.9			

[a] Key for radiation effects:

□	0-20% decrease of initial value
▧	20-50% decrease of initial value
▩	50-90% decrease of initial value
▒	90-100% decrease of initial value

Table C.16. (continued)

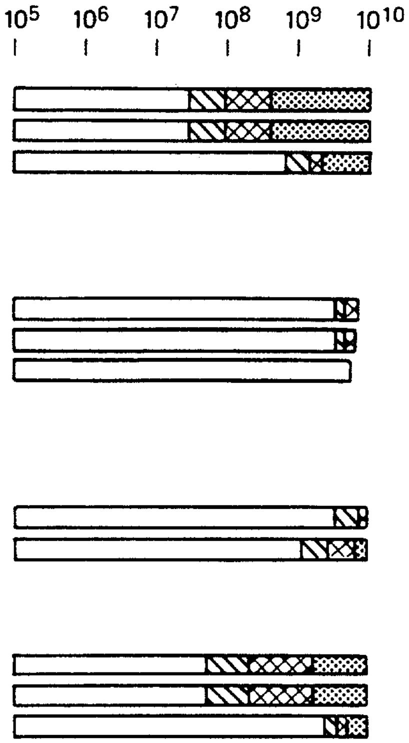
Material	Initial value	Dose Rate Mrads/h	Thickness, (in.)	Percent of initial value decreased at given dose (rads)[a]
				10^5 10^6 10^7 10^8 10^9 10^{10}
7. Linen fabric-filled phenolic				
Tensile strength, psi	11000	2	0.25	
Elongation at break, %	4.0			
Notch impact strength, ft-lb/in.	2.75			
8. Furane resin-graphite filled				
Tensile strength, psi	2200	1	0.37	
Elongation at break, %	0.39			
Notch impact strength ft-lb/in.	0.31			
9. Epoxy polymer				
a. Aromatic amine-cured (diamino diphenyl methane)				
Flexural strength, psi	17000	3	0.12	
b. Aliphatic amine-cured (piperidine)				
Flexural strength, psi	18500	3	0.12	
c. Acid anhydride-cured (hexahydrophthalic anhydride)				
Flexural strength, psi	18000	3	0.12	
d. Acid anhydride-cured (dodecenyl succinic anhydride) (long side chain)				
Flexural strength, psi	11500	3	0.12	
e. Araldite Type B Casting				
Shear strength, psi	8000	2	0.16	 ?
B. Nitrogen-containing polymers				
1. Polyurethane (Estane VC)				
Tensile strength, psi	6390			
Elongation at break, %	500			

[a] Key for radiation effects:

□	0-20% decrease of initial value
▧	20-50% decrease of initial value
▦	50-90% decrease of initial value
░	90-100% decrease of initial value

Table C.16. (continued)

Material	Initial value	Dose Rate Mrads/h	Thickness, (in.)	Percent of initial value decreased at given dose (rads)[a]
2. Cellulose pulp-filled urea-formaldehyde				
Tensile strength, psi	7800	2	0.12	
Elongation at break, %	0.5			
Notch impact strength, ft-lb/in.	0.3			
3. Aniline-formaldehyde polymer				
Tensile strength, psi	9200	2	0.20	
Elongation at break, %	1.8			
Notch impact strength, ft-lb/in.	0.2			
4. Polyimide polymer "H" film				
Tensile strength, psi	26000	2	0.002	
Elongation at break, %	65			
5. Cellulose pulp-filled melamine-formaldehyde				
Tensile strength, psi	9100	2	0.25	
Elongation at break, %	0.65			
Notch impact strength, ft-lb/in.	0.29			



[a] Key for radiation effects:

□ 0-20% decrease of initial value
▧ 20-50% decrease of initial value
▩ 50-90% decrease of initial value
▒ 90-100% decrease of initial value

NOTE: Irradiated in air unless otherwise noted.

Casein Resin

(Threshold - 4 × 10^6 rad for impact strength)

A 50% reduction in impact strength of Ameroid, which is a protein-based resin, was induced by irradiation to 3×10^7 rad. The shear and tensile strengths, and elongation were all initially changed at ~10^7 rad and reduced to 50% of the original value at ~10^8 rad. The elastic modulus was unchanged.[5]

Diallyl Phthalate (glass-filled)

(Threshold - 1.8 × 10^9 rad for tensile strength and elongation)

This material is technically a polyester; however, because of its radiation stability, it is addressed separately. For glass-filled DAP, only minor physical and electrical property changes have been noted for doses up to 10^{10} rad. At a neutron dose of 1×10^9 rad, diallyl phthalate was found to be suitable as a connector insulation.[2]

Epoxy Resins
(Threshold - 2×10^8 rad, or greater)

Novalac and glycidyl amine types are more radiation resistant than are standard epoxies. With some curing agents, doses of 4×10^9 rad have resulted in no loss of mechanical properties. Standard epoxy resins cured with aromatic amines were more radiation-resistant than those cured with aliphatic amines or acid anhydrides. The threshold damage occurred at 10^9 rad and 2×10^8 rad, respectively. Novalac has been found to be quite resistant to oxidation while many others are not. Electrical properties show some variation from exposure to radiation environments but are of adequate stability for use in most electronic circuits.[5]

Furane Resin
(Threshold - 3×10^8 rad for tensile strength and elongation)

Duralon, an asbestos and carbon black-filled, furane-based resin, shows very good radiation resistance. The properties measured (tensile and impact strength, elongation, and elastic modulus) showed initial degradation at 3×10^8 rad and 25% damage at 3×10^9 rad.[2]

Melamine Formaldehyde
(Threshold - 7.5×10^6 rad for tensile and elongation)

Melmac (cellulose filler) displayed approximately equal decrease in tensile strength and elongation with the threshold dose of 6.7×10^6 rad, a 25% decrease at 6.6×10^7 rad, and a 50% decrease at 1.6×10^8 rad. Wear strength exhibits the same threshold, but is reduced more slowly. A 25% decrease occurs at 3.9×10^8 rad and a 50% decrease at 9.1×10^8 rad. It's impact strength was little affected.[5]

Phenolic Resins
(Threshold - from 3×10^5 to 3.9×10^8 rad for elongation)

The phenolics that are unfilled or cellulose-filled are not particularly radiation-resistant. They become more susceptible to moisture damage and disintegration after irradiation. The phenolic laminates and mineral-filled phenolics show very good radiation resistance. Some phenolic laminates have been found unaffected by as much as 8×10^9 rad. The electrical properties are generally stable even at high doses. The least resistant phenolic resin found was linen fabric-filled, with 25% damage shown at 3×10^6 rad. The most radiation-resistant was asbestos-filled (Haveg 41), with 25% damage after 3.9×10^9 rad.[2,5]

Phenoxy Resins
(Threshold - unknown)

Although chemically similar to epoxy formulations, the radiation resistances of phenoxy resins appear to be generally less than that of epoxies. One test showed a loss of 75% of the initial tensile strength after 3×10^8 rad. Most of the material's ductility was also lost.[6]

~~Polyamide~~ Polyimide
(Threshold - 10^7 rad for elongation and tensile strength)

One polyamide file was initially affected at 10^7 rad. The tensile strength increased, then dropped gradually, but was still >50% of the original value after 10^9 rad. The elongation decreased gradually beyond the threshold dose and was reduced by one-half at 10^9 rad.

The Du Pont H-film shows threshold loss of elongation at 4 × 10^8 rad, 50% at 3 × 10^9 rad. The tensile strength was initially changed at 10^9 rad. In a vacuum, the elongation was first affected by 10^9 rad and retained better than 50% of its initial value at 10^{10} rad.[2]

The permanent electrical and physical properties of Kapton were stable to 10^9 rad and were not greatly degraded after 10^{10} rad. Dielectric breakdowns during electron irradiations have been observed to increase with increasing dose rate and/or elevated temperature.[2]

Kapton is polyimide

Polyester Resins

(Threshold - from 10^5 to 10^6 rad for elongation)

The radiation resistance of polyester resins is dependent upon the aromatic content and the nature of the cross-linking monomer. The threshold for damage to most resins that are unfilled is from 10^5 to 10^6 rad.[2] Like phenolics, polyester resins show dramatic increases in radiation resistance with inorganic fillers.[2] Elongation of an unfilled polyester resin (Selectron 5038) was reduced ~20% at 8 × 10^6 rad and 50% after 10^9 rad. One mineral-filled polyester (Plaskon Alkyd) showed damage thresholds for tensile, shear, impact strength, and elongation at 7.9 × 10^7 rad; 25% decrease occurred around 3.5 × 10^9 rad.[5] One polyester-glass laminate exhibited no change in tensile strength or elastic modulus after 4 × 10^8 rad. The permanent electrical properties of a mineral-filled polyester were unchanged after 2.5 × 10^9 rad.[6]

Polyurethane Resins

(Threshold - 10^7 rad for tensile strength)

Polyurethanes are polyester- or polyether-diisocyanates. Thermoplastics and elastomeric forms are also available. Various curing agents and additives result in a range of radiation resistances.[2]

CPR-20 and CPR-1021 thermal insulations showed little change in compressive strength at 10^9 rad. A urethane laminate exhibited initial weight loss at 1.75 × 10^8 rad and 1% weight loss after 7 × 10^9 rad. A minor decrease in flexural strength and elastic modulus were noted at 7 × 10^8 rad.[6] STA-Foam AA-402 (urethane foam insulation) was reduced in compressive strength to 34% of the original value by 8 × 10^7 rad when irradiated at 27°C.[2]

Pyrrone

(Threshold - ~10^8 rad for flexural strength and elastic modulus)

Pyrrones are polyimidazopyrrolone polymers. The condensed aromatic ring structure is quite stable in radiation fields. Threshold changes were reported for the flexural strength and the elastic modulus at 1 × 10^8 rad. Both properties increased gradually to 10^{10} rad. Irradiations to 1 × 10^{10} rad (E = 1 MeV) and 5 × 10^9 rad (E = 2 MeV) resulted in insignificant degradation of mechanical and permanent electrical properties. At 10^{10} rad, yield strength increased by ~70%, tensile strength was unaffected, and elongation was decreased by two-thirds of the original property value.[2]

Silicone Resins

(Threshold - ~10^6 rad for varied properties)

Silicone formulations, with the exception of glass-reinforced resins, show threshold doses to be ~10^6 rad. The threshold dose for loss of tensile strength for one unfilled silicone resin was found to be 7 × 10^6 rad and the 50% decrease dose for that property was 7 × 10^7 rad.[6]

Postirradiation degradation has been reported for silica-filled polysiloxanes in air. Phenyl methyl silicones are more stable than are dimethyl silicones. Elevated temperatures usually result in reduced radiation resistance.[2]

Urea Formaldehyde

(Threshold - 7.5 × 10^6 rad for tensile and elongation)

Plaskon Urea showed decreasing tensile and shear strengths and decreasing elongation. The threshold, 25% decrease, and 50% decrease in these properties was observed at 7.5 × 10^6, 3 × 10^7, and 7.3 × 10^7 rad, respectively. The elastic modulus decreased slightly after 3.2 × 10^7 rad. The impact strength decreased initially at 3.2 × 10^7 rad and was reduced by 25% at 5.8 × 10^8 rad.[5]

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