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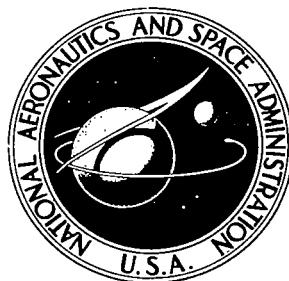
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RADIATION EFFECTS
DESIGN HANDBOOK

Section 5. The Radiations in Space
and Their Interactions With Matter

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16. Abstract

      This document summarizes the types and sources of radiation that may be encountered in space and how they interact with matter. The detection and measurement of these radiations also are discussed. A glossary is included.

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PREFACE

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

Other sections of the <u>Handbook</u> discuss such subjects as transistors, solar cells, thermal-control coatings, structural metals, electrical insulating materials, and capacitors.

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SECTION 5. THE RADIATIONS IN SPACE AND
THEIR INTERACTIONS WITH MATTER

INTRODUCTION

This section is provided as an introduction to the radiations to be encountered in the space environment, a description of these radiations, and the microscopic manner in which they interact with matter. Also included is a brief discussion of the correlation of the effects of different radiations, as well as a discussion of the units and techniques of measuring radiations. The primary purposes of this section are to serve as an introduction to these subjects, to provide some insight into the mechanisms involved when radiation interacts with matter, and to facilitate the understanding of subjects treated elsewhere in this Handbook for those unfamiliar with radiation physics. For a comprehensive treatment of the subjects dealt with in this section, the reader is directed to the references at the end of this section.

Logical additions to the content of this section include a brief description of the possibilities and limitations of simulating the effect of one type of radiation with another type of radiation and a description of the instruments used to measure radiation.

THE SOURCES OF RADIATION IN SPACE

As stated, in this section the interactions of space radiations with matter are dealt with. To put these radiations into perspective, the sources of these radiations and their relative intensities are covered briefly.

Sources of radiation that may be encountered in the space environment are:

(1)   The Van Allen belts are toroidal belts of charged particles surrounding the earth near the equator. There are two belts, the inner belt extends to about 45° north and south geomagnetic latitudes and from about 800 kilometers to about 8000 kilometers in altitude. The outer belt fluctuates

in size and intensity with solar activity but is symmetrical about the equator and extends to about 70° geomagnetic latitude north and south and to altitudes as high as 130,000 kilometers. Similar magnetically trapped concentrations of charged particles are thought to exist on the planets Jupiter and Saturn. The proton and electron fluxes that have been measured in the hearts of the Van Allen belts are given in Table 1. For more detailed information, contact the National Space Science Data Center at Goddard Space Flight Center, Greenbelt, Maryland.[45]

TABLE 1. VAN ALLEN RADIATION BELT INTENSITIES[5]

Particle	Energy	Flux
Heart of Inner Zone (Alt = 3600 km)		
Electrons	(E > 40 keV)	$\sim 10^8/(cm^2 \cdot s)$
Electrons	(E > 600 keV)	$\sim 2 \times 10^6/(cm^2 \cdot s)$
Protons	(E > 30 MeV)	$\sim 3 \times 10^4/(cm^2 \cdot s)$
Heart of Outer Zone (Alt = 25,000 km)		
Electrons	(E > 40 keV)	$\sim 10^7/(cm^2 \cdot s)$
Electrons	(1.5 < E < 5 MeV)	$\sim 10^4/(cm^2 \cdot s)$
Protons	(0.1 < E < 5 MeV)	$\sim 10^8/(cm^2 \cdot s)$
Protons	(E > 1 MeV)	$\sim 10^7/(cm^2 \cdot s)$
Protons	(E > 75 MeV)	$\sim 0.1/(cm^2 \cdot s)$

(2) Solar flares are bursts of high-energy particles originating in the sun. Although protons are the predominant particles in the solar flares, alpha particles and other nuclei are also present. The average percentage of alpha particles in the total integrated flux is unknown. But, over a short period of time, the number of alpha particles may be nearly equal to or greater than the number of protons. For example, in the event of November 15, 1960, $\frac{N(p)}{N(\alpha)} \simeq 1$ at an energy greater

than 30 MeV, whereas the November 12, 1960, event was much richer in alphas. It would be more accurate to assume that

$$\left[\frac{N(p)}{N(\alpha)}\right] \text{ integrated } \stackrel{\sim}{<} 0.05 \text{ at all values of rigidity.}$$

The frequency of occurrence of all flares — including both the big and the small — ranges from about two to fourteen per year. Solar flares severe enough to produce significant fluxes (Class 3 or 3+) occur about one or two times per year during periods of solar activity, last from 10 to 100 hours, and create proton fluences of up to 10^9 protons/cm^2 of energy greater than 30 MeV per flare. Proton energies ranging from 10^7 eV to 10^9 eV or higher have been observed in conjunction with solar-flare activities.[3, 5, 39] The radiations given are for a distance of one astronomical unit (A. U.) from the sun (1 A. U. = 92,950,000 miles, the mean distance from Sun to Earth).

(3) Galactic cosmic radiation originates outside the solar system. This radiation is about 85 percent protons, 14 percent helium ions, and the rest heavier nuclei. Energies range from 10^7 to 10^{19} eV with an average of about 10^{12} eV. The free-space proton flux near Earth is about 2.5 protons/ (cm^2·s) when solar activity is at a maximum and about 5.0 protons/(cm^2·s) at solar minimum.[3]

(4) Solar wind is an ionized plasma continuously emitted by the sun. The solar wind varies with the relative activity of the sun and distance from the sun. Typical fluxes and energies for the solar wind at 1 A. U[2] are given in Table 2.

TABLE 2. SOLAR WIND RADIATION INTENSITIES

Particles	Flux, particles/(cm^2·s) (1 A. U. from Sun)	Energy, eV
Protons	5×10^9 (normal)	2×10^3
	2×10^{13} (high activity)	2×10^4
Electrons	5×10^9 (normal)	2
	2×10^{13} (high activity)	11

An additional source of radiation is associated with vehicles powered by nuclear reactors. These reactors can produce extremely high neutron and gamma fluxes. Determination of radiation received from these reactors and shielding necessary must be made on a point-to-point basis determined by distance from the reactor, operating history of the reactor, operating power of the reactor, and intervening materials.

TYPES OF RADIATION AND THEIR INTERACTION WITH MATTER

Introduction

The different types of radiation that may be encountered in space are protons and heavy charged particles, electrons, neutrons, and electromagnetic radiation. Because these radiations have different characteristics, they interact with material in different ways. Following is a brief description of these radiations and a general description of the ways in which they interact with matter. A more detailed description of their interactions with descriptive equations is presented in the subsections on ionization and atomic displacements.

Protons and Heavy Charged Particles

A proton is a positively charged hydrogen ion. Most of the solar and galactic cosmic radiation and a large portion of the Van Allen-belt radiation that a spacecraft would encounter will be high-energy protons. Energies of protons will range from a few thousand electron volts for protons in the solar wind to 10^{19} eV for protons from galactic sources; however, most proton fluences of significance will be in the energy range 10^5 to 10^9 eV.

The primary process for energy loss by protons and heavy charged particles (i.e., particles of mass >> electron mass) is through Coulomb-force interactions with atomic electrons, leaving atoms along the path of the incident particle ionized or in an excited state (ionization is treated more thoroughly elsewhere in this section). A portion of the particle energy is expended in elastic collisions with atoms, which can result in displaced atoms.

Protons with energies in the tens of MeV can undergo inelastic colli-sion with nuclei in which subatomic particles (neutrons and protons) are knocked out of the target nucleus. At higher energies, a significant pro-portion of the incident protons interact in this manner (15 percent for 150 MeV protons).[6] In this interaction the incident proton knocks out several particles (neutrons and/or protons) by direct interaction with individual nucleons in the target nucleus, thus producing a multiplication of particles or cascade effect. These emitted particles, called cascade particles, have motions strongly concentrated in the forward direction relative to the incident-proton direction.

The target nucleus, after passage of the incident proton and emission of the cascade particles, is left in an excited state. The nucleus loses this excitation energy by an "evaporation" process whereby neutrons, protons, and light nuclei are emitted isotropically from the excited nucleus. These secondarily emitted cascade and "evaporation" particles have a much greater potential for radiation damage than does the incident proton, because of their greater number and slower velocities. The average number of incident neutrons and protons emitted per incident proton per inelastic collision for these two processes is a function of incident proton energy and atomic mass of the target nucleus.[15]

The nuclear, inelastic-scattering cross section for this interaction is approximately equal to the geometric cross section of the nucleus for incident particles whose energy is much greater than that of the Coulomb barrier, which is about 8 MeV. Thus, the cross section is given by

$$\sigma = \pi \ (1.3 \cdot 10^{-13} A^{1/3})^2 \ \text{cm}^2 \ ,$$

where A is the atomic mass of the target nucleus. The mean free path of a particle with respect to inelastic-scattering processes is then

$$\lambda_{in} = \left(\frac{\sigma N_o}{A} \right)^{-1} \ \text{g/cm}^{2*} \ ,$$

where N_o is Avogadro's number.

The fraction of the incident protons that will on the average undergo this type of interaction will be

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*The units g/cm^2 are frequently used to indicate the thickness of material required to attenuate radiation by a specified amount. The units are derived from the density of the material (g/cm^3) times the thickness of mate-rial (cm) required to attenuate the radiation by the specified amount.

$$F = 1 - e^{-x/\lambda \text{in}} \ ,$$

where x is the thickness of material traversed in units of g/cm^2.[9] To determine the importance of nuclear secondaries for specific cases, elaborate Monte Carlo or probabilistic calculations are required to follow the cascade process. Results are summarized in Reference (40).

An empirical formula for the range of protons in the energy range from 10 to 1000 MeV is given by[46]

$$R(E) = \frac{a}{2b} \ln (1 + 2bE^r) \ .$$

In general, for materials of atomic number, $Z < 20$, a value of $r = 1.78$ should be used, and for $Z > 20$, $r \leq 1.75$. The coefficients a and b for several materials are given in Table 3.

TABLE 3.   COEFFICIENTS FOR THE RANGE EQUATION

Material	r = 1.75		r = 1.78	
	a	b	a	b
Carbon	2.58×10^{-3}	1.2×10^{-6}	2.33×10^{-3}	2.0×10^{-6}
Aluminum	3.10×10^{-3}	1.9×10^{-6}	2.77×10^{-3}	2.5×10^{-6}
Iron	3.70×10^{-3}	2.6×10^{-6}	3.26×10^{-3}	3.0×10^{-6}
Copper	3.85×10^{-3}	2.7×10^{-6}	3.40×10^{-3}	3.25×10^{-6}
Silver	4.55×10^{-3}	3.7×10^{-6}	--	--
Tungsten	5.50×10^{-3}	4.2×10^{-6}	--	--
Polyethylene	2.15×10^{-3}	1.1×10^{-6}	1.95×10^{-3}	1.7×10^{-6}
Tissue	2.32×10^{-3}	1.2×10^{-6}	2.11×10^{-3}	2.0×10^{-6}
Water	2.32×10^{-3}	1.2×10^{-6}	2.10×10^{-3}	2.0×10^{-6}
Air	2.68×10^{-3}	1.4×10^{-6}	2.41×10^{-3}	2.1×10^{-6}
SiO_2	2.87×10^{-3}	1.7×10^{-6}	2.58×10^{-3}	2.5×10^{-6}
Glass	3.17×10^{-3}	2.1×10^{-6}	2.83×10^{-3}	2.8×10^{-6}

Electrons (Beta Particle)

An electron is a particle whose mass is about 1/1800 the mass of a proton and which carries a unit negative charge.* Electrons in the space environment are found primarily in the Van Allen belts and as secondary particles emitted as a result of the interaction of other radiations with matter. Electrons interact with matter primarily through ionization of the atoms in the absorbing material. Another mechanism for energy loss that is significant for high-energy electrons is the generation of X-rays, bremsstrahlung. The ratio of the energy loss per unit path length from ionization to that from bremsstrahlung generation is approximately

$$\frac{(DE/dx)_{bremsstrahlung}}{(dE/dx)_{ionization}} = \frac{E\,Z}{800} \quad,$$

where E is the electron's energy in MeV and Z is the atomic number of the absorber. The bremsstrahlung radiation thus created is much more pene-trating than the original electron and is an additional source of radiation damage.

The range of monoenergetic electrons is given approximately by the following empirical relationships:[38]

For energies from 0.01 MeV to ~3 MeV,

$$R_o \ (mg/cm^2) = 412\,E^n \quad,$$

where $n = 1.265 - 0.0954 \ln E$.

For energies from ~2.5 MeV to ~20 MeV ,

$$R_o \ (mg/cm^2) = 530E - 106 \quad,$$

where E is in MeV.

Electrons traveling at velocities near the speed of light (energies >0.51 MeV) may produce atomic displacements through Coulomb scattering.

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*A particle of equal mass but with positive charge is called a positron.

Neutrons

Neutrons are uncharged particles whose mass is nearly equal to that of a proton. Nuclear reactions are the only sources of neutrons. Neutrons created as the result of the fission of U^{235} or Pu^{239} (i.e., fission neutrons) have energies from 0.075 to 17 MeV and fit the energy distribution $N(E) = 0.484 \sinh (2E)^{1/2} e^{-E}$ where $N(E)$ is the number of neutrons of energy $E(MeV)$ per unit energy (MeV) interval for each neutron emitted. [21]

Neutrons also are produced by the interaction of α particles with the light elements beryllium, boron, and lithium by reactions such as

$$_4Be^9 + \alpha \rightarrow {}_6C^{12} + {}_0n \quad .$$
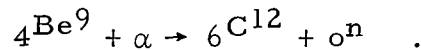
Nearly monoenergetic neutrons called photoneutrons also may be obtained from the interaction of gamma rays (or bremsstrahlung) with matter when the energy of the gamma ray is greater than the binding energy of the last neutron in the target nucleus. Beryllium and deuterium have low threshold energies (1.67 and 2.23 MeV) for this reaction. Using this reaction, electrons can be used to produce neutrons through the bremsstrahlung generated when high-energy electrons are slowed down in a high-density target. A reaction which produces nearly monoenergetic neutrons is the fusion reaction which occurs when deuterium (H^2) or tritium (H^3) is bombarded by deuterium ions with energies of about 50 to 200 keV.

Neutrons may be divided by energy into three groups: tnermal, epithermal, and fast. Thermal neutrons have kinetic energies similar to that of atoms in the medium ($E \sim 0.025$ eV at 20 C) and are produced by slowing down fast and epithermal neutrons through elastic and inelastic scattering processes. Epithermal neutrons have energies between those of fast and thermal neutrons. Neutrons whose kinetic energy is greater than ~ 10 keV may be considered fast neutrons. Reactions of thermal and epithermal neutrons will not be a major concern in space applications, except in nuclear-reactor-powered rockets, but fast neutrons can create atomic displacements and, indirectly, ionization. Mechanisms through which fast neutrons can produce ionization are:

(1) Elastic scattering, in which the recoil nucleus has sufficient energy to produce ionization

(2) Inelastic scattering, in which a gamma photon is emitted
     that can produce secondary ionization in addition to the
     ionization that may be created by the recoiling nucleus

(3) Nuclear reactions induced by neutrons in which an ionizing
     particle is emitted, such as (n, p) or (n, α) reactions.

In addition, boron and lithium have high capture cross sections for
thermal neutrons with the resultant emission of an alpha particle.

High-Energy Electromagnetic Radiation

Electromagnetic radiation may be thought of as a discrete quantity of
energy (one photon) which when emitted travels in a straight line at the
speed of light. The wavelike nature of electromagnetic radiation is revealed
by the photon's frequency given by $E = h\upsilon$ where h is Planck's constant and
υ is the frequency associated with the photon. In the energy range of interest,
there are three types of electromagnetic radiation (gamma rays, X-rays, and
ultraviolet light), which are distinguished primarily by the sources from
which they originate and to a lesser extent by their energies.

The electromagnetic radiations of highest energy are usually gamma
rays. They originate within the nucleus of an atom and generally have
energies greater than 0.1 MeV. X-rays usually are thought of as being of
lower energy than gamma rays and originate in interactions involving orbital
electrons, by blackbody radiation from a heated mass or by the inelastic
scattering of charged particles by a nucleus (bremsstrahlung). The terms
X-ray and gamma ray frequently are used interchangeably. Ultraviolet rays
are part of the spectral radiation from the sun (~7 to 9 percent), are lower
in energy than X-rays, and are only weakly ionizing. They have the ability
to produce light-absorbing color centers in glass, to change the emissivity
of some thermal-control surfaces, and to change the physical and optical
properties of some organic materials.

Electromagnetic radiation has a characteristic exponential attenuation
in matter which is dependent upon the energy of the photon and on the ab-
sorbing material. When describing the interaction of photons with matter,
units that frequently are used are the cross section per electron, σ_e, or the
cross section per atom, $\sigma = Z\sigma_e$, where Z is the atomic number of the
absorbing material and σ and σ_e are expressed in square centimeters or

barns (1 barn = 10^{-24} cm^2). A more useful term is the linear attenuation coefficient

$$\mu(cm^{-1}) = (\rho \, N_0 \sigma)/A \quad ,$$

where ρ is the material's density, N_0 is Avogadro's number, and A is the atomic mass of the material. The attenuation of a beam of photons passing through a medium is then

$$I = I_0 \, e^{-\mu x} \quad ,$$

where I is the intensity of a beam of photons of initial intensity I_0 after traversing a thickness (x) of material whose linear attenuation coefficient for that beam of photons is μ. The term mass-attenuation coefficient, μ/ρ, is sometimes used in place of linear-attenuation coefficient. This is just the linear-attenuation coefficient divided by the density of the material. The above equation is then expressed as

$$I = I_0 \, e^{-(\mu/\rho)\rho x} \quad .$$

Electromagnetic radiation interacts with matter through three primary mechanisms: pair production, the Compton effect, and the photoelectric effect. For lower energies, the predominant mechanism for energy transfer from incident photons to the absorbing material is the photoelectric effect. In this interaction, a tightly bound orbital electron (K or L shell) absorbs the entire energy of the photon and is ejected from the atom with an energy $E = E_0 - E_B$, where E_0 is the initial energy of the photon and E_B is the binding energy of the electron. The atom then loses the energy imparted to it by emission of X-rays or Auger electrons. Exact expressions for the cross section for photoelectric absorption are quite complex and will not be given here. This cross section[22] varies approximately as

$$\sigma = \text{const.} \ Z^4/E_0^3 \quad .$$

For photon energies from about 0.2 to 2 MeV, the Compton effect predominates in energy-transfer processes. In the Compton effect, the photon interacts with an orbital electron, the photon losing part of its energy to the electron. The energetic electron and lower energy photon then move off, the photon traveling at some angle ψ with respect to its former direction. The energy of the scattered photon is given by

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$$E_1 = h\upsilon_1 = \frac{E_o}{1 + \dfrac{E_o}{(m_oc^2)}(1 - \cos\psi)}$$

where m_o is the rest mass of an electron, c is the velocity of light, and E_o is the energy of the incident photon. For electrons, $m_oc^2 = 0.511$ MeV. The The kinetic energy of the electron is then given by

$$E_e = E_o - E_1 \quad .$$

The maximum energy that may be transferred to the Compton electron is

$$E_{e(max)} = \frac{2\,E_o^2}{m_oc^2 + 2\,E_o} \quad [\text{Reference (35)}] \quad .$$

In the energy range 0.2 to 2 MeV, which covers most fission gamma rays, the Compton effect predominates for low and moderate Z materials, and the energy imparted to the electron and thus readily available for ionization of the absorbing medium is nearly independent of energy and atomic number for low atomic numbers. This fact makes dosimetry in this energy range much simpler.

At photon energies above a few MeV, pair production begins to dominate energy-transfer processes. In this process the photon is completely absorbed, and in its place an electron-positron pair is formed. This reaction can take place only in the field of a charged particle, usually a nucleus. The energetics of this reaction can be described by

$$E_o = (E_{e-} + m_oc^2) + (E_{e+} + m_oc^2) = E_{e-} + E_{e+} + 1.02 \text{ MeV} \quad ,$$

where E_{e+} and E_{e-} are the kinetic energies of the positron and electron. The cross section for pair production is proportional to Z^2 and thus increases rapidly with increasing atomic number of the absorbing medium. The positron emitted usually loses energy by ionization until it is nearly at rest, at which time it interacts with an electron, both particles disappearing; two 0.51 MeV gamma rays then appear, moving off in opposite directions.

The total attenuation cross section for a particular gamma-ray energy is the sum of all contributing attenuation mechanisms. The cross section for each mechanism can be further broken down into cross sections for the energy of the scattered photon and cross sections for the energy imparted to the interacting electron or energy absorbed.

Figure 1 shows the separate energy-absorption coefficients (energy-absorption cross sections) for each mechanism and the total energy-absorption coefficients for several elements as a function of energy. These coefficients allow for the escape of all secondary photons, including bremsstrahlung from the absorbing medium. If all secondary and scattered photons are assumed to escape from the absorber without further interaction and all secondary electrons created are stopped in the absorber, then the energy transferred to the absorber will be given by the total gamma-ray absorption coefficient, which is the sum of the absorption coefficients for each type of interaction. The energetic electrons resulting from these reactions usually deposit energy in the absorber through ionization processes.

Reference (24) contains a very complete listing of cross sections for photon interactions.

EFFECTS OF THE INTERACTION OF RADIATION WITH MATTER

The two basic mechanisms by which radiation creates damage in materials are ionization and atomic displacement. All of the radiations discussed previously may directly or indirectly create damage in the absorbing material by ionization and by displacement of atoms in the material.

Ionization

Ionization is caused by the passage of charged particles through matter. A charged particle in passing through a medium may lose its kinetic energy by any of four principal interactions:

(1) Inelastic collision with a nucleus. An interaction in which the incident particle is deflected by the nucleus. In such collisions a portion of the particle energy goes into creating an emitted photon (bremsstrahlung) or into excitation of the nucleus.
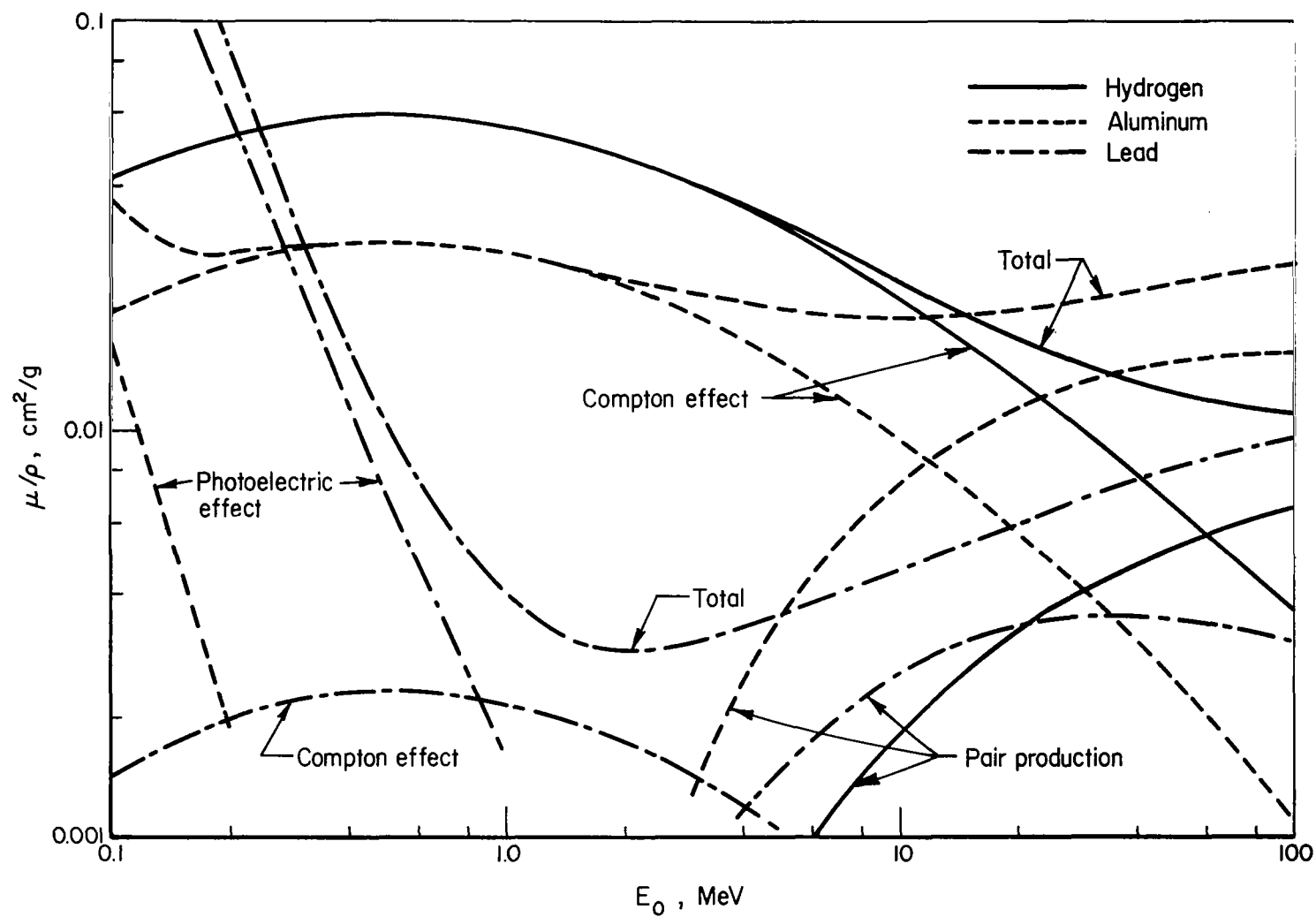
FIGURE 1. MASS ABSORPTION COEFFICIENTS FOR VARIOUS ELEMENTS[24]

(2) Elastic collision with a nucleus. An interaction in which
     the incident particle is deflected and part of its kinetic
     energy is given up in imparting a kinetic energy to the
     struck nucleus as required by conservation of momentum.

(3) Elastic collision with an atom. An interaction in which the
     incident particle is deflected elastically by the atom as a
     whole. The energy transfer in this interaction is usually
     less than the lowest quantity of energy required to remove
     any atomic electron from the atom.

(4) Inelastic collisions with atomic electrons. In this interaction,
     enough energy is imparted to one or more atomic electrons to
     experience a transition to a higher energy state (excitation)
     or is removed completely from the atom (ionization).

Inelastic collision with atomic electrons is the primary mechanism
through which energetic charged particles and, indirectly, electromagnetic
radiations affect or act upon materials. For a better understanding of the
mechanisms of electron excitation and ionization, a simplistic description
is given here for those not familiar with the processes. For a more
rigorous treatment, the interested reader is referred to Reference (22)
or any good basic atomic physics text.

Ionization is the removal of an orbital electron(s) from a neutral
atom or molecule. Atoms consist of a nucleus of protons and neutrons
surrounded by what may be considered a series of concentric shells of
orbital electrons. The number of electrons surrounding the nucleus
normally is equal to the number of protons inside the nucleus. The number
of protons in the nucleus, i.e., the atomic number, determines the identity
of the nucleus. The electron shells have been named from work in X-ray
spectroscopy. The innermost shell is the K shell, the next innermost, the
L shell, the next, the M shell, and so on. Each shell may contain only a
specified maximum number of electrons and the innermost shells must be
filled before an electron can remain in an outer shell. The closer an elec-
tron is to the nucleus, the more tightly it is bound to the nucleus, i.e., the
greater is the quantity of energy required to remove it from the nucleus.
The minimum quantity of energy necessary to move an electron from a
particular shell to a position where it is essentially free of the nucleus is
called the ionization potential, E_i. In practice, the average energy, $\overline{E}_p$,
that must be expended to remove an electron is two to four times greater
than the ionization potential, because of energy losses in other nonionizing
mechanisms such as excitation and kinetic energy of the ejected electron.

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The ejected electron can have sufficient energy to cause further ionization itself.

If an electron is removed from an inner shell, the vacancy (hole) created by its absence must be filled by an electron from a shell further removed from the nucleus. The electron that fills the vacancy has reduced its total energy in doing so. This energy is given up as a discrete quantity of energy called an X-ray photon whose energy just equals the difference in the energy of the electron before and after the transition to the shell closer to the nucleus. The energies of the photons emitted in this process are fixed for all possible transitions for any particular element and are called characteristic X-rays.

The ejected electron and the resultant positively charged atom constitute what is called an ion pair. The average energy, $\overline{E}_p$, required to create an ion pair varies with the temperature, the incident particle, and the incident particle's energy, $\overline{E}_p$ tending to be higher in gases for heavier incident particles. The possibility of theoretically calculating $\overline{E}_p$ is limited because of a lack of good cross-section data; thus, experimentally obtained values of $\overline{E}_p$ are more accurate. The ionization potential and the average energy expended per ion pair for several common materials are given in Table 4.

Measurement of ionization potentials in liquids, conducting solids, and insulators is very difficult, hence most studies of ionization have been limited to gases and semiconductors. The counterpart of the ion pair (ip) formed in gases is the electron-hole pair (ehp) formed in semiconductors. A charged particle loses energy in a semiconductor by moving an electron from the valence band of the semiconductor to the conduction band. The vacancy left behind by the electron has many of the properties of a positively charged particle. The energy-balance equation according to Shockley[26] is

$$\overline{E}_p = E_g + r\, E_r + 2\, E_F \quad ,$$

where E_g is the energy band gap in the semiconductor, r is the number of phonons generated per ionization, E_r is the phonon energy, and E_F is the residual electron or hole energy after an ion pair has been formed.

The value of $\overline{E}_p$ in gases and semiconductors is a relatively constant function of energy for incident particle energies above about $1/2\, m\, v_o^2$ where m is the mass of the incident particle and $v_o = 2\pi e^2/h$ is the velocity

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TABLE 4. AVERAGE ENERGY REQUIRED TO CREATE AN
ION PAIR OR ELECTRON-HOLE PAIR

Material	$\overline{E}_p$ γ and X-rays	$\overline{E}_p$ α Particles	$\overline{E}_p$ Protons	Miscellaneous
Gases	eV/ip	eV/ip	eV/ip	eV/ip
Air	33.73 ± 0.15	34.98 ± 0.05	36.0 ± 0.4	
Helium	41.5 ± 0.4	46.0 ± 0.5	$29.9\,^{+15}_{-0}$	
Hydrogen	36.6 ± 0.3	36.2 ± 0.2		
Oxygen	31.8 ± 0.3	32.3 ± 0.1	31.5 ± 2	31.0 ± 0.8[a]
Carbon dioxide	32.9 ± 0.3	34.1 ± 0.1	34.9 ± 0.5	
Water	30.1 ± 0.3	37.6		
Solids	eV/ehp	eV/ehp		eV/ehp
Silicon	3.8 - 4.2	3.57 ± 0.05		3.62 ± 0.04[b]
Germanium	2.8 - 4.5	2.89 ± 0.06		
Gallium arsenide				6.3[c]
Cadmium sulfide				5-10[c]

(a) For μ mesons.
(b) For 2.7-MeV tritium particles.
(c) Unspecified.

of an electron in the first Bohr orbit of hydrogen where e is the charge on an electron and h is Planck's constant. Below this energy, $\overline{E}_p$ tends to increase. The value of $\overline{E}_p$ is slightly temperature dependent, having temperature coefficients of -0.001 eV/(ehp-K) for electrons and -0.0015 eV/(ehp-K) for α particles in silicon. [25]

Atomic Displacement

Atomic-displacement damage is the result of atoms being displaced from their usual sites in crystal lattices. This effect is usually significant only in materials which have a highly ordered crystal structure and whose macroscopic material properties are changed by changes in this structure. The simplest form of this defect, a Frenkel defect, is a vacant lattice site (vacancy) and an extra atom inserted between lattice position (interstitial). A step-wise description of the production of displacement damage is as follows:

(1)   An incident energetic particle or a high-energy secondary particle collides with a lattice atom and imparts to it a recoil energy E_2.

(2)   The target atom leaves its lattice position, thus creating a vacancy.

(3)   The recoiling atom then dissipates its energy in ionization, in thermal excitation, and if its energy is great enough, by displacing other lattice atoms.

(4)   Eventually, all the recoil atoms come to thermal equilibrium in interstitial positions with the exception of the few that fall into vacancies. Some of the interstitials may be isolated (i.e., not in the strain field of other interstitials, vacancies, or impurity atoms), but for values of the recoil energy much greater than the displacement threshold energy, most will be associated with other defects.

(5)   The defects thus created tend to anneal, the simple defects and clusters moving through the crystal via thermal energy. Thus, the rate of annealing is temperature dependent.

(6) Eventually the mobile defects are either annihilated by the recombination of vacancy-interstitial pairs or are immobilized by the formation of stable defect complexes, or escape to a free surface.

(7) Meanwhile, the macroscopic properties of the material are generally changed by the presence of the defects.

Heavy Charged Particles

The primary mechanism for atomic displacement by charged particles is through Rutherford scattering. In this interaction an incident charged particle is deflected in the electrostatic field of another charged particle. The incident particle thus loses part of its energy to the target particle. Both particles then move away from the interaction site in directions determined by conservation of momentum. This is an elastic collision, and hence the total kinetic energy of the particles before and after the interaction is unchanged. In interactions of interest, the incident particle is assumed to be an energetic proton and the target particle, an atom.

Basic parameters in this interaction are:

v_0 = velocity of incident particle before interaction

E_0 = energy of incident particle before interaction

m_1 = mass of incident particle

m_2 = mass of struck (target) particle

Z_1 = charge number of incident particle

Z_2 = charge number of struck particle (equals atomic number for atoms)

e = unit electronic charge

E_1 and v_1 are the kinetic energy and velocity of recoiling incident particle

E_2 and v_2 are the kinetic energy and velocity of recoiling target particle

θ = the recoil angle in the center of mass coordinate system (C system)

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β = ratio of particle velocity to velocity of light = v_o/c

α = $Z_2/137$.

The nonrelativistic cross section then for transferring an energy be-tween E_2 and $E_2 + dE_2$ to a particle can be shown to be

$$d\sigma = \frac{2\pi (Z_1 Z_2 e^2)^2}{m_2 v_o^2} \frac{dE_2}{E_2^2} .$$

For relativistic interactions this becomes

$$d\sigma = \frac{2\pi (Z_1 Z_2 e^2)^2}{(m_2 c^2)\beta^2} \left[1 - \beta^2 \frac{E_2}{E_{2m}} + \pi \alpha \beta \left\{ \left(\frac{E_2}{E_{2m}} \right)^{1/2} \frac{E_2}{E_2^2} \right\} \right] \frac{dE_2}{E_2^2} ,$$

where E_{2m} is the maximum energy that can be transferred to the recoiling particle:

$$E_{2m} = \frac{4 m_1 m_2}{(m_1 + m_2)^2} E_o .$$

The spectrum of recoil energies, E_2, produced by monoenergetic incident particles varies as $(1/E_2)^2$; thus, most recoiling atoms will have energies much less than E_{2m}. [33]

In the energy range 0.01 to 50 MeV, this expression for E_{2m} holds for nonrelativistic particles and is valid for neutrons, protons, and other heavy particles. [35]

Integration of this to obtain the number of recoil atoms of energy greater than some energy E yields

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$$\sigma(E_2 > E) = \int_{E}^{E_{2m}} d\sigma$$

$$= \frac{P_2}{\beta^2} \left[\frac{1}{E} - \frac{1}{E_{2m}} - \frac{\beta^2 + \pi\alpha\beta}{E_{2m}} \ln\frac{E_{2m}}{E} \right.$$

$$\left. + \frac{1}{\ } \frac{\pi\alpha\beta}{(E_{2m})^{1/2}} \left(\frac{1}{(E)^{1/2}} - \frac{1}{(E_{2m})^{1/2}} \right) \right]$$

where

$$P_2 = \frac{2\pi (Z_1 Z_2 e^2)^2}{m_2 c^2} \quad ,$$

if $E_{2m} \gg E$, then

$$\sigma(E_2 > E) \cong \frac{P_2}{E\beta^2} \quad \text{[Reference (28)]} \quad .$$

Note: Since $E_o = 1/2 \, m_1 v_o^2 = 1/2 \, m_1 c^2 \beta^2$,

σ varies as $1/E_o$.

Electrons

Electrons, because of their small mass, must travel at relativistic velocities to produce atomic displacements. The calculations relating to the determination of these cross sections are rather complicated but the net result is that in the vicinity of the displacement threshold, the cross section rises steeply with increasing energy and then levels off and becomes nearly constant. This behavior is to be contrasted with the approximate $1/E_o$ dependence of heavier particle cross sections.

The maximum energy that can be transferred to a target particle of mass $m_2 \gg m_1$ by an electron of mass m_1 is, for $E_o \ll m_2 c^2$,

$$E_{2m} = \frac{2(E_o + 2m_1 c^2)}{m_2 c^2} E_o \quad .$$

The mean energy transferred to the displaced particle is approximately

$$\overline{E}_2 \cong \frac{E_d \; E_{2m}}{E_{2m} - E_d} \; \ln \frac{E_{2m}}{E_d} \quad ,$$

where E_d is the displacement threshold or the minimum energy that can be imparted to an atom and still displace it. [29]

The displacement cross section for relativistic electrons is: [30]

$$\sigma_d = \frac{\pi}{4} (b')^2 \left[\left(\frac{E_{2m}}{E_d} - 1 \right) - \beta^2 \ln \frac{E_{2m}}{E_d} + \pi \alpha \beta \left\{ 2 \left[\left(\frac{E_{2m}}{E_d} \right)^{1/2} - 1 - \right] \ln \frac{E_{2m}}{E_d} \right\} \right] \quad ,$$

where

$$\frac{\pi}{4} (b')^2 = \pi \, Z_2^{\;2} \left(\frac{e^2}{m_1 c^2} \right)^2 \frac{1}{\beta^4 (1 - \beta^2)} \qquad \frac{2.495 \times 10^{-25} \; (cm^2)}{\beta^4 (1 - \beta^2)} \, Z_2^{\;2} \quad .$$

As the cross section becomes constant it approaches the value

$$\sigma_d \cong \frac{\pi}{4} (b')^2 \frac{E_{2m}}{E_d} \quad .$$

In all practical cases the energy transferred to the displaced atom is only slightly larger than the threshold energy. The net result of electron radiation, then, is a pattern of isolated single displacements since the recoiling atom usually has insufficient energy to cause secondary displacements. [36]

Neutrons

The primary mechanism for energy loss for lower energy neutrons (E less than about 1 MeV for low Z materials) is elastic scattering with atoms in which the kinetic energy of the incident neutron is just equal to the total kinetic energy of the recoiling atom and recoiling neutron. For most elements, the elastic-scattering cross sections range from 2 to 10 barns for neutrons of low energy. The notable exception is hydrogen, for which the value is as high as 20 barns in the chemically unbound state

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and can be even higher at very low energies when the hydrogen is in the chemically bound state.[21] Exceptions to this general rule are resonance peaks in the cross section versus energy curves. Treatment of these peaks is not within the scope of this section. For exact values of neutron cross sections the interested reader is referred to Reference (31).

If

m_1 = mass of the neutron in atomic mass units = 1

m_2 = mass of the atom in atomic mass units = atomic mass

E_o = initial energy of the neutron

E_1 = recoil energy of the neutron

$E_{1_{min}}$ = minimum energy of recoil neutron

E_2 = kinetic energy imparted to the target atom,

the maximum fractional energy that a neutron can transfer to the target atom in a single collision, assuming isotropic scattering*, is

$$\frac{E_{2_{max}}}{E_o} = 1 - \frac{E_{1_{min}}}{E_o} = 1 - \left(\frac{m_2 - m_1}{m_2 + m_1}\right)^2 \cong 1 - \left(\frac{m_2 - 1}{m_2 + 1}\right)^2 = 1 - r^2 \quad .$$

Thus the maximum possible fractional energy loss per collision is higher for lower-atomic-number scatterers. For example, for aluminum $\frac{E_{2_{max}}}{E_o}$ = 0.14, but for lead $\frac{E_{2_{max}}}{E_o}$ = 0.02.

A more useful expression for energy loss would be the average energy lost per collision. A convenient way of describing this is as the average decrease in the logarithm(ξ) of the neutron's energy. This can be written as:

$$\xi = \overline{\ln E_o - \ln E_1)} = \overline{\ln (E_o/E_1)}$$

$$\xi = 1 + \frac{(m_2 - 1)^2}{2\,m_2} - \ln \frac{m_2 - 1}{m_2 + 1} \quad \text{[Reference (21)]} \quad .$$

---

*This equation should be multiplied by an anisotropy correction factor of between 1/2 and 2/3 for fission spectrum neutrons. At higher energies the anisotropy becomes greater.

For values of m_2 greater than 10, the approximation

$$\xi = \frac{2}{m_2 + 2/3}$$

can be used. For lower values of m_2, the error increases but is still only about 3 percent for $m_2 = 2$.

The average number of collisions a neutron of energy E_o undergoes in being slowed to an energy E_f is then

$$\text{average number collisions} = \frac{\ln (E_o/E_f)}{\xi} \quad .$$

Another useful expression is the average energy of a neutron after a collision, $\overline{E}_1$:

$$\overline{E}_1 = \frac{E_o}{2} \left[1 + \left(\frac{m_2 - 1}{m_2 + 1} \right)^2 \right] \quad ;$$

thus a neutron on the average will lose one-half of its kinetic energy in each collision with a hydrogen atom. This is why hydrogenous materials are so effective in slowing down fast neutrons.

The minimum energy that can be imparted to the recoiling nucleus is zero. Therefore, since the energy spectrum of recoiling nuclei is nearly uniform between $E_{2_{min}}$ and $E_{2_{max}}$, the average energy of the recoiling nucleus is

$$\overline{E}_2 = 1/2\, E_o (1 - r^2) \quad ,$$

or just one-half of the maximum value.

At high neutron energies (> 1 MeV), the cross section for elastic scattering and the cross section for absorption plus inelastic scattering both approach the geometrical cross section of the nucleus. Therefore, the total cross section approaches the limit of $2 \pi R^2$, where R is the radius of the nucleus and may be approximated by

$$R \approx 1.3 \times 10^{-13}\, (m_2)^{1/3} \text{ cm} \quad .$$

Typical values for the scattering cross section for fast neutrons are in the range of 2 to 4 barns for most nuclei.

The following expression relates the displacement cross section, σ_d, to the scattering cross section:

$$\sigma_d = \sigma_s \left(1 - \frac{m_2 \, E_d}{4 \, E_o} \right) \cong \sigma_s \text{ (for } E_o \gg E_d) \quad ,$$

where E_d is the threshold energy for displacement.

CORRELATION OF EFFECTS CREATED BY
DIFFERENT RADIATIONS

Theory can predict the effects of radiation on materials only to a limited extent. It is therefore desirable that samples of all of the materials or components proposed for use in the space environment be tested in the actual environment of space. Because of costs, time involved, and other practical considerations, all samples cannot be tested in this environment; therefore, the effects of this environment must be simulated in earth-bound laboratories.

The most obvious method of simulating the space environment is to reproduce this environment exactly in the laboratory. For several practical reasons, this cannot be done on the large scale required. The alternative method of testing materials is to expose them to other terrestrial radiations, and from their response to these radiations, determine what their response to space radiations will be. This method has the advantage that data from other radiation-effects studies can then be used to provide information on the response of materials to space radiations.

Attempting to correlate the effect of one radiation environment with the effect that another will have on matter must be done with extreme care. An understanding of the mechanisms of the radiation damage is essential. The microscopic changes in the material and how the radiation induces these microscopic changes must be understood. How these changes can be induced by other means, that is, by a different type of radiation, by radiation of a different energy spectra and flux, or by nonradiative mechanisms must be determined.

When attempting to utilize the laboratory irradiation of materials to simulate the effects that would result from space irradiation, the exact conditions of both irradiations must be known and given due consideration. The degree to which radiation affects a device or material is a complex function, dependent upon the environment (temperature, surrounding atmosphere, etc.), rate of irradiation, the spatial distribution of the defects created, the orientation of the sample with respect to the incident radiation, and the past history of the sample, in addition to the more obvious variables such as the type of radiation and energy spectra. Attempts to correlate the effects of one type of radiation in an environment to the effects that another radiation will produce in another environment should not be attempted unless the mechanisms for creating the damage are thoroughly understood. With this knowledge, the approximate equivalence of various environments can be deduced theoretically and then proven experimentally to reduce substantially the amount of experimental data required and to facilitate the application of existing radiation-effects data.

There are two basic mechanisms by which radiation can induce damage in materials — energy deposition and atomic displacement. Correlation of radiation effects is discussed separately for each of these two mechanisms.

Energy Deposition

Permanent radiation damage in many materials, particularly organic materials, depends primarily upon the amount of energy deposited in the material. The primary mechanism for energy transfer from the incident radiation to the absorbing material is through ionization of atoms or molecules of the material.

All radiations, providing their energy is high enough, can produce ionization. Charged particles are able to cause ionization by direct interactions, and neutrons and electromagnetic radiations cause ionization indirectly through the interaction of charged secondary particles and recoiling nuclei from scattering interactions. Since the probability of a charged particle ionizing an atom or molecule is a function of the time the charged particle spends in the vicinity of the atom, slower particles (i.e., greater mass or lower energy) are more effective in causing ionization. Table 5 shows the relative particle effectiveness for energy deposition in carbon for several particles. This table is given only to indicate relative

effectiveness. Actual values will vary for other samples because of different physical environments, material composition, physical size, and other factors.

TABLE 5. PARTICLE EFFECTIVENESS FOR ENERGY DEPOSITION IN CARBON[34][b]

Particle	Energy, MeV	Range in Carbon, cm	Integrated Flux for 1-Rad Dose in 1 Cm^3 of Carbon[a], particles/cm^2	Relative Effectiveness
Fission Neutron	1-2	>>1	102×10^{10}	0.17-0.08
Gamma Photon	1.25	>>1	1.7×10^9	1
Electron	0.3	0.08	3.2×10^7	53
Electron	1.7	0.8	3.3×10^7	51
Electron	5	1.1	3.0×10^7	57
Proton	18	0.2	2×10^6	850
Proton	110	>1	1×10^7	170
Proton	740	>1	3×10^7	57
Alpha	40	0.06	2×10^5	8500

(a) Particles whose range is < 1 cm deposit the 1-rad dose within a thickness equal to the particle range.
(b) This table is given as an example of relative effectiveness. Actual values may vary.

Although different radiations may deposit the same quantity of energy, they may deposit it differently. For example, 740 MeV protons and 0.3 MeV electrons have similar values of relative effectiveness, but the electron deposits its energy in the first 0.08 cm of material, while the proton requires more than 1.0 cm to deposit the same quantity of energy, the net result being different distributions of deposited energy. This may or may not affect the magnitude of the radiation-induced damage, depending upon the parameter of interest.

This example serves to point up the hazards of trying to correlate the relative effectiveness of the various radiations for depositing energy in a material. It can be done, but the exact conditions of the two irradiations and the manner in which they interact with the material must be known and be maintained throughout the experiments.

Displacement Effects

The primary mechanism for radiation-damage effects in materials with a crystalline structure is the displacement of atoms from their lattice sites with the subsequent creation of lattice vacancies and interstitial atoms. Displacements can be caused directly by fast neutrons, protons, and high-energy electrons and can result indirectly from incident gamma-ray photons, via the secondary electron.

To produce a displacement, the incident particle must transfer a minimum quantity of energy, that is, the threshold energy (E_d), to the struck atom. This energy is usually several times greater than the energy required to create a Frenkel pair by a thermodynamically reversible process. For monatomic solids, the threshold displacement energy typically ranges from 10 to 30 eV, but varies with temperature and crystallographic direction.

The energy imparted to the displaced atom in excess of that required to displace it goes into kinetic energy. Frequently, the displaced atom will have sufficient energy to create further displacements, which results in a cascade effect.

Expressions for the average energy transferred to the primary displaced atom by fission neutrons and by protons are given below. For the sake of comparison, values obtained by calculating the results of bombarding copper (E_d = 25 eV) with 1.5-MeV particles are given. *

By fission neutrons: $\overline{E_2} = 1/2 \ E_{2m} = E_o/2 \ (1 - r^2) = 5 \times 10^4$ eV

By heavy charged particles: $\overline{E_2} = \dfrac{E_d \ E_{2m}}{(E_{2m} - E_d)} \ln\left(\dfrac{E_{2m}}{E_d}\right) = 2 \times 10^2$ eV .

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*See elsewhere in this section for definitions of the terms in these equations.

It can be seen that the average energy transferred to a displaced atom by a fission neutron is much greater than that transferred by a charged particle. The neutron-displaced atoms will then be able to cause a relatively greater number of secondary and even tertiary displacements than are caused by atoms displaced by a charged particle. In the case of electrons, $\overline{E}_2$ is only slightly greater than E_d, and hence very few if any secondary displacements occur.

The energetic displaced atoms not only lose energy by displacing other atoms, but if the displaced atom has sufficient energy, it will be ionized and may dissipate energy by excitation of bound electrons and ionization of atoms in the crystal.

The average number of displaced atoms N_s $(\overline{E}_2)$ resulting when a primary recoil of energy $\overline{E}_2$ finally comes to rest is a function of the recoil atom only. Within the accuracy required for most displacement-effects work, it has the form:

$$N_s \ (E_2) = \frac{fE_2}{2\overline{E}_d} \quad ,$$

where $(1 - f)$ is the fraction of the recoil atom's energy which is consumed by ionization and $\overline{E}_d$ is an average over all crystal directions of the displacement threshold energy, E_d. The quantity f approaches unity for lower values of E_2 and is usually assumed to have the form calculated by Lindhard[41] and confirmed experimentally by Sattler.[42] These data are summarized in Figure 2 for silicon. E_d is somewhat higher (probably of the order of a factor of two) than the threshold, E_d, for the most favorable direction.[43]

For photon radiations, the values presented in Table 6 are the displacements due to the Compton electrons that are assumed to be in equilibrium with the photons.

FIGURE 2. FRACTIONAL ENERGY LOST IN IONIZATION VERSUS ENERGY OF RECOIL SILICON ATOM

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TABLE 6. THEORETICAL DISPLACEMENT PRODUCTION

	$\overline{N_S}$	
	Si[b]	Ge[b]
1-MeV neutrons[a]	500	300
14-MeV neutrons[a]	1500	700
1-MeV electrons	1.3	1.0
40-MeV electrons	5.0	4.4
1-MeV photons	1	1
10-MeV protons	6	5.6
100-MeV protons	7	7

(a) The neutron data take into account anisotropic scattering
events and a correction factor for the energy loss of the recoil
atoms in nondisplacing (inelastic) collisions.

(b) The values used for the displacement-energy threshold are
$\overline{E_d}$ (Ge) = 30 eV and $\overline{E_d}$ (Si) = 25 eV.

Distribution of Defects

As mentioned previously, electrons tend to create individual defects
consisting of one displaced atom. Since gamma rays produce displacements
via secondary electrons, the same can be said for them. Because of the low
penetrating power of electrons, the defects tend to be located near the sur-
face (within the range of the electron), while gamma-ray-induced defects are
more uniformly distributed throughout the irradiated material. This neat,
orderly description is somewhat clouded by the possibility of the generation
of bremsstrahlung by the incident electrons. Bremsstrahlung produces
defects just like those produced by gamma rays. For samples whose thick-
ness or sensitive region is comparable to or less than the range of the elec-
trons, the correlation between electron- and photon-induced damage may be
good. For example, correlation between 1-MeV gamma rays and electrons
whose energies are equal to or slightly less than 1 MeV would be expected to
be good since the gamma ray produces displacements via the secondary elec-
trons and the secondary electrons would have energies comparable to the
incident electrons.

Since the energy imparted to the displaced atom by an electron is slight, it may not travel more than a few atomic distances before it stops. The relatively close positions of the vacancy and interstitial could have a significant effect on the macroscopic property changes and annealing kinetics of the material.

Incident heavy charged particles lose a small portion of their energy in each primary interaction. Each primary displaced atom displaces on the order of 10 more atoms, forming a small cluster of defects in a region containing $\sim 10^3$ atoms. Since the incident particle loses only a small fraction of its energy in each primary interaction, it dissipates its energy by creating small clusters of defects, and an occasional larger one, distributed along its path. The defect clusters due to heavy charged particles are relatively uniformly distributed, with the cluster density being more dense toward the end of the incident particle's range.

Fast neutrons can transfer a much larger fraction of their energy in a primary displacement. The displaced atom then has sufficient energy to create a large number of defects through secondary and tertiary processes. The net result of a 1.5-MeV neutron displacing an atom could be a clustering of 10^2 to 10^3 defects in a volume of the crystal containing 10^5 to 10^6 atoms. Since most neutron fluxes are not monoenergetic but represent a range of energies, neutrons produce a variety of cluster sizes. For low exposures $(\lesssim 10^{17} \; n/cm^2)$ where clusters are still well separated, the damage tends to be very much more nonhomogeneous than for heavy charged particles. At fluences above this level, clusters tend to overlap and produce a more uniform but quite intense damage distribution.

From the preceding, it is obvious that different radiations produce different types of damage, both with regard to distribution and severity. The degree to which these differences are significant depends upon the material parameter that is being changed by the radiation. In a given material, two radiations that produce the same or not too dissimilar spectrum and density of primary recoil atoms will produce the same effect. If this is the case for two radiations and other conditions are not significantly different, a correlation can possibly be made.

Annealing

The treatment of defect creation predicts the number of defects created, but does not consider the annealing of defects. The defects created are usually

not thermally stable but will diffuse thermally until vacancies and interstitials recombine or form secondary, thermally stable defects. This annealing process can either enhance or detract from a material's properties, depending upon the property in question. The attainment of this thermally stable condition is both a function of time and temperature. The annealing behavior of irradiated substances is a complicated and not well-understood process. A treatment of the subject is beyond the scope of this section and it is mentioned only to make the reader aware of the existence of the phenomenon.

DOSIMETRY*

Introduction

Dosimetry is the task of measuring and providing a quantitative description of a radiation dose, preferably in terms relevant to the radiation effect being studied. In its most general form, the environment can be described by stating the (possibly time dependent) number of nuclear or atomic particles of various types and energies (the spectrum) which cross a given surface. Unfortunately, such a complete description is rarely available or economically measurable, but, fortunately, it is not required for most radiation-effects experiments. In mathematical terms, for a radiation spectrum $\phi(E)dE$ and a radiation effect with energy dependence $R(E)$, the total effect produced by the spectrum is

$$R = \int R(E) \, \phi(E) dE$$

For example, if a particular radiation effect of interest has a response, $R(E)$, which is fairly insensitive to energy, that is if $R(E)$ = constant, then the total effect is just

$$R \cong \text{constant} \int \phi(E)dE \cong \text{constant} \times \Phi \quad .$$

The integral in the above equation, denoted by Φ, is just the total neutron fluence, and the particular effect, used as the example, is one proportional

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*An excellent source of more detailed information on radiation dosimetry is contained in Volumes J, II, and III of Reference (1).

only to the total fluence. Since this effect is independent of spectral shape, the total radiation fluence is the relevant quantity and is all that must be determined when describing the environment. On the other hand, if an effect such as neutron-displacement damage in silicon, which is quite dependent on neutron energy, is being studied, the total effect is described by the first equation, in which case both the total fluence and its energy spectrum are relevant and should be determined.

The measurement of a radiation environment also entails the determination of a radiation effect. In this case a dosimeter with a known response function D(E) which has been calibrated with respect to the radiation field is used and a measurement

$$D = \int D(E) \, \phi(E) dE$$

is obtained. If the dosimeter response function, D(E), is approximately proportional to R(E) for the energy range of importance to these integrals, it is a fortuitously appropriate dosimeter. If it is not, other information, such as an estimate of the shape of $\phi(E)$, will be needed to relate the dosimeter reading, D, to the expected effect, R. The appropriateness of the detector is measured, therefore, by how closely its response function is related to the response function for the radiation effect being studied for the type of radiation considered. This same conclusion applies to the appropriateness of a dosimetry unit.

For example, it has been established that the magnitude of bulk-ionization effects in silicon is a function only of the ionization energy deposition. Therefore, the appropriate unit for describing ionizing radiation when interested in ionization-induced currents in a silicon device is a unit of energy deposition in silicon, e.g., rad (Si). Any dosimeters whose reading can easily be converted to rad (Si) in a way which is not sensitive to the detailed spectrum of the incident radiation is then useful. By way of contrast, displacement effects in silicon represent a totally different response to the radiation spectrum, and the rad (Si) is an inappropriate unit. In this case the total fluence and spectrum of neutrons measured or the equivalent fluence of some energy or spectrum of energies of neutrons which would produce the same concentration of displaced atoms in silicon [neutrons/(cm^2)-1 MeV equivalent] as the measured fluence and spectrum is frequently used.

Perhaps the most common error made in a radiation-effects experiment is to neglect the effect of the perturbation of the radiation spectrum created by the presence of the experiment. It is this perturbed spectrum and not the free-field spectrum which must be used in the correlation or in determining the total radiation fluence from a monitor dosimeter (or foil) used with the experiment.

Before proceeding with a definition of units and descriptions of dosimeters, it is appropriate to comment on two commonly used and misused terms: correlation and simulation. As applied to radiation effects, they are defined as follows:

Simulation is the production of a particular radiation effect by
        any means.

Correlation is the establishment of the relative intensities of
        different spectra or types of radiation required
        to produce the same effect.

Note that simulation does not necessarily imply any need to reproduce a radiation environment, only its effect. If the same effect can be produced by electrical or optical stimulation means rather than nuclear radiation, these are valid simulation techniques for that effect. Note also that the correlation between radiations must be established separately for each class of effect. For example, the correlation between different energy neutrons is much different for displacement effects than for ionization effects.

<div align="center">Neutron Measurements</div>

General Principles

In order to perform the weighting of different neutron energies, it is necessary to have a reasonably good picture of the neutron-energy spectrum for energies above 10 keV. The contribution to displacement effects or ionization from neutrons below 10 keV in reactor environments is usually negligible. Many neutron-producing facilities will be able to provide fairly detailed spectral information on the free-field neutron environment to experimenters utilizing the facility. These spectra are, in general, determined from data obtained from high-resolution spectrometers (recoil proton, Li^6,

He^3, etc.), from low-resolution measurements utilizing activation techniques, or from reactor physics calculations. In general, if a radiation-effects experiment is small, there is a good chance that the free-field spectrum will not be significantly perturbed and thus will be relevant to the experiment being conducted. If additional spectroscopy measurements are necessary, a decision must be made to determine the accuracies required. For high resolution measurements, fairly expensive, time-consuming spectrometer measurement should be made. In most cases, however, lower resolution measurements will be acceptable and activation spectroscopy measurements will suffice. Inasmuch as the techniques followed in a spectrometer measurement are highly dependent upon the instrumentation involved, and the calculation of the approximate spectrum is beyond the scope of this manual, no recommended procedures will be given in this document. General recommendation will, however, be given concerning foil activation techniques.

Foil Activation Measurements

Foil activation techniques utilize neutron-induced reactions, leading to radioactive isotopes, for which there is a threshold energy, or for which an artificial threshold can be produced by shielding. The process is illustrated schematically in Figure 3. The top graph shows a typical neutron spectrum. The middle graph shows an idealistic response function for a threshold foil. The product of these two functions is shown in the bottom graph. The area under this curve is the total foil response (which is proportional to the foil activity). It can be seen that, roughly, the neutrons with energy above E_t contribute to the response, and the effective response coefficient (cross section) is almost a constant, σ_{eff}. Therefore, the foil response is approximately proportional to $\Phi (E > E_t) \sigma_{eff}$.

A method based on irradiating a number of foils with different thresholds has proved to be very useful. The limitations to the foregoing approximate analysis are obvious: $\sigma(E)$ is not constant above E_t, and E_t itself is a function of the spectral shape. The steeper spectra tend to push E_t downward. In an actual situation, where the cross section is not constant but the spectral shape, $\Phi(E)$, is known, one can obtain a spectral averaged cross section from the expression

$$\overline{\sigma} = \frac{\displaystyle\int_0^\infty \sigma(E)\,\Phi(E)\,dE}{\displaystyle\int_{E_t}^\infty \Phi(E)\,dE} \quad .$$

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With this average cross section and the measured foil activity, the neutron fluence above the threshold energy, E_t, can be obtained. Since the spectrum is known, the total neutron fluence can thus be determined. This process is the most common measurement made in neutron-effects testing. The most commonly used monitor foil material is S-32, which has a threshold energy of approximately 3 MeV. The $Ni^{58}(n,p)Co^{58}$ reaction is also useful and is now seeing widespread use. If this method is used, one must be careful to insure that the experiment has not perturbed the spectrum, since large errors can unknowingly be introduced when utilizing this technique.
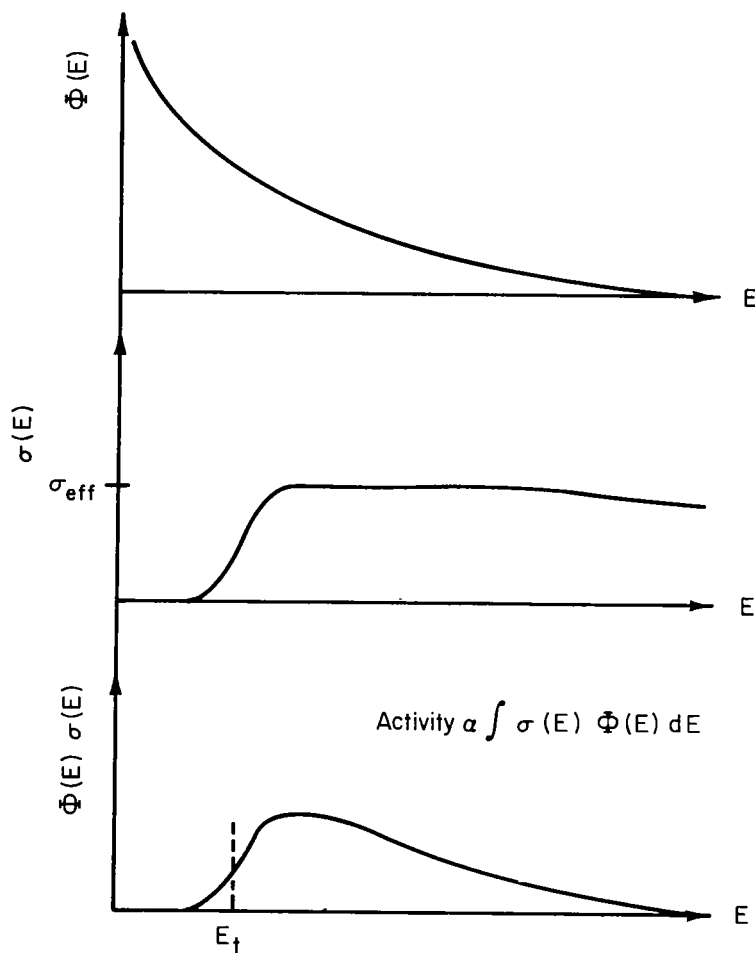
FIGURE 3. THRESHOLD FOIL METHOD

In situations where the spectral shape is not as well known, a series of threshold foils can be used. By assuming a spectral shape (e.g., a fission spectrum of "best estimate" for the particular reactor), an average cross section can be computed, and the fluence above the various thresholds, based upon the assumed cross section, determined. A curve of the integral fluence as a function of energy can be determined by this method. From this curve the ratio of total fluence to that above a monitor foil's threshold (e.g., S-32) can be determined so that further exposures can be made with the use of only the one monitor foil. Commonly used threshold reactions are listed in Table 7 together with their effective thresholds and cross sections for a fission spectrum. If the integral curve obtained in the previous manner differs considerably from an integral curve of the assumed spectrum, further data evaluation must be done.

TABLE 7. THRESHOLD REACTIONS

Foil	Effective Threshold, E_i, MeV	Effective Cross Section for Watt Fission Spectrum, $\bar{\sigma}$, barns
Au-197 (n, γ) Au-198	thermal	98.9
Pu-239 (n, f) f. p.	0.010[a]	1.7
Np-237 (n, f) f. p.	0.600[a]	1.65
U-238 (n, f) f. p.	1.50[a]	0.55
Ni-58 (n, p) Co-58	3.0	0.55
S-32 (n, p) P-32	3.00	0.30
Mg-24 (n, p) Na-24	6.30	0.067
Al-27 (n, α) Na-24	7.5	0.079

(a) Surrounded by 1-cm boron-10.

Computer codes have been developed, such as SAND II, RDMM, and SPECTRA, which can be used to extract further spectral information from the set of activation data. The SAND II and SPECTRA codes compute both differential and integral spectra, based upon iterative techniques, and utilize both the response-function differences of the various reactions over

the entire sensitive energy regions and other physical information available about the source to obtain these solutions. RDMM computes differential flux as a continuous analytical function. If the spectral shape is calculated by one of these codes for the particular experimental setup, and if no changes in the setup are made, a single monitor foil may be used for subsequent irradiations. It is wise, however, to check routinely to insure that the spectrum has not changed unknowingly. Obviously, the accuracy of the neutron-fluence measurements with foil activation techniques will be limited by the accuracy of the cross-section knowledge, the calibration of the counting equipment, and the degree of sophistication exercised in reducing the foil activities to fluence information.

The three codes may be obtained from the Atomic Energy Commission Radiation Shielding Information Center at Oak Ridge National Laboratory. Evaluated energy-dependent cross sections for neutron-detector reactions are also available from the center. being tabulated on magnetic tape (SAND II cross-section library format).

Photon, Proton, and Electron Measurements

General Principles

Photon, proton, and electron measurements are primarily measurements of ionization effects. Therefore, the dose (or ionization density) in the material of interest is most closely related to the effect. The response function relating this effect to the photon energy is known as the mass absorption coefficient. Shown in Figure 4 (see also Figure 1) are mass absorption coefficients for silicon (used as an example of a typical low Z material). As can be seen for these materials, the absorption coefficients are essentially independent of energy over the energy range, $150 \text{ keV} \leq E \leq 1 \text{ MeV}$, and are very slowly varying functions up to an energy as high as 10 MeV. On the basis of these characteristics, the absorbed dose per unit energy fluence for bremsstrahlung distributions over this energy range is fairly insensitive to the spectral shape, and dose measured in a low-Z dosimeter can be converted quite easily to dose in a low-to-medium-Z material of interest. For high-energy electrons and for the Compton effect of high-energy photons and low- or medium-Z material, an approximate rule of thumb (±5 percent) is that the dose is proportional to Z/A of the target material, where A is the mass number. For higher accuracies, even a

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crude spectral shape used with the equations given for D and R can convert dose measured in any dosimeter, D, to the dose in the material of interest, R, viz.,

$$R = D \frac{\int R(E) \, \phi(E) \, dE}{\int D(E) \, \phi(E) \, dE} .$$

For electron-beam exposures in a known spectrum, dose may be converted from one material to another by using the above equation and dE/dX values given in the literature. [44]
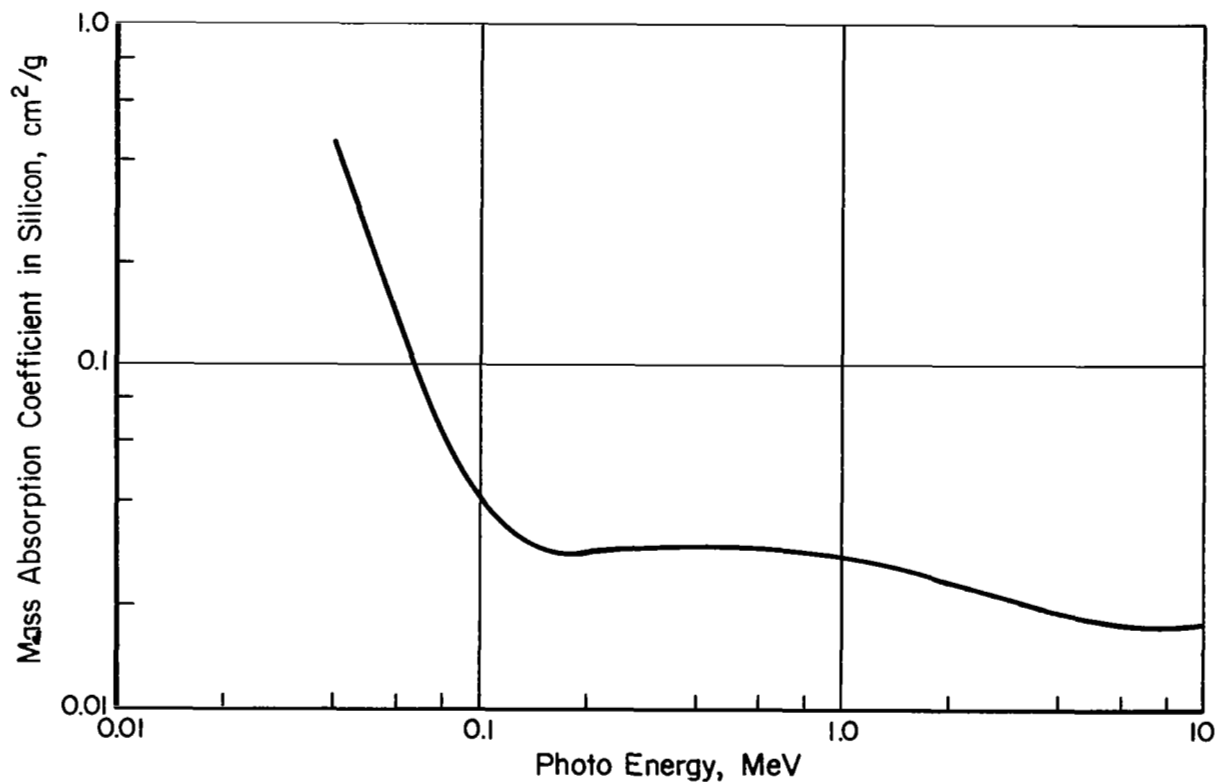

FIGURE 4. MASS ABSORPTION COEFFICIENT IN SILICON

The use of high-energy electrons, $0.5 \leq E \leq 15$ MeV, to produce ionization effects is straightforward. Their rate of energy deposition is almost

independent of energy and material, Z < 40. The only cautions are that the electron energy needs to be high enough to penetrate the target and radiative losses must be considered. In addition, thin plates can scatter a small-diameter electron beam into a cone-shaped beam. Therefore, objects in the beam ahead of the target, such as a chassis, must be in place during dosimetry calibration.

High-energy protons deposit energy primarily through ionization, but can create atomic displacement. The measurement and prediction of deposited dose from incident protons is complicated by the generation of secondary particles and photons in inelastic scattering processes. In general, for absorbers of thickness less than the range of the incident protons, the dose from the primary protons predominates. For a thickness greater than the primary proton's range, secondary particles and gamma rays can contribute significantly to the absorbed dose.[32]

Since photons (gamma or X-rays) are indirectly ionizing radiation and lose energy through the creation of high-energy electrons which subsequently lose energy through further ionization, extra care must be taken in accounting for lack of electron equilibrium. If a pure photon beam were incident on a slab of material, the energy deposition as a function of depth in the slab would be as shown schematically in Figure 5. Although the amount of energy initially imparted to the material by photons decreases with depth, the actual dose builds up to a maximum at a depth corresponding to the maximum electron
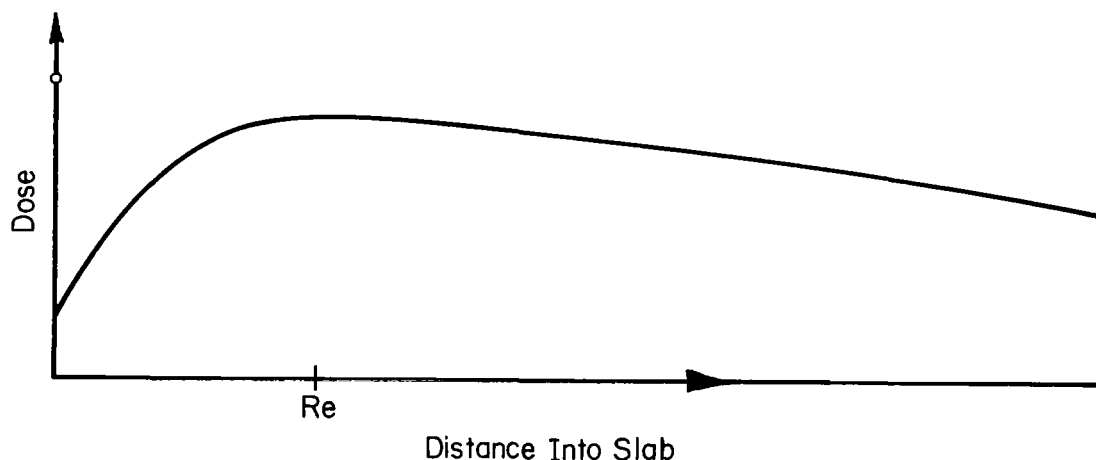
FIGURE 5. ENERGY DEPOSITION BY PHOTONS

range, then decreases very slowly at the rate of attenuation of the photon beam. This loss of dose to the material near the surface corresponds to that energy lost by the electrons which are scattered out of the material before all of their energy is deposited. At a point corresponding to the maximum electron range and beyond, the beam is in electron equilibrium, meaning that for every secondary electron leaving a small region of interest, another enters the region or, equivalently, the ratio of electrons to photons remains constant. For high photon energies (> 200 keV) in low- and medium-atomic-number materials (Z < 40), the ratio of electrons to photons is almost independent of material. At lower energy and higher Z, the ratio changes when the beam goes from one material to another, in a fashion similar to that shown in Figure 5. Therefore, in order to avoid complications from nonuniformity of dose and to provide accurate dosimetry, exposures should be performed under conditions of electron equilibrium. Unless electron equilibrium is established correctly in the radiation source, a foil of approximately the correct Z and an electron-range thickness should be interposed in front of the target. The same rule applies to the cases of dosimeters. The electron range is approximately

$$R_e = 412 \ E^{(1.265 - 0.0954 \ \log_e E)} \quad \text{for } 0.01 \text{ MeV} \leq E \leq 3 \text{ MeV}$$

$$R_e = 530 \ E-106 \quad \quad \quad \text{for } 2.5 \text{ MeV} \leq E \leq 20 \text{ MeV},$$

where R_e is in mg/cm^2, and E is in MeV.

When reporting absorbed-dose measurements, the unit rad, radiation absorbed dose, is used. One rad corresponds to the deposition of 100 ergs/g of radiation energy in a small volume of the material of interest at a point of interest. It is important to note that the material in which the energy is deposited must be specified when reporting with this unit of measure, i.e., rads (Si), rads (H_2O), etc. Dosimeters for use in experiments should be calibrated in known spectra to read rads (dosimetry material).

If nonconducting dosimetry materials or experiments are exposed to intense electron beams characteristic of flash X-ray machines, care must be taken to account for the effect of the potential buildup in the sample (from trapped electrons) on the dose to the sample.

The various dosimeters useful for ionization-effects studies with photons, protons, and electrons are described below.

Dosimetry Devices

Radio-Photo Luminescent Devices (RPL)

In RPL devices, irradiation produces stable fluorescence centers which may be stimulated by subsequent ultraviolet (UV) illumination to emit visible light. The total light emission is a measure of the absorbed dose in the RPL material (if in electron equilibrium) which was previously exposed.

An example of a RPL dosimeter is a silver metaphosphate glass rod or plate system. These dosimeters can also be used with special energy shields (e.g., ~1.2 g/cm^2 Pb, 0.6 g/cm^2 Sn, 0.2 g/cm^2 Al, and 0.11 g/cm^2 low-Z plastic) which suppress the low-energy response of the high-Z silver by absorption sufficiently that the total response is essentially independent of energy, yielding a reading proportional only to exposure (photon fluence) for photon spectra of energy 100 keV < E < 5 MeV. By knowing the total fluence and the spectral shape, one can evaluate the dose for any other material. With a thinner shield matching the average Z of the glass, it would measure dose in the glass.

Glass rods should be cleaned and read before irradiation for an expected dose of < 100 rads (glass). They should not be routinely reused. If absolutely necessary, annealing is possible using procedures documented in the literature. Extreme care should be taken to avoid glass-rod chipping.

For high-energy electron-beam dosimetry, the rods should be used directly on or in the experiment without shields; then one is measuring local absorbed dose, rads (glass).

Optical-Density Devices

In optical-density devices, radiation produces stable color centers which absorb light. Measurements of the optical transmission, usually at a fixed wavelength, can be related to the dose in the active material.

An example of an optical-transmissivity-change dosimeter is a cobalt-glass-chip system. At doses greater than 10^6 rads, saturation is approached and the readings can become very inaccurate. Other materials which are used as calorimetric dosimeters include dyed plastics such as blue cellophane,

cinemoid films, etc. Again these should be used within their accurate range (~10^6 rads) and corrections may be required at very high dose rates. Before using a particular dosimetry system, one should consult the literature to determine rate and environment effects which may be characteristic of the particular system.

Thermoluminescent Devices (TLD)

TLD irradiation produces metastable centers which can be induced to emit light by heating. The amount of light is related to the dose in the TLD material.

An example of a TLD dosimetry system uses lithium fluoride with a readout unit that heats the exposed material and registers the area under the luminescent peak. The heating rate should be checked for linearity or at least reproducibility, and for doses below 1 rad (LiF), the readout should be performed with the material in an inert or dry nitrogen atmosphere. Because of the radiation damage, low dose readings should always be taken with unused materials. The TLD materials can be annealed and reused only at high doses.

TLD materials can be obtained in several forms and chemical compositions. Examples include powders, extrusions, encapsulations in Teflon, etc. Chemically differing dosimeters including calcium fluoride, lithium chlorate, etc., are also available.

Because of their sensitivity to preirradiation heating history, TLD's should be used as delivered from the manufacturer or system vendor and no preirradiation annealing should be attempted in routine dosimetry.

Manganese-activated calcium fluoride is, for some applications, a more useful TLD material than LiF since: (1) it does not saturate at as low a dose; that is, it is not as easily damaged; and (2) its Z is closer to silicon, so that with an aluminum or silicon case one can get a good approximation of rad (Si).

The wall material surrounding the TLD material should match the TLD atomic number and should be thick enough to establish electron equilibrium. Then (if the calibration is correct) the dose measured will be rad (TLD material); otherwise the dose will be intermediate between rad (TLD material) and rad (wall material).

The TLD reader should be checked regularly for proper operation of the phototubes and heating units; a regular (daily or weekly) calibration made with cobalt-60 or other standard source, and a log kept to show trends. TLD-system manufacturers' recommendations for care of the reader should be followed. To check heating rates, and to allow for examination of the entire glow curve, the readout units should be provided with outputs for strip-chart recording of temperature and light output. Li dosimeters are reused, they should be periodically checked in a standard source to insure that radiation damage has not changed their sensitivities.

Thin Calorimeters

A thin calorimeter determines the dose by measuring the temperature rise in a small sample of known material. Since the temperature rise can be converted to energy deposition (dose) by the material's specific heat, the measurement is a direct determination of the average dose in the sample. If the sample is thin, i.e., it absorbs a negligible fraction of the incident radiation and the incident beam is in electron equilibrium for the calorimeter material, the temperature rise is independent of thickness.

The three important elements of a thin calorimeter are the absorber, the temperature sensor, and the thermal isolation. The absorber can be any material, preferably having approximately the correct atomic number as judged by the effect being studied, and also preferably a good thermal conductor to assure rapid thermal equilibrium. Metal foils (Be, Al, Fe, Cu, Ag, Pt, Au) as well as thin semiconductor chips (Si, Ge) have been used successfully.

The temperature sensor should represent a small perturbation on the absorber. A thermocouple satisfies this criterion well, particularly if it almost matches the atomic number of the absorber. A small copper-constantan thermocouple on a copper foil is a good example. A more sensitive calorimeter results from using a small thermistor as both absorber and temperature sensor. A chemical analysis of the thermistor can establish its effective atomic number, and a calibration against a known material is required to establish the combination of specific heat and temperature coefficient. Care must be taken in assembly to minimize the amount of solder used in attaching leads, because this may enhance the amount of higher Z material. Resistance welding can be used to eliminate this problem. If the thermistor is not thin to the radiation, the temperature measurement must be performed

for a sufficiently long duration in order to insure that thermal equilibrium is established within the thermistor (0.1 to 1 second).

In order to measure accurately a small, sudden temperature rise, some degree of thermal isolation is required. Obviously the leads to the temperature sensor should be small wire ($\approx$3 mils). For single-pulse measurements, a block of Styrofoam provides good isolation, but the heat lost to the inside layer of Styrofoam is a small correction, particularly for very thin calorimeters. Use of the calorimeter in vacuum also provides excellent isolation. For accurate measurements, expecially on a short string of LINAC pulses, the absorber can be suspended in a small, evacuated can with water-cooled constant-temperature walls and a thin window for beam entrance. The detailed design depends on the radiation beam being measured and the accuracy requirements, and may have to take into account scattering from the walls of the chamber.

For single pulses typical of flash X-ray machines, a cooling curve should be established and exponentially extrapolated to zero time to determine the temperature at the time of the burst.

The response of the calorimeter is calibrated by the specific heat of the absorber and the temperature calibration of the sensor. In electron-beam measurements, if the calorimeter material is the same as the experimental material being tested, rads (experimental material) can be measured directly. If, however, the dose to the calorimeter must be converted to dose in another material of significantly different atomic number, corrections must be made for differences in dE/dX, backscattering, and bremsstrahlung losses.

PIN Detectors

Reverse-biased PIN diodes (usually silicon, but a cooled germanium device can also be used) collect charges produced by ionization in the intrinsic semiconductor region. Calibration is based on the known efficiency for producing electron-hole pairs (3.7 eV/pair in silicon) and the active volume of the junction region. The charge collection time is short (~ns) and therefore a PIN diode can be used to measure not only the dose in the semiconductor but also the shape of the radiation pulse [dose rate (Si) versus time]. Care must be taken to use the detector only at low dose rates where the linearity is established. At high dose rates [~10^9 rads (Si)/s] the internal electric field is modified by the high currents and the output becomes nonlinear. It is

important to note that a PIN detector will not read rads (Si) unless electron equilibrium in the silicon active volume has been established. Many standard commercial detectors can derive measurable portions of their signal from the high-Z case or from their tantalum-plate contacts. One can, however, obtain from manufacturers, on special order, degenerate silicon contacts to which the leads are attached or with very thin contacts so that the detector may be placed in electron equilibrium through the introduction of additional silicon (or aluminum foils). One should be careful to determine whether the addition of inactive material to create electron equilibrium for the most energetic portion of a distributed spectrum has attenuated the low-energy portion of the spectrum and make a suitable correction to determine the dose of a thin silicon sample.

Compton Diode and SEMIRAD

The operation of compton diodes and SEMIRADS is based on the charge transfer of electrons between materials under irradiation. The calibration depends on the spectrum and is not uniquely related to dose in any material, except for a limited range of spectra. The time resolution is potentially excellent and such devices are very useful as pulse-shape monitors at high dose rates. For very high dose rates, Compton diodes are recommended since SEMIRADS will undergo saturation.

Scintillator - Photodiode Detectors

Various organic scintillators having both fast response and a large linear range are available for measurements of ionizing dose rate versus time. Examples are plastics such as Pilot B and NE102; organic liquids, such as NE211, and NE226, which have 2- to 3-ns resolution. At high dose rates the light emitted is intense, so that the photodiode needs to be designed so as to avoid space charge limitation. An FW114 photodiode is frequently used with adequate bias voltage to avoid saturation. This combination measures energy deposition in the scintillator, i.e., rad (scintillator). Organic scintillators have been shown to have nonlinear characteristics at high rates ($\sim 10^{11}$ rads/s) and should not be used at rates above this value.

Faraday Cup

A Faraday cup can be used for electron-fluence measurements, which are convertible to rad (Z) entrance-dose units in a material to be inserted in

the beam if the incident electron energy is known. Values of electron-energy loss rate, dE/dX, are given in Reference (44). When using a Faraday cup to monitor an electron beam, a guard voltage should be applied and a reentrant cup used with a low-Z stopping material, backed up with a higher Z shield material. The incident beam must be collimated and accompanying secondary electrons must be swept out by a magnetic analyzer. For accurate work, the whole cup should be placed in a vacuum; for fast-pulsed electron-beam work, if the pulse shape is to be determined, a coaxial cup design matched to the cable impedance may be desirable.

The accuracy achievable with the proper Faraday cup techniques is good enough to warrant their use as calibration tools. The much greater convenience in LINAC use of a simple, but less accurate, low-Z stopping block current collector renders this a useful tool also.

Summary of Typical Dosimeter Sensitivity

Tables 8 and 9 list typical gamma-ray and neutron sensitivities (much of it experimental, but some vendor's data) for a variety of dosimeters used. Some of these sensitivities may be varied by geometrical design, voltages applied, and other methods, so the data are to be taken as representative only. It should be noted that the thermal-neutron response of the dosimeters must be considered, as they are not necessarily negligible.

Spectrum Monitoring

In nuclear physics studies, elaborate tools have been developed for detailed photon spectrum measurements. However, for space requirements, the spectral-information accuracy requirements rarely justify such methods. Simpler techniques based on a knowledge of the general source character-istics and some absorption measurements, along with any spectral information provided by the facility operations group, are usually adequate.

A combination of dosimeters having different atomic numbers and shielding is recommended for spectral monitoring, for example: high- and low-Z bare glass rods, or LiF and CaF_2 (Mn) in plastic and aluminum con-tainer pairs, respectively, to read rads (low Z) and rads (high Z). The dose ratio is a measure only of the spectral quality, not of the spectral details; if the ratio is appreciably different from 1.0, the spectrum may be either

TABLE 8. GAMMA-RAY AND NEUTRON SENSITIVITY OF ACTIVE DOSIMETERS

Dosimeter Type	Model No., etc.	Gamma-Ray Sensitivity, coulomb $R(Co\text{-}60)$	Neutron Sensitivity, coulomb $n/cm^2(E)$
Silicon p-i-n	004-PIN-2501E	6×10^{-9}	5×10^{-17} (14 MeV) 2×10^{-18} (fission)
Photodiode- scintillator (FW114)	Pilot B NE 211 (xylene) NE 226 (C_6F_6)	2×10^{-8} 1×10^{-9} $\sim 1 \times 10^{-9}$	1×10^{-18} (fission) 1.5×10^{-19} (fission) 1×10^{-21} (fission)
Semirad Ti wall	Econ 7318	1.2×10^{-11}	3.5×10^{-20} (14 MeV) 1.5×10^{-21} (fission)
Stainless steel	Reuter Stokes – gamma sensitive	$1.7\text{-}6 \times 10^{-11}$	Negligible (fission) Not negligible (fusion)
Stainless steel U-238	Reuter Stokes – neutron sensitive	3.5×10^{-11}	3×10^{-22} (fission) 1×10^{-21} (14 MeV)
Compton diode	(Representative model, EG&G)	1.4×10^{-11}	5.3×10^{-21}
Cerenkov detector	(Representative model, EG&G)	2.5×10^{-10}	8×10^{-9}

Note: This table was developed from private communications to D. J. Hamman of Battelle Memorial Institute from Nancy Gibson of the U. S. Army Nuclear Defense Laboratory.

TABLE 9. NEUTRON SENSITIVITY OF PASSIVE GAMMA-RAY DOSIMETERS

Dosimeter Type	Material	Neutron Absorbed Dose[a], 10^{-10} R/(n·cm^{-2}), at Indicated Neutron Energies, MeV						
		Thermal	1	2	3	5.3	8	14.5
TLD	CaF_2: Mn							
	a. Vacuum tube type	1.41	0.67	0.81	0.65	6.2	0.14	2.1
	b. Micro TLD	1.00	1.9	2.0	--	8.2	6.7	4.4
	LiF							
	TLD-100	200	2.3	5.2	6.4	14.0	15.0	23.0
	TLD-600	625	8.9	11.0	11.0	22.0	18.0	48.0
	TLD-700	None	4.2	8.1	8.3	20.0	16.0	37.0
RPLD	$AgPO_4$ glass							
	High Z	3.6	≤ 1.6	1.5	--	≤ 1.7	2.8	6.4
	Low Z	28	≤ 2.3	≤ 3.4	--	≤ 8.2	2.5	5.1
UV transmission	Cobalt glass	36.3	58 ± 50% for fast neutrons					

Note: This table was developed from private communications to D. J. Hamman of Battelle Memorial Institute from Nancy Gibson of the U. S. Army Nuclear Defense Laboratory.

(a) Underlined values were obtained with dosimeters irradiated in an energy discrimination shield. All others were bare.

very soft (containing low-energy components < 200 keV) or of very high
energy (> 5 MeV). This point should be checked, if there is some doubt
considering the source, by measuring the broad-beam absorption curve or
first and second half-value layers in aluminum or copper and comparing
it with that for cobalt-60 (first HVL = 17 g/cm^2 aluminum or 9 g/cm^2 copper).

If too soft a spectrum is indicated, experimental design should be
changed, since environment correlation may be difficult, that is, the radia-
tion may be attenuated severely by transistor cans, which poses the problem
of determining rad (SI) in the device from an exposure or dose measurement
outside the can. A ratio of rad (Z = 29) to rad (Z = 13) higher than 1.5 indi-
cates an appreciable amount of radiation below 200 keV. Extreme care should
be taken in experimental design with such low energies to assure that the
dosimetry measures the doses desired at interior points of the experiment.

Since (1) in gamma-ray effect simulation the microscopic and macro-
scopic dose deposition pattern is the entity of interest, that is, the depth-dose
distribution and sometimes the LET, (2) the absorption coefficients for semi-
conductors and most insulator materials do not vary much for photon energies
in the range of 200 keV to 10 MeV, and (3) most useful sources have energies
within this range, it is not felt that detailed spectral information is needed for
routine work. However, gamma-ray simulation facilities should have enough
spectral information to be able to convert dose measurements in the dosimetry
materials used to absorbed dose in all materials.

GLOSSARY

absorbed dose. See dose.

alpha particle (alpha radiation). An energetic doubly ionized helium atom
    consisting of two protons and two neutrons.

astronomical unit. An interplanetary unit of measure equal to the mean
    distance between the Earth and the Sun. 1AU = 92,950,000 miles.

atomic displacement. The displacement of an atom from its usual site in a
    crystal lattice.

barn. A unit used for specifying nuclear cross sections, equal to 10^{-24} cm^2.

beta radiation (beta particle). A form of radiation consisting of energetic electrons.

bremsstrahlung. Electromagnetic radiation resulting from the inelastic collision of electrons or other charged particles with a nucleus, the interaction being between the charged particle and the coulomb field of the nucleus. The bremsstrahlung energy spectrum is continuous from zero to the maximum energy of the incident particles. Bremsstrahlung is synonomous with X-ray continuous spectra.

Compton effect. The collision of a photon with a free electron in which the photon gives up part of its energy to the electron, thus resulting in a recoiling electron (Compton electron) and a photon of lower energy. For this interaction, orbital electrons are essentially free electrons.

cross section. A measure of the probability of a particular process occurring. The cross section of an atom or nucleus for a particular reaction has the units of an area and is actually the effective target area presented to an incident particle or photon for a particular reaction. A commonly used unit for cross sections is the barn, equal to 10^{-24} cm^2.

dose. The absorbed dose (D) is the quotient of ΔE_D by Δm, where ΔE_D is the energy imparted by ionizing radiation to the matter in a volume element and Δm is the mass of matter in that volume element

$$D = \frac{\Delta E_D}{\Delta m} = (ergs/g, \ rads).$$

elastic scattering. Scattering in which the total kinetic energy of a two-particle system is unchanged after scattering.

electron (beta particle). A charged particle carrying a unit electronic charge either positive (positron) or negative (negatron). The term electron is commonly used instead of negatron when discussing the negatively charged particle. The mass of an electron is about 1/1800 of the mass of a proton.

exposure. The exposure is the quotient of ΔQ by Δm, where ΔQ is the sum of the electrical charges on all the ions of one sign produced in air when all the electrons (negatrons and positrons) liberated by photons in a volume element of air whose mass is Δm are completely stopped in air.

fission neutron. Neutrons produced in a fission process which have not yet been involved in interactions with other materials.

fission. The splitting of a nucleus into two (or vary rarely more) fragments — the fission products. Fission is accompanied by the emission of neutrons and the release of energy. It can be spontaneous or it can be brought about by the interaction of the nucleus with a fast charged particle, a photon, or more commonly, a neutron.

fission neutron spectrum. The energy spectrum of neutrons emerging from a fission reaction.

galactic cosmic radiation. High-energy particulate radiations originating outside the solar system.

gamma ray. Highly penetrating electromagnetic radiation from the nuclei of radioactive substances. They are of the same nature as X-rays differing only in their origin. Gamma rays are emitted with discrete energies. $E = h\nu$.

heavy charged particle. A charged particle whose mass is much greater than the mass of an electron.

inelastic scattering. Scattering in which the total kinetic energy of a two-particle system is decreased, and one or both of the particles is left in an excited state.

ionization. The separation of a normally electrically neutral atom or molecule into electrically charged components.

ionization potential. The minimum quantity of energy necessary to move an electron from a particular shell to a position where it is essentially free of the nucleus.

ionizing radiation. Any radiation consisting of directly or indirectly ionizing particles or a mixture of both.

mass attenuation coefficient. The quotient of dN by the product of ρ, N, and dl, where N is the number of particles (photons) incident normally upon a layer of thickness dl and density ρ, and dN is the number of particles (photons) that experience interactions in this layer. $\mu/\rho = \dfrac{1}{\rho N}\dfrac{dN}{dl}$ (cm^2/g). The term "interactions" refers to processes whereby the energy or direction of the incident particle (photon) is altered.

mass energy transfer coefficient. The quotient of dE_K, by the product of E, ρ, and dl, where E is the sum of the energies (excluding rest energies) of the indirectly ionizing particles incident normally upon a layer of thickness dl and density ρ, and dE_K is the sum of the kinetic energies of all the charged particles liberated in this layer. $\mu_K/\rho = \dfrac{1}{E\rho}\dfrac{dE_K}{dl}$ (cm^2/g).

mass energy absorption coefficient. The product of the mass energy transfer coefficient and (1-G), where G is the fraction of the energy of secondary charged particles that is lost to bremsstrahlung in the material.

neutron. A particle with no electrical charge, but with a mass approximately equal to that of a proton.

pair production. An interaction where a photon of energy Eγ, greater than 1.02 MeV, is absorbed in the field of a charged particle and in its place an electron-positron pair is created whose total energy, kinetic plus rest mass energy, is exactly equal to the energy of the incident photon. $E_\gamma = (E_{e-} + m_o c^2) + (E_{e+} + m_o c^2) = E_{e-} + E_{e+} + 1.02$ MeV.

photoelectric effect. An interaction in which a tightly bound orbital electron absorbs the entire energy of an incident photon and is ejected from the atom with an energy equal to the difference between the energy of the incident gamma-ray or X-ray photon and the binding energy of the electron. $E_e = E_\gamma - E_B$.

Planck's constant. A universal constant relating the frequency of a radiation to its energy such that E = hν, where E is the energy, ν is the frequency, and h is Planck's constant. h = 6.625 x 10^{-27} erg-s.

positron. A particle whose mass is the same as an electron's but which carries a unit positive charge.

proton. A positively charged high-energy hydrogen ion with a mass of 1.66 x 10^{-24} g.

rad (radiation absorbed dose). A unit of absorbed dose equal to 100 ergs/g. In defining a dose, the absorbing material must be given, e.g., rads absorbed in carbon = rads (C).

reactor neutron (spectrum). Neutrons and the energy spectra thereof, as found in nuclear reactors. That is, fission neutrons which have been degraded in energy and whose energy spectra have been broadened by interaction with materials in the reactor.

roentgen. The unit of exposure that produces charge in the amount of 2.58 x 10^{-14} coulomb/kg of air and is equivalent to a dose of 87.7 ergs/g in air [0.877 rads (air)].

solar flare. A localized region of exceptional brightness on the sun, that develops very suddenly, generally not too far from a sunspot group. Flares are graded as to their importance (brightness, duration, and dimensions) from 1- for a minor flare to a 3+ for the largest flares, with obvious graduations in between. Radiations of several different types may be emitted from a flare.

solar wind. An ionized plasma emitted continuously by the sun.

threshold displacement energy. The minimum quantity of energy required to displace an atom from its lattice side in an atomic collision.

threshold energy. The energy below which a particular reaction will not take place.

ultraviolet radiation. Spectral radiation with a wavelength (energy) between that of visible light and X-rays.

unit charge. The electronic charge carried by one electron, equal to 1.6 x 10^{-19} coulomb.

Van Allen belt(s). Toroidal belts of charged particles which surround the earth near the equator.

<u>X-ray</u>. High-frequency electromagnetic radiation produced by any of these processes: (1) radiation from a heated mass in accordance with Planck's radiation law, (2) bremsstrahlung, and (3) electron transition between atomic energy levels, usually excited by incident beams of high-energy particles, resulting in characteristic, discrete energy spectra.

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