8i. Health Physics[1]

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8i-1. Introduction. The practice of health physics utilizes knowledge gained in all sciences to furnish an understanding of the mechanisms of radiation damage and to provide adequate and reasonable limits for exposure, measurements of exposure, and the specification of conditions and procedures to ensure protection. It embodies

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[1] Work sponsored by the U.S. Atomic Energy Commission under contract with Union Carbide Corporation.

the application of many scientific and technical disciplines, i.e., physics, biology, chemistry, engineering, etc., to the end that any situation involving possible radiation hazard to man can be analyzed correctly, and suitable steps can be taken to prevent harm to man or to his environment. Health physics involves research, engineering, educational, and applied activities. It deals with the scattering and loss of energy of ionizing radiation and the damage produced by the passage of this radiation through matter. Thus, in addition to applied activities, there are many health-physics research and engineering problems such as (1) shielding, (2) dosimetry, (3) studies of physical parameters relating to dosimetry (e.g., stopping power, attachment coefficient, energy to produce an ion pair, etc.), (4) radioactive-waste disposal, (5) studies of human exposures, (6) determination of permissible exposure values, (7) studies of effects of ionizing radiation on the environment, etc. A health physicist is a person engaged in and dedicated to a study and practice of problems of providing radiation protection. He is concerned with obtaining an understanding of mechanisms of radiation damage and with the development and implementation of instruments, methods, and procedures so that he can determine the existence of hazardous ionizing radiation and provide protection to man and his environment from its unwarranted deleterious effects.

8i-2. Definition of Units and Terms Used in Health Physics.[1] *Absorbed Dose:* the amount of energy imparted by ionizing radiation to a sample of matter per unit mass. The unit of absorbed dose is the rad (= 100 ergs/g).

Absorption Coefficient ($\mu - \sigma_s$)*:* the difference between the attenuation coefficient and that for Compton scattering. This quantity, which is used to a good approximation to describe photon energy absorption, excludes the part of the original photon energy that escapes as a degraded photon from the site of interaction. The dimension of $\mu - \sigma_s$ is reciprocal distance (e.g., cm^{-1}).

Activity: the disintegration rate of a radionuclide. The unit of activity is the curie (1 Ci corresponds to 3.7×10^{10} disintegrations/sec).

Attenuation Coefficient μ (*Macroscopic Cross Section*)*:* the probability of interaction per unit distance traveled. The dimension of μ is reciprocal distance (e.g., cm^{-1}). EXAMPLE: The relative number of photons of a given energy that do not experience an interaction in traveling a distance x is $e^{-\mu x}$. In terms of σ_t, the total microscopic cross section (e.g., cm^2), $\mu = N\sigma_t$, where N = number of electrons per unit volume.

The *Bragg-Gray principle* and applications of it are used as the basis of many measurements of ionizing radiation. According to this principle the energy absorbed per unit mass $(dE/dm)_b$ in a given medium b is related to the ionization in a small gas-filled cavity in that medium by the expression

$$\left(\frac{dE}{dm}\right)_b = P_b W_g J_g \qquad (8i\text{-}1)$$

Here P_b is the relative mass stopping power of the medium b with respect to the gas g, W_g is the average energy required to produce an ion pair in the gas, and J_g, the quantity that is usually determined experimentally, is the number of ion pairs produced per unit mass of the gas in the cavity. It should be emphasized that, in order for this principle to hold always, the gas cavity must be small compared with the range of the ionizing particles, and both W_g and P_b must be independent of the energy of the radiation. When the walls of the chamber and the gas are made of the same material, e.g., air- or tissue-equivalent substances, the Bragg-Gray principle also applies with a cavity large compared with the range of the ionizing particles.

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[1] More detailed discussions are given in Radiation Quantities and Units, report 10a of the International Commission of Radiological Units and Measurements, *Natl. Bur. Standards Handbook* 84, 1962.

Curie, Ci: unit of activity: 1 Ci = 3.7×10^{10} disintegrations/sec. The millicurie (1 mCi = 10^{-3} Ci), microcurie (1 μCi = 10^{-6} Ci), nanocurie (1 nCi = 10^{-9} Ci), and picocurie (1 pCi = 10^{-12} Ci) are often used.

Dose Equivalent: defined for purposes of radiation protection as the product of the absorbed dose and relevant modifying factors, such as those for radiation quality (e.g., QF, which relates to LET, and the *H* factor, which relates to the damage from internally deposited, bone-seeking radionuclides relative to that of radium). The unit of dose equivalent is the rem. Dose equivalents from different sources of radiation are additive in protection work.

Exposure: the amount of charge (of either sign) produced in air by X- or gamma-ray photons per unit mass of air. The unit of exposure is the roentgen (= 2.58×10^{-4} coul/kg).

Fluence: the ratio of the number of particles or photons that enter a small, imaginary test sphere placed in a radiation field and the cross-sectional area of the sphere. The dimension of fluence is the square of reciprocal distance (e.g., cm^{-2}).

Flux Density: fluence per unit time. The dimensions of flux density are reciprocal area times reciprocal time (e.g., $\text{cm}^{-2}\ \text{sec}^{-1}$).

Linear Energy Transfer, LET: linear rate of energy loss along the track of a particle. LET is often expressed in keV/μm or MeV/cm (1 keV/μm = 10 MeV/cm).

Mass-absorption Coefficient, $(\mu - \sigma_s)/\rho$: the quotient of the absorption coefficient and the density of a material. Dimensions are area times reciprocal mass (e.g., cm^2/g).

Mass-attenuation Coefficient, μ/ρ: the quotient of the attenuation coefficient and the density of a material. Dimensions are area times reciprocal mass (e.g., cm^2/g).

Mass Stopping Power, P/ρ: the stopping power of a material divided by its density. Often expressed in $\text{MeV}/(\text{g}/\text{cm}^2)$ or $\text{ergs}/(\text{g}/\text{cm}^2)$. See Sec. 8i-3.1 and Fig. 8i-1.

Quality Factor, QF: numerical linear-energy-transfer-dependent factor, depending on the kind of incident radiation and its energy. The product of QF and absorbed dose gives the dose equivalent used for purposes of radiation protection. See tables given in Sec. 8i-13.

Rad: Unit of absorbed dose: 1 rad = 100 ergs/g.

Relative Biological Effectiveness, RBE: the biological effectiveness of any type and energy of ionizing radiation in producing a specific biological effect (e.g., a certain incidence or degree of leukemia, anemia, sterility, carcinomas, cataracts, shortening of life-span, etc.) relative to damage produced by X rays, having an energy of about 200 keV or a linear energy transfer in water of about 3 keV/μm delivered at a rate of about 10 rads/min. Gamma radiation from ^{60}Co is often used as the reference standard. The RBE is given frequently as an average value in the common energy range of a particular type of ion and/or throughout the medium under study.

Rem: roentgen-equivalent-man. Unit of dose equivalent.

Roentgen, R: unit of exposure: 1 R = 2.58×10^{-4} coul/kg. This quantity is numerically the same as that implied by the older definition of the roentgen as that quantity of X or gamma radiation that produces 1 esu of charge of either sign per 0.001293 g of dry air (1 cc at 0°C and 760 mm Hg).

Stopping Power, P or $-dE/dx$: mean rate of energy loss of a charged particle per unit distance traveled. The stopping power of a medium for a given particle is numerically equal to LET. Often expressed in ergs/cm or MeV/cm. (See mass stopping power.)

Specific Ionization S: the average number of ion pairs produced per unit distance along the track of a particle.

W Value: the average energy needed to produce an ion pair. (See page 8-296.)

8i-3. Useful Data and Equations. *Stopping Powers.* Figure 8i-1 shows the stopping powers of water for a number of particles. These values differ only slightly

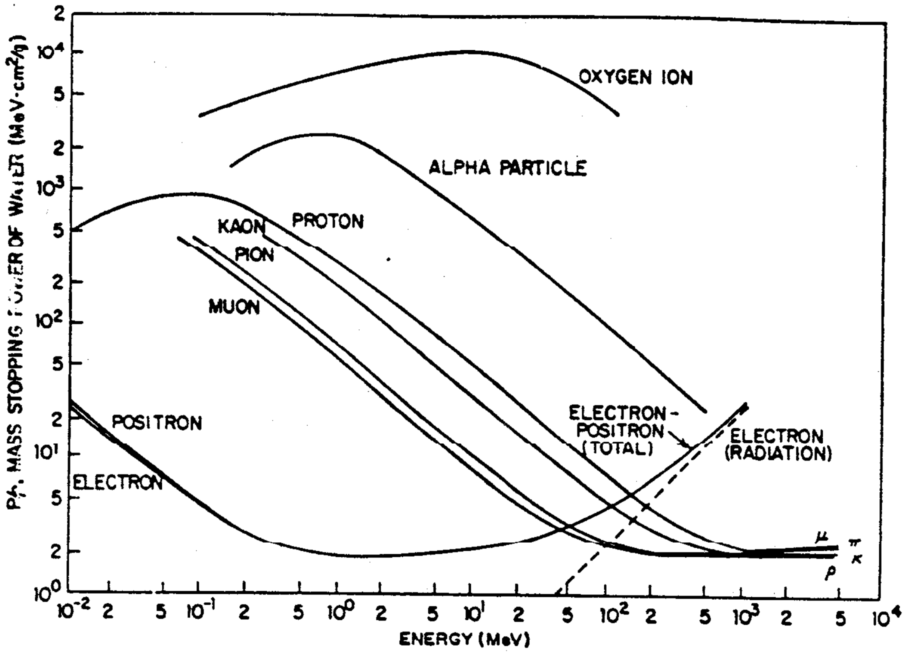

FIG. 8i-1. Mass stopping power of water for several particles. The dashed curve shows the contribution of radiation (bremsstrahlung) to the mass stopping power for electrons.

from those of muscle or other soft tissue. These curves are based on the following sources:

Barkas, W. H., and M. J. Berger: Studies in Penetration of Charged Particles, U. Fano ed., *Natl. Acad. Sci.–Natl. Res. Council Publ.* 1133, 1964.
Berger, M. J., and S. M. Seltzer: Studies in Penetration of Charged Particles, U. Fano, ed. See above. We are grateful to Dr. Berger for furnishing the positron data.
Bichsel, H.: "American Institute of Physics Handbook, 3d ed., D. W. Gray, ed., McGraw-Hill Book Company, New York, 1972. (This volume.)
Neufeld, J., and W. S. Snyder: in "Selected Topics in Radiation Dosimetry," International Atomic Energy Agency, Vienna, 1961.
Steward, P. G.: Stopping Power and Range for any Nucleus in the Specific Energy Interval 0.01–500 MeV/AMU in any Nongaseous Material, *LRL Rept.* UCRL-18127, 1968.
Whaling, W.: "Encyclopedia of Physics," vol. 34(2), p. 214, Springer-Verlag OHG, Berlin, 1958.

Stopping powers of a number of materials for different charged particles can be calculated over a wide range of energies from the information given by H. Bichsel in Sec. 8d of this Handbook.

Average stopping power $\bar{P}$ (MeV/cm) of particle of energy E (MeV) over its range R (cm):

$$\bar{P} = \frac{E}{R} \tag{8i-2}$$

Average mass stopping power (MeV cm²/g) is $\bar{P}/\rho$, where ρ is the density (g/cm³) of the medium traversed.

Ranges. The mean ranges of electrons, protons, and alpha particles in water, muscle, bone, and lead are shown in Fig. 8i-2. The ranges of these particles in air are given in Fig. 8i-3. These figures are based on the following sources:

Barkas, W. H., and M. J. Berger: *ibid.*
Berger, M. J., and S. M. Selzer: *ibid.*
Bethe, H. A., and J. Ashkin: "Experimental Nuclear Physics," vol. I, E. Segrè, ed., John Wiley & Sons, Inc., New York, 1953.

Evans, R. D.: "The Atomic Nucleus," McGraw-Hill Book Company, New York, 1955.
Snyder, W. S., and J. Neufeld: On the Energy Dissipation of Moving Ions in Tissue, *Oak Ridge Natl. Lab. Rept.* ORNL-1083, Oak Ridge, Tenn., 1951.
Steward, P. G.: *ibid.*

These mean ranges have been calculated at high energies without allowance for nuclear cascades, i.e., absorption of a proton by a nucleus.

Except at low velocities, where capture and loss of electrons by a moving ion occurs, the ranges of other heavy particles (e.g., muons, pions, deuterons, tritons) can be found from the range-energy curves given in Fig. 8i-2, since energy loss depends in a

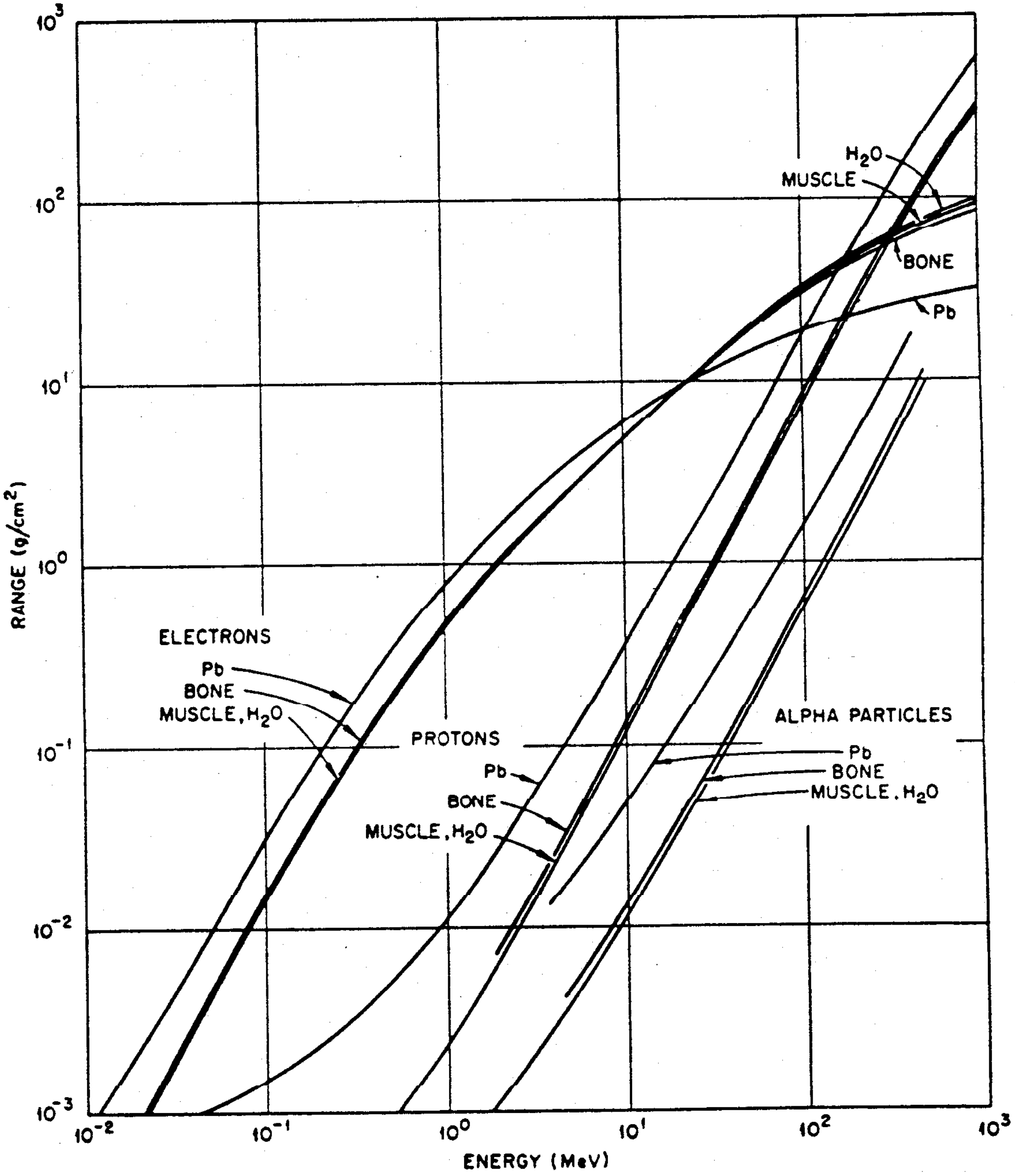

FIG. 8i-2. Mean ranges of electrons, protons, and α particles in water, muscle, bone, and lead. See text for determining ranges of other heavy particles. Ranges in other materials can be approximated from the water and lead curves by interpolating on the basis of average atomic number.

known way on charge and velocity. For example, the ranges $R_1(v)$ and $R_2(v)$ of two heavy particles, moving with the same speed v in a medium and having charges z_1 and z_2 and masses M_1 and M_2, are related by the equation

$$R_1(v) = \left(\frac{z_2}{z_1}\right)^2 \frac{M_1}{M_2} R_2(v) \tag{8i-3}$$

Nonrelativistically, the range $R_1(E)$ of one particle at energy E is given by

$$R_1(E) \doteq \left(\frac{z_2}{z_1}\right)^2 \frac{M_1}{M_2} R_2 \left(\frac{M_2E}{M_1}\right) \tag{8i-4}$$

where $R_2(M_2E/M_1)$ is the range of the other particle at energy $(M_2/M_1)E$. Electron and positron ranges are approximately the same.

W Values. The average energies needed to produce an ion pair in a number of gases are given in Table 8i-1. Although these values, regarded for simplicity as being independent of the type and energy of radiation, are appropriate in most health physics applications (e.g., with X rays, radiation from radioactive sources, and most types of accelerators), *W* values for slow-moving heavy ions (i.e., at ion velocities lower than that of the electron in first Bohr orbit) may be much larger than the values given in the table.

TABLE 8i-1. *W* VALUES IN eV FOR SEVERAL GASES*

He	42	CO_2	34
Ne	37	CH_4	28
Ar	26	C_2H_2	27
Kr	24	C_2H_4	27
Xe	22	C_2H_6	26
H_2	36	C_3H_8	26
N_2	36	C_4H_{10}	26
O_2	31	BF_3	36
Air	35		

* Based on data summarized by L. W. Cochran in chap. 5, "Principles of Radiation Protection," K. Z. Morgan and J. E. Turner, eds., John Wiley & Sons, Inc., New York, 1967.

Alpha Rays. Specific ionization (ion pairs/cm) in air:[1]

$$S \approx 11 \times 10^4 E^{-0.74} \tag{8i-5}$$

where E is in MeV. (<10 percent error for alpha energies $2 \leq E \leq 50$). See Table 8i-2 for numerical values.

Limited portions of the range R–energy E curve in Fig. 8i-3 can be fit by the formula

$$R = AE^k \tag{8i-6}$$

where A and k are constant over a particular portion. With R in cm and E in MeV, for example, the measured range in the neighborhood of 5 to 10 MeV is given accurately by $R = 0.31E^{1.5}$.

Beta Rays, Electrons, and Positrons. Range (cm) of electrons of energy E (MeV) in medium of density ρ (g/cm^3):[1]

$$R \approx \frac{1}{\rho}[0.54E - 0.13(1 - e^{-4E})] \tag{8i-7}$$

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[1] Empirical formula developed by K. Z. Morgan.

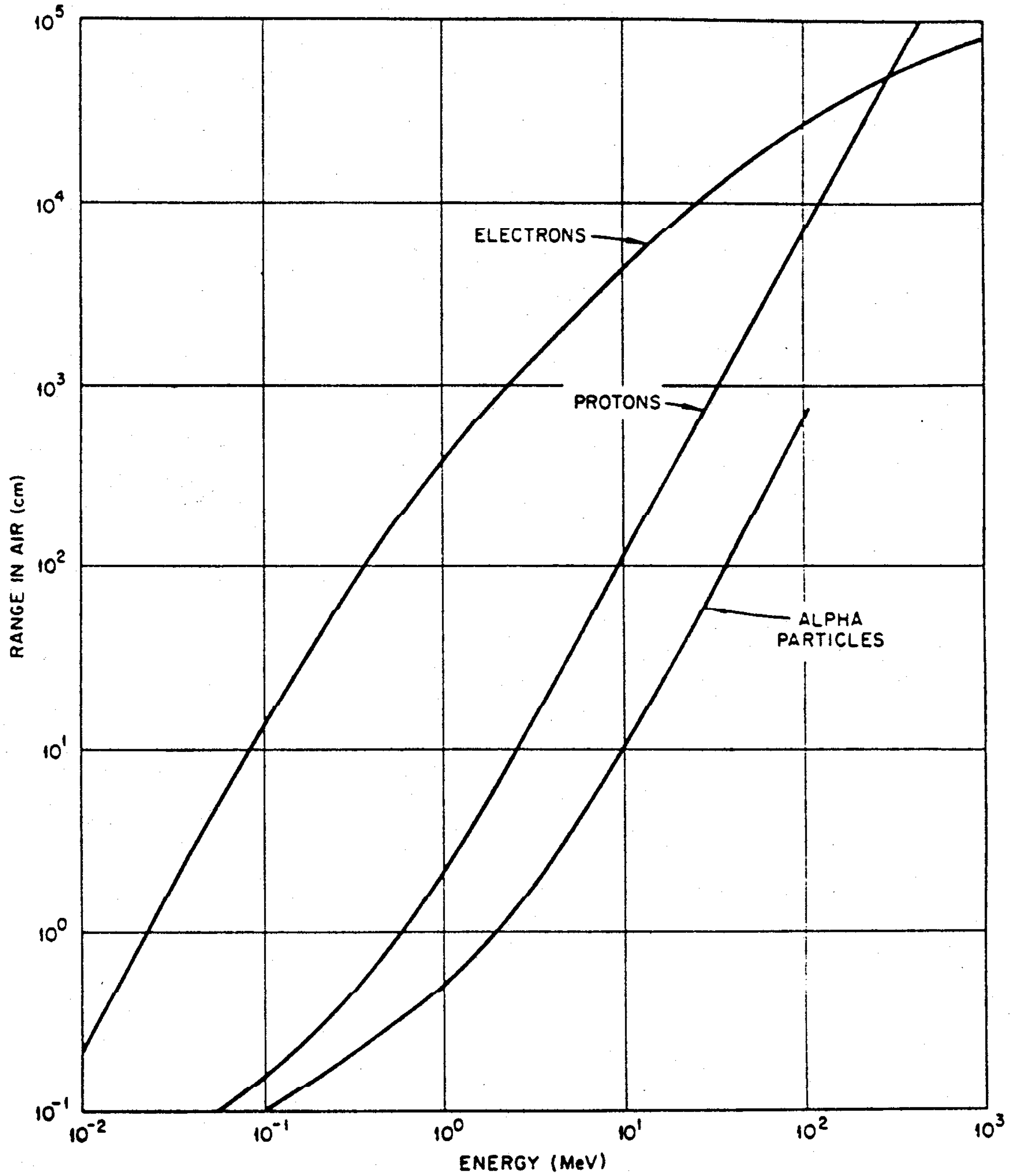

FIG. 8i-3. Mean ranges of electrons, protons, and α particles in air ($\rho = 0.001293$ g/cm^3. See text for determining ranges of other heavy particles.

(For water, this formula is in error by not more than ±25 percent for electron energies $0.01 \leq E \leq 30$.)

In the interval E (MeV) ≈ 1 to ≈ 20 the range R (g/cm^2) is given by[1]

$$R \approx 0.530E - 0.106 \qquad (8\text{i-}8)$$

(For water, this formula is in error by not more than ±15 percent for electron energies $1 \leq E \leq 20$.)

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[1] Katz L. and A. S. Penfold, *Rev. Mod. Phys.* **24**, 28 (1952).

Average energy $\bar{E}$ (MeV) of allowed β^- spectrum:[1]

$$\bar{E} \approx 0.099 E_m \left(1 - \frac{Z^{0.5}}{50}\right)(3 + E_m{}^{0.6}) \tag{8i-9}$$

where E_m (MeV) is the maximum beta-ray energy, and Z is the atomic number of the daughter. (<10 percent error for any value of Z in energy range $0.01 < E_m < 3$.)

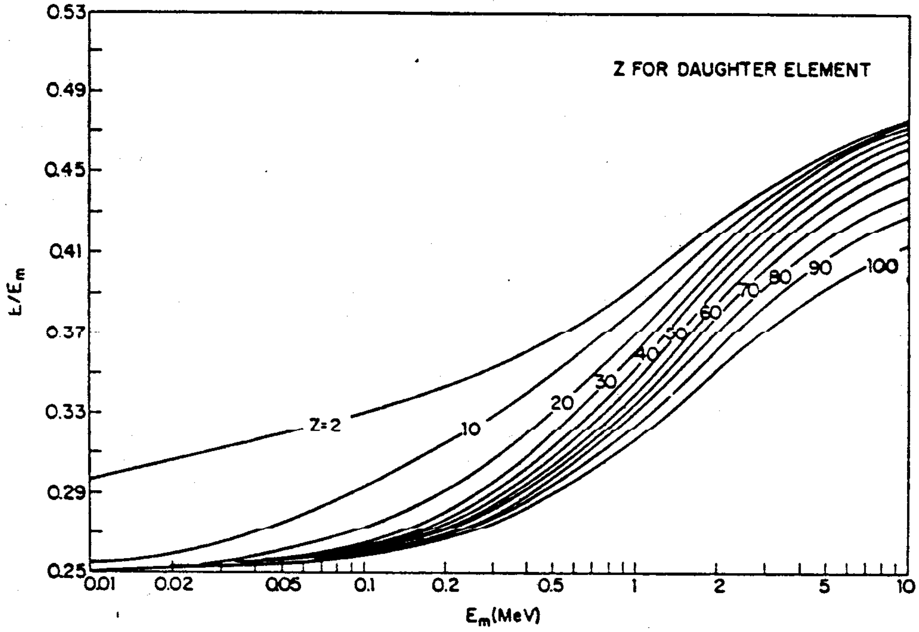

FIG. 8i-4a. Allowed β^- transitions. This graph also gives approximate values for the first forbidden nonunique transitions. [*L. T. Dillman, Oak Ridge Natl. Lab. Rept.* ORNL-4168, *pp.* 233*ff.*, *Oak Ridge, Tenn.* (1967).]

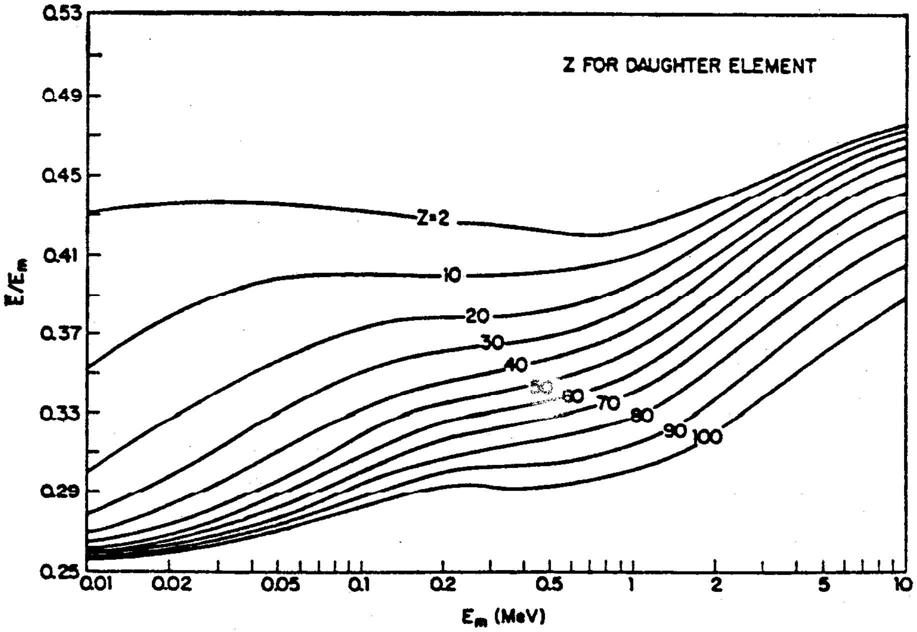

FIG. 8i-4b. First forbidden unique β^- transitions. This graph also gives approximate values for the second forbidden nonunique transitions. [*L. T. Dillman, ibid.*]

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[1] Empirical formula developed by K. Z. Morgan.

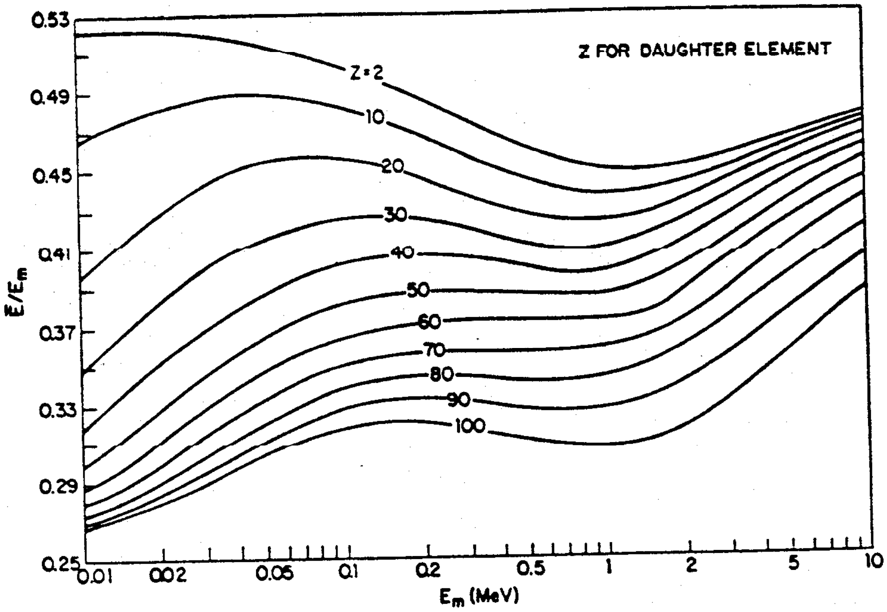

FIG. 8i-4c. Second forbidden unique β^- transitions. [*L. T. Dillman, ibid.*]

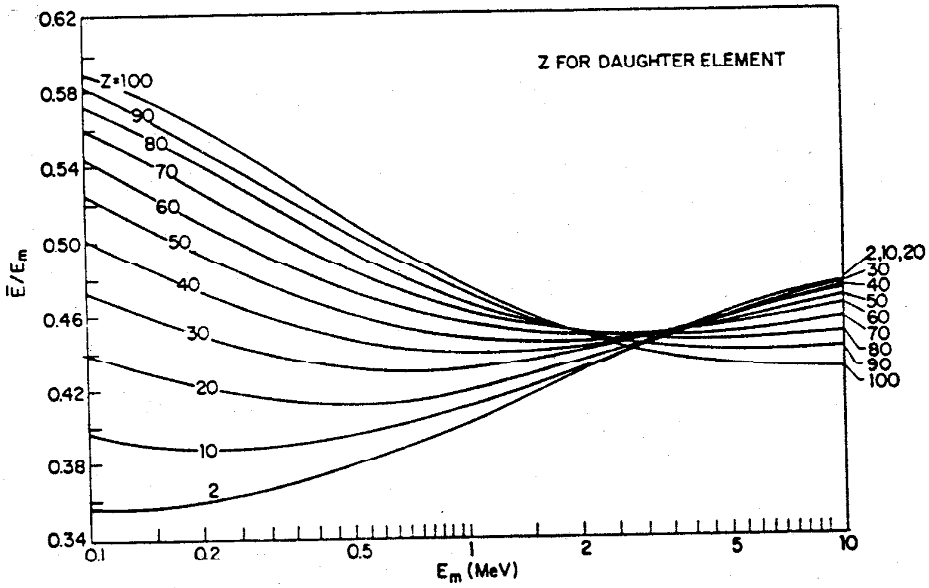

FIG. 8i-4*d*. Allowed β^+ transitions. This graph also gives approximate values for the first forbidden nonunique transitions. [*L. T. Dillman, ibid.*]

$\bar{E}$ has been calculated for electrons for a wide range of values of E_m and Z by James, Steel, and Story[1] and for both electrons and positrons by Dillman.[2] Figures 8i-4*a* through 8i-4*f* show values of $\bar{E}/E_m$ as obtained by Dillman. Note that in these figures values of Z are the atomic numbers of the daughter elements. The ratio $\bar{E}/E_m$ varies from about 0.25 to 0.63. As a rule of thumb, it is sometimes assumed that $\bar{E}/E_m \approx \frac{1}{3}$.

[1] M. F. James, B. G. Steel, and J. S. Story, Average Electron Energy in Beta Decay, *U.K. Atomic Energy Authority Rept.* AERE-M 640, Harwell, Berkshire, England, 1960.

[2] L. T. Dillman, see *Oak Ridge Natl. Lab. Rept.* ORNL-4168, pp. 233 ff., Oak Ridge, Tenn., 1967.

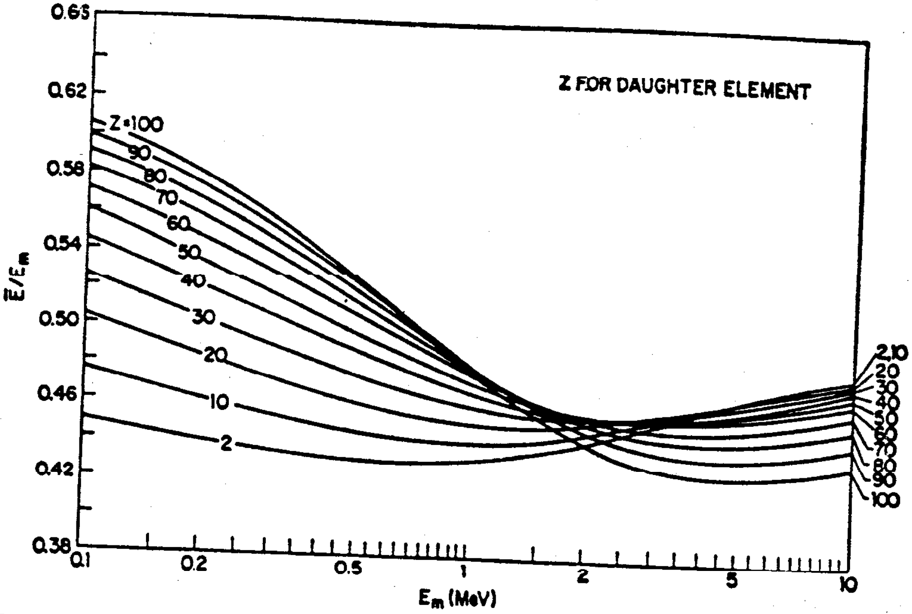

FIG. 8i-4*e*. First forbidden unique β^+ transitions. This graph also gives approximate values for the second forbidden nonunique transitions. [*L. T. Dillman, ibid.*]

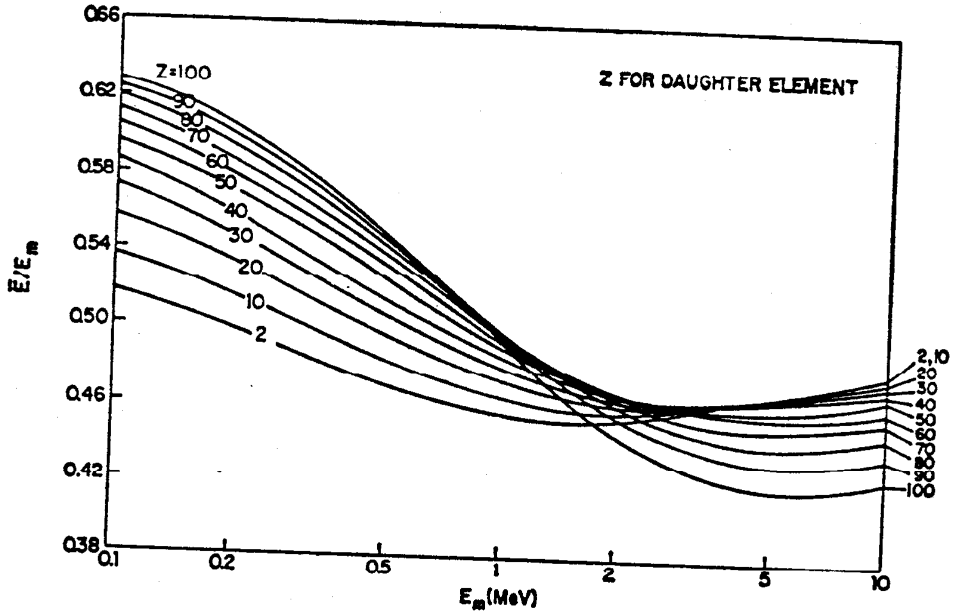

FIG. 8i 4*f*. Second forbidden unique β^+ transitions. [*L. T. Dillman, ibid.*]

Apparent absorption coefficient (cm^2/g) for beta particle of energy E (MeV) in tissue:[1]

$$\mu \approx 20E^{-1.49} \tag{8i-10}$$

(<10 percent error for $0.1 \leq E \leq 3.$)

Specific ionization (ion pairs/cm) for β^- with allowed spectrum and maximum energy E_m (MeV) in air:[1]

$$S \approx 33 + 63E_m{}^{-0.9} \tag{8i-11}$$

(<10 percent error for $0.05 \leq E \leq 2.$) See Table 8i-2.

[1] Empirical formula developed by K. Z. Morgan.

Table 8i-2. Specific Ionization and Ranges of Alpha and Beta Particles

Particle energy, MeV	Specific ionization in air,[a] ion pair/cm			Ranges, cm			
				Alpha particle		Beta particle	
	Alpha particle[b]	Electron[c,d]	Beta particle[e]	Air[a,f]	Soft tissue[g,h]	Air[a,c]	Soft tissue[c]
0.01	......	750	2,100	......	......	0.22	0.00025
0.05	31,000	220	900	0.06	......	3.8	0.0043
0.1	39,000	140	540	0.10	......	13	0.014
0.4	61,000	72	175	0.26	......	110	0.13
0.6	68.000	66	130	0.34	......	200	0.23
0.8	71,000	64	110	0.43	......	290	0.33
1.0	71,000	63	97	0.52	0.0007	380	0.43
1.2	69,000	63	89	0.60	0.0008	470	0.54
1.5	62,000	63	80	0.74	0.0009	610	0.70
2.0	52,000	64	73	1.01	0.0012	840	0.96
3.0	39,000	66	69	1.67	0.0020	1,300	1.5
4.0	33,000	68	70	2.50	0.0030	1,700	2.0
5.0	29,000	70	71	3.52	0.0041	2,100	2.4
6.0	25,000	71	71	4.67	0.0054	2,500	2.9
7.0	23,000	72	72	5.96	0.0068	2,900	3.4
8.0	20,000	73	73	7.36	0.0084	3,300	3.8
10	17,000	75	75	10.5	0.012	4,000	4.7
20	9,900	81	81	34	0.037	7,300	8.6
50	......	88	.....	170	0.17	15,000	18
100	......	93	.....	590	0.58	25,000	30
400	......	99	.....	......	7.0	53,000	65
1,000	......	100	.....	......	......	77,000	96

[a] 15°C, 760 mm Hg.

[b] M. S. Livingston and H. A. Bethe, *Rev. Mod. Phys.* **9**, 270 (1937). The value $W = 35.5$ eV/ion pair was used for α particles in air.

[c] M. J. Berger and S. M. Seltzer, Studies in Penetration of Charged Particles, U. Fano, ed., *Natl. Acad. Sci.–Natl. Res. Council Publ.* 1133, 1964.

[d] The value $W = 34$ eV/ion pair was used for electrons in air.

[e] Calculated on the basis of electron values by R. D. Birkhoff, Oak Ridge National Laboratory. The specific ionization in this column is given for the mixture of β-particle energies having the Fermi distribution for which column 1 shows the maximum energy.

[f] H. A. Bethe and J. Ashkin in "Experimental Nuclear Physics," vol. I, p. 180, E. Segrè, ed., John Wiley & Sons, Inc., New York, 1953.

[g] W. S. Snyder and J. Neufeld, *Oak Ridge Natl. Lab. Rept.* ORNL-1083, Oak Ridge, Tenn., 1951.

[h] P. G. Steward, *Univ. Calif. Rept.* UCRL-18127, Berkeley, 1968.

Specific ionization (ion pairs/cm) of electrons of energy E (MeV) in air:[1]

$$S \approx 55 + 9E^{-1} \tag{8i-12}$$

(<10 percent error for $0.01 \leq E \leq 2$.) See Table 8i-2.

Stopping power in MeV/(g/cm^2) at depth x cm in a medium of density ρ (g/cm^3) from particles of average initial energy $\bar{E}$:

$$P = \frac{\mu \bar{E} e^{-\mu x}}{\rho} \tag{8i-13}$$

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[1] Empirical formula developed by K. Z. Morgan.

Ratio of radiative (bremsstrahlung) and ionization energy-loss rates of an electron with total energy E (MeV) moving in a medium with atomic number Z:

$$\frac{(-dE/dx)\text{ radiation}}{(-dE/dx)\text{ ionization}} \approx \frac{EZ}{800} \qquad (8\text{i-}14)$$

Fraction of energy of an incident electron of kinetic energy E (MeV) converted into bremsstrahlung in a thick target of atomic number Z:

$$f \approx 0.0007ZE \qquad (8\text{i-}15)$$

($E \lesssim$ several MeV.)

X and Gamma Rays. Figure 8i-5 shows the relative importance of the photoelectric effect, Compton scattering, and pair production in absorbers of different atomic number Z. With $Z = 50$, for example, the figure shows that the photoelectric and Compton attenuation coefficients are equal at a photon energy of about 0.3 MeV; and the Compton and pair-production coefficients, at about 6 MeV.

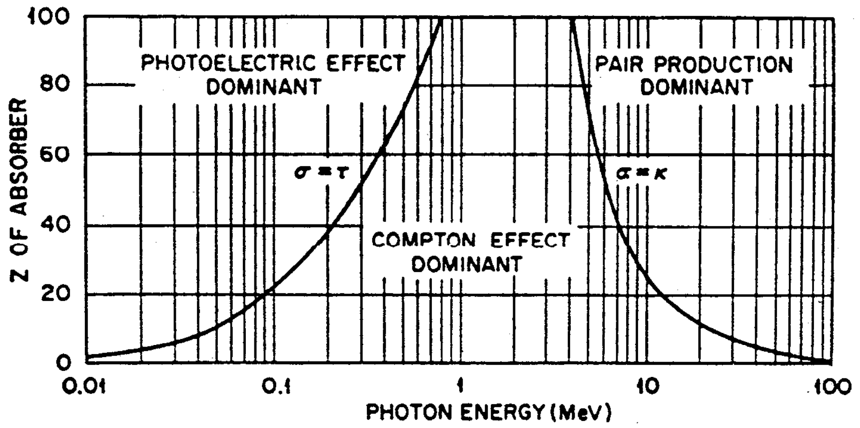

FIG. 8i-5. Relative importance of the three major types of γ-ray interaction. The lines show the values of atomic number Z and photon energy for which the two neighboring effects are just equal. (*From R. D. Evans, "The Atomic Nucleus," McGraw-Hill Book Company, New York,* 1955.)

At low photon energies $h\nu$, the photoelectric cross section for a given Z varies as $(h\nu)^{-\frac{7}{2}}$. At a given (low) photon energy, the cross section for the K-shell photoelectric interaction, which is the dominant process, is proportional to Z^5. The Compton cross section at a given energy is almost independent of Z, and the attenuation coefficient is proportional to the number of electrons per unit volume. The mass attenuation coefficient is thus roughly the same for any absorber in the Compton region. The average fraction of the energy of the incident photon imparted to a Compton electron increases with photon energy. Pair production can occur only when $h\nu \geq 1.02$ MeV. The pair-production cross section at energies of several MeV and greater increases approximately as Z^2 and very slowly with $h\nu$.

Figures 8i-6 through 8i-9 give the mass-attenuation and mass-absorption coefficients of a number of materials. These figures are taken from "Principles of Radiation Protection," K. Z. Morgan and J. E. Turner, eds., John Wiley & Sons, Inc., New York, 1967.

Neutrons. Classification by energies:[1]

THERMAL. In thermal equilibrium with their surroundings, neutrons have a Maxwellian velocity distributiom. At 23°C the most probable speed is 2,200 me-

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[1] Measurement of Absorbed Dose of Neutrons and of Mixtures of Neutrons and Gamma Rays, *Natl. Bur. Standards Handbook* 75, 1961.

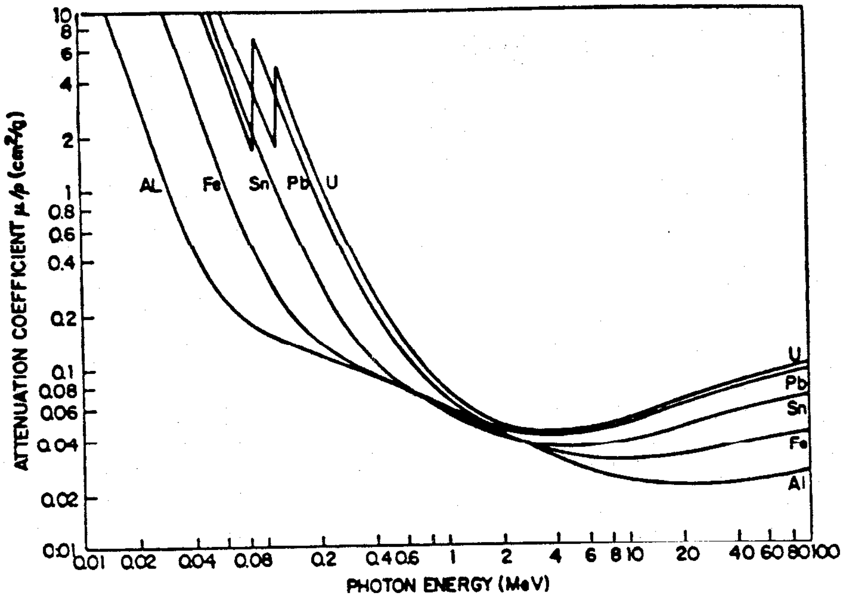

FIG. 8i-6. Mass-attenuation coefficients for various elements. (*D. Z. Morgan and J. E. Turner, eds., "Principles of Radiation Protection," John Wiley & Sons., Inc., New York,* 1967.)

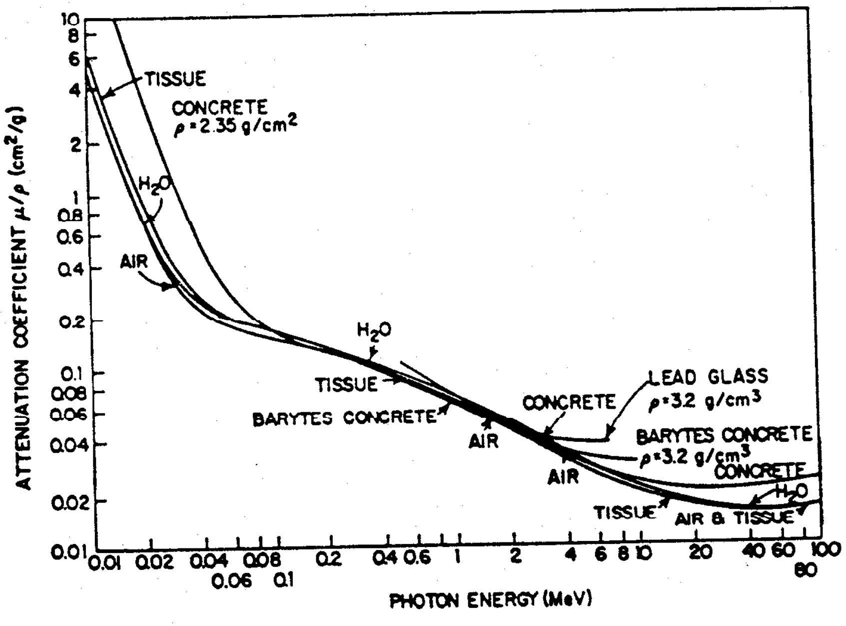

FIG. 8i-7. Mass-attenuation coefficients for various materials. (*D. Z. Morgan and J. E. Turner, ibid.*)

ters/sec; the most probably energy is 0.025 eV. The most important interactions are those involving neutron capture, such as (n,γ) and (n,p) reactions. In tissue the reaction ${}^{1}_{1}H(n,\gamma){}^{2}_{1}H$ produces a 2.2-MeV gamma ray and the ${}^{14}_{7}N(n,p){}^{14}_{6}C$ reaction produces a 0.6-MeV proton. The reaction ${}^{10}_{5}B(n,\alpha){}^{7}_{3}Li$, which releases 2.8 MeV of energy, is utilized in a number of low-energy neutron detectors. Many reaction cross sections are inversely proportional to the neutron velocity ($1/v$ law).

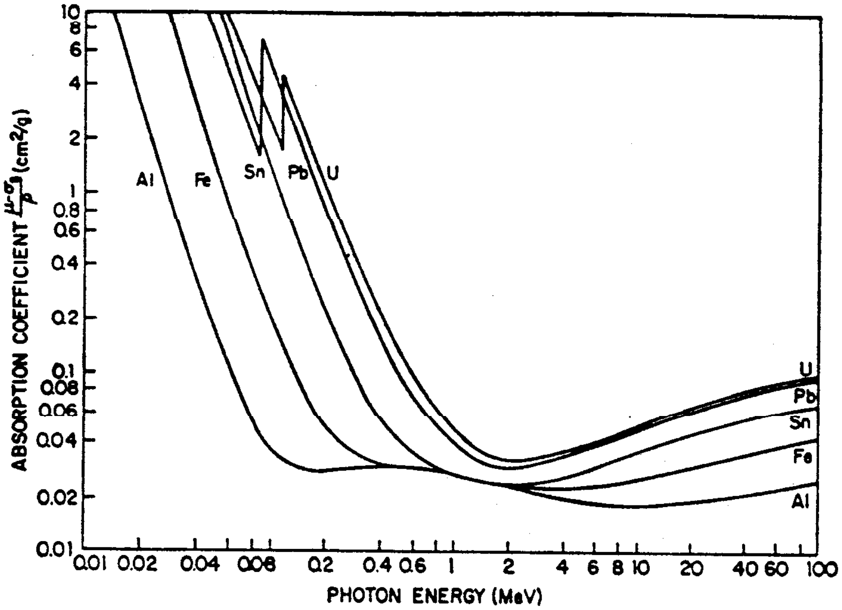

FIG. 8i-8. Mass-absorption coefficients for various elements. *(D. Z. Morgan and J. E. Turner, ibid.)*

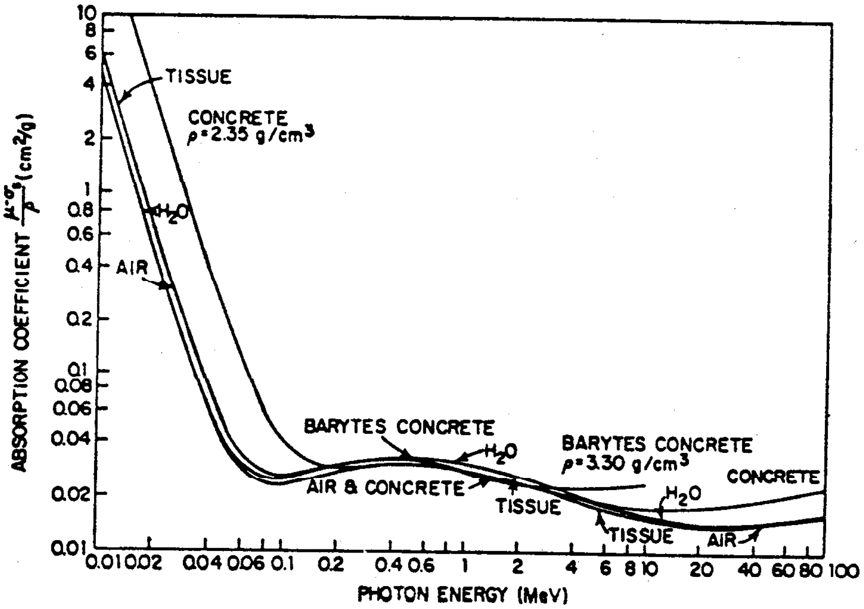

FIG. 8i-9. Mass-absorption coefficients for various materials. *(D. Z. Morgan and J. E. Turner, ibid.)*

INTERMEDIATE ENERGIES (0.5 eV to 10 keV). Neutrons with energies above thermal are sometimes called *epithermal*. Reaction cross sections are characterized by resonance structure.

FAST NEUTRONS (10 keV to 14 MeV). Elastic scattering is usually the most important interaction in the lower portion of this energy range. Inelastic scattering becomes important at the higher energies ($\gtrsim$10MeV). The average energy lost by a neutron (mass m and energy E) scattered elastically and isotropically (in the center-of-mass coordinate system) by a nucleus of mass M is

$$\overline{\Delta E} = \frac{2mME}{(m + M)^2} \tag{8i-16}$$

This expression describes neutron scattering from hydrogen from a few eV to ~14 MeV. With heavier elements this formula is restricted to lower energies. In soft tissue, which is rich in hydrogen, collisions with hydrogen produce $\gtrsim 85$ percent of the first-collision absorbed dose with neutron energies $E \leq 10$ MeV and ~76 percent with $E \lesssim 14$ MeV.[1]

HIGHER ENERGIES (>14 MeV). Inelastic processes, involving ejection of secondary particles, are important with nuclei other than hydrogen in this energy range. Further discussion is included in the next paragraph.

High-energy Protons and Neutrons (50 *MeV to* 2 *GeV*). A high-energy proton passing through tissue deposits energy by ionizing atoms and, like a high-energy neutron, by means of nuclear reactions. Entering a nucleus, a high-energy nucleon can cause a cascade in which a number of secondary nucleons and pions are emitted. The residual nucleus generally returns to its ground state by evaporating additional nucleons and/or heavier nuclear fragments and by emitting gamma rays. As a rough estimate, the total attenuation coefficient of soft tissue for a high-energy nucleon is ≈ 0.01 cm^{-1}. Approximately 30 percent of the nucleons incident normally on a soft-tissue slab have a nuclear reaction in penetrating to a depth of 30 cm, roughly the thickness of the human torso.

Exposure-to-fluence Conversion in Air

$$1 \text{ roentgen} = \frac{2.08 \times 10^3\, W}{E(\mu - \sigma_s)_a} \text{ photons/cm}^2 \approx \frac{2.15 \times 10^9}{E} \text{ photons/cm}^2 \tag{8i-17}$$

Here W (eV/ion pair) is the average energy needed to produce an ion pair in air, E (MeV) is the photon energy, and $(\mu - \sigma_s)_a$ is the absorption coefficient of air (cm^{-1}). The final, approximate equation is not in error by more than ±13 percent in the range $0.07 \leq E \leq 2.0$. The value $W = 34$ eV was used for secondary electrons produced by the photons.

Values in Air Equivalent to an Exposure of 1 *Roentgen*

2.58×10^{-4} coul/kg (definition of the roentgen)
773 esu/g
1.61×10^{12} ion pairs/g
5.47×10^{13} eV/g
87.7 ergs/g = 0.8770 rad
2.10×10^{-6} cal/g(20°C)

(These values are based on $W = 34$ eV/ion pair for secondary electrons.)

Absorbed Dose-to-Fluence Conversion in Soft Tissue. For photons,

$$1 \text{ rad} = \frac{6.24 \times 10^7 \rho_t}{E(\mu - \sigma_s)_t} \text{ photons/cm}^2 \approx \frac{2.17 \times 10^9}{E} \text{ photons/cm}^2 \tag{8i-18}$$

For charged particles,

$$1 \text{ rad} = \frac{6.24 \times 10^{13} \rho_a}{SWP} \text{ particles/cm}^2 \tag{8i-19}$$

Here $\rho_t = 1$ g/cm^3 and $\rho_a = 0.001293$ g/cm^3 are the densities of tissue and air, E (MeV) is the photon energy, $(\mu - \sigma_s)_t$ is the absorption coefficient of tissue (cm^{-1}), S is the average specific ionization in air (ion pairs/cm), W (eV) is the average energy needed to produce an ion pair in air, and P is the mass stopping power of tissue

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[1] *Natl. Bur. Standards Handbook* 75, *ibid.*

relative to air. The approximate equation for photons is in error by no more than ±13 percent in the range $0.07 \leq E \leq 2.0$ MeV. For most purposes one can assume that $W = 35$ eV. For more accurate work, the value W should be taken as 34 eV for electrons from X or gamma radiation or for beta particles, and 35.5 eV for alpha particles. As noted on page 8-296, however, W values for slowly moving heavy ions are often larger, and one should consult the literature.

Values in Soft Tissue Equivalent to an Absorbed Dose of 1 *Rad.*

2.94×10^{-4} coul/kg
882 esu/g
1.84×10^{12} ion pairs/g
(These values are based on an assumed value $W = 34$ eV/ion pair.)
6.24×10^{13} eV/g
100 ergs/g (definition of the rad)
2.39×10^{-6} cal/g

Quality Factors. X rays, gamma rays, electrons, and positrons: QF = 1. Values for heavy charged particles and neutrons are shown in Tables 8i-3 and 8i-4.

TABLE 8i-3. LET–QUALITY FACTOR RELATIONSHIP FOR HEAVY CHARGED PARTICLES*

Average LET, keV/μm in water†	QF
≤3.5	1
3.5–7.0	1–2
7.0–23	2–5
23–53	5–10
53–175	10–20

* Report of the RBE Committee to the ICRP and ICRU, *Health Phys.* **9**, 357 (1963).
† 1 keV/μm = 10 MeV/cm.

TABLE 8i-4. NEUTRON QUALITY FACTORS*

Neutron energy, MeV	QF	Neutron energy, MeV	QF
Thermal	3	10	6.5
10^{-4}	2	50	5
0.02	5	400	3.5
0.1	8	1000	~10 at surface ~2.5 at depth 20–30 cm
0.5	10		
2.5	8	2000	~10 at surface ~2.5 at depth 20–30 cm
5.0	7		

* Values for energies through 10 MeV are given in *Natl. Bur. Standards Handbook* 63, 1957; values at 50 and 400 MeV are based on work of J. Neufeld, W. S. Snyder, J. E. Turner, and H. A. Wright, *Health Phys.* **12**, 227 (1966); values at 1000 and 2000 MeV are based on calculations of H. A. Wright, V. E. Anderson, J. E. Turner, J. Neufeld, and W. S. Snyder, **16**, 13 (1969) *Health Phys.*

Estimates of quality factors for high-energy (50-MeV to 2-GeV) protons and neutrons have been made by applying the values shown in Table 8i-3 to detailed studies of nuclear interactions. For protons, QF ≅ 1.5 in the region from 50 to 600 MeV[1,2] and rises to about 2 at 2 GeV.[2] For neutrons, QF decreases from ~5 at 50 MeV to ~3.5 at 400 MeV.[1] Owing to the build-up of secondary protons (low

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[1] J. Neufeld, W. S. Snyder, J. E. Turner, and H. A. Wright, *Health Phys.* **12**, 227 (1966).
[2] H. A. Wright, V. E. Anderson, J. E. Turner, J. Neufeld, and W. S. Snyder, *Health Phys.* **16**, 13(1969).

LET), the neutron quality factor decreases with increasing depth, this effect becoming more pronounced at higher neutron energies. At 2 GeV, the neutron quality factor decreases from ~10 at the surface of a tissue phantom to ~2.5 at a depth of 20 to 30 cm.[1]

8i-4. External Dose Equations

1. Exposure from a 1-curie point source in time t (hr) at distance r (cm):

$$\epsilon_\gamma = \frac{1.5 \sum_i (\mu - \sigma_s)_i E_i e^{-\mu_i x} f_i B_i t 10^8}{r^2} \quad \text{roentgens} \qquad (8i\text{-}20)$$

where μ_i = attenuation coefficient (cm^{-1}) of medium between source and point of measurement, f_i = fraction of emitted photons having energy E_i, $(\mu - \sigma_s)_i$ = absorption coefficient (cm^{-1}) of air for photons of energy E_i. Figures 8i-6 through 8i-9 can be used to obtain values of μ and $\mu - \sigma_s$. The term B_i is the build-up factor due to the scattered radiation of energy E_i. Its value[2,3] depends upon the width of the beam and the distance, volume, and atomic number of the scattering medium. When the medium is air ($x = r$) and ϵ_γ is measured at not too great a distance r from the point source (i.e., a few meters), then

$$e^{-\mu_i x} B_i \approx 1$$

Some values of ϵ_γ and corresponding absorbed doses are given as a function of E_i in Table 8i-5.

TABLE 8i-5. THEORETICAL VALUES OF EXPOSURE AND ABSORBED DOSE IN AN INFINITESIMAL VOLUME 1 METER FROM A 1-CURIE SOURCE*

Energy, MeV	Exposure ϵ_γ, R/hr	Absorbed dose in tissue, rads/hr	Energy, MeV	Exposure ϵ_γ, R/hr	Absorbed dose in tissue, rads/hr
0.02	0.19	0.19	2.0	0.89	0.85
0.04	0.060	0.051	4.0	1.5	1.4
0.06	0.041	0.035	6.0	2.0	1.8
0.08	0.039	0.037	8.0	2.5	2.3
0.10	0.045	0.042	10	2.9	2.7
0.20	0.10	0.098	20	5.4	4.8
0.40	0.22	0.22	40	11	8.8
0.60	0.34	0.33	60	16	14
0.80	0.43	0.42	100	29	24
1.0	0.52	0.51			

* W. S. Snyder and J. L. Powell, *Oak Ridge Natl. Lab. Rept.* ORNL-421, March, 1950. These values do not include contributions due to air scattering and absorption. Inclusion of absorption by air reduces the exposure rate at 1 meter by 8 percent at a photon energy of 0.02 MeV, by 3 percent at 0.04 MeV, and by one percent at 0.06 MeV. The reduction is insignificant at higher energies.

2. Absorbed dose in a small volume surrounded by a radioactive material uniformly distributed in an infinite medium of density ρ_m (g/cm^3) in t days:

$$D = \frac{51\ C\bar{E}P_t t}{\rho_m} \quad \text{rads} \qquad (8i\text{-}21)$$

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[1] H. A. Wright, V. E. Anderson, J. E. Turner, J. Neufeld, and W. S. Snyder, *ibid.*

[2] H. Goldstein and J. E. Wilkins, Report NYO-3075, Office Tech. Serv. Rept., U.S. Department of Commerce, 1954.

[3] T. Rockwell III, ed., "Reactor Shielding Design Manual," D. Van Nostrand Company, Inc., Princeton, N.J., 1956.

The medium contains (a constant) activity C (μCi/cm^3) of a radionuclide that emits per disintegration an average energy $\bar{E}$ (MeV). When the dose is in tissue, P_t is the mass stopping power of tissue relative to the medium.

3. First-collision absorbed dose in a small volume of tissue in t days from thermal neutrons with a flux density N neutrons/(sec)(cm^2) and energy E MeV due to the (n,p) reaction with nitrogen:

$$D_{N_t} = 1.38 \times 10^{-3}\, N t f_N \sigma_N E = 1.8 \times 10^{-6}\, N t \qquad \text{rads} \tag{8i-22}$$

There are f_N atoms of nitrogen per gram of tissue having a thermal-neutron absorption cross section σ_N cm^2. In this case the ${}^1_1\text{H}(n,\gamma){}^2_1\text{D}$ reaction accounts for more energy loss than the ${}^{14}_{7}\text{N}(n,p){}^{14}_{6}\text{C}$ reaction but is less significant at the peak of the dose equivalent (at about 3 mm depth in tissue) because of the large QF that must be applied to the proton energy.[1]

4. First-collision absorbed dose to tissue in t days from fast neutrons:

$$\begin{aligned} D_{N_f} &= 1.38 \times 10^{-3}\, N E t \sum_i f_i \sigma_i e_i \qquad \text{rads} \\ f_i &= \text{atoms of } i\text{th type per g of tissue} = \frac{6.02 \times 10^{23} F_i}{A_i} \\ c_i &= \text{fraction of energy lost per collision} = \frac{2 M_i m}{(M_i + m)^2} \end{aligned} \tag{8i-23}$$

Here σ_i is the cross section (cm^2) for neutrons of energy E (MeV), F_i is the fraction by weight of the ith element in tissue, A_i is the atomic weight of the ith element, M_i is the mass of the atoms of the ith element, and m is the mass of the neutron.

5. Absorbed dose from ionizing particles (α, β, p, etc.) in t days:

$$D_i = 1.38 \times 10^{-9} N P t \qquad \text{rads} \tag{8i-24}$$

Here P (eV × cm^2/g) is the stopping power of the medium, and N is the flux density of ionizing particles (cm^{-2} sec^{-1}).

6. Exposure from a flux density N/photons/(sec/cm^2) of X or gamma radiation in t days:

$$D_x = 1.22 N E t (\mu - \sigma_s)_a \qquad \text{roentgens} \tag{8i-25}$$

when the photons of energy E (MeV) have an absorption coefficient $(\mu - \sigma_s)_a$ (cm^{-1}) in air.

7. Absorbed dose from a flux density N/photons/(sec/cm^2) of X or gamma radiation in t days:

$$D_x = \frac{1.38 \times 10^{-3} N E t (\mu - \sigma_s)_m}{\rho_m} \qquad \text{rads} \tag{8i-26}$$

when the photons of energy E (MeV) have an absorption coefficient $(\mu - \sigma_s)_m$ (cm^{-1}) in medium m of density ρ_m (g/cm^3).

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[1] Snyder, W. S. *Nucleonics* **6**(2), 46 (1950).

8i-5. Internal Dose Equations[1]

1. Effective half life of a radionuclide:

$$T = \frac{T_r T_b}{T_r + T_b} \tag{8i-27}$$

in which T_r is the radioactive half life, and T_b is the biological half life of the radionuclide in a body organ.

2. Maximum permissible body burden:

$$q = \frac{2.8 \times 10^{-3} mR}{f_2 \Sigma E(\mathrm{QF})H} \quad \mu\mathrm{Ci} \tag{8i-28}$$

in which q (μCi) in the total body delivers a dose equivalent rate of R (rem/week) to the critical body organ of mass m(g). The relative hazard factor H is taken as 5 for alpha, beta, and atomic-recoil components of energy emitted by radioisotopes for which the bone is the critical organ, with the exception of the case when the parent element of the chain is an isotope of radium, in which case H is 1. The term f_2 is the fraction in the critical organ of that in the total body, E is the average energy (MeV) absorbed in the organ per disintegration, and QF is the quality factor of the radiation. (See Table 8i-3: QF = 1 for β^+, β^-, e^-, X, and gamma radiation; 10 for alpha; and 20 for atomic recoils. In the special case when $E_{\max} \leq 0.03$ MeV for β^+, β^-, or e^-, QF = 1.7.) The critical body organ is the organ receiving the radioisotope that results in the greatest body damage.

In the case of alpha- or beta-emitting radioisotopes for which the bone is the critical organ, use is made of the long-standing generally accepted value of $q = 0.1$ μCi for ^{226}Ra by making a comparison on an effective energy basis with ^{226}Ra by means of the equation

$$q = \frac{11}{f_2 \Sigma E(\mathrm{QF})H} \quad \mu\mathrm{Ci} \tag{8i-29}$$

3. Maximum permissible concentration in air $(\mathrm{MPC})_a$ and water $(\mathrm{MPC})_w$:

$$(\mathrm{MPC})_a = \frac{10^{-7} q f_2}{T f_a (1 - e^{-0.693t/T})} \quad \mu\mathrm{Ci/cc} \tag{8i-30}$$

$$(\mathrm{MPC})_w = \frac{9.2 \times 10^{-4} q f_2}{T f_w (1 - e^{-0.693t/T})} \quad \mu\mathrm{Ci/cc} \tag{8i-31}$$

Here $(\mathrm{MPC})_a$ and $(\mathrm{MPC})_w$ are given in μCi/cc of air and water, respectively, that will result in a maximum permissible burden qf_2 in the critical organ after an occupational exposure, 40 hr/week, 50 weeks/year, for a time t days equal to 50 years. f_a and f_w are the fractions that arrive in the critical organ from inhalation and ingestion, respectively. T is the effective half life in days in the critical organ.

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[1] For detailed information on maximum permissible exposure levels, refer to "Maximum Permissible Body Burdens and Maximum Permissible Concentrations of Radionuclides in Air and in Water for Occupational Exposure," Handbook 69, Superintendent of Documents, Washington, D.C.; *ICRP Publ.* 2, Report of Committee II on Permissible Dose for Internal Radiation, 1959, *Health Phys.* **3**, 1 (1960); and Recommendations of the International Commission on Radiological Protection, *ICRP Publ.* 6, Pergamon Press, New York, 1962; K. Z. Morgan and M. R. Ford, Developments in Internal Dose Determinations, *Nucleonics* **12**(6), 32–39 (June, 1954); K. Z. Morgan, W. S. Snyder, and M. R. Ford, Maximum Permissible Concentrations of Radioisotopes in Air and Water for Short Period Exposure, in "Peaceful Uses of Atomic Energy," vol. 13, United Nations, 1956; and "Background Material for the Development of Radiation Protection Standards," Federal Radiation Council, Superintendent of Documents, Washington, D.C., May, 1960; September, 1961; July, 1964; and May, 1965.

In the case of an inert gas,

$$(\mathrm{MPC})_a = \frac{0.024R\rho_a P_a}{\Sigma E(\mathrm{QF})HP_t} \quad \mu\mathrm{Ci/cc} \tag{8i-32}$$

and when the maximum permissible equivalent rate R is 0.1 rem/week,

$$(\mathrm{MPC})_a = \frac{2.6 \times 10^{-6}}{\Sigma E(\mathrm{QF})H} \quad \mu\mathrm{Ci/cc} \tag{8i-33}$$

In these equations R = dose-equivalent rate (rem/week), ρ_a = density of air (= 0.001293 g/cc), P_a/P_t = stopping power of air relative to tissue (= 1/1.13 for beta, X, and gamma radiation).

4. Dose equivalent delivered to the critical body organ after a single intake:

$$D = \frac{74\Sigma E(\mathrm{QF})HfI_0T}{m}(1 - e^{-0.693t/T}) \quad \mathrm{rem} \tag{8i-34}$$

in which D is the dose equivalent (rem) delivered to the critical organ of mass m (g) in time t (days) when I_0 (μCi) is taken into the body in a single event, and the fraction f is deposited in the critical organ.

5. Dose equivalent in t days to the body organ containing a constant burden of qf_2 (μCi):

$$D = \frac{51qf_2t\Sigma E(\mathrm{QF})H}{m} \quad \mathrm{rem} \tag{8i-35}$$

6. Dose equivalent to lower large intestine from single intake I_0 (μCi):

$$D_{GI} = \frac{0.13fI_0\Sigma E(\mathrm{QF})H}{G} \quad \mathrm{rem} \tag{8i-36}$$

Except for radionuclides of very short radioactive half life, the lower large intestine receives the largest dose of any portion of the GI tract. In this equation G is given by the relation

$$G = \frac{0.693(h_1 - h_0)}{(e^{-0.693h_0/T_r} - e^{-0.693h_1/T_r})T_r} \tag{8i-37}$$

Usually h_0/T_r and h_1/T_r are small, and in such cases $G = 1$. In these equations f = fraction of ingested or inhaled radionuclide going to the lower large intestine, h_0 = time of arrival in lower large intestine (= 13/24 days), h_1 = time of departure from lower large intestine (= 31/24 days).

7. Dose equivalent in t weeks at distance r (cm) from a microscopic radioactive particle lodged in the body in which Q = μCi of particle, S_a = specific ionization of beta radiation in air (ion pair/cm), W_a = energy to produce ion pair (eV/ip), P_t = stopping power tissue relative to air, μ_t = coefficient of attenuation of beta radiation (cm^{-1}), and T_r = radioactive half life of radionuclide (weeks):

$$D_p = \frac{4.1 \times 10^{-5}T_rQS_aW_aP_t(\mathrm{QF})He^{-\mu_t r}(1 - e^{-0.693t/T_r})}{r^2\rho_a} \quad \mathrm{rem} \tag{8i-38}$$

It should be noted that S_aW_a/ρ_a eV/(g/cm^2) is the stopping power of air and $S_aW_aP_t/\rho_a = P$ eV/(g/cm^2) is the stopping power of the tissue. Values of stopping power for water may be found from Fig. 1, and average values over the range of the particle may be found for various media from Figs. 8i-2 and 8i-3 by using the relation $P = \bar{E}/R$, in which $\bar{E}$ is the average energy (eV), and R is the range (g/cm^2).

8. Average dose equivalent in time t (weeks) in a sphere of radius r (cm) resulting from a microscopic radioactive particle lodged in tissue at the center of the sphere (in this case, $r <$ range of beta rays):

$$D_p = \frac{1.23 \times 10^{-4} T_r Q S_a W_a P_t (\mathrm{QF}) H (1 - e^{-\mu_t r})(1 - e^{-0.693t/T_r})}{r^3 \mu_t \rho_a} \quad \text{rem} \qquad (8\text{i-}39)$$

9. Average dose equivalent in time t (weeks) in a sphere of radius r (cm) $\geq$ range of alpha or beta radiation resulting from a microscopic radioactive particle lodged in tissue at the center of the sphere:

$$D_p = \frac{1.23 \times 10^{2} T_r Q \Sigma E (\mathrm{QF}) H (1 - e^{-0.693t/T_r})}{r^3} \quad \text{rem} \qquad (8\text{i-}40)$$

10. Dose equivalent from fallout from a nuclear detonation:

$$D_f = 5 t_0 \dot{D}_0 \left[1 - \left(\frac{t_0}{t_1} \right)^{0.2} \right] \quad \text{rem} \qquad (8\text{i-}41)$$

In this case D_f is the dose equivalent during time $t_1 - t_0$, and $\dot{D}_0$ is the dose-equivalent rate measured at time t_0 since the nuclear detonation. It is assumed that $\dot{D}_0 \propto t^{-1.2}$.

8i-6. Radiation Protection Guides and Standards. One should avoid unnecessary exposure to ionizing radiation. The Federal Radiation Council has stated[1] that ". . . the establishment of radiation protection standards involves a balancing of the benefits to be derived from the controlled use of radiation and atomic energy against the risk of radiation exposure." Table 8i-6 summarizes some of the 1968 values of maximum permissible dose in general use for occupational exposure. These amounts, permitted when necessary in order to carry out operations, are independent of an individual's exposure for medical reasons or his exposure to natural background radiation. The recommendations of various organizations differ in some respects from one another, and specific recommendations may be different from the values given in Table 8i-6. Generally, values one-tenth those for occupational exposure are applied to exposure of individuals in uncontrolled areas or to the critical segments

TABLE 8i-6. PERMISSIBLE DOSE EQUIVALENT TO BODY ORGANS OF WORKERS AS RECOMMENDED (1968) BY THE NATIONAL COUNCIL ON RADIATION PROTECTION

Organs	Maximum permissible dose equivalent in any 13-week period, rem	Annual maximum permissible dose equivalent, rem
Red bone marrow, total body, head, trunk, gonads, lenses of the eyes*	3	5
Skin, thyroid, bone	10(15)*	30
Feet, ankles, hands, forearms	25(38)*	75
Other single organs	5(8)*	15

* The values recommended by the ICRP are identical to those recommended by the NCRP with exception of the ICRP values given in parentheses. Also, the ICRP now includes the lenses of the eyes with the "other single organs."

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[1] Report No. 2, Washington, D.C., 1961.

of this population. Further information and details are given in the following publications:

Recommendations of the International Commission on Radiological Protection (ICRP), Pergamon Press, London:
  Publ. 1, 1959.
  Publ. 2, 1959; and *Health Phys.* **3**, 1 (1960). The bibliography of ICRP Publ. 2 appears only in the latter.
  Publ. 3, 1960.
  Publ. 4, 1963.
  Publ. 5, 1964.
  Publ. 6, 1964.
  Publ. 7, 1965.
  Publ. 8, 1966.
  Publ. 9, 1966.
  Health Phys. **12**, 129 (1966).
  "Principles of Radiation Protection," K. Z. Morgan and J. E. Turner, eds., John Wiley & Sons, Inc., New York, 1967.
Recommendations of the National Council on Radiation Protection and Measurements (NCRP):
  National Bureau of Standards Handbook 52, 1953.
  National Bureau of Standards Handbook 59, supplements, Jan. 8, 1957, and Apr. 15, 1958.
  National Bureau of Standards Handbook 59, 1959.
  Radiology **75**, 122 (1960).
Federal Radiation Council, Washington, D.C.:
  Rept. 1, 1960.
  Rept. 2, 1961.
  Rept. 5, 1964.
  Rept. 7, 1965.
  Federal Register, p. 6953, May 22, 1965.

Perhaps the most important recent development in radiation protection standards is the concept of maximum permissible dose commitment. Obviously it would not be proper to permit an employee to accumulate a maximum permissible body burden of a radionuclide with a long effective half life during, for example, one year of employment because for a long period thereafter he could be permitted no further external or internal exposure. To avoid this, the International Commission on Radiological Protection set the limit at an annual permissible dose commitment which is defined as the dose resulting from a body intake of a radionuclide by a person occupationally exposed for one year at the maximum permissible concentration, MPC, of a radionuclide. It can be shown that if the period of body intake of the radionuclide is τ years, the critical body-organ dose equivalent integrated over $50 + \tau/2$ years as a result of a dose commitment would be equal numerically to the annual permissible dose-equivalent value R_{50} as given in Table 8i-6 for the critical organ multiplied by τ. Table 8i-7[1] summarizes values of maximum permissible dose commitment for the three categories of occupational exposure: (A) routine application, (B) single exposure or quarterly dose, and (C) planned special exposures. In this table R_{50} corresponds to the dose rate reached in the critical body organ after occupational exposure at the MPC of a radionuclide for 50 years.

Time-average neutron flux densities that deliver 100 mrem in a 40-hr work week are given in Table 8i-8. Additional flux densities have been calculated for neutron energies up to 400 MeV.[2] For normally incident beams it is estimated that the maximum permissible flux density decreases smoothly from about 15 neutrons/(sec/cm^2) at 60 MeV to about 10 neutrons/(sec/cm^2) at 400 MeV.

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[1] Taken from "Principles of Radiation Protection," K. Z. Morgan and J. E. Turner, eds., John Wiley & Sons, Inc., New York, 1967.

[2] J. Neufeld, W. S. Snyder, J. E. Turner, and H. A. Wright, *Health Phys.* **12**, 227 (1966).

TABLE 8i-7. OCCUPATIONAL EXPOSURE LEVELS* RECOMMENDED BY ICRP

Categories of exposure	Maximum dose equivalent for external exposure and/or internal exposure to radionuclides with a short effective half life		Dose equivalent integrated over a 50-year period resulting from a permissible quarterly dose equivalent or from a planned special exposure	Maximum permissible intake of any radionuclide for single, quarterly, or planned exposure corresponds to an intake:	
	rem in 13 weeks	rem in 1 year ‡	rem in 50 years†	For 13 weeks at:	At the MPC for:
A. Maximum permissible dose equivalent for routine application	$R_{50}/4$	R_{50}	$R_{50}/4$	1 × MPC	$\frac{1}{4}$ year
B. Maximum permissible dose equivalent for single exposures or for exposures on a quarterly basis	$R_{50}/2$‡	$2R_{50}$‡ to total body, gonads, or red bone marrow if $5(N - 18)$ is not exceeded. R_{50}‡ to all other organs	$R_{50}/2$	2 × MPC	$\frac{1}{2}$ year
C. Planned special exposures§	$2R_{50}$ committed in any single event to any body organ		$2R_{50}$	8 × MPC	2 years
D. Summation of all planned special exposures in a lifetime	$5R_{50}$ committed in a lifetime to any body organ from planned special exposures		$5R_{50}$	20 × MPC	5 years

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* Exposure levels are given in terms of the annual permissible dose equivalent R_{50}. Values of R_{50} for individual body organs in various radiosensitivity organ groups are as follows:

Group 1 for gonads, total body, and red bone marrow: $R_{50} = 5$, $R_{50}/2 \rightarrow 3$, $2R_{50} \rightarrow 12$, and $5R_{50} = 25$ rem.
Group 2 for thyroid, skin, and bone: $R_{50} = 30$, $R_{50}/2 = 15$, $2R_{50} = 60$, and $5R_{50} = 150$ rem.
Group 3 for hands, forearms, feet, and ankles: $R_{50} = 75$, $R_{50}/2 \rightarrow 38$, $2R_{50} = 150$, and $5R_{50} = 375$ rem.
Group 4 for all other body organs (including the lenses of the eyes): $R_{50} = 15$, $R_{50}/2 \rightarrow 8$, $2R_{50} = 30$, and $5R_{50} = 75$ rem.

† Actually, over a period of $50 + \tau/2$ years for external and/or internal exposures to radionuclides of any effective half life, τ is period of intake of a radionuclide.

‡ The ICRP states that it would be undesirable to repeat this quarterly dose equivalent of $R_{50}/2$ at close intervals, but to provide flexibility, it is permitted on infrequent occasions to receive $2R_{50}$ in a year to the gonads, total body, and red bone marrow, provided the accumulated dose equivalent of $5(N - 18)$ rem is not exceeded. Ordinarily, the annual dose equivalent R_{50} should not be exceeded for exposure to any of the body organs.

§ Planned special exposures are not permitted if a single exposure in excess of $R_{50}/2$ has been received in the previous 12 months or if at any time the worker has received an abnormal exposure in excess of $5R_{50}$. Planned special exposures are not permitted to women of reproductive capacity. They are not permitted to gonads, total body, or red bone marrow if as a consequence $5(N - 18)$ rem is exceeded.

Maximum permissible concentrations of specific radionuclides in water and in air are recommended by the International Commission on Radiological Protection, Publication 2, *Health Phys.* **3**, 1 (1960). Concentrations of unidentified radionuclides in water and air are given in Tables 8i-9 and 8i-10.

TABLE 8i-8. MAXIMUM PERMISSIBLE NEUTRON FLUX DENSITIES AS GIVEN BY THE NATIONAL COUNCIL ON RADIATION PROTECTION*

Neutron energy, MeV	Average flux density, $cm^{-2}\ sec^{-1}$	Neutron energy, MeV	Average flux density, $cm^{-2}\ sec^{-1}$
Thermal	670	2.5	20
10^{-4}	500	5.0	18
0.02	280	7.5	17
0.1	80	10	17
0.5	30	10–30	10
1.0	18		

* *Natl. Bur. Standards Handbook* 63, 1957.

TABLE 8i-9. MAXIMUM PERMISSIBLE CONCENTRATION OF UNIDENTIFIED RADIONUCLIDES IN WATER, $(MPCU)_w$ VALUES* FOR CONTINUOUS OCCUPATIONAL EXPOSURE

Limitations	μCi/cc *of water*†
If no one of the radionuclides ^{90}Sr, ^{126}I, ^{129}I, ^{131}I, ^{210}Pb, ^{210}Po, ^{211}At, ^{223}Ra, ^{224}Ra, ^{226}Ra, ^{228}Ra, ^{227}Ac, ^{230}Th, ^{231}Pa, ^{232}Th, and Th-nat is present, then the $(MPCU)_w$ is	3×10^{-5}
If no one of the radionuclides ^{90}Sr, ^{129}I, ^{210}Pb, ^{210}Po, ^{223}Ra, ^{226}Ra, ^{228}Ra, ^{231}Pa, and Th-nat is present, then the $(MPCU)_w$ is	2×10^{-5}
If no one of the radionuclides ^{90}Sr, ^{129}I, ^{210}Pb, ^{226}Ra, and ^{228}Ra is present, then the $(MPCU)_w$ is	7×10^{-6}
If neither ^{226}Ra nor ^{228}Ra is present, then the $(MPCU)_w$ is	10^{-6}
If no analysis of the water is made, then the $(MPCU)_w$ is	10^{-7}

* Each $(MPCU)_w$ value is the smallest $(MPC)_w$ value of the National Council on Radiation Protection—*Natl. Bur. Standards Handbook* 69, June 5, 1959, or *ICRP Publ.* 2, 1959, for radionuclides other than those listed opposite the value. Thus these $(MPCU)_w$ values are permissible levels for continuous occupational exposure (168 hr/week) for any radionuclide or mixture of radionuclides where the indicated isotopes are not present [i.e., where the concentration of the radionuclide in water is small compared with the $(MPC)_w$ value for this radionuclide]. The $(MPCU)_w$ may be much smaller than the more exact maximum permissible concentration of the material, but the determination of this $(MPC)_w$ often requires expensive and time-consuming identification of the radionuclides present and the concentration of each.

† Use one-tenth of these values for interim application in the neighborhood of an atomic-energy plant or other controlled area.

Regulations for the Shipment of Radioactive Materials. The reader should refer to official publications[1] for detailed information on the shipment of radioactive materials.

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[1] Robley D. Evans, Chairman of the Subcommittee on Shipment of Radioactive Substances, "Physical, Biological and Administrative Problems Associated with the Transportation of Radioactive Substances." ICC shipping regulations are given in Title 49, parts 71 to 78, of the Code of Federal Regulations; Civil Aeronautics Board regulations are given in part 49 of the Civil Air Regulations, "Transportation of Explosives and Other Dangerous Articles"; regulations of the United States Coast Guard are given in the Federal Register, July 17, 1952, pp. 6460ff.; regulations governing the transportation of radioactive materials in the United States mails are given in the U.S. Postal Manual, parts 124.24 and 125.24.

TABLE 8i-10. MAXIMUM PERMISSIBLE CONCENTRATION OF UNIDENTIFIED RADIONUCLIDES IN AIR, $(MPCU)_a$ VALUES* FOR CONTINUOUS OCCUPATIONAL EXPOSURE

Limitations	μCi/cc *of air*†
If there are no α-emitting radionuclides, and if no one of the β-emitting radionuclides ^{90}Sr, ^{129}I, ^{210}Pb, ^{227}Ac, ^{228}Ra, ^{230}Pa, ^{241}Pu, and ^{249}Bk is present, then the $(MPCU)_a$ is	10^{-9}
If there are no α-emitting radionuclides, and if no one of the β-emitting radionuclides ^{210}Pb, ^{227}Ac, ^{228}Ra, and ^{241}Pu is present, then the $(MPCU)_a$ is	10^{-10}
If there are no α-emitting radionuclides, and if the β-emitting radionuclide ^{227}Ac is not present, then the $(MPCU)_a$ is	10^{-11}
If no one of the radionuclides ^{227}Ac, ^{230}Th, ^{231}Pa, ^{232}Th, Th-nat, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{242}Pu, and ^{249}Cf is present, then the $(MPCU)_a$ is	10^{-12}
If no one of the radionuclides ^{231}Pa, Th-nat, ^{239}Pu, ^{240}Pu, ^{242}Pu, and ^{249}Cf is present, then the $(MPCU)_a$ is	7×10^{-13}
If no analysis of the air is made, then the $(MPCU)_a$ is	4×10^{-13}

* Each $(MPCU)_a$ value is the smallest $(MPC)_a$ value of the National Council on Radiation Protection—*Natl. Bur. Standards Handbook* 69, June 5, 1959, or of *Intern. Comm. Radiol. Protec. Publ.* 2, 1959, for radionuclides other than those listed opposite the value. Thus these $(MPCU)_a$ values are permissible levels for continuous occupational exposure (168 hr/week) for any radionuclide or mixture of radionuclides where the indicated isotopes are not present [i.e., where the concentration of the radionuclide in air is small compared with the $(MPC)_a$ value for this radionuclide]. The $(MPCU)_a$ value may be much smaller than the more exact maximum permissible concentration of the material, but the determination of this $(MPC)_a$ often requires expensive and time-consuming identification of the radionuclides present and the concentration of each.

† Use one-tenth of these values for interim application in the neighborhood of an atomic-energy plant or other controlled area.

General limitations for the shipment of radioisotopes are:

1. A package must not be less than 4 in. in its smallest outside dimension.
2. A single package must not contain more than 2 curies (2.7 curies of less dangerous radioisotopes) or as noted below.[1]
3. The surface of the package must contain no significant contamination.
4. The dose rate at any accessible surface must not exceed 200 mR/hr (or equivalent in mrem/hr).
5. The dose rate at 1 m must not exceed 10 mR/hr.
6. Shipments of radioactive materials by rail and motor express, air, and boat fall into five categories (groups I, II, III, IV, and exempt). Only exempt shipments may be made by mail.

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[1] Not more than 300 curies of solid cesium-137, cobalt-60, gold-198, or iridium-192 may be packed in one outside container for shipment by rail freight, rail express, or highway except by special arrangements and under conditions approved by the Bureau of Explosives.