



Standard Practice for Calculating Absorbed Dose From Gamma or X Radiation¹

This standard is issued under the fixed designation E 666; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

This standard has been approved for use by agencies of the Department of Defense.

1. Scope

1.1 This practice presents a technique for calculating the absorbed dose in a material from knowledge of the radiation field, the composition of the material, (1-5)^{2,3} and a related measurement. The procedure is applicable for X and gamma radiation provided the energy of the photons fall within the range from 0.01 to 20 MeV.

1.2 A method is given for calculating the absorbed dose in a material from the knowledge of the absorbed dose in another material exposed to the same radiation field. The procedure is restricted to homogeneous materials composed of the elements for which absorption coefficients have been tabulated (2). It also requires some knowledge of the energy spectrum of the radiation field produced by the source under consideration. Generally, the accuracy of this method is limited by the accuracy to which the energy spectrum of the radiation field is known.

1.3 The results of this practice are only valid if charged particle equilibrium exists in the material and at the depth of interest. Thus, this practice is not applicable for determining absorbed dose in the immediate vicinity of boundaries between materials of widely differing atomic numbers. For more information on this topic, see Practice E 1249.

1.4 Energy transport computer codes⁴ exist that are formulated to calculate absorbed dose in materials more precisely than this method. To use these codes, more effort, time, and expense are required. If the situation warrants, such calculations should be used rather than the method described here.

1.5 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appro-*

priate safety and health practices and determine the applicability of regulatory limitations prior to use.

2. Referenced Documents

2.1 ASTM Standards:

E 170 Terminology Relating to Radiation Measurements and Dosimetry⁵

E 380 Practice for Use of the International System of Units (SI) (the Modernized Metric System)⁶

E 665 Practice for Determining Absorbed Dose Versus Depth in Materials Exposed to the X-Ray Output of Flash X-Ray Machines⁵

E 668 Practice for Application of Thermoluminescence-Dosimetry (TLD) Systems for Determining Absorbed Dose in Radiation-Hardness Testing of Electronic Devices⁵

E 1249 Practice for Minimizing Dosimetry Errors in Radiation Hardness Testing of Silicon Electronic Devices Using Co-60 Sources⁵

2.2 International Commission on Radiation Units and Measurements (ICRU) Reports:

ICRU Report 14—Radiation Dosimetry: X Rays and Gamma Rays with Maximum Photon Energies Between 0.6 and 60 MeV⁷

ICRU Report 18—Specification of High Activity Gamma-Ray Sources⁷

ICRU Report 21—Radiation Dosimetry: Electrons with Initial Energies Between 1 and 50 MeV⁷

ICRU Report 33—Radiation Quantities and Units⁷

ICRU Report 34—The Dosimetry of Pulsed Radiation⁷

3. Significance and Use

3.1 The absorbed dose is a more meaningful parameter than exposure for use in relating the effects of radiation on materials. It expresses the energy absorbed by the irradiated material per unit mass, whereas exposure is related to the amount of charge produced in air per unit mass. Absorbed dose, as referred to here, implies that the measurement is made under conditions of charged particle (electron) equilibrium (see Appendix X1). In practice, such conditions are not rigorously

¹ This practice is under the jurisdiction of ASTM Committee E-10 on Nuclear Technology and Applications and is the direct responsibility of Subcommittee E 10.07 on Radiation Dosimetry for Radiation Effects on Materials and Devices.

Current edition approved June 10, 1997. Published May 1998.

² The boldface numbers in parentheses refer to the list of references appended to this practice.

³ For calculation of absorbed dose in biological materials such as tissue or bone, etc., ICRU Report 14 provides more information and procedures for a more accurate calculation than this practice.

⁴ Information on and packages of computer codes can be obtained from The Radiation Safety Information Computational Center, Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, TN 37831-6362. This information center collects, organizes, evaluates, and disseminates shielding information related to radiation from reactors, weapons, and accelerators and to radiation occurring in space.

⁵ *Annual Book of ASTM Standards*, Vol 12.02.

⁶ *Annual Book of ASTM Standards*, Vol 14.02.

⁷ Available from International Commission on Radiation Units and Measurements (ICRU), 7910 Woodmont Ave., Suite 800, Bethesda, MD 20814.

achievable but, under some circumstances, can be approximated closely.

3.2 Different materials, when exposed to the same radiation field, absorb different amounts of energy. In order to relate absorbed dose in one material to absorbed dose in another material, the condition of charged particle equilibrium must exist. On the other hand, if the radiation is attenuated by a significant thickness of an absorber, the energy spectrum of the radiation will be changed, and it will be necessary to correct for this.

NOTE 1—For comprehensive discussions of various dosimetry methods applicable to the radiation types and energies and absorbed dose rate ranges discussed in this method, see ICRU Reports 14, 21, and 34.

4. Calculation of Absorbed Dose

4.1 The absorbed dose, D , at a point may be expressed as:

$$D = I \int_0^{\infty} \psi(E) [\mu_{\text{en}}(E)/\rho] dE \quad (1)$$

where $\psi(E)$ is the energy fluence per unit energy at the point of interest; $\mu_{\text{en}}(E)/\rho$ is the mass energy absorption coefficient (2); and I is a normalizing factor. If all of the variables in Eq 1 are expressed in SI units, $I = 1$. In this case the units for D are Gy (J kg^{-1}), of $\psi(E)$, are m^{-2} , of μ_{en}/ρ are $\text{m}^2 \text{kg}^{-1}$, and of E are J. For an alternative use of the normalizing factor I , see Appendix X2. For further information on the use of energy absorption coefficients to calculate absorbed dose see the discussion in Attix (1). The energy fluence spectrum, $\psi(E)$, is that which is incident at the point where the dose is to be determined. In practice, the limits of integration are the limits of energy over which $\psi(E)$ is of a significant magnitude. If material intervenes between the source and the point of dose determination, then the spectrum used in the calculation must be the output spectrum of the source modified by the absorbing effects of the intervening material. The values of $\mu_{\text{en}}(E)/\rho$ are found in the tables of Ref 2.

NOTE 2—For units and terminology in reports of data, E 170 and ICRU Report 33 may be used as guides.

4.2 If the material in which the absorbed dose is to be calculated is a homogeneous combination of materials not listed in the tables of Ref 2, $\mu_{\text{en}}(E)/\rho$ is determined as follows:

4.2.1 From Ref 2, obtain values of $\mu_{\text{en}}^i(E)/\rho$ for each component, i .

4.2.2 Determine the atomic fraction, f_i , for each component.

4.2.3 Calculate $\mu_{\text{en}}(E)/\rho$ from the following equation:

$$\mu_{\text{en}}(E)/\rho = \sum_i f_i [\mu_{\text{en}}^i(E)/\rho] \quad (2)$$

4.2.4 Values of $\mu_{\text{en}}(E)/\rho$ must be determined for each value of E for which $\psi(E)$ is significant, where E is the photon energy.

4.3 The integral contained in Eq 1 is evaluated numerically. The values of $\mu_{\text{en}}(E)/\rho$ in Ref 2 are tabulated for specific energies. In evaluation of the integral referred to in actual practice, it is often desirable to choose energy intervals that would not correspond to the tabulated values in Ref 2. In such cases, the appropriate value of $\mu_{\text{en}}(E)/\rho$ for the chosen energies should be determined by an acceptable interpolation procedure. The range of energy over the total photon spectrum is divided

into energy intervals or bins. The width of these bins is somewhat flexible but should be chosen small enough so as not to distort the shape of the spectrum. For the purpose of selecting appropriate values of $\mu_{\text{en}}(E)/\rho$, the energy value selected for each energy interval can be taken either as that energy at the beginning or midpoint of each energy interval over the entire spectrum.

4.4 The spectrum, $\psi(E)$, is commonly given in arbitrary units and may be normalized to some source parameter. If a standard or calibrated dosimeter is used, then the integral in Eq 1 must be calculated for the material from which this dosimeter is constructed. The value of I is then given by the observed dose, D , measured by the dosimeter divided by the value of the integral.

5. Estimating the Absorbed Dose in One Material from That Measured in Another Material

5.1 If the absorbed dose is known in one material, A, then the absorbed dose can be estimated in another material, B, using the method described in this section.

5.1.1 The absorbed dose observed in A occurs at some depth in the region of material A; similarly, it is desired to know the absorbed dose in material B at some depth in the region of material B. If it is presumed that we know the surface energy fluence spectrum $\psi_o(E)$ (the energy fluence spectrum incident on the surface of materials A and B) then the energy fluence spectrum $\psi_t(E)$ to be used in Eq 1 must be related to the known surface energy fluence spectrum $\psi_o(E)$. A good approximation to the integral attenuated energy fluence spectrum at mass-depth t is given by

$$\int_0^{\infty} \psi_t(E) dE = \int_0^{\infty} \psi_o(E) e^{-[\mu_{\text{en}}(E)/\rho]t} dE \quad (3)$$

where t is the mass-thickness (in $\text{kg}\cdot\text{m}^{-2}$) of material between the surface and the depth of interest, E is a particular energy represented in the spectrum, and $\psi_t(E)$ is the energy fluence per unit energy at mass-depth t . For a derivation of Eq 3 see Appendix X4. See also the qualifications of 5.1.3 and 5.1.4. For a demonstration of the experimental plausibility of Eq 3, see Appendix X5.

5.1.2 Using Eq 1 and 3, the relationship between the known dose D_A and the desired dose D_B can be expressed as

$$\frac{D_A}{D_B} = \frac{\int_0^{\infty} [\psi_o(E) e^{-[\mu_{\text{en}}^A(E)/\rho_A]t_A}] [\mu_{\text{en}}^A(E)/\rho_A] dE}{\int_0^{\infty} [\psi_o(E) e^{-[\mu_{\text{en}}^B(E)/\rho_B]t_B}] [\mu_{\text{en}}^B(E)/\rho_B] dE} \quad (4)$$

where μ_{en}^A , ρ_A , and t_A are the mass energy absorption coefficient, the density and the relevant mass-thickness for material A, and where similar notation is used for material B. For further details on the derivation of Eq 4, see Appendix X6. All the variables in Eq 4 are presumed to be known except the desired value for D_B . The integrals in Eq 4 must be performed numerically.

5.1.3 The use of Eq 3 is based on the existence of charged particle equilibrium (for further discussion see 1.3). This condition may be reasonably well met when the region of interest is at a sufficient distance from boundaries representing changes in atomic number or material density (see Appendix X1).

5.1.4 Wide Beam vs. Narrow Beam Approximation.

5.1.4.1 The use of the mass energy absorption coefficient, μ_{en} , in Eq 3 is based on the assumption that the irradiation approaches the “wide beam” as opposed to “narrow beam” condition. The wide beam and narrow beam conditions represent limiting cases which are only approximately realized for real experiments. In the narrow beam case, photons which are scattered out of the narrow beam are assumed to be lost from the beam, and are assumed to have no further importance to the experiment. In the broad beam case, photons which are scattered out of a given small region of the broad beam are presumed to be replaced by photons scattering in from adjacent regions of the beam. For the narrow beam limiting case, Eq 3 should be replaced by

$$\psi_t(D) = \psi_o(E)e^{-[\mu(E)/\rho]t} \quad (5)$$

where μ is the photon attenuation coefficient. Values of $\mu(E)/\rho$ are found in the tables of Ref 2. For most practical problems the results of photon attenuation lie between the results of Eq 3 and Eq 5.

5.1.4.2 It is possible to determine the magnitude of the change which would have resulted had Eq 1 and Eq 5 been used rather than using Eq 1 and Eq 3 in order to develop Eq 4. The resulting change in the ratio D_A/D_B calculated by Eq 4 is related to the factor

$$F(E) = \frac{e^{-[\mu_{en}^B(E)/\rho_B]t} e^{-[\mu^A(E)/\rho_A]t}}{e^{-[\mu^B(E)/\rho_B]t} e^{-[\mu_{en}^A(E)/\rho_A]t}} \quad (6)$$

If, over the energy range of interest, $F(E)$ differs from unity by a percentage which is greater than the acceptable dosimetry error, then the application of this practice may be inappropriate. In that case an appropriate transport calculation is recommended (see 1.5).

6. Accuracy

6.1 The accuracy of this practice depends primarily on the accuracy to which the incident energy spectrum is known. In general, even a poor estimate of a spectrum will give a better estimate of the absorbed dose at a given location than one would get by assuming some sort of single “effective photon energy.” Although ^{60}Co and ^{137}Cs have well-defined primary gamma-ray energies, the radiation energy spectrum from most practical sources contains a significant Compton scattered component that could lead to significant errors if neglected (see ICRU Report 18).

6.2 As stated in 1.3, the results of this practice are not valid unless charged particle equilibrium conditions exist in the material at the depth of application. For depths less than that required for equilibrium, the absorbed dose could be higher or lower than this method would predict. At depths greater than required for equilibrium, the accuracy of the results depends primarily upon the accuracy of the attenuation correction applied in Eq 3 and the knowledge of the incident energy spectrum.

6.3 The procedures used in this method neglect the possible nonlocality of energy deposition by secondary electrons but do correct for production of bremsstrahlung by secondary electrons. For the energy range specified in this practice, these considerations contribute about 5 % or less to the overall uncertainty.

7. Keywords

7.1 calculation of absorbed dose; charged particle equilibrium; radiation dosimetry

APPENDICES

(Nonmandatory Information)

X1. CHARGED PARTICLE EQUILIBRIUM THICKNESS

X1.1 Whenever a material is irradiated with X or gamma rays, there is initially an increase in energy absorption as the radiation penetrates the material. After some finite thickness, the radiation energy absorption reaches a maximum and then decreases. The thickness necessary to reach the maximum energy deposition is commonly called the “charged particle equilibrium” thickness and is a function of the radiation energy and the mass energy absorption coefficient of the material being irradiated.

X1.2 Fig. X1.1 is a typical plot of energy deposition as a function of depth in a material. The absorbed dose of 0.85 is used for illustration purposes only. Each source and absorbing material combination will have its own characteristic curve. Whenever a specimen is irradiated from all sides, it is necessary to surround the specimen with an absorber in order to ensure charged particle equilibrium throughout the speci-

men. However, when a specimen is irradiated unidirectionally, approximate charged particle equilibrium can be achieved by placing absorbers only in contact with the front and back surfaces of the specimen.

X1.3 In some instances, the equilibrium thickness should be taken to be equal to the practical range, R_p , of the maximum energy secondary electrons. For aluminum, R_p , in $\text{g}\cdot\text{cm}^{-2}$ can be calculated from the following equation taken from ICRU Report 21:

$$R_p = 0.530 E_o - 0.106 \quad (X1.1)$$

where E_o is the energy in MeV of the maximum energy secondary electrons generated by the photons from the source. The value of equilibrium thickness determined by this method is greater than that described in X1.1 and X1.2. (See Appendix X3 of Practice E 666 for a detailed discussion of the conditions for applying each method.)

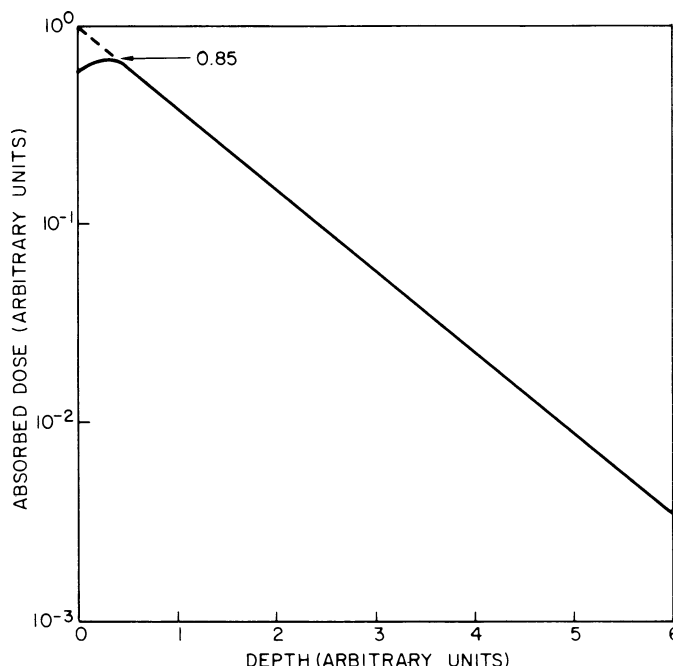


FIG. X1.1 Typical Absorbed Dose versus Depth in a Material

X2. SAMPLE CALCULATION OF ABSORBED DOSE FOR BROAD PHOTON ENERGY SPECTRA

X2.1 To illustrate this method, a sample calculation is presented here. It is based on the following assumptions:

X2.1.1 A properly used silicon dosimeter has measured the output from a flash X-ray machine to be 15 Gy (1.5×10^3 rad) at a specific location.

NOTE X2.1—Gy symbolizes gray which is the SI unit for absorbed dose. One gray = one joule per kilogram. (See Practice E 380.) The old unit of absorbed dose was the rad. 1 Gy = 100 rad.

X2.1.2 The output X-ray spectrum from the machine varies as $1/E$ from 100 keV to 1 MeV as shown in Fig. X2.1, where E is the photon energy. The output photon fluence of the flash

X-ray machine is shown in Fig. X2.1 to be normalized to the photon energy in keV at the point of measurement and the input energy to the machine in joules. Therefore, the units of the arbitrary scale of the abscissa are photons $\text{cm}^{-2} \cdot \text{keV}^{-1} \cdot \text{J}^{-1}$.

X2.2 Since the quantity of interest is the absorbed dose, the normalized output energy fluence is required rather than photon fluence. The normalized energy fluence for each energy interval can be obtained by multiplying the normalized photon fluence in Fig. X2.1 by the corresponding value of the photon energy per energy interval. The results are shown in Fig. X2.2, where the normalized energy fluence has a constant value equal to $100 \text{ keV} \cdot \text{cm}^{-2} \cdot \text{keV}^{-1} \cdot \text{J}^{-1}$ over the entire energy range.

X2.3 At this point, consider the dosimeter that is calibrated in terms of absorbed dose in silicon and is contained in a layer

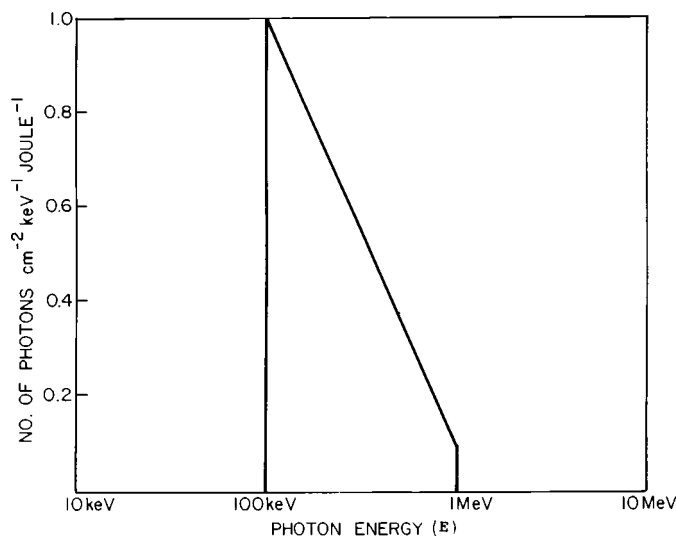


FIG. X2.1 Assumed Number-Energy Spectrum of X Rays from a Flash Machine

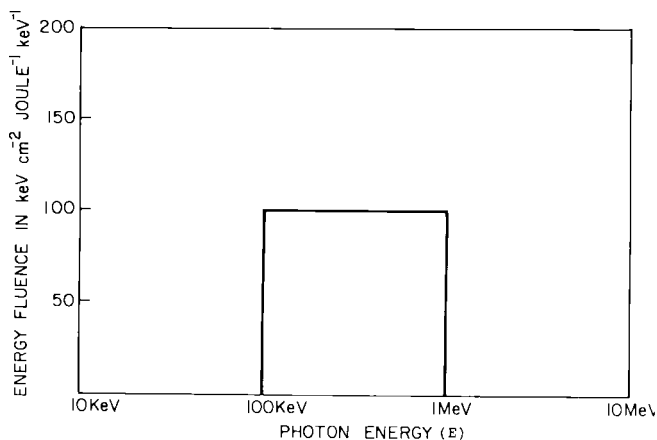


FIG. X2.2 Assumed Energy Fluence Spectrum of X Rays from a Flash Machine