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Standard Terminology Relating to Radiation Measurements and Dosimetry[1]

This standard is issued under the fixed designation E 170; 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.

INTRODUCTION

This terminology generally covers terms that apply to radiation measurements and dosimetry associated with energy deposition and radiation effects, or damage, in materials caused by interactions by high-energy radiation fields. The common radiation fields considered are X-rays, gamma rays, electrons, alpha particles, neutrons, and mixtures of these fields. This treatment is not intended to be exhaustive but reflects special and common terms used in technology and applications of interest to Committee E10, as for example, in areas of radiation effects on components of nuclear power reactors, radiation hardness testing of electronics, and radiation processing of materials.

This terminology uses recommended definitions and concepts of quantities, with units, for radiation measurements as contained in the International Commission on Radiation Units and Measurements (ICRU) Report 60 on "Fundamental Quantities and Units for Ionizing Radiation," December 30, 1998.[2] Those terms that are defined essentially according to the terminology of ICRU Report 60 will be followed by ICRU in parentheses. It should also be noted that the units for quantities used are the latest adopted according to the International System of Units (SI) which are contained in Appendix X1 as taken from a table in ICRU Report 33.[2] This terminology also uses recommended definitions of two ISO documents[3], namely "International Vocabulary of Basic and General Terms in Metrology." (VIM, 1993) and "Guide to the Expression of Uncertainty in Measurement" (GUM, 1995). Those terms that are defined essentially according to the terminology of these documents will be followed by either VIM or GUM in parentheses.

1. Referenced Documents

1.1 *ASTM Standards:*[4]

E 380 Practice for the Use of the International System of Units (SI) (The Modernized Metric System)[5]

E 456 Terminology Relating to Quality and Statistics

E 706 Master Matrix for Light-Water Reactor Pressure Vessel Surveillance Standards, E 706(0)

E 722 Practice for Characterizing Neutron Energy Fluence Spectra in Terms of an Equivalent Monoenergetic Neutron Fluence for Radiation-Hardness Testing of Electronics

E 910 Test Method for Application and Analysis of Helium Accumulation Fluence Monitors for Reactor Vessel Surveillance, E706 (IIIC)

1.2 *ISO Standards:*[3]

GUM Guide to the Expression of Uncertainty in Measurement, ISO 1995

VIM International Vocabulary of Basic and General Terms in Metrology, ISO 1993

1.3 *ICRU Documents:*[2]

ICRU 33 Radiation Quantities and Units

ICRU 60 Fundamental Quantities and Units for Ionizing Radiation, December 30, 1998

[1] This terminology is under the jurisdiction of ASTM Committee E10 on Nuclear Technology and Applications and is the direct responsibility of Subcommittee E10.93 on Editorial.

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[2] ICRU Report 33 has been superceded by ICRU Report 60 on "Fundamental Quantities and Units for Ionizing Radiation," December 30, 1998. Both of these documents are available from International Commission on Radiation Units and Measurements (ICRU), 7910 Woodmont Ave., Suite 800, Bethesda, MD 20814.

[3] Available from International Organization for Standardization (ISO), 1 Rue de Varembe, Case Postale 56, CH-1211, Geneva 20, Switzerland, http://www.iso.ch.

[4] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[5] Withdrawn.

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1.4 *NIST Document:*[6]

NIST Technical Note 1297 Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results, 1994

2. Terminology

absorbed dose (D)—Quantity of ionizing radiation energy imparted per unit mass of a specified material. The SI unit of absorbed dose is the gray (Gy), where 1 gray is equivalent to the absorption of 1 joule per kilogram of the specified material (1 Gy = 1 J/kg). The mathematical relationship is the quotient of $d\bar{\varepsilon}$ by dm, where $d\bar{\varepsilon}$ is the mean incremental energy imparted by ionizing radiation to matter of incremental mass dm. (ICRU)

$$D = d\bar{\varepsilon} / dm \quad (1)$$

Discussion— The discontinued unit for absorbed dose is the rad (1 rad = 100 erg/g = 0.01 Gy). Absorbed dose is sometimes referred to simply as dose. For a photon source under conditions of charged particle equilibrium, the absorbed dose, D, may be expressed as follows:

$$D = \Phi \cdot E \cdot \mu_{en}/\rho, \quad (2)$$

where:

Φ = **particle fluence** (particles/m ^{2}),
E = energy of the ionizing radiation (J), and
μ_{en}/ρ = **mass energy absorption coefficient** (m^2/kg).

If bremsstrahlung production within the specified material is negligible, the mass energy absorption coefficient (μ_{en}/ρ) is equal to the mass energy transfer coefficient (μ_{tr}/ρ), and absorbed dose is equal to kerma if, in addition, charged particle equilibrium exists.

absorbed dose rate, $\dot{D}$—the absorbed dose in a material per incremental time interval, that is, the quotient of d D by d t (see ICRU Report 33).

$$\dot{D} = dD/dt \quad (3)$$

SI unit: $Gy \cdot s^{-1}$.

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Discussion—The absorbed-dose rate is often specified in terms of the average value of D over longer time intervals, for example, in units of $Gy \cdot min^{-1}$ or $Gy \cdot h^{-1}$.

accuracy—the closeness of agreement between a measurement result and an accepted reference value (see Terminology E 456).

activation cross section—the cross section for processes in which the product nucleus is radioactive (see **cross section**).

activity, *A*—of an amount of radioactive nuclide in a particular energy state at a given time, the quotient of dN by dt, where dN is the expectation value of the number of spontaneous nuclear transitions from that energy state in the time interval dt (ICRU).

$$A = dN/dt \quad (4)$$

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Unit: s^{-1}

The special name for the unit of activity is the becquerel (Bq).

$$1\ Bq = 1\ s^{-1} \quad (5)$$

Discussion—The former special unit of activity was the curie (Ci).

$$1\ Ci = 3.7 \times 10^{10}\ s^{-1}\ (\text{exactly}) . \quad (6)$$

The "particular energy state" is the ground state of the nuclide unless otherwise specified. The activity of an amount of radioactive nuclide in a particular energy state is equal to the product of the decay constant for that state and the number of nuclei in that state (that is, $A = N\lambda$). (See **decay constant**.)

analysis bandwidth—spectral band used in a photometric instrument, such as a densitometer, for the measurement of optical absorbance or reflectance.

analysis wavelength—wavelength used in a spectrophotometric instrument for the measurement of optical absorbance or reflectance.

annihilation radiation—gamma radiation produced by the annihilation of a positron and an electron. For particles at rest, two photons are produced, each having an energy corresponding to the rest mass of an electron (511 keV).

backscatter peak—a peak in the observed photon spectrum (normally below about 0.25 MeV) resulting from large-angle (>110°) Compton scattering of gamma rays from materials near the detector. This peak will not have the same shape as the full-energy peaks (being wider and skewed toward lower energy).

benchmark neutron field—a well-characterized neutron field which will provide a fluence of neutrons for validation or calibration of experimental techniques and methods and for validation of cross sections and other nuclear data. The following classification of benchmark neutron fields for reactor dosimetry has been made:[7]

[6] Available from National Institute of Standards and Technology (NIST), 100 Bureau Dr., Stop 1070, Gaithersburg, MD 20899-1070, USA, http://www.nist.gov

[7] *Neutron Cross Sections for Reactor Dosimetry*, International Atomic Energy Agency, Laboratory Activities, Vienna, 1978, Vol 1, p. 62.

controlled neutron field—a neutron field physically well-defined, and with some spectrum definition, employed for a restricted set of validation experiments.

reference neutron field—a permanent and reproducible neutron field less well characterized than a standard field but accepted as a measurement reference by a community of users.

standard neutron field—a permanent and reproducible neutron field with neutron fluence rate and energy spectra, and their associated spatial and angular distributions characterized to state-of-the-art accuracy. Important field quantities must be verified by interlaboratory measurements and calculations.

buildup factor—for radiation passing through a medium, the ratio of the total value of a specified radiation quantity (such as absorbed dose) at any point in that medium to the contribution to that quantity from the incident uncollided radiation reaching that point.

cadmium ratio—the ratio of the neutron reaction rate measured with a given bare neutron detector to the neutron reaction rate measured with an identical neutron detector enclosed by a particular cadmium cover and exposed in the same neutron field at the same or an equivalent spatial location.

Discussion—In practice, meaningful experimental values can be obtained in an isotropic neutron field by using a cadmium filter approximately 1 mm thick.

calibrated instrument—an instrument for which the response has been documented upon being directly compared with the response of a standard instrument, both having been exposed to the same radiation field under the same conditions; or one for which the response has been documented upon being exposed to a standard radiation field under well-defined conditions.

calibration source or field—see **electron standard field, γ-ray standard field,** and **X-ray standard field.**

calorimeter—an instrument capable of making absolute measurements of energy deposition (or absorbed dose) in a material through measurement of its change in temperature and a knowledge of the characteristics of its material construction.

certified reference material—a material that has been characterized by a recognized standard or testing laboratory, for some of its chemical or physical properties, and that is generally used for calibration of a measurement system, or for development or evaluation of a measurement method.

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Discussion—Certification of a reference material can be obtained by one of the following three established routes of measurement of properties: (*1*) using a previously validated reference method; (*2*) using two or more independent, reliable measurement methods; and (*3*) using an *ad hoc* network of cooperating laboratories, technically competent, and thoroughly knowledgeable with the materials being tested. The certified reference materials provided by the United States National Institute of Standards and Technology are called Standard Reference Materials.

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charged particle equilibrium—a condition that exists in an incremental volume within a material under irradiation if the kinetic energies and number of charged particles (of each type) entering that volume are equal to those leaving that volume.

Discussion—When electrons are the predominatnt charged particle, the term "electron equilibrium" is often used to describe charged particle equilibrium. See also the discussions attached to the definitions of kerma and absorbed dose in E 170.

coincidence sum peak—a peak in the observed photon spectrum produced at an energy corresponding to the sum of the energies of two or more gamma- or x-rays from a single nuclear event when the emitted photons interact with the detector within the resolving time of the detector.

Compton edge (E_c)—the maximum energy value of electrons of the Compton scattering continuum. The energy value of the Compton edge is

$$E_c = E_\gamma - \frac{E_\gamma}{1 + \frac{2E_\gamma}{0.511}} \tag{7}$$

which corresponds to 180° scattering of the primary photon of energy E_γ (MeV). For a 1 MeV photon, the Compton edge is about 0.8 MeV.

Compton scattering—elastic scattering of a photon by an atomic electron, under the condition of conservation of momentum, that is, the vector sum of the momenta of the outgoing electron and photon is equal to the momentum of the incident photon. The scattered photon energy, E'_γ, is given by

$$E'_\gamma = \frac{E_\gamma}{1 + \frac{E_\gamma (1 - \cos\theta)}{0.511}} \tag{8}$$

where E_γ is the incident photon energy in MeV and θ is the angle between the direction of the primary and scattered photon. The electron energy, E_e, is equal to $E_\gamma - E'_\gamma$.

continuum—the smooth distribution of energy deposited in a gamma detector arising from partial energy absorption from Compton scattering or other processes (for example, Bremsstrahlung). See **Compton scattering.**

cross section, σ—the quotient of *P* by Φ, where *P* is the probability of the interaction for one target entity when subjected to the particle fluence Φ (ICRU).

$$\sigma = P/\Phi \quad (9)$$

Unit: m^2

The special unit of cross section is the barn, *b*.

$$1\ b = 10^{-28}\ m^2 \quad (10)$$

decay constant, λ—of a radioactive nuclide in a particular energy state, the quotient of d *P* by d*t*, where d*P* is the probability of a given nucleus undergoing a spontaneous nuclear transition from that energy state in the time interval d*t* (ICRU).

$$\lambda = dP/dt \quad (11)$$

Unit: s^{-1}

DISCUSSION—The quantity (ln 2)/λ is commonly called the half-life, $T½$, of the radioactive nuclide, that is, the time taken for the activity of an amount of radioactive nuclide to become half its initial value.

depth-dose distribution—variation of absorbed dose with depth from the incident surface of a material exposed to a given radiation.

displacement dose (D_d)—the quotient of d $\bar{\varepsilon}_d$ by d*m*, where d $\bar{\varepsilon}_d$ is that part of the mean energy imparted by radiation to matter which produces atomic displacements (that is, excluding the part that produces ionization and excitation of electrons) in a volume element of mass d *m*.

$$D_d = d\,\bar{\varepsilon}_d/dm \quad (12)$$

Unit: $J \cdot kg^{-1}$

DISCUSSION—A more common unit is **displacements per atom (dpa)**, (see definition).

displacements per atom (dpa)—the mean number of times each atom of a solid is displaced from its lattice site during an exposure to displacing radiation, as calculated following standard procedures (see **displacement dose**).

dosimeter—a device that, when irradiated, exhibits a quantifiable change that can be related to absorbed dose in a given material using appropriate measurement instrument(s) and procedures.

dosimetry system—a system used for determining absorbed dose, consisting of dosimeters, measurement instruments and their associated reference standards, and procedures for the system's use.

effective cadmium cut-off energy (E_c)—the energy at which a specified cadmium container performs like a theoretically perfect filter and, therefore, has the following properties:

(1) for all energies below E_c, no neutron reactions occur, and

(2) for all energies above E_c, neutron reactions occur at the same rate as if the cadmium were not present.

DISCUSSION—E_c varies with cadmium thickness, geometry of the container, angular distribution of incident neutrons, and ambient temperature.

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efficiency—see **total efficiency** and **full-energy peak efficiency.**

electron equilibrium—charged-particle equilibrium for electrons.

electron standard field—an electron field whose particle energy and direction, spatial uniformity, and particle fluence rate uniformity are well established and reproducible.

energy calibration—a process of establishing the relationship between photon or particle energy and channel number in the spectrometer. The energy calibration may be as simple as building a table of two or more energy-channel pairs or as complex as using a least squares algorithm to establish a function describing the energy versus channel relationship.

epithermal neutrons—a general classification of neutrons with energies above those of thermal neutrons; or frequently, neutrons with energies in the resonance range, between the thermal limit and some upper limit, such as 0.1 MeV (see **thermal neutrons**).

DISCUSSION—The term "epithermal neutrons" is generally used in thermal neutron systems when two groups of neutrons are considered. The term is not used to describe high energy neutrons in other types of systems such as fast or fusion reactors.

equivalent fission fluence—the fluence of fission spectrum neutrons that would give a detector or material response for a particular reaction equal to that in a given neutron field.

equivalent 2200 m/s fluence, Φ_o—a measure of the thermal neutron fluence made with a l/v detector and using the 2200 m/s cross section.

$$\Phi_o = n\, v_o\, t \quad (13)$$

where:

n = neutron density,
v_o = 2200 m/s, and
t = exposure time of the detector.

equivalent monoenergetic neutron fluence, $\Phi_{eq}(E_o)$—characterizes an incident energy fluence spectrum, $\Phi(E)$, in terms of the fluence of monoenergetic neutrons at a specific energy, E_o, required to produce the same displacement kerma, K_o, in a specific material (for example, silicon) as Φ (E).

DISCUSSION—In applying this definition, total kerma is divided into two parts, ionization and displacement kerma (see Practice E 722).

escape or pair production peak—a peak in a gamma ray spectrum resulting from the pair production process within the detector, annihilation of the positron produced, and escape from the detector of one or more of the annihilation photons (see **pair production** and **annihilation radiation**).

single escape peak—the gamma ray spectrum peak corresponding to escape of one of the annihilation photons from the active volume of the detector. The energy of the single escape peak is equal to the original gamma ray energy minus 511 keV.

double escape peak—the gamma ray spectrum peak corresponding to escape of both of the annihilation photons from the active volume of the detector. The energy of the double escape peak is equal to the original gamma ray energy minus 1.022 MeV.

exposure, X—the quotient of dQ by dm, where the value of dQ is the absolute value of the total charge of the ions of one sign produced in air when all the electrons (negatrons and positrons) liberated by photons in air of mass dm are completely stopped in air (ICRU).

$$X = \mathrm{d}Q/\mathrm{d}m \quad (14)$$

Unit: $C \cdot kg^{-1}$

DISCUSSION—Formerly, the special unit of exposure was the röntgen (R).

$$1\ \mathrm{R} = 2.58 \times 10^{-4}\ \mathrm{C \cdot kg^{-1}}\ \text{(exactly)} \quad (15)$$

exposure rate, $\dot{\mathbf{X}}$**—**the quotient of dX by dt, where d X is the increment of exposure in the time interval, d t (ICRU).

$$X = \mathrm{d}X/\mathrm{d}t \quad (16)$$

Unit: $C \cdot kg^{-1}\ s^{-1}$

fast neutrons—a term for designating neutrons of energy exceeding some threshold that must be specified (typically 0.1 or 1 MeV); often associated with those neutrons predominantly responsible for displacement damage of materials in neutron radiation fields.

ferrous sulfate—cupric sulfate dosimeter—a liquid chemical radiation dosimetry system composed of water with ferrous sulfate or ferrous-ammonium sulfate and cupric sulfate in aqueous sulfuric acid solution and whose response is based quantitatively on the amount of oxidation of ferrous to ferric ions by ionizing radiation, as analyzed by spectrophotometry. It is considered to be a reference standard dosimeter.

fission chamber—an ionization chamber containing one or more surfaces coated with fissionable material.

Fricke dosimetry system—consists of a liquid chemical dosimeter (composed of ferrous sulfate or ferrous ammonium sulfate in aqueous sulfuric acid solution), a spectrophotometer (to measure optical absorbance) and its associated reference standards, and procedures for its use.

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DISCUSSION—

(1) It is considered to be a reference-standard dosimetry system.
(2) Sodium chloride is usually added to dosimetric solution to minimize the effects of organic impurities.

full-energy peak—the peak in an energy spectrum recorded by a photon detector that occurs when the full energy of an incident photon is absorbed by the detector. This is sometimes referred to as the photopeak.

full-energy peak efficiency—the ratio of the net count rate in the full-energy peak to the emission rate of the photons from a sample giving rise to the peak. The value is dependent on the source-detector-shield geometry and the photon energy. This is sometimes referred to as the photopeak efficiency.

gamma-ray standard field—a gamma ray field produced by a particular radioactive nuclide (such as ^{60}Co) that is well established and reproducible as to the absorbed dose rate produced in a specific material at a designated location within the field at any given time.

*G value***—**see **radiation chemical yield.**

*half-life***—**see **decay constant.**

helium accumulation fluence monitor (HAFM)— a passive neutron dosimeter whose measured reaction product is helium. The neutron fluence is obtained by dividing the helium concentration by the spectrum-averaged cross section (see **spectrum-averaged cross section**). (See also Test Method E 910 and ASTM Master Matrix E 706)

influence quantity—quantity that is not the measurand but that affects the result of the measurement (VIM).

instrument traceability—the ability to demonstrate that a particular measuring instrument or artifact standard has been calibrated at acceptable time intervals against a national or international standard or against a secondary standard which has been in turn calibrated against the national standard or transfer standard.

integral neutron fluence—the fluence of neutrons integrated over all energies.

$$\Phi = \int_0^\infty \Phi(E)\, \mathrm{d}E \quad (17)$$

ionization—a process in which a charged particle is created from a parent atom or molecule or other bound state.

ionizing radiation—any type of radiation consisting of *charged* particles or *uncharged* particles, or both, that as a result of physical interaction, creates ions by either primary or secondary processes. (For example, *charged* particles could be positrons or electrons, protons, or other heavy ions, and *uncharged* particles could be X rays, gamma rays, or neutrons.)

kerma, K—the quotient of dE_{tr} by d m, where dE_{tr} is the sum of the initial kinetic energies of all the charged ~~ionizing~~ particles liberated by uncharged ~~ionizing~~ particles in a ~~material of~~ mass dm ~~(ICRU).~~ of material (ICRU).

$$K = dE_{tr}/dm \tag{18}$$

The special name of the unit of kerma is the gray (Gy).

$$1\ Gy = 1\ J \cdot kg^{-1} \tag{19}$$

Discussion—For uncharged ~~ionizing~~ radiation of energy E (excluding rest energy), the kerma, K, may also be written as:

$$K = \Phi\left[E\left(\frac{\mu_{tr}}{\rho}\right)\right] \tag{20}$$

where:

μ_{tr}/ρ = mass energy transfer coefficient and the term

$$\left[E\left(\frac{\mu_{tr}}{\rho}\right)\right] \tag{21}$$

is called the kerma factor. Φ is the **particle fluence** (see definition).

Since E_{tr} is the sum of the kinetic energies of charged ionizing particles liberated by the uncharged ionizing particles, it also includes the energy that these particles radiate in bremsstrahlung (ICRU).

It may often be convenient to refer to a value of kerma or kerma rate for a specified material in free space, or inside a different material. In such a case, the value will be that which would be obtained if a small quantity of specified material were placed at the point of interest.

For the purpose of dosimetry it may be convenient to describe the field of indirectly ionizing particles in terms of kerma rate for a suitable material.

For measurements of kerma, the mass element should be so small that its introduction does not appreciably disturb the field of uncharged ionizing particles; however, if this is not so, appropriate corrections must be applied.

Equality of absorbed dose and kerma is approached to the degree that charged particle equilibrium exists and bremsstrahlung is negligible.

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mass energy-absorption coefficient, μ_{en}/ρ—*of a material for uncharged ionizing particles*, the product of the mass energy transfer coefficient, μ_{tr}/ρ, and (1- g), where g is the fraction of the energy of secondary charged particles that is lost to bremsstrahlung in the material (ICRU).

$$(\mu_{en}/\rho) = (\mu_{tr}/\rho)(1 - g) \tag{22}$$

Unit: $m^2 \cdot kg^{-1}$

mass energy-transfer coefficient (μ_{tr}/ρ)—*of a material for uncharged ionizing particles*, the quotient of d E_{tr}/EN by ρdl, where E is the energy of each particle (excluding rest energy), N is the number of particles, and dE_{tr}/EN is the fraction of incident particle energy that is transferred to kinetic energy of charged particles by interactions in transversing a distance dl in the material of density ρ (ICRU).

$$(\mu_{tr}/\rho) = 1/\rho EN \cdot dE_{tr}/dl \tag{23}$$

Unit: $m^2 \cdot kg^{-1}$

mass stopping power, S/ρ—*of a material for charged particles*, the quotient of dE by ρ dl , where dE is the energy lost by a charged particle in traversing a distance, dl, in the material of density ρ (ICRU).

$$S/\rho = (1/\rho)\ dE/dl \tag{24}$$

Unit : $J \cdot m^2 \cdot kg^{-1}$
($eV \cdot m^2 \cdot kg^{-1}$ is also used).

Discussion—S is the linear stopping power. For energies at which nuclear interactions can be neglected, the mass stopping power is

$$S/\rho = 1/\rho\ (dE/dl)_{col} + 1/\rho\ (dE/dl)_{rad} \tag{25}$$

where:

$(dE/dl)_{col} = S_{col}$ = the linear collision stopping power
$(dE/dl)_{rad} = S_{rad}$ = the linear radiative stopping power.

measurand—specific quantity subject to measurement (VIM).

measurement quality assurance plan—a documented program for the measurement process that ensures that the expanded