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Standard Terminology Relating to Radiation Measurements and Dosimetry[1]

This standard is issued under the fixed designation E170; 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 85a on "Fundamental Quantities and Units for Ionizing Radiation," October 2011.[2] Those terms that are defined essentially according to the terminology of ICRU Report 85a 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 85a.[2] This terminology also uses recommended definitions of two JCGM documents,[3] namely "International vocabulary of metrology" (VIM, 2012, unless indicated otherwise) and "Guide to the expression of uncertainty in measurement" (GUM, 2008). Those terms that are defined essentially according to the terminology of these documents will be followed by either VIM or GUM in parentheses.

A term is boldfaced when it is defined in this standard. For some terms, text in italics is used just before the definition to limit its field of application, for example, see **activity**.

1. Referenced Documents

1.1 *ASTM Standards:*[4]

E380 Practice for Use of the International System of Units (SI) (the Modernized Metric System) (Withdrawn 1997)[5]

E722 Practice for Characterizing Neutron Fluence Spectra in Terms of an Equivalent Monoenergetic Neutron Fluence for Radiation-Hardness Testing of Electronics

E910 Test Method for Application and Analysis of Helium Accumulation Fluence Monitors for Reactor Vessel Surveillance, E706 (IIIC)

1.2 *Joint Committee for Guides in Metrology (JCGM) Reports:*[3]

JCGM 100:2008, GUM 1995 , with minor corrections, Evaluation of measurement data – Guide to the expression of uncertainty in measurement

JCGM 200:2012, VIM International vocabulary of metrology – Basic and general concepts and associated terms

[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 60 has been superseded by ICRU Report 85a on "Fundamental Quantities and Units for Ionizing Radiation," October 2011. Both of these documents are available from International Commission on Radiation Units and Measurements (ICRU), 7910 Woodmont Ave., Suite 800, Bethesda, MD 20814.

[3] Document produced by Working Groups of the Joint Committee for Guides in Metrology (JCGM). Available free of charge at BIPM website (http://www.bipm.org).

[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] The last approved version of this historical standard is referenced on www.astm.org.

1.3 *ICRU Documents:*[2]

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

ICRU 85a Fundamental Quantities and Units for Ionizing Radiation, October, 2011

1.4 *NIST Document:*[6]

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

1.5 *ISO Standard:*[7]

ISO 10012 Measurement management systems – Requirements for measurement processes and measuring equipment

2. Terminology

absorbed dose (*D*)**—**quotient of $d\bar{\varepsilon}$ by d*m*, where $d\bar{\varepsilon}$ is the mean incremental energy imparted by ionizing radiation to matter of incremental mass d*m*. (ICRU), thus

$$D = d\bar{\varepsilon}/dm \tag{1}$$

DISCUSSION—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 unit rad (1 rad = 100 erg/g = 0.01 Gy) is still widely used in the nuclear community; however, its continued use is not encouraged. For a photon source under conditions of charged particle equilibrium, the absorbed dose, *D*, may be expressed as follows:

$$D = \Phi \cdot E \cdot \mu_{en}/\rho, \tag{2}$$

where:

Φ = **fluence** (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 ($\dot{D}$)—quotient of d*D* by d*t* where d*D* is the increment of absorbed dose in the time interval d*t* (ICRU), thus

$$\dot{D} = dD/dt \tag{3}$$

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

DISCUSSION—The absorbed-dose rate is often specified as an average value over a longer time interval, for example, in units of $Gy \cdot min^{-1}$ or $Gy \cdot h^{-1}$.

accuracy—closeness of agreement between a measured **quantity value** and a true quantity value of a **measurand** (VIM).

DISCUSSION—

(1) The concept "accuracy" is not a quantity and is not given a numerical quantity value. A measurement is said to be more accurate when it offers a smaller measurement error.

(2) The term "accuracy" should not be used for measurement trueness and the term "**precision**" should not be used for "accuracy," which, however, is related to both these concepts.

(3) "Accuracy" is sometimes understood as closeness of agreement between measured quantity values that are being attributed to the measurand.

activation cross section—cross section for a specific direct or compound nuclear interaction in which the product nucleus is radioactive.

DISCUSSION—Fission and spallation processes produce a statistical ensemble of outgoing nuclear channels, but they are not considered to be activation reactions.

activity ***(A)—of an amount of radionuclide in a particular energy state at a given time***, quotient of –d*N* by d*t*, where d*N* is the mean change in the number of nuclei in that energy state due to spontaneous nuclear transformations in the time interval d*t* (ICRU), thus

$$A = -dN/dt \tag{4}$$

Unit: s^{-1}

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

$$1\ Bq = 1\ s^{-1} \tag{5}$$

DISCUSSION—The former special unit of activity was the curie (Ci), where

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

The negative sign in Eq 4 is an indication that the activity is decreasing with time. The "particular energy state" is the ground state of the nuclide unless otherwise specified. The activity of an amount of radionuclide 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**.)

aleatory uncertainty—uncertainty representing random uncertainty contributors where there is little possibility of reducing this uncertainty contributor by consideration of a more controlled scenario.

DISCUSSION—

(1) One paradigm decomposes uncertainty into epistemic and aleatory components. This division of uncertainty categories is very dependent upon what question is being posed in a given application. Aleatory uncertainties can be transformed into epistemic uncertainties depending upon the application. The uncertainties underlying a quantity may be classified as aleatory or epistemic according to the goals of the process.

(2) Aleatory uncertainty, also referred to as variability, stochastic uncertainty or irreducible uncertainty, is used to describe inherent variation associated with a quantity or phenomenon of interest. The determination of material properties or operating conditions of a physical system typically leads to aleatory uncertainties; additional experimental characterization might provide more conclusive description of the variability but cannot eliminate it completely. Aleatory uncertainty is normally characterized using probabilistic approaches.

analysis bandwidth—spectral band used in an instrument, such as a densitometer, for a measurement.

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.

[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] Available from International Organization for Standardization (ISO), ISO Central Secretariat, BIBC II, Chemin de Blandonnet 8, CP 401, 1214 Vernier, Geneva, Switzerland, http://www.iso.org.

Discussion—For particles at rest, two photons are produced, each having an energy corresponding to the rest mass of an electron (511 keV).

backscatter peak—peak in the observed photon spectrum resulting from large-angle (>110°) Compton scattering of gamma rays from materials near the detector.

Discussion—This peak is normally below about 0.25 MeV. Also, it will not have the same shape as the full-energy peaks (being wider and skewed toward lower energy).

benchmark neutron field—well-characterized irradiation environment which provides a fluence or fluence rate of neutrons suitable for the validation or calibration of experimental techniques and methods as well as for validation of cross sections and other nuclear data, where following classification for reactor dosimetry has been made:[8]

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

reference neutron field—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—permanent and reproducible neutron field that is characterized to state-of-the-art accuracy in terms of neutron fluence rate and energy spectra, and their associated spatial and angular distributions, where important field quantities need to be verified by interlaboratory measurements.

Discussion—A type of neutron field is considered to be a "standard" over a specified energy range and there is only one type of "standard neutron field" for a given energy range. Currently, the ^{252}Cf spontaneous fission field is a "standard neutron field" from 0.5 MeV to 8 MeV. The deuterium-tritium (DT) accelerator field is considered to be the "standard neutron field" from 13.5 to 15 MeV. The thermal Maxwellian and epithermal 1/E slowing-down field are also considered to be "standard neutron fields."

bremsstrahlung—broad-spectrum electromagnetic radiation emitted when an energetic charged particle is influenced by a strong electric field, such as the Coulomb field of an atomic nucleus.

Discussion—In radiation processing, bremsstrahlung photons are generated by the deceleration or deflection of energetic electrons in a target material. When an electron passes close to an atomic nucleus, the strong Coulomb field causes the electron to deviate from its original motion. This interaction results in a loss of kinetic energy by the electron with the emission of electromagnetic radiation; the photon energy distribution extends up to the maximum kinetic energy of the incident electron. This bremsstrahlung spectrum depends on the electron energy, the composition and thickness of the target, and the angle of emission with respect to the incident electron.

buildup factor—*for radiation passing through a medium*, 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.

[8] The following three definitions are derived from: *Neutron Cross Sections for Reactor Dosimetry*, International Atomic Energy Agency, Laboratory Activities, Vienna, Vol 1, 1978, p. 62 and Vlasov, M., IAEA Program on Benchmark Neutron Fields Applications for Reactor Dosimetry, Report INDC(SEC)-54/L+Dos, IAEA, Vienna, 1976.

cadmium ratio—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—instrument that has been through a **calibration** process at established time intervals.

Discussion—Measurements carried out by this instrument have metrological traceability to the reference standard if calibration is properly carried out.

calibration—set of operations that establish, under specified conditions, the relationship between values of quantities indicated by a measuring instrument or measuring system, or values represented by a material measure or a reference material, and the corresponding values realized by standards (VIM: 1993).

Discussion—

(1) Calibration conditions include environmental and irradiation conditions present during calibration.

(2) These standards should have metrological traceability to a national or international standard.

(3) To be reliable, calibration should be carried out at regular time intervals – frequency may depend on the final use of the data. Often, the frequency is specified by regulatory authorities.

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

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

Discussion—Calorimeter is generally designated as a **primary-standard dosimeter**.

certified reference material (CRM)—reference material, accompanied by documentation issued by an authoritative body and providing one or more specified property values with associated uncertainties and traceabilities, using valid procedures (VIM).

Discussion—"Certified reference material" should be differentiated from "Standard Reference Material" which is a National Institute of Standards and Technology (NIST) trademarked nomenclature.

charged particle equilibrium—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 predominant 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**.

coincidence sum peak—*for gamma spectroscopy*, 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 measurement system.

combined standard uncertainty—standard uncertainty that is obtained using the individual standard uncertainties associated with the input quantities in a measurement model (VIM).

DISCUSSION—In case of correlations of input quantities contributing to the resulting uncertainty, covariances must also be taken into account when calculating the combined standard uncertainty.

Compton edge (E_c)—maximum energy value of electrons of the Compton scattering continuum, which is given by:

$$E_c = E_\gamma - \frac{E_\gamma}{1 + \frac{2E_\gamma}{0.511}} \quad (7)$$

DISCUSSION—This value 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.

DISCUSSION—The scattered photon energy, E'_γ (in MeV), is given by

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

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

continuum—*for gamma spectroscopy*, 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**.

coverage factor (*k*)—number larger than one by which a **combined standard uncertainty** is multiplied to obtain an **expanded uncertainty** (VIM).

DISCUSSION—Coverage factor is typically in the range of 2 to 3.

cross section (σ)—*of a target entity, for a particular interaction produced by incident charged or uncharged particles of a given type and energy*, quotient of N_{int} by Φ, where N_{int} is the mean number of such interactions per target entity subjected to the **fluence** Φ (adapted from ICRU), thus

$$\sigma = N_{int}/\Phi \quad (9)$$

Unit: m^2

DISCUSSION—The special unit of cross section is the barn, b, where

$$1\ \text{b} = 10^{-28}\ \text{m}^2 = 10^{-24}\ \text{cm}^2 \quad (10)$$

cumulative fission yield—total number of atoms of a specific nuclide produced directly by a fission event and via radioactive decay of the precursors.

DISCUSSION—This definition is from INDC(NDS)-0534.[9] The fission yield (either independent or cumulative) varies with the energy of the neutron that initiates the fission event. The fission yields for a spontaneous fission event are distinct from those for a thermal or fast neutron-induced fission.

decay constant (λ)—*of a radionuclide in a particular energy state*, quotient of $-dN/N$ by d*t*, where dN/N is the mean fractional change in the number of nuclei in that energy state due to spontaneous nuclear transformations in the time interval d*t* (ICRU), thus

$$\lambda = \frac{-dN/N}{dt} \quad (11)$$

Unit: s^{-1}

DISCUSSION—The quantity (ln 2)/*λ* is commonly called the half-life, $T_{½}$, of the radionuclide, that is, the time taken for the activity of an amount of radionuclide 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)—quotient of $d\bar{\varepsilon}_d$ by d*m*, where $d\bar{\varepsilon}_d$ is that part of the mean incremental energy which produces atomic displacements (that is, excluding the energy that produces ionization and excitation of electrons) imparted by radiation to matter of incremental mass d*m*, thus

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

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

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

displacements per atom (dpa)—mean number of times each atom of a solid is displaced from its lattice site during its exposure to radiation.

DISCUSSION—This quantity is calculated from the displacement dose using a dislocation efficiency model such as Kinchin-Pease[10] or Norget-Robinson-Torrens (NRT) model.[11]

displacement threshold energy (E_d)—minimum kinetic energy imparted to a lattice atom to permanently displace it from its initial lattice site.

DISCUSSION—This energy refers to the energy required to create the initial Frenkel pair, that is, a vacancy-interstitial defect pair, and is independent of subsequent defect interaction or thermal recombination effects. This energy can have an angle-dependence and, in polyatomic lattices, can be different for different types of lattice atoms. Displacement threshold energies in typical solids are on the order of 10-50 eV.

dosimeter—device that, when irradiated, exhibits a quantifiable change that can be related to a dosimetric quantity using appropriate measurement instrument(s) and procedures.

DISCUSSION—As discussed in ICRU-85a, dosimetric quantities provide a physical measure to correlate with actual or potential effects. They are products of radiometric quantities and interaction coefficients. In calculations, the values of these quantities and coefficients must be known, while measurements might not require this information. Dosimetric quantities include air **kerma**, **exposure** and **absorbed dose to a specified material**.

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[9] Handbook of Nuclear Data for Safeguards: Database Extensions, August 2008.

[10] Kinchin, G. H., and Pease, R. S., "The Displacement of Atoms in Solids by Radiation," *Reports on Progress in Physics*, Vol 18, 1955, pp. 1-51.

[11] Norgett, M. J., Robinson, M. T., and Torrens, I. M., "A Proposed Method of Calculating Displacement Dose Rates," *Nuclear Engineering and Design*, Vol 33, 1975, pp. 50-54.

dosimetry system—interrelated elements used for determining a dosimetric quantity, including **dosimeters**, measurement instruments and their associated reference standards, and procedures for their use.

DISCUSSION—As discussed in ICRU-85a, dosimetric quantities provide a physical measure to correlate with actual or potential effects. They are products of radiometric quantities and interaction coefficients. In calculations, the values of these quantities and coefficients must be known, while measurements might not require this information. Dosimetric quantities include air **kerma**, **exposure** and **absorbed dose to a specified material**.

effective cadmium cut-off energy (E_{Cd})—energy at which a specified thickness of cadmium results in the same reaction rate in a 1/*v* detector as a perfect filter which has the following properties in a neutron field with a 1/*E* energy dependence of the neutron fluence spectrum:

(1) for all energies below E_{Cd}, no neutrons are present after the filter, and

(2) for all energies above E_{Cd}, neutron reactions after the filter occur at the same rate as if the cadmium were not present.

DISCUSSION—E_{Cd} varies with cadmium thickness used as the filter and geometry, angular distribution of incident neutrons, and ambient temperature. The definition is applicable for detectors whose cross sections do no depart significantly from a 1/*v* dependence in the region of the cut-off energy, and also for neutron fields whose neutron fluence spectrum does not depart significantly from a 1/*E* energy dependence in region of the cut-off energy.

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

electron equilibrium—charged-particle equilibrium for electrons.

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

energy calibration—process of establishing the relationship between photon or particle energy and channel number in the spectrometer.

DISCUSSION—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.

epistemic uncertainty—uncertainty component solely due to a lack of knowledge.

DISCUSSION—

(1) One paradigm decomposes uncertainty into epistemic and aleatory components. This division of uncertainty categories is very dependent upon what question is being posed in a given application. Epistemic uncertainties can be transformed into aleatory uncertainties depending upon the application. The uncertainties underlying a quantity may be classified as aleatory or epistemic according to the goals of the process.

(2) The epistemic component is also called the reducible uncertainty and can arise from assumptions introduced in the derivation of the mathematical model used or simplifications related to the correlation or dependence between physical processes. This epistemic uncertainty has the possibility of being reduced if one can gather more data or refine modeling assumptions. Epistemic uncertainty is not well characterized by probabilistic approaches because it might be difficult to infer any statistical information due to the nominal lack of knowledge.

epithermal neutrons—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—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_w)—measure of the effective thermal neutron fluence made with an ideal l/*v* detector and using the **2200 m/s cross section**, thus

$$\Phi_w = \int_0^{t_i} n(t) v_0 dt \tag{13}$$

where:

$n(t)$ = neutron density, at time *t* after the beginning of the exposure of the detector,
v_0 = 2200 m/s, and
t_i = duration of the exposure of the detector.

DISCUSSION—The equivalent 2200 m/s fluence is often referred to as the Westcott convention fluence, or simply the Westcott fluence.[12] The symbol nv_0t is sometimes used. All neutrons are included in $n(t)$ (not just thermal neutrons). The equivalent 2200 m/s is especially useful when cadmium is not being used.

$$\text{Reactions} = \int_0^\infty \int_0^\infty n(E,t) v \sigma(E) E dt = \int_0^\infty \int_0^\infty n(E,t) v \frac{\sigma_0 v_0}{v} dE dt$$

$$= \int_0^\infty n(t) \sigma_0 v_0 dt = \Phi_w \sigma_0 \tag{14}$$

$\sigma(E)$ may be expressed as $\frac{\sigma_0 v_0}{v}$ for a l/*v* cross section. Φ_w may not be a measured value (that is, made with a 1/*v* detector). It may be a calculated quantity.

equivalent monoenergetic neutron fluence ($\Phi_{eq}(E_o)$)—measure of an incident energy fluence spectrum, $\Phi(E)$, in terms of the fluence of monoenergetic neutrons at a specific energy, E_o, that produces the same displacement kerma, K_D, in a specific material (for example, silicon) as $\Phi(E)$.

DISCUSSION—In applying this definition, total kerma is divided into two parts, ionization and displacement kerma (see Practice E722).

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

[12] Westcott, C. H., Walker, W. H., and Alexander, T. K., "Effective Cross Sections and Cadmium Ratios for the Neutron Spectra of Thermal Reactors," Proceedings of the International Conference on Peaceful Uses of Atomic Energy, United Nations, Vol 16, 1958, p. 70.

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

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

expanded uncertainty—quantity defining an interval about the result of a measurement that may be expected to encompass a large fraction of the distribution of values that could reasonably be attributed to the **measurand** (GUM).

(1) The fractions may be viewed as the coverage probability or level of confidence of the interval.

(2) To associate a specific level of confidence with the interval defined by the expanded uncertainty requires explicit or implicit assumptions regarding the probability distribution characterized by the measurement result and its **combined standard uncertainty**. The level of confidence that may be attributed to this interval can be known only to the extent to which such assumptions may be justified.

(3) Expanded uncertainty is also referred to as overall uncertainty.

exposure *(X)***—**quotient of d*q* by d*m*, where d*q* is the absolute value of the mean total charge of the ions of one sign produced when all electrons and positrons liberated or created by photons incident on a mass d*m* of dry air are completely stopped in dry air (ICRU), thus

$$X = \mathrm{d}q/\mathrm{d}m \tag{15}$$

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

Discussion—Formerly, the special unit of exposure was the röntgen (R), where

$$1\ \mathrm{R} = 2.58 \times 10^{-4}\ \mathrm{C{\cdot}kg^{-1}}\ (\mathrm{exactly}) \tag{16}$$

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

$$\dot{X} = \mathrm{d}X/\mathrm{d}t \tag{17}$$

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

fast neutrons—neutrons of energy exceeding some threshold that must be specified (typically 0.1 or 1 MeV).

Discussion—This term is often associated with those neutrons predominantly responsible for displacement damage of materials in neutron radiation fields.

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

fluence (Φ)—quotient of d*N* by d*a*, where d*N* is the number of particles incident on a sphere of cross-sectional area d*a* (ICRU), thus

$$\Phi = \mathrm{d}N/\mathrm{d}a \tag{18}$$

Unit: m^{-2}

Discussion—In order to distinguish this quantity from the energy fluence, this term is sometimes referred to as "particle fluence." The fluence may also be expressed as the time integral of the fluence rate.

fluence rate (φ)—quotient of d*Φ* by d*t*, where d*Φ* is the increment of fluence in the time interval d*t* (ICRU), thus

$$\varphi = \frac{\mathrm{d}\Phi}{\mathrm{d}t} = \frac{\mathrm{d}^2N}{\mathrm{d}a\,\mathrm{d}t} \tag{19}$$

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

Discussion—In order to distinguish this quantity from the energy fluence rate, this term is sometimes referred to as "particle fluence rate." The term **flux density** may be used but the term fluence rate conforms to the adoption of a uniform set of terms and units as prescribed by ICRU and SI units. Historically, the term *neutron flux* has been understood to mean neutron flux density (fluence rate). This term still is widely used in the nuclear community.

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.

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—*for gamma spectroscopy*, 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.

Discussion—This is sometimes referred to as the photopeak.

full-energy peak efficiency—*for gamma spectroscopy*, 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.

Discussion—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—well-characterized gamma-ray field that is well established and reproducible at a designated location and it used for validation or calibration of experimental techniques and methods.

Discussion—An example is the gamma-ray field produce by ^{60}Co.

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

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

helium accumulation fluence monitor (HAFM)—passive neutron dosimeter where the neutron fluence is obtained by dividing the measured concentration of the reaction product helium by the **spectrum-averaged cross section**. (See Test Method E910).

independent fission yield—number of atoms of a specific nuclide produced directly by a fission event (not via radioactive decay of the precursors).

Discussion—This definition is from INDC (NDS)-0534.[9] The fission yield (either independent or cumulative) varies with the energy of the neutron that initiates the fission event. The fission yields for a spontaneous fission event are distinct from those for a thermal or fast neutron-induced fission.

influence quantity—quantity that, in a direct measurement, does not affect the quantity that is actually measured, but affects the relation between the indication and the measurement result (VIM).

integral neutron fluence—fluence of neutrons integrated over all energies, thus

$$\Phi = \int_0^\infty \Phi(E)\, dE \quad (20)$$

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

ionizing radiation—charged particles (for example, electrons or protons) and uncharged particles (for example, photons or neutrons) that can produce **ionizations** in a medium or can initiate nuclear or elementary-particle transformations that then result in ionization or the production of ionizing radiation. **(ICRU)**

kerma *(K)*—*for ionizing uncharged particles*, quotient of dE_{tr} by dm, where dE_{tr} is the mean sum of the initial kinetic energies of all the charged particles liberated in a mass dm of a material by the uncharged particles incident on dm (ICRU), thus

$$K = dE_{tr}/dm \quad (21)$$

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

$$1\ \text{Gy} = 1\ \text{J}\cdot\text{kg}^{-1} \quad (22)$$

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

$$K = \Phi \left[E \left(\frac{\mu_{tr}}{\rho} \right) \right] \quad (23)$$

where:

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

$$\left[E \left(\frac{\mu_{tr}}{\rho} \right) \right] \quad (24)$$

is called the kerma factor. Φ is the **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.

mass energy-absorption coefficient (μ_{en}/ρ)—*of a material for uncharged ionizing particles*, 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), thus

$$(\mu_{en}/\rho) = (\mu_{tr}/\rho)(1 - g) \quad (25)$$

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

mass energy-transfer coefficient (μ_{tr}/ρ)—*of a material, for uncharged particles of a given type and energy*, quotient of dR_{tr}/R by ρdl, where dR_{tr} is the mean energy that is transferred to kinetic energy of charged particles by interactions of the uncharged particles of incident **radiant energy** R in traversing a distance dl in the material of density ρ (ICRU), thus

$$(\mu_{tr}/\rho) = (dR_{tr}/R)/(\rho dl) \quad (26)$$

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

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

$$S/\rho = (1/\rho)\, dE/dl \quad (27)$$

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

$$S/\rho = 1/\rho\, (dE/dl)_{col} + 1/\rho\, (dE/dl)_{rad} \quad (28)$$

where:

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

measurand—quantity intended to be measured (VIM).

measurement management system—set of interrelated or interacting elements necessary to achieve metrological confirmation and continual control of measurement processes (ISO 10012).

measurement system—specific combinations of instrumentation, operator, and procedure used to make a particular measurement.

metrological traceability—property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty (VIM).

DISCUSSION—

(1) The unbroken chain of calibrations is referred to as a "traceability chain."

(2) Metrological traceability of a measurement result does not ensure that the measurement uncertainty is adequate for a given purpose or that there is an absence of mistakes.

(3) The abbreviated term "traceability" is sometimes used to mean 'metrological traceability' as well as other concepts, such as 'sample traceability' or 'document traceability' or 'instrument traceability' or 'material traceability,' where the history ("trace") of an item is meant. Therefore, the full term of "metrological traceability" is preferred if there is any risk of confusion.

(4) It is also sometimes referred to as "measurement traceability."

measurement uncertainty—non-negative parameter characterizing the dispersion of the quantity values being attributed to a **measurand**, based on the information used (VIM).

DISCUSSION—

(1) Measurement uncertainty includes components arising from systematic effects, such as components associated with

corrections and the assigned quantity values of measurement standards, as well as the definitional uncertainty. Sometimes estimated systematic effects are not corrected for, but instead, associated measurement uncertainty components are incorporated.

(2) The parameter may be, for example, a standard deviation (referred to as standard measurement uncertainty) or a specified multiple of it, or the half-width of an interval, having a stated coverage probability.

(3) Measurement uncertainty comprises, in general, many components. Some of these may be evaluated from the statistical distribution of the quantity values from series of measurements (referred to as Type A evaluation of measurement uncertainty) and can be characterized by standard deviations. The other components may be evaluated from probability density functions based on experience or other information (referred to as Type B evaluation of measurement uncertainty), which can also be characterized by standard deviations.

(4) It is understood that the result of the measurement is the best estimate of the value of the measurand. In general, for a given set of information, it is understood that the measurement uncertainty is associated with a stated quantity value attributed to the measurand. A modification of this value results in a modification of the associated uncertainty.

(5) Besides Type A and Type B evaluation of uncertainty, components of uncertainty may also be characterized as random and systematic. Uncertainty can also be characterized as arising from epistemic or aleatory terms. This division is commonly used to characterize uncertainties associated with measurements when that data is used in computational simulations.

molar linear absorption coefficient (ε_m)**—**constant relating the spectrophotometric absorbance, A_λ, of an optically absorbing molecular species at a given wavelength, λ, per unit pathlength, *d*, to the molar concentration, *c*, of that species in solution, thus

$$\varepsilon_m = A_\lambda/(d \times c) \tag{29}$$

SI Unit: $m^2\ mol^{-1}$

DISCUSSION—The measurement is sometimes expressed in units of $L\ mol^{-1}\ cm^{-1}$.

multigroup cross section—average fluence-weighted cross section in an energy interval of a multigroup model. (See also **multigroup model**), thus

$$\sigma_i = \int_{E_i}^{E_{i+1}} \Phi(E)\,\sigma(E)\ dE / \int_{E_i}^{E_{i+1}} \Phi(E)\,dE \tag{30}$$

multigroup model—subdivision of an energy spectrum into a number of subintervals: (E_i, E_{i+1}), where: $i = 1, 2, ...\ n$.

multigroup particle fluence—fluence in the energy intervals of a multigroup model (see also **multigroup model**), thus

$$\Phi = \int_{E_i}^{E_{i+1}} \Phi(E)\,dE \tag{31}$$

national standard—artifact, such as a well-characterized instrument or radiation source, that embodies the international definition of primary physical measurement standard for national use.

national standards laboratory—laboratory which maintains a nation's measurement standards, such as the National Institute of Standards and Technology in the United States of America.

net count rate—count rate recorded in a spectrometer after correcting for background and coincidence events.

neutron activation detector—neutron fluence sensing device, well-characterized with respect to geometry, mass, composition and cross section which produces a radionuclide (or radionuclides) with a sufficiently long **half-life** to permit its measurement after withdrawal from the neutron field.

*neutron fluence***—**see **fluence.**

*neutron fluence rate***—**see **fluence rate.**

*neutron flux***—**see **fluence rate.**

*neutron spectrum***—**see **particle fluence spectrum**.

nuclide—species of an atom characterized by its mass number, atomic number, and its nuclear energy state.

nuclear reaction rate—number of a given reaction that occurs per target nucleus per unit time.

DISCUSSION—When appropriate, this term may be interpreted as a probability of reaction per unit time. When the context makes it clear, this is sometimes referred to as 'reaction rate.'

pair production—process that results in the creation of an electron-positron pair by the interaction of a gamma ray in the field of charged particles, where the energy of the gamma ray exceeds 1.022 MeV.

DISCUSSION—

(1) The energy of the gamma ray must exceed 1.022 MeV as this is the total rest mass of an electron-positron pair.

(2) The presence of the field of charged particles is essential for this process, since it absorbs momentum while the process conserves both energy and momentum. This mainly happens in the nuclear field, but also to some degree in the field of an electron.

particle number—number of particles emitted, transferred or received (ICRU).

particle number density (*n*)**—**quotient of d*N* by d*V*, where d*N* is the number of particles in the volume d*V* (ICRU), thus

$$n = dN/dV \tag{32}$$

DISCUSSION—

(1) This term is also referred to as "volumetric particle number."

(2) The particle number density spectrum (that is, distribution of the particle number density) is thus (ICRU)

$$n_E = dn/dE \tag{33}$$

particle number fluence spectrum ($\varphi(E)$)**—**quotient of dΦ by d*E*, where dΦ is the **fluence** of particles in the interval *E* to *E* + d*E* (ICRU), thus

$$\varphi(E) = d\Phi/dE \tag{34}$$

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

DISCUSSION—The term "particle spectrum" is commonly used in E10 standards to indicate particle number fluence spectrum. It should not be confused with the particle density spectrum (see Discussion under **particle number density**).

precision—closeness of agreement between indications or measured **quantity values** obtained by replicate measurements on the same or similar objects under specified conditions (VIM).

Discussion—

(1) Precision is usually expressed numerically by measures of imprecision, such as standard deviation, variance, or coefficient of variation under the specified conditions of measurement.

(2) The "specified conditions" can be, for example, repeatability conditions of measurement, intermediate precision conditions of measurement, or reproducibility conditions of measurement.

(3) Precision is used to define **repeatability**, intermediate precision, and **reproducibility**.

(4) Sometimes "precision" is erroneously used to mean **accuracy**.

primary-standard dosimeter—dosimeter of the highest metrological quality, established and maintained as an absorbed-dose standard by a national or international standards organization.

quality assurance—all systematic actions necessary to provide adequate confidence that a calibration, measurement, or process is performed to a predefined level of quality.

quantity value (value of a quantity)—number and reference together expressing magnitude of a quantity (VIM).

Discussion—An example: Length of a given rod is 5.34 m or 534 cm.

radiant energy (*R*)—energy (excluding rest energy) of the particles that are emitted, transferred or received (ICRU-85a).

Unit: J

Discussion—For particles of energy E (excluding rest energy), the radiant energy, R, is equal to the product NE, where N is the **particle number**.

radiation chemical yield *(G(x))***—***of an entity x*, quotient of $n(x)$ by $\bar{\varepsilon}$ where $n(x)$ is the mean amount of substance of that entity produced, destroyed or changed in a system by the mean energy imparted, $\bar{\varepsilon}$, to the matter of that system (ICRU), thus

$$G(x) = \mathrm{n}(x)/\bar{\varepsilon} \quad (35)$$

SI Unit: mol J^{-1}

Discussion—This is often referred to as G value. The former special unit was $(100\ \mathrm{eV})^{-1}$. For example, for the Fricke dosimeter, $G(Fe^{3+})$ is 15.5 $(100\ \mathrm{eV})^{-1}$ or 1.61 μ mol·J^{-1} for ^{60}Co gamma rays.

radioactivation—interaction process in which the product nucleus is radioactive.

reference neutron field—see **benchmark neutron field.**

reference-standard dosimeter—dosimeter of high metrological quality, used as a standard to provide measurements traceable to measurements made using primary-standard dosimeters.

repeatability (of results of measurements)—closeness of the agreement between the results of successive measurements of the same measurand carried out subject to all of the following conditions: the same measurement procedure, the same observer, the same measuring instrument, used under the same conditions, the same location, and repetition over a short period of time (GUM).

Discussion—These conditions are called 'repeatability conditions.' Repeatability may be expressed quantitatively in terms of the dispersion characteristics of the results, for example, **precision**.

reproducibility (of results of measurements)—closeness of agreement between the results of measurements of the same measurand, where the measurements are carried out under changed conditions such as differing principle or method of measurement, observer, measuring instrument, location, conditions of use, or time (GUM).

Discussion—A valid statement of reproducibility requires specification of the conditions changed. Reproducibility may be expressed quantitatively in terms of dispersion characteristics of the results, for example, **precision**. In this context, results of measurement are understood to be corrected results.

routine dosimeter—dosimeter calibrated against a primary-, reference-, or transfer-standard dosimeter and used for routine absorbed-dose measurement.

saturation activity—number of disintegrations per unit time for the steady-state condition in which the rate of production of a nuclide is equal to the rate of loss by radioactive decay or nuclear transmutation.

shape calibration—process which establishes a relationship between the expected peak shape and energy.

Discussion—The shape calibration may be as simple as the user supplying a few peak full-width at half maximum (FWHM)/energy (or channel) pairs or as complex as using a least squares algorithm to establish several parameters characterizing the peak width and its deviation from a pure Gaussian. Shape calibration may be an explicitly defined function of an analysis program or implicitly done in connection with some other operation (typically the energy calibration).

solid state track recorder (SSTR)—plastic, mineral, or emulsion material that records the passage of energetic ionizing particles as latent tracks that may be chemically enlarged or developed for microscopy or other techniques.

Discussion—Track characteristics, such as track density, length, or diameter, can be used to obtain reaction rate, dose, energy spectrum, or other types of data (see **track etch technique**).

spectrum averaged cross section ($\bar{\sigma}$)—cross section averaged over the energy distribution of the neutron fluence, where the energy limits of integration are chosen according to the neutron spectrum and reaction cross section considered, thus

$$\bar{\sigma} = \int \sigma(E)\, \Phi(E) \mathrm{d}E / \int \Phi(E) \mathrm{d}E \quad (36)$$

standard neutron field—see **benchmark neutron field**.

standard uncertainty—measurement uncertainty of the results of a measurement expressed as a standard deviation (GUM).

thermal neutrons—neutrons in thermal equilibrium with the medium through which they are traveling or diffusing.

thermoluminescence dosimeter (TLD)—dosimeter made of a material that stores energy when irradiated by **ionizing radiation** and then releases that energy in the form of visible light when heated.

Discussion—The light output of a heated TLD is measured photometrically. TLDs are secondary-standard dosimeters. Examples of commonly available TLDs include lithium fluoride (LiF), calcium fluoride with various trace activators (such as $CaF_2 : Mn$ and $CaF_2 : Dy$), calcium sulfate ($CaSO_4 : Mn$ and $CaSO_4 : Dy$), and lithium borate ($Li_2B_4O_7 : Mn$).

threshold neutron activation detector—device containing a particular nuclide that is not significantly activated by neutrons below a certain threshold energy.

total efficiency—*for a gamma ray spectrometer system*, ratio of the net count rate for all energies in the gamma ray spectrometer system to the gamma ray emission rate of mono-energetic photons from a sample.

Discussion—The value is dependent on the source-detector-shield geometry and the photon energy. If gamma rays of more than one energy are emitted by the source, it may be necessary to determine a separate total efficiency for each such energy.

track etch technique—measurement method consisting of a dielectric material that records the passage of energetic heavy ionizing particles as latent tracks that can be developed or enlarged by various chemical methods and observed by microscopy methods or other techniques.

transfer-standard dosimeter—dosimeter, often a reference-standard dosimeter suitable for transport between different locations, used to compare absorbed-dose measurements.

true value—value of measurand that would be obtained by a perfect measurement.

Discussion—True values are by nature indeterminate and only an idealized concept. The terms "true value of a measurand" and "value of a measurand" are viewed as equivalent.

Type A evaluation of measurement uncertainty—evaluation of a component of **measurement uncertainty** by a statistical analysis of measured **quantity values** obtained under defined measurement conditions (VIM).

Discussion—The estimated standard deviation obtained from this evaluation is generally referred to as Type A standard uncertainty.

Type B evaluation of measurement uncertainty—evaluation of a component of **measurement uncertainty** determined by means other than a **Type A evaluation of measurement uncertainty** (VIM).

Discussion—

(1) For example, evaluation based on information:
- associated with authoritative published quantity values,
- associated with the quantity value of a certified reference material (if not identified as Type A or B),
- obtained from a calibration certificate (if not identified as Type A or B),
- obtained from the accuracy class of a verified measuring instrument,
- obtained from limits deduced through personal experience.

(2) The estimated standard deviation obtained from this evaluation is generally referred to as Type B standard uncertainty.

X-ray standard field—X-ray field that is well characterized as to the temporal profile, energy and direction, and spacial uniformity produced in a specified material, at a specified location within the field for a given source configuration.

year—1 year = 365.242198 days = 31556926 s.

Discussion—

(1) This definition is to be used for radiation metrology applications. It is consistent with the definition found in the standard for nuclear decay constants.[13]

(2) Many different definitions exist for a year, for example, tropical or sidereal, and these definitions vary with the date due to the slowing down of the earth's rotation. Based on non-relativistic estimate of the astronomical decrease, this rate is 0.530 s per century. For this reason it is important that whenever one uses the unit of year that the definition used is clear to the user. Not all nuclear-related databases use the BIPM-5 definition, so it is important that users look to the original source used for the nuclear data to ensure that the data is correctly interpreted.

(3) Some communities, such as astronomers, use a Julian year which is defined as exactly 365.25 days (or 31,557,600 s). The Julian year is the basis for the definition of the light year.

(4) Proposals have been made to the International Union of Pure and Applied Chemistry (IUPAC)[14] to define a standard year corresponding to the epoch 2000.0 tropical year, which is 3.1556925445×10^7 s.

1/*E* fluence—that fluence in the portion of the neutron spectrum produced by moderating media for which the fluence per unit energy, ideally, is inversely proportional to the neutron energy.

1/*v* detector—*for neutrons*, detector whose sensitive element is a nuclide whose cross section for a particular reaction of interest (for example, (n, γ), (n, p), (n, α)) varies as the reciprocal of the velocity of the impinging neutrons.

Discussion—The 1/*v* property of the detector is valid only over a restricted energy range and usually below 10 keV (see **2200 m/s cross section**).

2200 m/s cross section ($\sigma(v_o)$)**—**neutron cross section at v_o = 2200 m/s (*E* is about 0.0253 eV).

[13] Bé, M. M., Chiste, V., Dulieu, C., Browne, E., Chechev, V., Kuzmenko, N., Helmer, R., Nichols, A., Schönfeld, E., Dersch, R., Monographie BIPM-5, Table of Radionuclides, Vol 2 - A = 151 to 242, 2004.

[14] Holden, N., Bonardi, M., DeBieve, P., Renne, P., and Villa, I., "IUPAC-IUGS common definition and convention on the use of the year as a derived unit of time (IUPAC Recommendations 2011)," *Pure Appl. Chem.*, Vol 83, No 5, 2011, pp. 1159-1162.

APPENDIXES

(Nonmandatory Information)

X1. RECOMMENDED QUANTITIES AND UNITS

TABLE X1.1 ICRU Recommended Quantities and Units (from ICRU 85a)

Quantity		Unit Symbols	
Name	Symbol	SI	SI Restricted Name[A]
Particle number	N	1	
Fluence	Φ	m^{-2}	
Fluence rate[B]	$\dot{\Phi}$	$m^{-2}\ s^{-1}$	
Mass energy transfer coefficient	μ_{tr}/ρ	$m^2\ kg^{-1}$	
Mass energy absorption coefficient	μ_{en}/ρ	$m^2\ kg^{-1}$	
Total mass stopping power	S/ρ	$J\ m^2\ kg^{-1}$	
Radiation chemical yield	$G(x)$	$mol\ J^{-1}$	
Absorbed dose	D	$J\ kg^{-1}$	Gy
Absorbed dose rate[B]	$\dot{D}$	$J\ kg^{-1}\ s^{-1}$	$Gy\ s^{-1}$
Kerma	K	$J\ kg^{-1}$	Gy
Kerma rate[B]	$\dot{K}$	$J\ kg^{-1}\ s^{-1}$	$Gy\ s^{-1}$
Exposure	X	$C\ kg^{-1}$	
Exposure rate[B]	$\dot{X}$	$C\ kg^{-1}\ s^{-1}$	
Activity[B]	A	s^{-1}	Bq
Decay constant	λ	s^{-1}	

[A]The symbol for the special name for the SI unit restricted to specified quantities.
[B]Day (d), hour (h), and minute (min) may be used instead of second (s).

X2. COMMENTARY ON UNITS

TABLE X2.1 Old and New Radiation Units

Quantity	SI Unit	Old Unit
activity	becquerel (Bq) (1/second)	curie (Ci) 1 Ci = 3.7×10^{10} Bq
absorbed dose and kerma	gray (Gy) (joule/kilogram) J/kg	rad 1 rad = 0.01 Gy
exposure	coulomb/kilogram (C/kg)	roentgen (R) 1 R = 2.58×10^{-4} C/kg

X2.1 The units associated with physical quantities defined or used in definitions in this standard are SI (The International System of Units). For a detailed discussion of SI units, see Practice E380.

X2.2 In recent years, the several traditional units having special names in radiation measurements and dosimetry have been replaced by others. In particular, this applies to the units for activity, kerma, absorbed dose, and exposure. Activity previously expressed in curies is now expressed in becquerels. The unit for kerma and absorbed dose has changed from rad to gray. Exposure expressed now in the unit named roentgen should more properly have the units of coulomb per kilogram.

X2.3 It is recommended that the use of the old units for quantities with special names be avoided; however, if it is deemed necessary to use them for clarity, then values of quantities should be expressed first in the new units followed by values in the old units in parentheses. Table X2.1 summarizes the relationship between the old and new units for the quantities of interest.