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Standard Guide for Selection and Use of Mathematical Methods for Calculating Absorbed Dose in Radiation Processing Applications[1]

This standard is issued under the fixed designation E2232; 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.

1. Scope

1.1 This guide describes different mathematical methods that may be used to calculate absorbed dose and criteria for their selection. Absorbed-dose calculations can determine the effectiveness of the radiation process, estimate the absorbed-dose distribution in product, or supplement or complement, or both, the measurement of absorbed dose.

1.2 Radiation processing is an evolving field and annotated examples are provided in Annex A6 to illustrate the applications where mathematical methods have been successfully applied. While not limited by the applications cited in these examples, applications specific to neutron transport, radiation therapy and shielding design are not addressed in this document.

1.3 This guide covers the calculation of radiation transport of electrons and photons with energies up to 25 MeV.

1.4 The mathematical methods described include Monte Carlo, point kernel, discrete ordinate, semi-empirical and empirical methods.

1.5 This guide is limited to the use of general purpose software packages for the calculation of the transport of charged or uncharged particles and photons, or both, from various types of sources of ionizing radiation. This standard is limited to the use of these software packages or other mathematical methods for the determination of spatial dose distributions for photons emitted following the decay of ^{137}Cs or ^{60}Co, for energetic electrons from particle accelerators, or for X-rays generated by electron accelerators.

1.6 This guide assists the user in determining if mathematical methods are a useful tool. This guide may assist the user in selecting an appropriate method for calculating absorbed dose. The user must determine whether any of these mathematical methods are appropriate for the solution to their specific application and what, if any, software to apply.

NOTE 1—The user is urged to apply these predictive techniques while being aware of the need for experience and also the inherent limitations of both the method and the available software. Information pertaining to availability and updates to codes for modeling radiation transport, courses, workshops and meetings can be found in Annex A1. For a basic understanding of radiation physics and a brief overview of method selection, refer to Annex A3.

1.7 *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 appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.8 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E482 Guide for Application of Neutron Transport Methods for Reactor Vessel Surveillance

E3083 Terminology Relating to Radiation Processing: Dosimetry and Applications

2.2 *ISO/ASTM Standards:*[2]

51707 Guide for Estimating Uncertainties in Dosimetry for Radiation Processing

52628 Practice for Dosimetry in Radiation Processing

2.3 *ISO Standard:*[3]

ISO 12749-4 Nuclear energy, nuclear technologies, and radiological protection — Vocabulary — Part 4: Dosimetry for radiation processing

[1] This guide is under the jurisdiction of ASTM Committee E61 on Radiation Processing and is the direct responsibility of Subcommittee E61.04 on Specialty Application.

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[2] For referenced ASTM and ISO/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.

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

2.4 *International Commission on Radiation Units and Measurements Reports:*[4]

ICRU Report 85a Fundamental Quantities and Units for Ionizing Radiation

2.5 *JCGM Documents:*[5]

JCGM 100:2008 GUM 1995, with minor corrections Evaluation of measurement date - Guide to the Expression of Uncertainty in Measurement

JCGM 200:2012 VIM International Vocabulary of Metrology - Basic and General Concepts and Associated Terms

3. Terminology

3.1 *Definitions:*

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

3.1.2 *benchmarking*—comparing model predictions to independent measurements or calculations under similar conditions using defined criteria of uncertainty.

3.1.2.1 *Discussion*—Benchmarking is a prerequisite before routine use of a mathematical model. Refer to 8.1 and Annex A5.

3.1.3 *biasing (in a Monte Carlo simulation)*—adjustment of the source particle selection or the transported particle weight, or both, in a statistically valid manner so as to increase the particles in a region where the detector response is most important.

3.1.3.1 *Discussion*—Biasing is a method used to reduce the estimated uncertainty or computer run times of Monte Carlo simulations. Monte Carlo simulations using the natural probabilities of physical events may require unacceptably long run times to accumulate statistics for rare events. The simulated probabilities may be altered to achieve the uncertainty goals for the simulation in acceptable run times by biasing the sampling from the probability distributions. The number of particles tracked and the particle weights may be adjusted so as to ensure a statistically valid sample from the probability distributions. Appropriate biasing requires a detailed knowledge of the model and the influence of rare events. As with all simulations, results should be compared with benchmark measurements or simulation results originated by a different code.

3.1.4 *build-up factor*—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 un-collided radiation reaching that point.

3.1.4.1 *Discussion*—The concept of build-up applies to the transport of photons.

3.1.5 *deterministic method*—a mathematical method using transport equations to directly calculate the radiation field over all space as a function of radiation source and boundary conditions.

3.1.5.1 *Discussion*—The point kernel and discrete ordinate methods are examples of deterministic methods.

3.1.6 *discrete ordinate method*—a deterministic method for approximate numerical solution of the transport equation in which the direction of motion is divided into a finite number of discrete ordinate angles.

3.1.6.1 *Discussion*—In the discrete ordinates approximation, the transport equation becomes a set of coupled equations, one for each discrete ordinate. Particle behaviors along paths intermediate to described paths are approximated by a weighted average (numerical quadrature) of adjacent paths (**1**).[6] The method is useful for both electron and photon sources when appropriate assumptions can be made.

3.1.7 *empirical method*—a method derived from fitting an approximating function to experimental data or Monte Carlo calculation result.

3.1.7.1 *Discussion*—Empirical models are generally developed by fitting equations (for example, polynomial) to experimental data or simulation output derived from another mathematical method.

3.1.8 *history (of a particle)*—record of all simulated interactions along particle's track as used in stochastic simulations (for example, Monte Carlo).

3.1.8.1 *Discussion*—A particle history begins with the starting position, energy and direction of a particle, follows all its interactions, and terminates in one of several outcomes such as absorption, escape from the boundary of the problem, or reaching a cut-off limit (such as a cut-off energy). A particle history is the systematic generation of a random, simulated particle track that is obtained according to the known physical interactions of either electrons or photons with the material being traversed. History and particle history are considered synonymous.

3.1.9 *mathematical method*—a method of solution of an electron or photon transport problem, or both, using algebraic relations and mathematical operations to represent the system and its dynamics.

3.1.10 *mathematical model*—a mathematical description of a physical problem based on physical laws or empirical correlation, or both.

3.1.11 *Monte Carlo method*—a simulation method used for calculating absorbed dose, energy spectra, charge, fluence and fluence rate in a volume of interest using a statistical summary of the radiation interactions.

3.1.11.1 *Discussion*—A Monte Carlo calculation consists of running a large number of particle histories (simulations) until some acceptable statistical uncertainty in the desired calculated quantity (such as dose) has been reached. This calculation method is suitable for problems involving either electrons or photons or both. This technique produces a probabilistic approximation to the solution of a problem by using statistical sampling techniques. See also *stochastic* and *history*.

3.1.12 *numerical convergence*—process in which the iterative solution of an equation or set of equations changes by less than some defined value.

[4] Available from International Commission on Radiation Units and Measurements, 7910 Woodmont Ave., Suite 800, Bethesda, MD 20815 USA.

[5] Available from JCGM-BIPM website at: http://www.bipm.org.

[6] The boldface numbers in parentheses refer to the list of references at the end of this standard.