Designation: E2381 – 04 (Reapproved2010)

Standard Guide for
Dosimetry In Radiation Processing of Fluidized Beds and Fluid Streams[1]

This standard is issued under the fixed designation E2381; 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 several dosimetry systems and methods suitable for the documentation of the irradiation of product transported as fluid or in a fluidized bed.

1.2 The sources of penetrating ionizing radiation included in this guide are electron beams, X-rays (bremsstrahlung) and gamma rays.

1.3 Absorbed doses from 10 to 100,000 gray are considered, including applications such as disinfestation, disinfection, bioburden reduction, sterilization, crosslinking and graft modification of products, particularly powders and aggregates.

1.4 *This guide does not purport to address the safety concerns, if any, associated with the use of fluidized beds and streams incorporating sources of ionizing radiation. It is the responsibility of the user of this guide to establish appropriate safety and health practices and to determine compliance with regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E170 Terminology Relating to Radiation Measurements and Dosimetry

E666 Practice for Calculating Absorbed Dose From Gamma or X Radiation

E1026 Practice for Using the Fricke Dosimetry System

E2232 Guide for Selection and Use of Mathematical Methods for Calculating Absorbed Dose in Radiation Processing Applications

F1355 Guide for Irradiation of Fresh Agricultural Produce as a Phytosanitary Treatment

F1885 Guide for Irradiation of Dried Spices, Herbs, and Vegetable Seasonings to Control Pathogens and Other Microorganisms

2.2 *ISO/ASTM Standards:*

51204 Standard Practice for Dosimetry in Gamma Irradiation Facilities for Food Processing

51261 Guide for Selection and Calibration of Dosimetry Systems for Radiation Processing

51275 Practice for Use of a Radiochromic Film Dosimetry System

51310 Practice for the Use of a Radiochromic Optical Waveguide Dosimetry Systems

51400 Practice for Characterization and Performance of a High-Dose Radiation Dosimetry Calibration Laboratory

51431 Practice for Dosimetry in Electron and X-Ray (Bremsstrahlung) Irradiation Facilities for Food Processing

51538 Practice for Use of the Ethanol-Chlorobenzene Dosimetry System

51540 Practice for Use of a Radiochromic Liquid Dosimetry System

51607 Practice for Use of the Alanine-EPR Dosimetry System

51608 Practice for Dosimetry in an X-Ray (Bremsstrahlung) Facility for Radiation Processing

51649 Practice for Dosimetry in an Electron Beam Facility for Radiation Processing at Energies between 300 keV and 25 MeV

51702 Practice for Dosimetry in a Gamma Irradiation Facility for Radiation Processing

51707 Guide for Estimating Uncertainties in Dosimetry for Radiation Processing

51818 Practice for Dosimetry in an Electron Beam Facility for Radiation Processing at Energies Between 80 and 300 keV

51956 Practice for Application of Thermoluminescence Dosimetry (TLD) Systems for Radiation Processing

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[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.

Current edition approved Dec. 1, 2010. Published January 2011. Originally approved in 2004. Last previous edition approved in 2004 as E2381–04. DOI: 10.1520/E2381-04R10.

[2] 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.

2.3 *International Commission on Radiation Units and Measurements Reports*[3]

ICRU Report 14 Radiation Dosimetry: X-Rays and Gamma Rays with Maximum Photon Energies Between 0.6 and 50 MeV

ICRU Report 17 Radiation Dosimetry: X-Rays Generated at Potentials of 5 to 150 kV

ICRU Report 30 International Comparison of Radiological Units and Measurements: Quantitative Concepts and Dosimetry in Radiobiology

ICRU Report 34 The Dosimetry of Pulsed Radiation

ICRU Report 35 Radiation Dosimetry: Electron Beams with Energies Between 1 and 50 MeV

ICRU Report 37 Stopping Powers for Electrons and Positrons

ICRU Report 60 Fundamental Quantities and Units for Ionizing Radiation

2.4 *National Committee for Radiation Protection*

NCRP Report 69 Dosimetry of X-Ray and Gamma-Ray Beams for Radiation Therapy in the Energy Range 10 keV to 50 MeV

3. Terminology

3.1 *Definitions:*

3.1.1 *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^{-1}). The mathematical relationship for dose is the quotient of $d\varepsilon$ by dm, where $d\varepsilon$ is the mean incremental energy imparted by ionizing radiation to matter of incremental mass dm (see ICRU 60).

3.1.1.1 *Discussion*—discontinued unit for absorbed dose is the rad (1 rad = 0.01 Gy). Absorbed dose is sometimes referred to simply as dose.

3.1.2 *absorbed dose mapping*—measurement of absorbed dose within a process stream using dosimeters transported at specified locations to produce a one or two-dimensional distribution of absorbed dose, thus rendering a map of absorbed-dose values.

3.1.3 *absorbed dose rate*—absorbed dose in a material per incremental time interval, i.e. the quotient of dD by dt (see ICRU 60) Unit: Gy s^{-1}

3.1.3.1 *Discussion*—absorbed dose rate can be specified in terms of the average value of dD by dt over long-time intervals, for example, in units of Gy min^{-1} or Gy h^{-1}

3.1.4 *areal density*—thickness of an object normalized by density. The SI unit is kg m^{-2}.

3.1.4.1 *Discussion*—the abbreviation gsm is also used in referring to areal density in grams per square meter in some technical literature.

3.1.5 *bed control*—technique used for determining the fluidized bed thickness and maintaining it between the limits required for controlled application of the process.

3.1.6 *bed thickness*—total thickness of the fluidized bed, which includes the product being processed and the carrier medium, both normalized by density. The SI unit is kg. m^{-2}.

3.1.6.1 *Discussion*—thickness is typically quoted in g. m^{-2} due to its numerical equivalence to thickness in micrometers for unit density matter.

3.1.7 *Bremsstrahlung*—broad-spectrum electromagnetic radiation (X-rays) emitted when an energetic electron is influenced by strong electric field or magnetic field such as that in the vicinity of an atomic nucleus.

3.1.7.1 *Discussion*—bremsstrahlung is produced when an electron beam strikes any material (converter). The bremsstrahlung spectrum depends on the electron energy, the converter material and its thickness, and contains energies up to the maximum kinetic energy of the incident electrons (see ISO/ASTM Practice 51608).

3.1.8 *calibration curve*—graphical representation of the dosimetry system's response function.

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

3.1.10 *dose uniformity ratio*—ratio of the maximum to the minimum absorbed dose within the irradiated object or process stream.

3.1.10.1 *Discussion*—the concept is also referred to as the max/min dose ratio and is significantly influenced by the turbulence of the product flow.

3.1.11 *dosimeter*—device that, when irradiated, exhibits a quantifiable change in some property of the device which can be related to absorbed dose in a given material using appropriate analytical instrumentation and techniques.

3.1.12 *dosimeter response*—reproducible, quantifiable radiation effect on a dosimeter produced by a given absorbed dose.

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

3.1.14 *electron energy*—kinetic energy of the accelerated electrons. The electron energy at the product is equal to its accelerated energy in vacuum less its energy losses in the accelerator's window and the air gap separating the product and the window.

3.1.15 *electron fluence*—amount of electronic charge traversing a unit area of the target, usually expressed in microcoulombs per square centimeter. It is the integral of flux over total exposure time

3.1.16 *fluidized bed or stream*—means by which the product is transported and presented to the radiation source. The carrier medium may be gaseous or liquid. The product distribution within the carrier medium may not be uniform.

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

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[3] Available from the International Commission on Radiation Units and Measurements, 7910 Woodmont Avenue, Suite 800, Bethesda, MD, 20814,USA

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

3.1.19 *real time dose monitor*—instrument capable of continuously providing measured data on dose delivered during processing.

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

3.1.21 *response function*—mathematical representation of the relationship between dosimeter response and absorbed dose for a given dosimetry system.

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

3.1.23 *self-shielded system*—product transport-irradiation unit with integral shielding.

3.1.23.1 *Discussion*—this type of conformal shielding is typically used at lower radiation energies where rather thin layers of lead can protect the surrounding environment from virtually all of the radiation generated by the irradiator.

3.1.24 *simulated product*—mass of material with attenuation and scattering properties similar to those of the product, material or substance to be irradiated, sometimes called a dummy product.

3.1.25 *surface dose*—absorbed dose at the surface of the product.

3.1.25.1 *Discussion*—This definition becomes particularly important where low energy radiation is used to treat only the surface of particulates.

3.1.26 *target dose*—absorbed dose delivered to the surface of the bed which will produce the required absorbed dose distribution within the remainder of the product irradiated in the fluidized bed.

3.1.27 *traceability*—ability to demonstrate by means of an unbroken chain of comparisons that a measurement is in agreement within acceptable limits of uncertainty with comparable nationally or internationally recognized standards.

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

3.1.29 *uncertainty*—parameter associated with the result of any measurement that characterizes the dispersion of the values that could reasonably be attributed to the measured or derived quantity.

3.1.30 *validation*—establishment of documented evidence, which provides a high degree of assurance that a specified process will consistently produce a product meeting its predetermined specifications and quality attributes.

3.2 Definitions of other terms used in this standard that pertain to radiation measurement and dosimetry may be found in ASTM Terminology E170. Definitions in E170 are compatible with ICRU 60; that document, therefore, may be used as an alternative reference.

4. Significance and Use

4.1 *Dosimetric Techniques*—The processes addressed here utilize a variety of techniques for the dynamic presentation of the product to the radiation source. This may involve gravitational flow or simple pneumatic transport about or past the radiation source. In the case of fluidized beds, the product may be presented to the radiation source while supported in a gaseous or liquid stream moving at relatively high velocities. This document provides a guide to the dosimetric techniques suitable for these processes.

4.2 *Food Products*—Food products may be treated with ionizing radiation, such as energetic electrons from accelerators or gamma rays from ^{60}Co or ^{137}Cs sources, or X-rays, for numerous purposes, including control of parasites and pathogenic microorganisms, insect disinfestation, growth and maturation inhibition, and shelf-life extension.

NOTE 1—Food irradiation specifications usually include upper and lower limits of absorbed dose: a minimum to ensure the intended beneficial effect and a maximum to avoid product degradation. For a given application, one or both of these values may be prescribed by regulations that have been established on the basis of available scientific data. Therefore, it is necessary to determine the capability of an irradiation facility to process within these absorbed-dose limits prior to the irradiation of the food product. Once this capability is established, it may be necessary to monitor and record the dose range delivered to the product during each production run to verify compliance with the process specifications within a predetermined level of confidence.

4.3 *Randomized Flow*—In a stream of randomized flow; i.e. turbulent instead of laminar, variations occur which lead to a dose distribution for the particles entrained in the stream. The "idealized" maximum and minimum doses possible can be calculated based upon knowledge of the applied dose rate, the product dwell time in the irradiation cell and the product or bed thickness. The experimentally determined maximum and minimum doses delivered to each particle, should not be confused with these idealized dose limits.

4.4 *Treatment range*—The location of the product (or of the dosimeter) in the fluidized bed or stream will determine its absorbed dose during passage through the radiation field. The experimental dose measurements in the fluidized bed or stream will define the range of product dose. The desired effect imparted to the product by irradiation will then be based upon this range of product dose and not upon maximum or minimum dose.

NOTE 2—In situations where a randomized mixing within the fluidized bed occurs with the intention that the particles or fluid elements pass through several radiation zones and accumulate a total dose with different dose rates, maximum and minimum dose values are difficult to determine and must be based on the results for the experimental dosimetry irradiated with the product . In the case of fluids, stirring after processing results only in effective treatment at a mean dose; no max and min dose measurement. For example, lethality curves will be determined as a function of this range of product treatment to the product in the fluidized bed or stream as determined by dosimetric techniques.

5. Types of Facilities, Source Characteristics and Fluidized Bed Parameters

5.1 Conventional gamma-ray sources (^{60}Co or ^{137}Cs), due to their low intrinsic dose rates, are useful for fluidized bed processing only when the irradiator is designed for the application.

5.2 The high dose rates typical of bremsstrahlung and electron beam sources are most suitable for fluidized bed treatment of product. Electron energies in the 0.3 to 3 MeV range are largely used for these applications, often in self-shielded systems under 0.5 MeV. Selection of the energies used will depend upon whether bulk or surface treatment of the particles carried in the fluidized bed is desired.

5.3 *Fluidized Bed Parameters—*

5.3.1 *Thickness*—The areal densities or bed thicknesses are typically in the range of 5 kg m^{-2} (5000 g m^{-2}) or less.

NOTE 3—Uniformity of product distribution in the stream is not critical as long as efficient product transport results at an acceptable bed thickness (see ISO/ASTM Guide 51261).

NOTE 4—Continuous (dc) electron beam systems are typically operated with accelerator current (at preset voltage or beam energy) coupled to stream velocity to achieve the desired dose.

5.3.2 *Velocity*—In the use of pulsed or scanned sources of energetic electrons for stream processing, care must be exercised. Limitations on product/stream velocity may be imposed by the pulse repetition or scanning frequencies of the source to ensure uniform product treatment. A generalized calculation formula for dose uniformity as a function of the product/stream velocity in scanned sources of energetic electrons for processing has been described **(1)**.

5.3.3 *Product flow rates*—Processing systems are also designed to limit product flow rates to levels compatible with the fixed source dose rate, as in the case of radioisotope sources. Areal density of the bed is controlled to ensure that the penetration of the radiation is sufficient to yield acceptable stream treatment uniformity.

6. Dosimetry Systems and Methods Suitable for Dose Measurements in Fluidized Beds and Fluid Streams.

6.1 *Description of Dosimeter Classes*

6.1.1 Dosimeters may be divided into four basic classes according to their relative quality and areas of application, primary-standard, reference-standard, transfer-standard, and routine dosimeters. ISO/ASTM Guide 51261 provides information about the selection of dosimetry systems for different applications. All classes of dosimeters except the primary-standards require calibration before their use.

6.1.1.1 *Primary-Standard Dosimeter*—Primary-standard dosimeters are established and maintained by national standards laboratories for calibration of radiation environments (fields) and other classes of dosimeters. The two most commonly used primary-standard dosimeters are ionization chambers and calorimeters.

6.1.1.2 *Reference-Standard Dosimeters*—Reference-standard dosimeters are used to calibrate radiation environments and routine dosimeters. Reference-standard dosimeters may also be used as routine dosimeters. Examples of reference-standard dosimeters along with their useful dose ranges are given in ISO/ASTM Guide 51261.

6.1.1.3 *Transfer-Standard Dosimeters*—Transfer-standard dosimeters are specially selected dosimeters used for transferring absorbed-dose information from an accredited or national standards laboratory to an irradiation facility in order to establish traceability for that facility. These dosimeters should be carefully used under conditions that are carefully controlled by the issuing laboratory. Transfer-standard dosimeters may be selected from either reference-standard dosimeters or routine dosimeters taking into consideration the criteria listed in ISO/ASTM Guide 51261.

6.1.1.4 *Routine Dosimeters*—Routine dosimeters may be used for process quality control, dose monitoring and dose mapping. Proper dosimetric techniques, including calibration, shall be employed to ensure that measurements are reliable and accurate. Examples of routine dosimeters, along with their useful dose ranges, are given in ISO/ASTM Guide 51261.

6.2 *Calibration of the Dosimetry System*

6.2.1 Prior to use, the dosimetry system (consisting of a specific batch of dosimeters and specific measurement instruments) shall be calibrated in accordance with the user's documented procedure that specifies details of the calibration process and quality assurance requirements. This calibration procedure shall be repeated at regular intervals to ensure that the accuracy of the absorbed dose measurement is maintained within required limits. Calibration methods are described in ISO/ASTM Guide 51261.

NOTE 5—At the time of publication of this document, no reference standard dosimeter was available from an accredited calibration laboratory to perform full *in situ* calibrations or *in situ* laboratory calibration verification for low electron beam energy. Also there is no low energy (80-300 kV) source of electron beam laboratory calibration available. Therefore users must perform a laboratory calibration using a high energy beam or gamma ray source and include an appropriate component of uncertainty in the estimate of overall uncertainty. It should also be noted that calibration under high energy electron beam conditions provided good agreement with a low energy in-line calorimeter.

6.2.2 Irradiation is a critical component of the calibration of the dosimetry system.

6.2.3 *Calibration Irradiation of Reference- or Transfer-Standard Dosimeters*—Calibration irradiations shall be performed at an accredited calibration laboratory, or in-house calibration facility meeting the requirements of ISO/ASTM Practice 51400, that provides an absorbed dose (or absorbed-dose rate) having measurement traceability to nationally or internationally recognized standards.

6.2.4 *Calibration Irradiation of Routine Dosimeters*—Calibration irradiations may be performed per 6.2.3, or at a production or research irradiation facility together with reference- or transfer-standard dosimeters that have measurement traceability to nationally or internationally recognized standards. This clause also applies when reference-standard dosimeters are used as routine dosimeters.

6.2.5 *Measurement Instrument Calibration and Performance Verification*—For the calibration of the instruments, and for the verification of instrument performance between calibrations, see ISO/ASTM Guide 51261, the corresponding