

# Standard Guide for Dosimetry in Radiation Research on Food and Agricultural Products<sup>1</sup>

## 1. Scope

1.1 This guide covers the minimum requirements for dosimetry and absorbed-dose validation needed to conduct research on the irradiation of food and agricultural products. Such research includes establishment of the quantitative relationship between the absorbed dose and the relevant effects in these products. This guide also describes the overall need for dosimetry in such research, and in reporting of the results.

1.2 This guide is intended for use by research scientists in the food and agricultural communities, and not just scientists conducting irradiation research. It, therefore, includes more tutorial information than most other ASTM dosimetry standards for radiation processing.

1.3 This guide is in no way intended to limit the flexibility of the experimenter in the experimental design. However, the radiation source and experimental set up should be chosen such that the results of the experiment will be beneficial and understandable to other scientists, regulatory agencies, and the food and agricultural communities.

1.4 The effects produced by ionizing radiation in biological systems depend on a large number of factors which may be physical, physiological, or chemical. Although not treated in detail in this guide, quantitative data of environmental factors that may affect the absorbed-dose response of dosimeters, such as temperature and moisture content in the food or agricultural products should be reported.

1.5 The overall uncertainty in the absorbed-dose measurement and the inherent absorbed-dose range within the specimen should be taken into account in the design of an experiment.

1.6 The guide covers research conducted using the following types of ionizing radiation: gamma rays, bremsstrahlung X-rays, and electron beams.

1.7 This guide does not include other aspects of radiation processing research, such as planning of the experimental design. Dosimetry must be considered as an integral part of the experimental design.

1.8 The guide does not include dosimetry for irradiator characterization, process qualification and routine dosimetry;

these subjects are described in Practices E 1204, E 1431, E 1608, E 1649, and E 1702. The selection and calibration of dosimetry systems is specified in Guide E 1261.

1.9 *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 and health practices and determine the applicability of regulatory limitations prior to use.*

## 2. Referenced Documents

### 2.1 ASTM Standards:

- E 170 Terminology Relating to Radiation Measurements and Dosimetry<sup>2</sup>
- E 177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods<sup>3</sup>
- E 275 Practice for Describing and Measuring Performance of Ultraviolet, Visible, and Near Infrared Spectrophotometers<sup>4</sup>
- E 456 Terminology Relating to Quality and Statistics<sup>5</sup>
- E 666 Practice for Calculating Absorbed Dose from Gamma or X Radiation<sup>2</sup>
- E 668 Practice for Application of Thermoluminescence Dosimetry (TLD) Systems for Determining Absorbed Dose in Radiation Hardness Testing of Electronic Devices<sup>2</sup>
- E 925 Practice for the Periodic Calibration of Narrow Band Pass Spectrophotometers<sup>4</sup>
- E 958 Practice for Measuring Practical Spectral Bandwidth of Ultraviolet Visible Spectrophotometers<sup>4</sup>
- E 1026 Practice for Using the Fricke Reference Standard Dosimetry System<sup>2</sup>
- E 1204 Practice for Dosimetry in Gamma Irradiation Facilities for Food Processing<sup>2</sup>
- E 1261 Guide for Selection and Calibration of Dosimetry Systems for Radiation Processing<sup>2</sup>
- E 1275 Practice for Use of a Radiochromic Film Dosimetry System<sup>2</sup>
- E 1431 Practice for Dosimetry in Electron and Bremsstrahlung Irradiation Facilities for Food Processing<sup>2</sup>
- E 1539 Guide for the Use of Radiation-Sensitive Indicators<sup>2</sup>

E 1540 Practice for Use of a Radiochromic Liquid Dosimetry System<sup>2</sup>

E 1607 Practice for Use of the Alanine-EPR Dosimetry System<sup>2</sup>

E 1608 Practice for Dosimetry in an X-ray (Bremsstrahlung) Facility for Radiation Processing<sup>2</sup>

E 1649 Practice for Dosimetry in Electron Beam Facility for Radiation Processing at Energies between 300 keV and 25 MeV<sup>2</sup>

E 1702 Practice for Dosimetry in a Gamma Irradiation Facility for Radiation Processing<sup>2</sup>

E 1707 Guide for Estimating Uncertainties in Dosimetry for Radiation Processing<sup>2</sup>

F 1355 Guide for the Irradiation of Fresh Fruits for Insect Disinfestation as a Quarantine Treatment<sup>6</sup>

F 1356 Guide for the Irradiation of Fresh and Frozen Red Meats and Poultry (to Control Pathogens)<sup>6</sup>

F 1640 Guide for Packaging Materials for Foods to be Irradiated<sup>6</sup>

F 1736 Guide for the Irradiation of Finfish and Shellfish to Control Pathogens and Spoilage Microorganisms<sup>6</sup>

## 2.2 International Commission on Radiation Units and Measurements (ICRU) Reports<sup>7</sup>

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

ICRU 17, Radiation Dosimetry: X-rays Generated at Potentials of 5 to 150 kV

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

ICRU 33, Radiation Quantities and Units

ICRU 34, The Dosimetry of Pulsed Radiation

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

## 2.3 NCRP Publications<sup>8</sup>

NCRP Report No. 69, Dosimetry of X-Ray and Gamma-Ray Beams for Radiation Therapy in the Energy Range 10 keV to 50 MeV, December 1981

## 2.4 Methods for Calculating Absorbed Dose and Dose Distribution<sup>9</sup>

ZTRAN Monte Carlo Code

Integrated Tiger Series (ITS) Monte Carlo Codes

Energy Deposition in Multiple Layers (EDMULT) Electron Gamma Shower (EGS43)

Monte Carlo Codes

## 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/kg of the specified material (1 Gy = 1 J/kg). The mathematical relationship is the quotient of  $d\bar{\epsilon}$  by  $dm$ , where  $d\bar{\epsilon}$  is the mean incremental energy imparted by ionizing radiation to matter of incremental mass  $dm$  (see ICRU 33).

$$D = \frac{d\bar{\epsilon}}{dm}$$

### DISCUSSION :

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

$$D = \phi[E(\mu_{en}/\rho)]$$

where:

$\phi$  = particle fluence (particles/m<sup>2</sup>),

$E$  = energy of the ionizing radiation (J), and

$\mu_{en}/\rho$  = mass energy absorption coefficient (m<sup>2</sup>/kg)

4. If bremsstrahlung production within the specified material is negligible, the mass energy absorption coefficient  $\mu_{en}/\rho$  is equal to the mass energy transfer coefficient ( $\mu_{tr}/\rho$ ), and absorbed dose is equal to kerma.

3.1.2 *absorbed-dose rate ( $\dot{D}$ )*—the absorbed dose in a material per incremental time interval, that is, the quotient of  $dD$  by  $dt$ .

$$\dot{D} = \frac{dD}{dt}$$

Unit: Gy · s<sup>-1</sup>

DISCUSSION—The absorbed dose rate can be specified in terms of average value of  $D$  over long-time intervals, for example, in units of Gy · min<sup>-1</sup> or Gy · h<sup>-1</sup>.

3.1.3 *bremsstrahlung*—broad-spectrum electromagnetic radiation emitted when an energetic electron is influenced by strong electric field, such as that in the vicinity of an atomic nucleus. Particularly, 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.

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

3.1.5 *charged particle equilibrium*—a condition that exists in a material under irradiation if the kinetic energies, numbers, and direction of the secondary electrons induced by the radiation are uniform throughout the measurement volume of interest. Thus, the sum of the kinetic energies of the secondary electrons entering the volume equals the sum of the kinetic energies of the secondary electrons leaving the volume.

DISCUSSION—Electron equilibrium often is referred to as charged-particle equilibrium.

3.1.6 *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.

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

<sup>6</sup> Annual Book of ASTM Standards, Vol 15.09.

<sup>7</sup> Available from the International Commission on Radiation Units and Measurements, 7910 Woodmont Ave., Suite 800, Bethesda, MD 20814 USA.

<sup>8</sup> Available from the National Council on Radiation Units and Measurements, 7910 Woodmont Ave., Bethesda, MD 20814 USA.

<sup>9</sup> Available from the Radiation Shielding Information Center (RSIC) Oak Ridge National Laboratory (ORNL) P.O. Box 2008, Oak Ridge, TN 37381 USA.

the specimen uniformly. In practice, a certain variation in absorbed dose through the specimen will exist. Absorbed-dose mapping should determine the magnitude, location, and reproducibility of the maximum ( $D_{max}$ ) and minimum absorbed dose ( $D_{min}$ ) for a given set of experimental parameters. When pronounced absorbed-dose gradients exist, it is important to use dosimeters that are suitable for measuring these variations. For example, very small dosimeters may be needed to measure the change in absorbed dose across the interface between materials.

4.3 Theoretical calculations may provide useful information about absorbed-dose distribution in the irradiated specimen, especially near material interfaces (see *Methods for Calculation in Absorbed Dose and Dose Distribution*<sup>9</sup> and Refs (1) and (2)).<sup>10</sup>

4.4 Proper reporting of the experimental set-up is important since the degree of biological effect may be a function of various factors such as the absorbed-dose rate, energy of the incident radiation and the type of incident radiation. For example, the total absorbed dose received by a specimen may be the same for two different applications, but the effect of the irradiations on the food or agricultural products may be different because the absorbed-dose rates were different.

4.5 Factors that may alter the response of agricultural products to ionizing radiation include genus, species, variety, vigor, life-stage, initial quality, state of ripeness, temperature, moisture content, pH, packaging, shipping and storage time, and conditions. Although these factors are not discussed elsewhere in this guide, they should be considered in the experimental design (see Guides F 1355, F 1356, and F 1736).

## 5. Type of Facilities and Modes of Operation

5.1 This guide covers the following types of radiation sources and modes of operation, which may be used to irradiate food and agricultural products for the purpose of conducting research.

5.2 *Self Contained Research Irradiators*—Self-contained, dry-storage research irradiators are devices that house the radiation source (usually  $^{137}\text{Cs}$  or  $^{60}\text{Co}$ ) in a protective lead shield (or other high atomic number material), and may have a mechanism to rotate or lower the specimen from the load/unload position to the irradiate position. The most common method of use is to rotate the specimen on an irradiator turntable in front of the source. The second method is to distribute the source in a circular array. The irradiated specimen is located at the center of the array, resulting in a uniform dose distribution.

5.3 *Electron Accelerator (Electron and Bremsstrahlung X-ray Modes)*—Accelerator-generated radiation can be in the form of electrons or bremsstrahlung X-rays. For this type of accelerator, radiation is emitted or generated and directed at the specimen placed beneath a collimator. The collimator is used to create a highly defined beam of radiation.

5.3.1 For an electron accelerator system, the principle system parameters affecting absorbed dose are the energy

spectrum, average beam current, beam dispersion, and conveyor speed (where applicable). The electron energy spectrum dictates the variation of absorbed dose with depth in a given material (see Practices E 1431, E 1608, and E 1649).

5.3.2 A bremsstrahlung X-ray accelerator emits short-wavelength electromagnetic radiation, similar in energy to nuclear gamma radiation. Although their effects on materials generally are similar, these kinds of radiation differ in their energy spectra, angular distributions, depth-dose distributions and absorbed-dose rates (see Practices E 1431, E 1608 and E 1649). Spectrum filtration can be used to reduce the low-energy component of the radiation, thus improving the dose uniformity ratio in the specimen.

5.3.3 Specimens may be irradiated using a self-contained bremsstrahlung X-ray irradiator. The x-rays are produced in a conventional manner, but the unit is totally self-contained. Spectrum filtration can be used to reduce the low-energy component of the radiation, thus improving the dose uniformity ratio in the specimen. In some cases, irradiator turntables are used.

5.4 *Radiation Processing Facilities*—Commercial radiation processing facilities also can be used for conducting research on food and agricultural products (see Practices E 1204 and E 1431). These facilities can be categorized by irradiator type (for example, container or bulk flow), conveyor system (for example, shuffle-dwell or continuous), and operating mode (for example, batch or continuous).

## 6. Radiation Source Characteristics

6.1 The gamma-ray sources used in a facility considered in this guide consist of sealed elements (usually of  $^{60}\text{Co}$  or  $^{137}\text{Cs}$ ), which are typically linear rods or pencils arranged singly, or in one or more planar or cylindrical arrays.

6.1.1 Cobalt-60 emits photons with energies of approximately 1.17 and 1.33 MeV in nearly equal proportions. Cesium-137 produces photons with energies of approximately 0.662 MeV (3, 4).

6.1.2 For gamma-ray sources, the only variation in the source output is the known reduction in the activity caused by radioactive decay. The reduction in the source strength, and the corresponding increase in the irradiation time, may be calculated or obtained from source-decay tables.

6.1.3 The half-lives for  $^{60}\text{Co}$  and  $^{137}\text{Cs}$  are approximately 5.27 years and 30.2 years, respectively (3).

NOTE 1—Although the output of gamma-ray sources may be expected to be constant (except for radioactive decay), errors may be introduced by the existence of radioactive impurities (for example,  $^{134}\text{Cs}$  radioactive impurities in  $^{137}\text{Cs}$ ).

6.2 Direct-action electron accelerators, which employ dc or pulsed high-voltage generators can produce electron energies up to 5 MeV. Indirect-action electron accelerators use microwave or very high frequency (vhf) ac power to produce electron energies typically from 5 MeV to 15 MeV.

6.3 The continuous energy spectrum of the bremsstrahlung X-rays varies from almost zero up to the maximum energy of the electrons incident on the converter (See Reference (5) and Practice E 1608).

component of the radiation field.

6.4 For food and agricultural products, regulations in some countries limit the maximum electron energy to 10 MeV and photon energy to 5 MeV to avoid the possibility of induced radioactivity in the product.

## 7. Dosimetry Systems

7.1 Dosimetry systems used to determine absorbed dose shall cover the absorbed-dose range of interest and shall be calibrated before use.

7.2 Evaluate the dosimetry system for those parameters associated with the radiation source and experimental set-up that may influence dosimeter response; for example, source, energy, and environmental conditions, such as temperature, humidity and light. For purposes of research, several different types of dosimeters may be used. For the selection of dosimeters, see Guide E 1261.

7.3 Dosimeters may be divided into four basic classes according to their relative accuracy and areas of applications: primary-standard, reference-standard, transfer standard, and routine dosimeters (see Guide E 1261).

7.3.1 *Primary Standard Dosimeters*—Primary standard dosimeters are established and maintained by national standards laboratories for calibration of radiation environments. The two most commonly used primary standard dosimeters are ionization chambers and calorimeters (see Guide E 1261, ICRU Reports 14, 17, 34, and 35, and NCRP Report 69).

7.3.2 *Reference Standard Dosimeters*—Reference standard dosimeters are used to calibrate radiation environments and routine dosimeters (see Guide E 1261).

NOTE 3—Most self-contained dry-storage irradiator manufacturers measure an absorbed-dose rate, using a reference standard dosimetry system, at a reference location (see 10.4.1) within a simulated product, such as the center of the product or simulated product volume, or air medium.

7.3.3 *Transfer Standard Dosimeters*—Transfer standard dosimeters are specially selected dosimeters used for transferring absorbed-dose information from an accredited or national standards laboratory to a local irradiation facility in order to establish traceability for the local calibration facility. Normally, these dosimeters are used under conditions that are carefully controlled by the issuing laboratory. They are either reference standard or routine dosimeters (see Guide E 1261).

7.3.4 *Routine Dosimeters*—Routine dosimeters may be used during research for quality control and process monitoring. Proper dosimetric techniques, including calibration, shall be employed to ensure that the measurements are reliable and accurate.

### 7.4 Calibration of Dosimetry Systems:

7.4.1 Prior to use, dosimetry systems 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. Irradiation is a critical component of the calibration of the dosimetry system. Detailed calibration procedures are provided in Guide E 1261.

7.4.2 *Calibration Irradiation of Reference or Transfer Dosimeters*—Calibration irradiations shall be performed by irradiating the reference or transfer standard dosimeters using a calibration facility that provides an absorbed dose or an absorbed-dose rate having measurement traceability to nationally or internationally recognized standards.

7.4.3 *Calibration Irradiation of Routine Dosimeters*—Calibration irradiations may be performed in several ways, including irradiating the routine dosimeters using:

7.4.3.1 A calibration facility that provides an absorbed dose or an absorbed-dose rate having measurement traceability to nationally or internationally recognized standards,

7.4.3.2 An in-house calibration facility that provides an absorbed dose or an absorbed-dose rate having measurement traceability to nationally or internationally recognized standards, or

7.4.3.3 A production or research irradiation facility together with reference or transfer standard dosimeters that have measurement traceability to nationally or internationally recognized standards.

7.4.4 When a reference or transfer standard dosimeter is to be used as a routine dosimeter, calibration also may be performed as stated in 7.4.3.2 or 7.4.3.3.

7.4.5 *Instrument Calibration*—Calibrations of the individual instruments used in the analysis of the dosimeters shall be verified at periodic intervals. These calibrations shall be traceable to nationally or internationally recognized standards. For example, if an optical absorbance-measuring instrument, such as a spectrophotometer or densitometer is used, then appropriate standards shall be used to verify the accuracy of the optical absorbance at a specified wavelength(s). See Practices E 275, E 925, and E 958.

7.5 *Factors That Affect the Response of Dosimeters*—Factors that affect the response of dosimeters, including environmental conditions and variation of such conditions within the processing facility, should be known and taken into account (see Guide E 1261). The associated analytical instrumentation shall be calibrated.

## 8. Radiation-Sensitive Indicators

8.1 The purpose of radiation-sensitive indicators is to determine visually whether or not a product has been irradiated, rather than to measure different absorbed-dose levels. Indicators are used to show that a specific product has been exposed to ionizing radiation (see Guide E 1539). Indicators do not give a quantitative value of absorbed dose, and therefore, are not a substitute for routine dosimeters used in routine process monitoring.

8.2 Radiation-sensitive indicators are neither a substitute for nor a complement to dosimetry (see Guide E 1539).

## 9. Experimental Design

9.1 *Objective*—The purpose of dosimetry in experimental design is to establish baseline data for evaluating the effectiveness, predictability, and reproducibility of the experiment under a range of conditions. For example, dosimetry should be used to establish relationships between absorbed dose for a reproducible geometry and the experimental parameters, to characterize absorbed-dose

variations when conditions fluctuate statistically and through normal experimental conditions, and to measure absorbed-dose distributions in the irradiated specimen.

**9.2 Determination of an Optimal Absorbed Dose**—The design of experiments usually includes choosing several nominal absorbed doses in order to analyze the effect, and to help determine the optimal range of absorbed dose. It is essential that the nominal doses take into account the inherent range of actual doses throughout the specimen. The step width between nominal doses should be larger than the range between the maximum and minimum absorbed dose for the respective nominal doses.

**9.3 Equipment Qualification Documentation**—Establish and document a qualification program to demonstrate that the experimental procedure will produce a reproducible absorbed-dose distribution in a given specimen. Documentation shall include descriptions of instrumentation and equipment necessary for the precise repetition of the experiment.

#### **9.4 Equipment Testing and Calibration:**

**9.4.1 Processing Equipment**—The absorbed dose in the specimen depends on the experimental parameters.

**9.4.1.1** Test all equipment and instrumentation that may influence absorbed dose in the specimen.

**9.4.1.2** Implement a documented calibration program to assure that all equipment and instrumentation that may influence absorbed-dose interpretation are calibrated periodically. Examples are the calibration of the timing mechanism, and verification of the turntable rotation.

**9.4.2 Analytical Equipment**—The accuracy of the absorbed-dose measurement depends on the correct operation and calibration of the analytical equipment used in the analysis of the dosimeters.

**9.4.2.1** Check the performance of the analytical equipment periodically to ensure that the equipment is functioning according to performance specifications. Repeat this check following any equipment modification or servicing and prior to the use of the equipment for a dosimetry system calibration. This check can be accomplished by using standards, such as calibrated optical density filters, wavelength standards, or calibrated thickness gages supplied by the manufacturer or national or accredited standards laboratories.

**9.4.2.2** Implement a documented calibration program to assure that all analytical equipment used in the analysis of dosimeters is calibrated periodically.

#### **9.5 Characterization of the Experiment:**

**9.5.1** The absorbed dose received by any portion of a specimen depends on experimental parameters, such as the source activity at the time of irradiation (if a radioisotope source is used) the geometry of the source, the source-to-product distance, and the irradiation geometry; and, on processing parameters, such as the irradiation time, the product composition and density, and the product loading configuration.

**9.5.2 Transit Dose**—The effects caused by movement of the product or source to and from the irradiation position shall be considered and quantified.

**9.5.3 Dose Mapping**—The characterization of the experiment includes mapping the absorbed-dose distributions

throughout the specimen or package, whether this comprises a single item, such as an orange, or group of items such as a box of oranges. This can be achieved by placing dosimeters throughout the specimen, both on the surface and within the specimen. Select placement patterns that can identify the locations of maximum absorbed dose and minimum absorbed dose. Dosimetry data from previously performed experiments or theoretical calculations may provide useful information for determining the number and location of dosimeters needed for this characterization process.

**NOTE 4**—In the case of static irradiations, such as when the product is located at the center of a circular source array, the dosimetry placement should be done in three dimensions. When product is irradiated on turntables, the dosimetry placement can be done in two dimensions, such as an arbitrary vertical plane through the axis of rotation. In this case, the result is a three-dimensional mapping due to the product rotation.

**NOTE 5**—In cases where the irradiated specimen is mixed before, during, or after irradiation, for example, fluids or powders, absorbed-dose mapping may not be practicable. In those cases, theoretical calculations of the absorbed-dose distribution may be appropriate.

**9.5.3.1** Ideally, the radiation process should be designed to irradiate the specimen uniformly. In practice, a certain variation in absorbed-dose through the specimen will exist. Absorbed-dose mapping is used to determine the magnitude and locations of maximum and minimum absorbed doses for a given set of experimental parameters, for example, timer setting, product loading configuration. In some applications the irradiated specimen may be relatively close to the radiation sources, resulting in a pronounced absorbed-dose gradient near the periphery of the specimen. It is important, therefore, to choose a dosimetry system which is able to detect these gradients. Small dimension dosimeters or dosimeter film in strips or sheets may be employed to obtain useful information about dose gradients likely to occur within an irradiated specimen.

**9.5.3.2** Changes in the product handling system and radiation source characteristics may affect the absorbed-dose distribution and thus require further dosimetry.

**9.5.4  $D_{\max}$  and  $D_{\min}$** —Locations and values of the absorbed-dose extremes (maximum and minimum absorbed doses,  $D_{\max}$  and  $D_{\min}$  respectively) in the specimen shall be determined and reported. In cases where there is a significant difference between  $D_{\max}$  and  $D_{\min}$  in the specimen, radiation effects at a specific location in the specimen should be correlated with those locations.

**NOTE 6**—For example, if a carton of lemons is irradiated on a rotating platform, or from two or four sides, there may be a range of absorbed dose, such that the lemons in the center of the box will receive an absorbed dose that is less than those on the sides or corners. It is important, therefore, that the lemons are not mixed after irradiation. They should be removed carefully so that the research data on individual lemons can be correlated properly with the specific dose that was received.

**9.5.5 Reference Position**—If the locations of absorbed-dose extremes identified during the mapping procedure are not readily accessible during routine processing (see Section 10), alternative reference positions may be used. The relationships between the absorbed dose at these reference positions and the absorbed-dose extremes shall be established, shown to be reproducible, and documented.

9.5.6 Factors that may affect the absorbed-dose distribution in the agricultural specimen include:

9.5.6.1 In general, radiation intensity decreases with distance from the source:

9.5.6.2 Secondary radiation, such as electrons and bremsstrahlung is generated as radiation passes through the agricultural specimen and other material. Secondary radiation may influence absorbed doses on the surface of the test material;

9.5.6.3 Characteristics of the container or apparatus used to hold the specimen to be irradiated, as well as the atomic composition of the food or agricultural product;

9.5.6.4 Inherent characteristics, for example, geometry, of the radiation source; and,

9.5.6.5 Characteristics of the product, for example, mass density, electron density, geometry, composition.

NOTE 7—The flux of secondary charged particles depends on the atomic composition of the region surrounding the point of interest up to a distance that is equal to the maximum range of the secondary particles. Absorbed-dose variations are particularly pronounced within bone and at bone-tissue interfaces.

9.5.7 The dose nonuniformity in the specimen may be improved by irradiating the specimen on a rotating turntable, or by irradiating it from two or four sides.

9.5.8 Due to the scatter of radiation, the absorbed dose near the surface of the specimen may rise as any material, such as supports or other objects are brought near. The contribution of scatter to the total absorbed dose should be understood, especially when deciding where to place the dosimeters for the dose mapping. An experiment may require conditions of maximal scatter, so conventional depth-dose data can be used, or minimal scatter, so that the radiation quality is well-defined.

9.5.9 If the incident radiation is attenuated substantially in the irradiated volume, large absorbed-dose gradients may exist. A more penetrating radiation, or bilateral or multilateral exposure may be used to improve the dose uniformity. The specimen can be rotated in front of the source or its equivalent: rotation of the source around the stationary specimen. An important step in obtaining good dose uniformity is achieved in the progression from unilateral to bilateral exposure.

9.5.10 Except for studies designed to explore their effects, arrangements yielding complex or unusual radiation patterns should be avoided, for example, filtration of very high or very low energy X-rays, or irradiating microorganisms in contact with high- or medium-atomic number material.

NOTE 8—The complications associated with more complex irradiation configurations may be difficult to justify.

9.5.11 The establishment of electron equilibrium could require an appreciable depth of build-up material. The appropriate thickness of such material depends on the energy of the incident radiation (see Practices E 666 and E 668).

NOTE 9—The degree to which nonequilibrium conditions contribute to dose nonuniformity depends on the size of the irradiated specimen and the energy of the incident radiation.

9.5.12 To reduce the effect of scattering of radiation, the container or apparatus used to hold the specimen may be selected as to have similar composition to the irradiated specimen. A high degree of dose uniformity may be achieved

if the object is irradiated in cavities of tissue-equivalent materials. Such material also will absorb the secondary electrons generated during the passage of gamma rays or bremsstrahlung through the steel walls of an irradiation chamber. Small dosimeters, for example, radiochromic film, which are placed near a metal interface also should be surrounded by an appropriate thickness of build-up material (see Practices E 666 and E 668) unless they are being used to measure the effects.

9.5.13 In some irradiation geometries, especially when the gamma-rays or bremsstrahlung X-rays are collimated, the absorbed dose at the surface of the specimen may be significantly lower than the equilibrium dose, which occurs at a depth in the material equivalent to the maximum range of the secondary electrons. If the range of the secondary electrons is appreciable, the absorbed dose may vary greatly within a significant portion of the irradiated specimen. For example, when high voltage X-rays impinge on a specimen, the absorbed dose in the material near the first surface is relatively low.

9.5.14 For gamma-rays and bremsstrahlung X-rays, the variation of absorbed dose with depth is affected by the spectrum composition and spectral hardening with depth. Spectral hardening, often called beam hardening, is the increase in the average energy of the particles because of preferential loss at lower energies by absorption or scattering.

## 10. Routine Dosimetry Following the Experiment Set-Up

10.1 *Objective*—Once the reproducibility of the absorbed-dose distribution has been determined for a given set of experimental conditions, perform periodic routine monitoring to show that the experiment is within specification. This may be accomplished by monitoring at the minimum or maximum absorbed-dose locations, or at a reference dose position (see 9.5.5). In a reproducible experiment, the absorbed-dose measurement at any of these locations should be sufficient to indicate that the experiment is within specification.

10.2 *Specimen Loading Configuration*—A loading configuration for the irradiation shall be established for each specimen type. The documentation for this loading configuration shall include specifications for parameters such as specimen size, mass or density, which influence the absorbed-dose distribution.

10.3 *Establishment and Control of Experimental Parameters*—For each irradiated specimen, there is a minimum dose to achieve the desired effect, and a maximum dose that the specimen can tolerate without degradation in quality. Often the experiment is defined by targeting a known dose to the center of the specimen, while achieving the required minimum dose everywhere else. All critical experimental parameters that can affect the absorbed-dose distribution must be controlled and monitored during subsequent experiments.

NOTE 10—This does not preclude the possibility of research solely for the determination of  $D_{\max}$  and  $D_{\min}$ .

### 10.4 Routine Dosimetry:

10.4.1 Routine measurements of absorbed dose will help ensure that the specimen has been treated with at least the minimum dose prescribed by the process. If the  $D_{\min}$  location

is not readily accessible, dosimeters may be placed at one or more reference positions for routine monitoring (see 9.5.5).

NOTE 11—All equipment functions and personnel activities that ensure the effectiveness of the experiment are components of process control. Process control may include specimen handling and loading/unloading practices and the monitoring of experimental parameters.

10.4.2 Routine dosimetry is part of the verification process for establishing that the experiment is under control.

10.4.3 Ensure that the specimen receives the required absorbed-dose by employing proper dosimetric measurement procedures, with appropriate statistical controls and documentation. These procedures involve the use of routine in-plant dosimetry performed as described below.

10.4.4 *Dosimeter Location*—Place a dosimeter or dosimeters in, or on the specimen at predetermined locations of the maximum and minimum absorbed dose, or alternatively at one or more reference positions (see 9.5.5).

NOTE 12—The absorbed-dose distribution in the specimen is already known from the dose mapping effort and from the experimental parameters. However, the use of a sufficient number of strategically placed dosimeter sets serves to confirm that the absorbed doses within the specified range have been achieved.

10.4.5 *Environmental Effects*—If there is a change in the environment, for example, temperature, humidity, of a dosimeter during the experiment, the response of the dosimeter may be affected. If required, correct the dosimeter response for any such effect. Care also must be taken in handling and storage of dosimeters before and after irradiation (see Guide E 1261).

10.4.6 *Chilled or Frozen Specimens*—If the response of dosimeters is temperature dependent, exercise care when determining the temperature of the dosimeter during irradiation of chilled or frozen specimens and when applying the appropriate temperature correction. Dosimeters that exhibit a highly temperature-dependent response should not be placed in locations with large temperature gradients (see Guide E 1261).

10.4.7 *Radiation-Sensitive Indicators*—The use of radiation-sensitive indicators is neither a substitute for nor a complement to the dosimetry procedures (see Guide E 1539).

10.4.8 Absorbed-dose measurements made in the specimen at regular intervals can provide the experimenter with an independent quality control record for the process. The ability to measure that absorbed dose with proper statistics is a critical requisite of Good Laboratory Practices (GLPs).

10.4.9 Statistical analysis of routine absorbed-dose measurements should be used in quality control to monitor unexpected changes in the experiment.

10.4.10 Adequate dosimetry should be performed to establish baseline data for evaluating the effectiveness, predictability, and reproducibility of the system under the range of experimental conditions. After the baseline data have been determined, less frequent dosimetry may be performed depending on the reproducibility of the experiment. Regular dosimetry is recommended for quantitative experimental and quality control.

## 11. Documentation

11.1 In all cases, record and report the following information:

11.1.1 The type of irradiator and the type (or types) of radiation emitted by the radiation source;

11.1.2 The radiation energy spectrum, including any filtration;

NOTE 13—If the gamma-ray source energy spectrum source incident on the specimen is not available, the information on the radiation source geometry, such as pellet and cladding thickness, should be documented and reported. For bremsstrahlung sources, the composition and thickness of the conversion target should be documented and reported.

11.1.3 The distance between the source and the surface or center of the irradiated specimen;

11.1.4 Physical data on the irradiated specimen, for example, dimensions, mass, composition;

11.1.5 Characteristics of the container or apparatus used to hold the specimen during the irradiation;

11.1.6 Source geometry, including radionuclide distribution (if applicable);

11.1.7 Uniformity of the absorbed-dose rate at positions within the irradiation chamber;

11.1.8 Temperature and atmospheric conditions maintained around the specimen during the irradiation;

11.1.9 The type(s) and number(s) of dosimeters used, including their packaging and placement within the specimen;

11.1.10 A description of the response function or calibration curve that is appropriate to the actual experimental conditions, and its traceability to national or international standards;

11.1.11 Moisture content, pH, packaging of the irradiated specimen;

11.1.12 Number of experimental replications;

11.1.13 Complete description of the specimen being irradiated, for example, genus, species, life-stage of insects or protozoa, growth phase of bacteria. In the case of fruit, include: variety, age, vigor, ripeness, maturity, color, evidence of phytotoxic effects (if any), method, length, and temperature of storage before and after irradiation. In the case of meat or poultry, identify the exact product being irradiated, whether bone was included, the cut of tissue, age, rigor, when slaughtered, method of storage and/or transport, and the physical dimensions. In general, include details about factors that have been noted as affecting the quality of the product by any other processing technology, and,

11.1.14 description of packaging or packaging materials that are in contact with the specimen, or might influence the atmospheric conditions, at the time of irradiation.

11.2 The laboratory shall retain all original observations, calculations, derived data and calibration records (for at least five years). The records of each measurement or calculation shall contain enough information to permit their repetition. These records include the identity of all personnel involved in the measurement or calculation.

## 12. Precision and Bias <sup>11</sup>

12.1 To be meaningful, a measurement of absorbed dose shall be accompanied by an estimate of uncertainty. Components of uncertainty shall be identified as belonging to one of two groups:

<sup>11</sup> Measurement uncertainty is a more accurate description of this section.

- (A) Those that are evaluated by statistical methods, or
- (B) Those that are evaluated by other means.

Additional information is given in Guide E 1707 and references (6) and (7), where these components are referred to as Type A and Type B, respectively. In reporting uncertainty, other classifications, such as *precision* and *bias* may be useful.

NOTE 14—The identification of Type A and Type B uncertainties is based on the methodology adopted in 1993 by the International Organization for Standardization (ISO) for estimating uncertainty (7). This is different to the way uncertainty has been traditionally expressed in terms of “precision” and “bias”, where precision is a measure of the extent to which replicate measurements made under specific conditions are in agreement, and bias is a systematic error (see Terminology E 170 and E 456 and Practice E 177). The purpose of using the method of expressing uncertainties as Type A and Type B is to promote an understanding of how uncertainty statements are arrived at, and to provide a basis for the international comparison of measurement results.

NOTE 15—Guide E 1707 defines possible sources of error in dosimetry performed in radiation processing facilities and offers procedures for estimating the resulting magnitude of the uncertainties in the measurement results. Basic concepts of measurement, estimate of the measured value of a quantity, “true” value, error and uncertainty are defined and discussed. Components of uncertainty are discussed and methods are given for evaluating and estimating their values. Their contributions to the standard uncertainty in the reported values of absorbed dose are considered and

methods are given for calculating the combined standard uncertainty and an estimate of overall (expanded) uncertainty.

12.2 The components of uncertainty involved in a measurement shall be estimated or determined. The overall uncertainty in the measurement may be estimated from a combination of these components, and the procedure for combining these components shall be stated or referenced specifically in all results.

12.3 The accuracy of the absorbed-dose measurement is a function of the dosimetry system used. All dosimeters have environmental dependences that should be compensated for in the final results (see Guide E 1261). These corrections would introduce uncertainties in the measured absorbed-dose values, and they must be included in the estimate in the evaluation of the dosimetry system’s overall uncertainty (see Guide E 1707).

### 13. Keywords

13.1 absorbed dose; absorbed-dose mapping; absorbed-dose measurement; dosimetry system; electron beam; experimental design; food and agriculture; gamma radiation; ionizing radiation; measurement uncertainty; primary standard dosimeter; radiation-sensitive indicator; reference standard dosimeter; routine dosimeter; transfer standard dosimeter

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