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Guide for dosimetry in radiation research on food and agricultural products

Guide de la dosimétrie pour la recherche dans le domaine de l'irradiation des produits alimentaires et agricoles

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75% of the member bodies casting a vote.

ASTM International is one of the world's largest voluntary standards development organizations with global participation from affected stakeholders. ASTM technical committees follow rigorous due process balloting procedures.

A pilot project between ISO and ASTM International has been formed to develop and maintain a group of ISO/ASTM radiation processing dosimetry standards. Under this pilot project, ASTM Subcommittee E10.01, Dosimetry for Radiation Processing, is responsible for the development and maintenance of these dosimetry standards with unrestricted participation and input from appropriate ISO member bodies.

Attention is drawn to the possibility that some of the elements of this International Standard may be the subject of patent rights. Neither ISO nor ASTM International shall be held responsible for identifying any or all such patent rights.

International Standard ISO/ASTM 51900 was developed by ASTM Committee E10, Nuclear Technology and Applications, through Subcommittee E10.01, and by Technical Committee ISO/TC 85, Nuclear Energy.

Standard Guide for Dosimetry in Radiation Research on Food and Agricultural Products[1]

This standard is issued under the fixed designation ISO/ASTM 51900; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision.

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 and ISO/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 ISO/ASTM Practices 51204, 51431, 51608, 51649, and 51702. The selection and calibration of dosimetry systems is specified in ISO/ASTM Guide 51261.

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[2]

E 177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods[3]

E 275 Practice for Describing and Measuring Performance of Ultraviolet, Visible, and Near Infrared Spectrophotometers[4]

E 456 Terminology Relating to Quality and Statistics[5]

E 666 Practice for Calculating Absorbed Dose from Gamma or X Radiation[2]

E 668 Practice for Application of Thermoluminescence Dosimetry (TLD) Systems for Determining Absorbed Dose in Radiation Hardness Testing of Electronic Devices[2]

E 925 Practice for the Periodic Calibration of Narrow Band Pass Spectrophotometers[4]

E 958 Practice for Measuring Practical Spectral Bandwidth of Ultraviolet Visible Spectrophotometers[4]

E 1026 Practice for Using the Fricke Reference Standard Dosimetry System[2]

F 1355 Guide for the Irradiation of Fresh Fruits as a Phytosanitary Treatment[2]

F 1356 Guide for the Irradiation of Fresh and Frozen Red Meat and Poultry to Control Pathogens and other Microorganisms[2]

F 1640 Guide for Packaging Materials for Foods to be Irradiated[2]

F 1736 Guide for the Irradiation of Finfish and Shellfish to Control Pathogens and Spoilage Microorganisms[2]

2.2 *ISO/ASTM Standards:*

51204 Practice for Dosimetry in Gamma Irradiation Facilities for Food Processing[2]

51261 Guide for Selection and Calibration of Dosimetry Systems for Radiation Processing[2]

[1] This guide is under the jurisdiction of ASTM Committee E10 on Nuclear Technology and Applications and is the direct responsibility of Subcommittee E10.01 on Dosimetry for Radiation Processing, and is also under the jurisdiction of ISO/TC 85/WG 3.

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[2] *Annual Book of ASTM Standards*, Vol 12.02.

[3] *Annual Book of ASTM Standards*, Vol 04.02.

[4] *Annual Book of ASTM Standards*, Vol 03.06.

[5] *Annual Book of ASTM Standards*, Vol 14.02.

51275 Practice for Use of a Radiochromic Film Dosimetry System[2]
51431 Practice for Dosimetry in Electron and Bremsstrahlung Irradiation Facilities for Food Processing[2]
51539 Guide for the Use of Radiation-Sensitive Indicators[2]
51540 Practice for Use of a Radiochromic Liquid Dosimetry System[2]
51607 Practice for Use of the Alanine-EPR Dosimetry System[2]
51608 Practice for Dosimetry in an X-ray (Bremsstrahlung) Facility for Radiation Processing[2]
51649 Practice for Dosimetry in Electron Beam Facility for Radiation Processing at Energies between 300 keV and 25 MeV[2]
51702 Practice for Dosimetry in a Gamma Irradiation Facility for Radiation Processing[2]
51707 Guide for Estimating Uncertainties in Dosimetry for Radiation Processing[2]

2.3 *International Commission on Radiation Units and Measurements (ICRU) Reports*[6]

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 34 The Dosimetry of Pulsed Radiation
ICRU 35 Radiation Dosimetry: Electron Beams with Energies Between 1 and 50 MeV
ICRU 60 Radiation Quantities and Units

2.4 *NCRP Publications*[7]

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

2.5 *Methods for Calculating Absorbed Dose and Dose Distribution*[8]

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 60).

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

3.1.1.1 *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 expresssed as follows:

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

where:

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

(*4*) If bremsstrahlung production within the specified material is negligble, 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.

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^{-1}

3.1.2.1 *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^{-1} or Gy · h^{-1}.

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.

3.1.5.1 *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.

[6] Available from the International Commission on Radiation Units and Measurements, 7910 Woodmont Ave., Suite 800, Bethesda, MD 20814 USA.
[7] Available from the National Council on Radiation Protection and Measurements, 7910 Woodmont Ave., Bethesda, MD 20814 USA.
[8] Available from the Radiation Shielding Information Center (RSIC) Oak Ridge National Laboratory (ORNL) P.O. Box 2008, Oak Ridge, TN 37381 USA.

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

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

3.1.9 *electron equilibrium*—charged particle equilibrium for electrons.

3.1.10 *equilibrium absorbed dose*—the absorbed dose in a finite volume within the material in which the condition of approximate electron equilibrium exists.

3.1.11 *irradiator turntable*—device used to rotate the sample during the irradiation to improve the dose uniformity ratio.

3.1.11.1 *Discussion*—Some research irradiators use turntables instead of a transport or conveyor system for the purpose of dose homogeneity improvement.

3.1.12 *phantom material*—a mass of material with attenuation and scattering properties similar to those of the product, material, or substance to be irradiated.

3.1.12.1 *Discussion*—Phantom material may be used during the accelerator or irradiator characterization, or during absorbed-dose mapping as a substitute for the actual product, material or substance to be irradiated. When used in routine production runs, sometimes it is referred to as compensating dummy.

3.1.13 *primary-standard dosimeter*—a dosimeter of the highest metrological quality, established and maintained as an absorbed dose standard by a national or international standards organization (see ISO/ASTM Guide 51261).

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

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

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

3.1.17 *routine dosimeter*—dosimeter calibrated against a primary-, reference-, or transfer-standard dosimeter and used for routine absorbed-dose measurement (see ISO/ASTM Guide 51261).

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

3.1.19 *traceability*—the documentation demonstrating 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.

3.1.20 *transfer-standard dosimeter*—a dosimeter often a reference–standard dosimeter suitable for transport between different locations, used to compare absorbed-dose measurements (see ISO/ASTM Guide 51261).

3.1.21 *uncertainty*—a parameter associated with the result of a measurement, that characterizes the dispersion of the values that reasonably could be attributed to the measurand or derived quantity.

3.1.21.1 *Discussion*—(*1*) The parameter, for example, may be a standard deviation (or a given multiple of it), or the half-width or an interval having a stated level of confidence. (*2*) Uncertainty of measurement comprises, in general, many components. Some of these components may be evaluated from the statistical distribution of the results of a series of measurements and can be characterized by experimental standard deviations. The other components, which also can be characterized by standard deviations, are evaluated from assumed probability distributions based on experience or other information. (*3*) It is understood that the result of the measurement is the best estimate of the value of the measurand, and that all components of uncertainty, including those arising from systematic effects, such as components associated with corrections and reference standards, contribute to the dispersion. (*4*) The term overall uncertainty associated witha a measurand should take into account all components of error.

3.1.22 *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 Terms Specific to This Standard:*

3.2.1 *absorbed-dose mapping*—measurement of absorbed-dose within the irradiated specimen using dosimeters placed at specified locations to produce a one-, two- or three-dimensional distribution of absorbed dose, thus rendering a map of absorbed-dose values.

3.2.2 *dose uniformity ratio*—ratio of the maximum to the minimum absorbed dose within the irradiated specimen. The concept also is referred to as the max/min dose ratio.

3.2.3 *secondary radiation*—electrons or photons produced by the action of primary radiation on matter, such as Compton recoil electrons, photoelectric electrons, and pair-production electrons.

3.2.4 *target dose*—absorbed dose delivered to a specific location in, or on the specimen that results in an acceptable absorbed-dose distribution within the rest of the specimen.

3.2.5 *transit dose*—absorbed dose delivered to product, material, or substance as it moves from the load/unload position to the irradiate position, and back to the load/unload position.

4. Significance and Use

4.1 This guide is intended to provide direction on the dosimetry aspects of experiments in food and agricultural research. Research concerning the effectiveness of irradiation of food and agricultural products to achieve a defined benefit necessarily involves very different operating parameters from one study to another. For example, the absorbed dose required to sterilize fruit flies is much lower than the doses required to inactivate some bacterial pathogens in meat, or to decontaminate spices. Furthermore, the kind and design of the facility, including type of radiation source that may be used in these studies are often very different. Yet the investigators must report to the scientific community sufficient information to characterize adequately their studies so that these studies can be repeated by another competent researcher, and so that the absorbed dose may be reproduced properly during the conduct of the experiment.

4.2 Ideally, an experiment should be designed to irradiate 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[8] and Refs **(1)** and **(2)**.[9]

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 ASTM Guides F 1355, F 1356, and F 1736).

5. Types 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}Cs or ^{60}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 ISO/ASTM Practices 51431, 51608, and 51649).

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 ISO/ASTM Practices 51431, 51608, and 51649). 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 ISO/ASTM Practices 51204 and 51431). 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}Co or ^{137}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}Co and ^{137}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}Cs radioactive impurities in ^{137}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

[9] The boldface numbers in parentheses refer to the bibliography at the end of this standard.

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 ISO/ASTM Practice 51608).

NOTE 2—Spectrum filtration often is used to eliminate the low-energy 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 ISO/ASTM Guide 51261.

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 ISO/ASTM Guide 51261).

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 ISO/ASTM Guide 51261, 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 ISO/ASTM Guide 51261).

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 ISO/ASTM Guide 51261).

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 ISO/ASTM Guide 51261.

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 ASTM 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 ISO/ASTM Guide 51261). 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 ISO/ASTM Guide 51539). 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