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Guide for dosimetry for sterile insects release programs

Guide de la dosimétrie pour des programmes de lâchers d'insectes stériles

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Contents

Page

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 Committee E61, 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 document 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 51940 was developed by ASTM Committee E61, Radiation Processing, through Subcommittee E61.04, Specialty Application, and by Technical Committee ISO/TC 85, Nuclear energy, nuclear technologies and radiological protection.

An American National Standard

Standard Guide for Dosimetry for Sterile Insects Release Programs[1]

This standard is issued under the fixed designation ISO/ASTM 51940; 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 outlines dosimetric procedures to be followed for the radiation-induced reproductive sterilization of live insects for use in pest management programs. The primary use of such insects is in the Sterile Insect Technique, where large numbers of reproductively sterile insects are released into the field to mate with and thus control pest populations of the same species. A secondary use of sterile insects is as benign hosts for rearing insect parasitoids. The procedures outlined in this guide will help ensure that insects processed with ionizing radiation from gamma, electron, or X-ray sources receive absorbed doses within a predetermined range. Information on effective dose ranges for specific applications of insect sterilization, or on methodology for determining effective dose ranges, is not within the scope of this guide.

NOTE 1—Dosimetry is only one component of a total quality assurance program to ensure that irradiated insects are adequately sterilized and fully competitive or otherwise suitable for their intended purpose.

1.2 This guide provides information on dosimetry for the irradiation of insects for these types of irradiators: self-contained dry-storage ^{137}Cs or ^{60}Co irradiators, self-contained low-energy X-ray irradiators (maximum processing energies from 150 to 300 keV), large-scale gamma irradiators, and electron accelerators (electron and X-ray modes).

NOTE 2—Additional, detailed information on dosimetric procedures to be followed in installation qualification, operational qualification, performance qualification, and routine product processing can be found in ISO/ASTM Practices 51608 (X-ray [bremsstrahlung] facilities processing at energies over 300 keV), 51649 (electron beam facilities), 51702 (large-scale gamma facilities), and 52116 (self-contained dry-storage gamma facilities), and in Ref (**1**)[2] (self-contained X-ray facilities).

1.3 The absorbed dose for insect sterilization is typically within the range of 20 to 600 Gy.

1.4 This guide refers, throughout the text, specifically to reproductive sterilization of insects. It is equally applicable to radiation sterilization of invertebrates from other taxa (for example, Acarina, Gastropoda) and to irradiation of live insects or other invertebrates for other purposes (for example, inducing mutations), provided the absorbed dose is within the range specified in 1.3.

1.5 This guide also covers the use of radiation-sensitive indicators for the visual and qualitative indication that the insects have been irradiated.

1.6 This document is one of a set of standards that provides recommendations for properly implementing and utilizing dosimetry in radiation processing and describes a means of achieving compliance with the requirements of ASTM Practice E2628. It is intended to be read in conjunction with ASTM E2628.

1.7 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced documents

2.1 *ASTM Standards:*[3]

E170 Terminology Relating to Radiation Measurements and Dosimetry

E2303 Guide for Absorbed-Dose Mapping in Radiation Processing Facilities

E2628 Practice for Dosimetry in Radiation Processing

E2701 Guide for Performance Characterization of Dosimeters and Dosimetry Systems for Use in Radiation Processing

2.2 *ISO/ASTM Standards:*[3]

51261 Practice for Calibration of Routine Dosimetry Systems for Radiation Processing

51275 Practice for Use of a Radiochromic Film Dosimetry System

51310 Practice for Use of a Radiochromic Optical Waveguide Dosimetry System

51539 Guide for the Use of Radiation-Sensitive Indicators

51607 Practice for Use of an 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 Facility for Radiation Processing

51707 Guide for Estimating Uncertainties in Dosimetry for Radiation Processing

51956 Practice for Use of Thermoluminescence-Dosimetry

[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, and is also under the jurisdiction of ISO/TC 85/WG 3.

Current edition approved Dec. 26, 2012. Published April 2013. Originally published as ASTM E 1940–98. Last previous ASTM edition E 1940–98. The present International Standard ISO/ASTM 51940:2013(E) replaces ASTM E 1940–98 and is a major revision of the last previous edition ISO/ASTM 51940:2004(E).

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

[3] For referenced ASTM and ISO/ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

(TLD) Systems for Radiation Processing

52116 Practice for Dosimetry for a Self-Contained Dry-Storage Gamma-Ray Irradiator

2.3 *International Commission on Radiation Units and Measurements (ICRU) Reports:*[4]

ICRU 85a Fundamental Units and Quantities for Ionizing Radiation

2.4 *ISO Standards:*[5]

ISO/IEC 17025 General Requirements for the Competence of Testing and Calibration Laboratories

2.5 *Joint Committee for Guides in Metrology (JCGM) Reports:*

JCGM 100:2008, GUM, with minor corrections, Evaluation of measurement data – Guide to the Expression of Uncertainty in Measurement[6]

JCGM 100:2008, VIM International vocabulary of metrology – Basis and general concepts and associated terms[7]

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). The mathematical relationship is the quotient of $d\epsilon$ by dm, where $d\epsilon$ is the mean incremental energy imparted by ionizing radiation to matter of incremental mass dm (see ICRU 85a).

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

3.1.1.1 *Discussion*—The discontinued unit for absorbed dose is the rad (1 rad = 100 erg/g = 0.01 Gy). Absorbed dose is sometimes referred to simply as dose.

3.1.2 *absorbed-dose mapping*—measurement of absorbed-dose within an irradiated product to produce a one-, two- or three-dimensional distribution of absorbed dose, thus rendering a map of absorbed-dose values.

3.1.3 *absorbed-dose rate, $\dot{D}$*—absorbed dose in a material per incremental time interval, that is, the quotient of dD by dt. Also see ASTM E170. The SI unit is $Gy \cdot s^{-1}$

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

3.1.3.1 *Discussion*—The absorbed-dose rate can be specified in terms of its average value over long-time intervals, for example in units of $Gy \cdot min^{-1}$ or $Gy \cdot h^{-1}$

3.1.4 *approved laboratory*—laboratory that is a recognized national metrology institute, or has been formally accredited to ISO/IEC 17025, or has a quality system consistent with the requirements of ISO/IEC 17025.

3.1.4.1 *Discussion*—A recognized national metrology institute or other calibration laboratory accredited to ISO/IEC 17025 should be used in order to ensure traceability to a national or international standard. A calibration certificate provided by a laboratory not having formal recognition or accreditation will not necessarily be proof of traceability to a national or international standard.

3.1.5 *calibration [VIM*, 6.11]—set of operations that establish, under specified conditions, the relationship between values of quantities indicated by a measuring instrument or measuring system, or values represented by a material measure or a reference material, and the corresponding values realized by standards.

3.1.5.1 *Discussion*—Calibration conditions include environmental and irradiation conditions present during irradiation, storage and measurement of the dosimeters that are used for the generation of a calibration curve. To achieve stable environmental conditions, it may be necessary to condition the dosimeters before performing the calibration procedure.

3.1.6 *dose uniformity ratio*—ratio of maximum to minimum absorbed dose within the irradiated product.

3.1.6.1 *Discussion*—The concept is also referred to as the max/min dose ratio.

3.1.7 *dosimeter*—device that, when irradiated, exhibits a quantifiable change that can be related to absorbed dose in a given material using appropriate measurement instruments and procedures.

3.1.8 *dosimeter batch*—quantity of dosimeters made from a specific mass of material with uniform composition, fabricated in a single production run under controlled, consistent conditions and having a unique identification code.

3.1.9 *dosimeter set*—one or more dosimeters used to measure the absorbed dose at a location and whose average reading is used to determine absorbed dose at that location.

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

3.1.11 *influence quantity*—quantity that is not the measurand but that affects the result of the measurement.

3.1.11.1 *Discussion*—In radiation processing dosimetry, this term includes temperature, relative humidity, time intervals, light, radiation energy, absorbed-dose rate, and other factors that might affect dosimeter response, as well as quantities associated with the measurement instrument.

3.1.12 *in-situ/in-plant calibration*—calibration where the dosimeter irradiation is performed in the place of use of the routine dosimeters.

3.1.12.1 *Discussion*—In-situ/in-plant calibration of dosimetry systems refers to irradiation of dosimeters along with reference or transfer dosimeters, under operating conditions that are representative of the routine processing environment, for the purpose of developing a calibration curve for the routine dosimetry systems.

3.1.13 *installation qualification*—process of obtaining and documenting evidence that equipment has been provided and installed in accordance with its specification.

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

[5] Available from International Organization for Standardization (ISO), 1 Rue de Varembé, Case Postale 56, CH-1211, Geneva 20, Switzerland.

[6] Document produced by Working Group 1 of the Joint Committee for Guides in Metrology (JCGM/WG 1). Available free of charge at the BIPM website (http://www.bipm.org).

[7] Document produced by Working Group 2 of the Joint Committee for Guides in Metrology (JCGM/WG 2). Available free of charge at the BIPM website (http://www.bipm.org).

3.1.14 *irradiation container*—holder in which product is placed during the irradiation process.

3.1.14.1 *Discussion*—For insect irradiation, the configuration of irradiation containers varies widely with such factors as type and energy of radiation, irradiator design, insect species, insect stage being irradiated, and other process specifications (for example, some insects are irradiated in reduced-oxygen atmospheres, requiring air-tight containers). Irradiation containers for insects range from single-use items such as paper cylinders or plastic bags to reusable canisters of stainless steel or other durable material. When canisters are used, insects are often held secondarily within the canister in a plastic bag or other disposable container.

3.1.15 *irradiator turntable*—device used to rotate the sample during the irradiation process so as to improve dose uniformity.

3.1.15.1 *Discussion*—An irradiator turntable is often referred to as a turntable. Some irradiator geometries, for example, with an annular array of radiation sources surrounding the product, may not need a turntable.

3.1.16 *operational qualification (OQ)*—process of obtaining and documenting evidence that installed equipment operates within predetermined limits when used in accordance with its operational procedures.

3.1.17 *performance qualification (PQ)*—process of obtaining and documenting evidence that the equipment, as installed and operated in accordance with operation procedures, consistently performs in accordance with predetermined criteria and thereby yields product meeting its specification.

3.1.18 *radiation-sensitive indicator*—material such as a coated or impregnated adhesive-backed substrate, ink, coating or other materials which may be affixed to or printed on the product or irradiation container and which undergoes a visual change when exposed to ionizing radiation (see ISO/ASTM Guide 51539).

3.1.18.1 *Discussion*—Radiation-sensitive indicators are often referred to as "indicators." Indicators may be used to show that products have been exposed to ionizing radiation. They can be used to provide a visual and qualitative indication of radiation exposure and can be used to distinguish between irradiated and unirradiated samples. Indicators cannot be used as a substitute for proper dosimetry.

3.1.19 *reference standard dosimetry system*—dosimetry system, generally having the highest metrological quality available at a given location or in a given organization, from which measurements made there are derived.

3.1.20 *routine dosimetry system*—dosimetry system calibrated against a reference standard dosimetry system and used for routine absorbed-dose measurements, including dose mapping and process monitoring.

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

3.1.21.1 *Discussion*—Simulated product is used during irradiator characterization as a substitute for the actual product, material, or substance to be irradiated. When used in routine production runs in order to compensate for the absence of product, it is sometimes referred to as compensating dummy. When used for absorbed-dose mapping, simulated product is sometimes referred to as a phantom material.

3.1.22 *traceability*—property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties.

3.1.22.1 *Discussion*—The unbroken chain of comparisons is called a "traceability chain."

3.1.23 *transfer standard dosimetry system*—dosimetry system used as an intermediary to calibrate other dosimetry systems.

3.1.24 *transit dose*—absorbed dose delivered to a product (or a dosimeter) while it travels between the non-irradiation position and the irradiation position, or in the case of a movable source while the source moves into and out of its irradiation position.

3.1.25 *type I dosimeter*—dosimeter of high metrological quality, the response of which is affected by individual influence quantities in a well-defined way that can be expressed in terms of independent correction factors.

3.1.26 *type II dosimeter*—dosimeter, the response of which is affected by influence quantities in a complex way that cannot practically be expressed in terms of independent correction factors.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *factory-reared insects*—insects that are reared in large quantity in a laboratory or factory setting for use, following reproductive sterilization through irradiation, as live animals in pest management programs.

3.3 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 85a; that document, therefore, may be used as an alternative reference.

4. Significance and use

4.1 The major use of factory-reared insects is in sterile insect release programs (for example, Sterile Insect Technique, or SIT) for suppressing or eradicating pest populations **(2,3)**. Large numbers of reproductively sterile (irradiated) insects are released into an area where a wild "target population" of the same species exists. The wild population is reduced to the extent that the sterile males are successful in mating with wild females. The radiation dose absorbed by the factory-reared insects should be within a range that induces the desired level of sterility without substantially reducing the ability of factory-reared males to compete with wild males for mates. Species targeted by SIT programs are typically major pests affecting agriculture or human health, so the assurance by standardized dosimetry that insects have been properly irradiated is of crucial importance to agriculture growers, agricultural regulators, public health officials, and the public **(3)**. The irradiator operator must demonstrate by means of accurate absorbed-dose measurements that all insects have received absorbed dose within the specified range.

4.2 Another use of factory-reared insects is in the production of parasitoids for release against populations of insect pests **(4)**. Parasitoids are insects that spend the larval stage feeding within or on the body of a "host" species, typically killing the host. In some parasitoid programs, factory-reared host insects are irradiated before being offered to parasitoids. This eliminates the need to separate unparasitized hosts from parasitoids so that fertile, unparasitized host insects are not inadvertently released into the field.

4.3 Factory-reared insects may be treated with ionizing radiation, such as gamma radiation from ^{137}Cs or ^{60}Co sources, or X-radiation or electrons from accelerators. Gamma irradiation of insects is often carried out in small, fixed-geometry, dry-storage irradiators **(5)**. Dosimetry methods for gamma and X-ray irradiation of insects have been demonstrated and include useful procedures for measuring the absorbed dose distribution throughout the volume of the irradiation container(s) in these small irradiators (ASTM Practice 52116 and Refs **(1,6)**) as well as large-scale gamma irradiators (ISO/ASTM Practice 51702 and Ref **(7)**).

4.4 Specifications for irradiation of factory-reared insects include a lower limit of absorbed dose and may include a central target dose and an upper limit. These values are based on program requirements and on scientific data on effects of absorbed dose on the sterility, viability, and competitiveness of the factory-reared insects.

4.5 To demonstrate control of the radiation process, the absorbed dose must be measured using a calibrated dosimetry system. Regulations or policies under which the facility operates may require the calibration to be traceable to appropriate national or international standards. The radiation-induced change in the dosimeter is evaluated and related to absorbed dose through calibration (ISO/ASTM Practice 51261).

4.6 For each irradiator, absorbed-dose rate at a reference position within the irradiated volume of insects or simulated product is measured using a transfer or reference standard dosimetry system. That measurement provides a basis for calculating the duration of irradiation, conveyor speed, or other parameter required to deliver the specified absorbed dose to the insects.

4.7 Absorbed-dose mapping for establishing magnitudes and locations of minimum dose (D_{min}) and maximum dose (D_{max}) is performed using actual product or simulated product **(5)**.

5. Types of facilities and modes of operation

5.1 *Self-Contained Irradiators* —These devices house the radiation source in a protective shield of lead (or other appropriate high atomic number material), and require no additional or external shielding against radiation. The radiation source could be either a radionuclide or an X-ray tube.

5.1.1 *Gamma Irradiators (IAEA Category I, Ref (*8,9*)*—Currently, most reproductive sterilization of insects is accomplished by using gamma radiation from either ^{137}Cs or ^{60}Co in dry-storage, self-contained irradiators. These irradiators often have a mechanism to move the irradiation container from the load/unload position to the irradiation position and back, or to rotate the irradiation container from a load position to the irradiation position and then to a separate unload position.

5.1.1.1 In a typical configuration, the radionuclide is housed in rods or "pencils" (see 6.1.1) that are distributed in an annular array around the irradiation chamber. For processing, the irradiation container is located at the center of the array, where the absorbed-dose rate is relatively uniform.

5.1.1.2 In an alternative configuration, the radionuclide is contained in a single rod. In this case, the irradiation container is rotated on an irradiator turntable within the irradiation chamber to achieve an acceptably uniform dose. The axis of rotation is parallel to the source rod, which is vertical.

5.1.2 *Low-energy X-ray irradiators*—Low-energy X-ray irradiators utilize X-ray tubes that consist of an electron source (generally a heated wire, a filament which emits electrons), an electrostatic field to accelerate these electrons and a converter to generate X-radiation. In the currently available irradiators, the converter is present throughout the curved surface of the tube, and hence the X-radiation is emitted in all directions.

5.1.2.1 One method is to operate the irradiator in a batch mode where several canisters of insects are placed around and parallel to the X-ray tube, and revolve around the tube during irradiation while maintaining their orientation (much like chairs on a Ferris wheel), achieving acceptable dose uniformity.

5.1.2.2 An alternate method is to continuously pass trays with insects between two X-ray tubes, providing irradiation from two sides.

5.2 *Large-Scale Panoramic Gamma Irradiators*—Gamma irradiation of insects is also carried out in large-scale irradiators, either wet-storage or dry-storage. In these facilities, the source typically consists of either a single rod or a series of rods (pencils) that contain ^{60}Co and can be raised or lowered into a large irradiation room. When retracted from the irradiation room, the source is shielded by water (wet-storage; IAEA Category IV **(10)**, or lead or other appropriate high atomic number material (dry-storage; IAEA Category II **(10)**, or both.

5.2.1 *Continuous Operation*—A common method of use is for irradiation containers to be carried on a conveyor in one or more revolutions around a central source, resulting in a relatively uniform absorbed dose. The source is retracted from the irradiation room only when the irradiator is not in use.

5.2.2 *Batch Operation*—An alternative method of use is to place irradiation container(s) of insects into the irradiation room while the source is shielded, and then raise or lower the source into the irradiation room for the length of time required to achieve the desired absorbed dose. For this mode of operation, each irradiation container is typically rotated around its own axis to improve dose uniformity.

5.3 *Electron Accelerator*—Accelerator-generated high energy (3-10 MeV) electrons can also be used for insect irradiation. Such irradiators are housed in heavily shielded rooms.

5.3.1 Typically, accelerators produce a narrow electron beam that is scanned to cover the length and width of the insect container, generally a tray.

5.3.2 X-radiation (bremsstrahlung) produced by striking an X-ray target with an electron beam can also be used for this purpose. The target is made of tungsten, tantalum, or other metal with a high atomic number, high melting temperature, and high thermal conductivity.

5.3.3 For processing, insects are typically carried on a moving conveyor through the electron or X-ray beam. Because of the narrow angular distribution of the radiation, use of continuously moving conveyors (rather than static-irradiation or shuffle-dwell systems) enhances dose uniformity.

5.3.4 Additional information on electron and X-ray facilities and their modes of operation may be found in ISO/ASTM Practices 51649 (electrons) and 51608 (X-radiation).

6. Radiation source characteristics

6.1 *Gamma Irradiators*:

6.1.1 The radiation source used in the gamma facilities considered in this guide consists of sealed elements of ^{60}Co or ^{137}Cs which are typically linear rods or "pencils" arranged in one or more planar or cylindrical arrays.

6.1.2 Cobalt-60 emits photons with energies of approximately 1.17 and 1.33 MeV in nearly equal proportions. Cesium-137 emits photons with energies of approximately 0.662 MeV **(11)**.

6.1.3 The radioactive decay half-lives for ^{60}Co and ^{137}Cs are regularly reviewed and updated. The most recent publication by the National Institute of Standards and Technology **(12)** gave values of 1925.20 (±0.25) days for ^{60}Co and 11018.3 (±9.5) days for ^{137}Cs. In addition, the ^{137}Cs radiation source may contain radioimpurities which should be quantified by the source manufacturer.

6.1.4 For gamma sources, the only variation in the source output is the known reduction in the activity caused by radioactive decay. The reduction in the activity (source strength), and the corresponding required increase in the irradiation time, may be calculated (see 8.2.3) or obtained from tables provided by the irradiator manufacturer.

6.2 *Self-Contained Low-Energy X-ray Irradiators*—The electrons that generate X-radiation (bremsstrahlung) are electrostatically accelerated through a small potential difference to energies in the range of a few hundred keV **(13,14)**.

6.2.1 Currently, available low-energy X-ray irradiators use tubes that generate X-radiation with a maximum energy of 150 keV. The continuous energy spectrum of the X-radiation extends from approximately 35 keV up to the energy of the electrons **(1)**.

NOTE 3—Because of the low photon energy, some dosimetry systems that are commonly used with gamma irradiators and accelerators are not applicable to low-energy X-ray irradiators (see Annex A1 and Refs **(1,13)**). For example, Farmer-type ionization chambers are appropriate as reference standard dosimetry systems for low-energy X-ray irradiators **(1,13,15)**.

6.2.2 Energy of the X-radiation influences the size and shape of the irradiation container needed to achieve the desired level of dose uniformity. The tube current influences the absorbed-dose rate and thus time of irradiation.

6.3 *Electron Accelerator (Electron and X-ray Modes)*:

6.3.1 For an electron accelerator, the two principal beam characteristics are the energy spectrum and the average beam current. The electron energy spectrum affects the variation of absorbed dose with depth in a given material, and the average beam current affects the absorbed-dose rate. Because of low penetration of electrons, electron energy of at least 3 MeV is necessary to achieve useful dose uniformity.

6.3.1.1 Direct-action electron accelerators that employ dc or pulsed high-voltage generators typically produce electron energies up to 5 MeV.

6.3.1.2 Indirect-action electron accelerators use microwave or very high frequency (VHF) ac power to produce electron energies typically from 5 to 15 MeV.

6.3.2 For an X-ray (bremsstrahlung) facility, besides beam characteristics noted in 6.3.1, X-ray target design is a critical parameter. X-radiation is similar to gamma radiation from radioactive isotopic sources. Although their effects on materials are generally similar, these kinds of radiation differ in their energy spectra, angular distributions, and absorbed-dose rates. The continuous energy spectrum of the X-radiation (bremsstrahlung) extends from approximately 35 keV up to the maximum energy of the electrons incident on the X-ray target (see ISO/ASTM Practice 51608). In some X-ray facilities, spectrum filtration is used to reduce the low energy component of the radiation, thus improving dose uniformity.

7. Dosimetry systems

7.1 *Description of Dosimeters and Dosimetry Systems*—Classification of dosimeters and dosimetry systems is based on the inherent metrological dosimeter properties and the field of application of the dosimetry system (see ASTM Practice E2628). These classifications influence both the selection and calibration of dosimetry systems.

7.1.1 *Classification of Dosimeters*—Classification of dosimeters is based on their inherent metrological properties. The method of measurement may be important in the classification (see below), but the classification does not include consideration of the actual instrumentation used, or the quality of preparation (manufacture) of the dosimeter.

7.1.1.1 *Type I Dosimeters*—In order for a dosimeter to be classified as a type I dosimeter, it must be possible to apply accurate, independent corrections to its response to account for the effects of influence quantities, such as temperature and dose rate. In classifying a dosimeter as a type I dosimeter, it may be necessary to specify the method of measurement. For example, free radicals produced in irradiated alanine can, in principle, be measured by a number of different techniques; however, only the EPR technique has been shown to provide the high metrological quality necessary to classify alanine as a type I dosimeter. Refer to ASTM Practice E2628 for a list of type I dosimeters.

7.1.1.2 *Type II Dosimeters*—The classification of a dosimeter as a type II dosimeter is based on the complexity of interaction between influence quantities, such as temperature and dose rate, which makes it impractical to apply independent correction factors to the dosimeter response. Refer to ASTM Practice E2628 for a list of type II dosimeters.

7.1.2 *Classification of Dosimetry Systems*:

7.1.2.1 *Reference Standard Dosimetry Systems*: