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Guidance for dosimetry for sterile insects release programs

Lignes directrices de la dosimétrie pour des programmes de lâchers d'insectes stériles

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Foreword

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For an explanation on the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see the following URL: www.iso.org/iso/foreword.html.

This document was prepared by ASTM Committee E61 Radiation Processing and by Technical Committee ISO/TC 85, nuclear energy, nuclear technologies and radiological protection.

This fourth edition cancels and replaces the third edition (ISO/ASTM 51940:2013), which has been technically revised.

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

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Standard Guidance for Dosimetry for Sterile Insect 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.

INTRODUCTION

The purpose of this document is to present information on the use of ionizing energy (radiation) for the radiation-induced reproductive sterilization of live insects for use in pest management programs.

This document is intended to serve as a recommendation to be followed when using irradiation technology where approved by an appropriate regulatory authority. It is not to be construed as a requirement for the use of irradiation nor as a required code of practice. While the use of irradiation involves certain essential requirements to attain the objective of the treatment, some parameters can be varied in optimizing the process.

1. Scope

1.1 This document 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. A third use is for testing detection traps for fruit flies and moths, and testing mating disruption products for moths. The procedures outlined in this document 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 document.

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 document 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 keV 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 values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard except for the non-SI units of minute (min) hour (h) and day (d). These non-SI units are accepted for use within the SI system.

1.4 This document is one of a set of standards that provides recommendations for properly implementing and utilizing radiation processing. It is intended to be read in conjunction with ISO/ASTM Practice 52628.

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

1.6 This document 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 1.5.

1.7 This document also covers the use of radiation-sensitive indicators for the visual and qualitative indication that the insects have been irradiated (see ISO/ASTM Guide 51539).

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

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[1] This document 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.

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

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

2. Referenced documents

2.1 *ASTM Standards:*[3]

E3083 Terminology Relating to Radiation Processing: Dosimetry and Applications

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 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 at Energies Between 50 keV and 7.5 MeV

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 Estimation of Measurement Uncertainty in Dosimetry for Radiation Processing

51956 Practice for Use of a Thermoluminescence-Dosimetry System (TLD System) for Radiation Processing

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

52303 Guide for Absorbed-Dose Mapping in Radiation Processing Facilities

52628 Practice for Dosimetry in Radiation Processing

52701 Guide for Performance Characterization of Dosimeters and Dosimetry Systems for Use in Radiation Processing

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

ICRU Report 80 Dosimetry Systems for Use in Radiation Processing

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

ISO 12749-4 Nuclear energy – Vocabulary – Part 4: Dosimetry for radiation processing

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

JCGM 100:2008, GUM 1995, with minor corrections, Evaluation of measurement data – Guide to the Expression of Uncertainty in Measurement[6]

JCGM 200:2012, VIM International Vocabulary of Metrology – Basic and General Concepts and Associated Terms[7]

3. Terminology

3.1 *Definitions:*

3.1.1 *absorbed dose (D)*—quotient of $d\bar{\varepsilon}$ by dm, where $d\bar{\varepsilon}$ is the mean energy imparted by ionizing radiation to matter of mass dm thus

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

3.1.1.1 *Discussion*—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).

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 Terminology E3083. 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

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[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.

[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 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 Metrology (JCGM/WG 2). Available free of charge at the BIPM website (http://www.bipm.org).

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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 or DUR.

3.1.7 *dosimeter*—device that, when irradiated, exhibits a quantifiable change that can be related to a dosimetric quantity 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*—interrelated elements used for measuring a dosimetric quantity, including dosimeters, instruments and their associated reference standards, and procedures for their use.

3.1.11 *influence quantity*—quantity that, in a direct measurement, does not affect the quantity that is actually measured, but affects the relation between the indication and the measurement result.

3.1.11.1 *Discussion—(1)* In dosimetry for radiation processing, typical examples of influence quantities include radiation type and energy, irradiation temperature, dose rate and the time interval between irradiation and determination of the indication of the dosimeter. *(2)* The dosimeter's response (e.g. color change) is measured and related to dose via the calibration curve. The dosimeter's signal may be susceptible to the influence quantity, and therefore the interpretation of dose, not the actual dose.

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 routine 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.

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.

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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 way that is well-defined and capable of expression 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 raised in large quantities 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 ISO/ASTM Practice 52628. Other terms that pertain to radiation measurement and dosimetry may be found in ASTM Terminology E3083 and ISO Terminology ISO 12749-4. Where appropriate, definitions used in these standards have been derived from, and are consistent with definitions in ICRU Report 85a, and general metrological definitions given in the VIM.

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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, or sterile insects are released into an area as a preventative measure to protect against the wild pest establishing. 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. In some cases, sterile females may also be released as part of an SIT program. 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 An additional use of factory-reared insects is for testing detection traps for fruit flies and moths, and testing mating disruption products for moths.

4.4 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**)).

4.5 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.

4.6 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).

4.7 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.

4.8 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*—Self-contained irradiators expose samples to gamma irradiation produced by isotopes of either ^{137}Cs or ^{60}Co (**8, 9**) (ISO/ASTM Practice 52116), or to low energy X-radiation (bremsstrahlung) produced by an X-ray tube. These irradiators house their radiation source in a protective lead shield or other appropriate high atomic number material in accordance with the safety requirements. Currently

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available units using low energy X-radiation (bremsstrahlung) require less shielding than units containing gamma-emitting radioactive isotopes. Such units containing radionuclides usually have a mechanism to move the canister from the load/unload position to the irradiation position.

5.1.1 Some common methods used for improving absorbed dose uniformity in the insect canister are to either rotate the canister holding the insects in front of the radiation source or to have multiple sources irradiating the product from different directions.

5.2 *Large-Scale Panoramic Gamma Irradiators* (see ISO/ASTM Practice 51702)—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 source of gamma radiation used in the irradiators considered in this practice consists of sealed ^{137}Cs or ^{60}Co radionuclides that are typically linear rods arranged in one or more planar or annular arrays.

6.1.2 Cobalt-60 emits photons with energies of approximately 1.17 MeV 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 d (±0.25 d) for ^{60}Co and 11018.3 d (±9.5 d) 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. This reduction in the source output and the required increase in the irradiation time to deliver the same dose may be calculated (see Eq 1 and Eq 2 or Eq 3 from 8.2.3) or obtained from tables provided by the irradiator manufacturer.

6.2 *X-ray Irradiators:*

6.2.1 Low energy X-ray irradiators use 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 (**13**, **14**).

6.2.2 An X-ray (bremsstrahlung) irradiator emits short wavelength electromagnetic radiation, which is analogous to gamma radiation from radioactive sources. Although their effects on irradiated materials are generally similar, these kinds of radiation differ in their energy spectra (see 6.2.3), angular distribution, and dose rates. The physical characteristics of the X-radiation (bremsstrahlung) field depend on the design of the X-ray tube.

6.2.3 Currently available low-energy X-ray irradiators generate X-radiation with a maximum energy of a few hundred keV. The spectrum of the X-ray energy extends from the maximum energy to approximately 30 keV. Effective energy or other energy spectrum characteristics are needed for characterization of dosimeter response (see Ref **15**).

NOTE 3—With lower photon energy, some dosimetry systems that are commonly used with gamma irradiators and accelerators are not applicable to low-energy X-ray irradiators (see Table 1 and Table 2, and Refs (**1**, **13**, **15**, **16**). For example, Farmer-type ionization chambers are appropriate as reference standard dosimetry systems for low-energy X-ray irradiators (**1**, **13**, **17**).

6.2.4 The energy of the X-radiation influences the size and shape of the canister needed to achieve the desired level of dose uniformity in the insect canister. Filters are used to reduce the low-energy components to improve dose uniformity in the canister. These filters may form part of the X-ray tube or may be material added to the irradiator or canister. Reflectors may also be used to improve the dose uniformity.

6.2.5 The absorbed-dose rate and thus time of irradiation is determined by the tube current.

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

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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 MeV 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 ISO/ASTM Practice 52628). 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, but the classification does not include consideration of the actual instrumentation used, or the quality of preparation (manufacturer) of the dosimeter. See ISO/ASTM Practice 52628 for a list of type I and type II dosimeters.

7.1.2 *Classification of Dosimetry Systems:*

7.1.2.1 *Reference Standard Dosimetry Systems:*

(1) The classification of a dosimetry system as a reference standard dosimetry system is based on its application. Reference standard dosimetry systems are used as standards to calibrate other dosimetry systems that are used for routine measurements. In addition, the reference standard dosimetry systems are used to certify the absorbed-dose rate at a reference position within the irradiator. The uncertainty of the reference standard dosimetry system will affect the uncertainty of the system being calibrated and thus the uncertainty in the absorbed dose value for the product being irradiated.

(2) Reference standard dosimetry systems may take the form of systems held at a given location or they may take the form of transfer standard dosimetry systems operated by a national standards laboratory or an approved laboratory. In the case of transfer standard dosimetry systems, dosimeters are sent to a facility for irradiation and then returned to the issuing laboratory for measurement. The requirement that dosimeters be transported without unduly increasing the measurement uncertainty restricts the type of dosimeter that can be used. Alanine/EPR, dichromate and Ceric-Cerous dosimetry systems are commonly used in this way.

(3) The dosimeter used in a reference standard dosimetry system is generally a type I dosimeter. The expanded uncertainty achievable with measurements made using a reference standard dosimetry system is typically of the order of ±3% (at the 95 % confidence level).

(4) Examples of reference standard dosimetry systems are given in Table 1.

7.1.2.2 *Routine Dosimetry Systems:*

(1) The classification of a dosimetry system as a routine dosimetry system is based on its application, that is, routine absorbed-dose measurements, including dose mapping and process monitoring.

(2) The dosimeter used in a routine dosimetry system is generally a type II dosimeter, although there may be exceptions, for example the use of type I alanine dosimeters. The expanded uncertainty achievable with measurements made using a routine dosimetry system is typically of the order of 6 % (at the 95 % confidence level).

(3) Examples of routine dosimetry systems are listed in Table 2.

7.2 *Routine Dosimetry System Calibration:*

7.2.1 Dosimetry systems consist of dosimeters, measurement instruments and their associated reference standards, and procedures for the system's use. Prior to use, routine dosimetry systems shall be calibrated in accordance with documented procedures that specify details of the calibration process. Detailed calibration procedures are provided in ISO/ASTM 51261. All dosimetry equipment requires either calibration traceable to appropriate standards or performance checks to verify its operation (for more information, see the specific ISO/ASTM standard for the dosimetry system being used). Similarly, the dosimetry system shall be calibrated for each dosimeter batch used at the facility. If required by regulation or policy, it is necessary to demonstrate that dose measurements are traceable to recognized national or international standards.

7.2.2 Irradiation of calibration dosimeters is a critical component of the calibration of the dosimetry system. There are two methods for irradiating dosimeters for calibration:

7.2.2.1 Calibration irradiations performed at an approved laboratory followed by a calibration verification exercise for the actual conditions of use (see ISO/ASTM 51261), and

TABLE 1 Examples of reference-standard dosimetry systems

Dosimeter	Readout System	Useful Absorbed-dose Range (Gy)	Reference
Alanine	EPR spectrometer	1 Gy to 10^5 Gy	ISO/ASTM 51607
Ionization chamber	Electrometer	Can be easily applied to the insect irradiation dose range	**(1)**

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