INTERNATIONAL STANDARD

ISO/ASTM 51431

First edition
2002-03-15

Practice for dosimetry in electron and bremsstrahlung irradiation facilities for food processing

Pratique de la dosimétrie dans les installations de traitement des produits alimentaires irradiés par électrons et bremsstrahlung

Reference number
ISO/ASTM 51431:2002(E)

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ISO copyright office
Case postale 56 • CH-1211 Geneva 20
Tel. +41 22 749 01 11
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ASTM International, 100 Barr Harbor Drive, PO Box C700,
West Conshohocken, PA 19428-2959, USA
Tel. +610 832 9634
Fax +610 832 9635
E-mail khooper@astm.org
Web www.astm.org

Printed in the United States

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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 51431 was developed by ASTM Committee E10, Nuclear Technology and Applications, through Subcommittee E10.01, and by Technical Committee ISO/TC 85, Nuclear Energy.

Standard Practice for Dosimetry in Electron and bremsstrahlung Irradiation Facilities for Food Processing[1]

This standard is issued under the fixed designation ISO/ASTM 51431; 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 practice describes dosimetric procedures to be followed in facility characterization, process qualification, and routine processing for electron beam and bremsstrahlung irradiation facilities for food processing to ensure that product receives an acceptable range of absorbed doses. Other procedures related to facility characterization, process qualification, and routine product processing that may influence and be used to monitor absorbed dose in the product are also discussed. Information about effective or regulatory dose limits for food products is not within the scope of this practice (see ASTM Guides F 1355 and F 1356).

NOTE 1—Dosimetry is only one component of a total quality assurance program for adherence to good manufacturing practices used in the production of safe and wholesome food.

1.2 The electron energy range covered in this practice is from 0.3 MeV to 10 MeV. Such electrons can be generated in continuous or pulse modes.

1.3 The maximum electron energy of bremsstrahlung facilities covered in this practice is 10 MeV. A photon beam can be generated by inserting a bremsstrahlung converter in the electron beam path (See ISO/ASTM Practice 51608).

NOTE 2—For guidance in the selection, calibration, and use of specific dosimeters and interpretation of absorbed dose in the product from dose measurements, see the documents listed in ISO/ASTM Guide 51261 and practices for individual dosimetry systems listed in 2.1.

NOTE 3—Bremsstrahlung from machine sources and gamma rays from radioactive isotopic sources are similar in characteristics, especially as dosimetry is concerned. See ISO/ASTM Practice 51204 for the applications of dosimetry in characterization and operation of gamma-ray irradiation facilities for food processing. For information concerning electron beam irradiation technology and dosimetry, see ISO/ASTM Practice 51649.

1.4 *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 456 Terminology Relating to Quality and Statistics[3]

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]

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 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]

51275 Practice for Use of a Radiochromic Film Dosimetry System[2]

51276 Practice for Use of a Polymethylmethacrylate Dosimetry System[2]

51310 Practice for Use of a Radiochromic Optical Waveguide Dosimetry System[2]

51539 Guide for Use of Radiation-Sensitive Indicators[2]

51608 Practice for Dosimetry in an X-ray (Bremsstrahlung) Irradiation Facility for Radiation Processing[2]

51607 Practice for Use of the Alanine-EPR Dosimetry System[2]

51631 Practice for Use of Calorimetric Dosimetry Systems for Electron Beam Dose Measurements and Dosimeter Calibrations[2]

51649 Practice for Dosimetry in an Electron Beam Facility for Radiation Processing at Energies Between 300 keV and 25 MeV[2]

51650 Practice for Use of Cellulose Acetate Dosimetry Systems[2]

51707 Guide for Estimating Uncertainties in Dosimetry for

[1] This practice 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.

Current edition approved Jan. 22, 2002. Published March 15, 2002. Originally published as E 143–91. Last previous ASTM edition E 1431–98$^{\epsilon1}$. ASTM E 1431–91 was adopted by ISO in 1998 with the intermediate designation ISO 15562:1998(E). The present International Standard ISO/ASTM 51431:2002(E) is a revision of ISO 15562.

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

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

Radiation Processing[2]

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

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

ICRU Report 34 The Dosimetry of Pulsed Radiation

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

ICRU Report 37 Stopping Powers for Electrons and Positrons

ICRU Report 60 Radiation Quantities and Units

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 $d\bar{\epsilon}$ by dm, where $d\bar{\epsilon}$ is the mean incremental energy imparted by ionizing radiation to matter of incremental mass dm (see ICRU 60).

$$D = d\bar{\epsilon}/dm \quad (1)$$

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.

3. For a photon source under conditions of charged particle equilibrium, the absorbed dose, D, may be expressed as follows:

$$D = \Phi[E(\mu_{en}/\rho)], \quad (2)$$

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 negligible, the mass energy absorption coefficient (μ_{en}/ρ) is equal to the mass energy transfer coefficient (μ_{tr}), and absorbed dose is equal to air kerma.

3.1.2 *average beam current*—time-averaged electron beam current; for a pulsed machine, the averaging shall be done over a large number of pulses.

3.1.3 *beam width*—dimension of the irradiation zone perpendicular to the beam length and direction of the electron beam specified at a specific distance from where the beam exits the accelerator.

3.1.3.1 *Discussion*—For a radiation processing facility with a conveyor system, the beam width is usually perpendicular to the direction of motion of the conveyor (see Fig. 1). Beam width is the distance between the points along the dose profile which are at a defined level from the maximum dose region in the profile (see Fig. 2). Various techniques may be employed to produce an electron beam width adequate to cover the processing zone, for example, use of electromagnetic scanning of pencil beam (in which case beam width is also referred to as scan width), defocussing elements, and scattering foils.

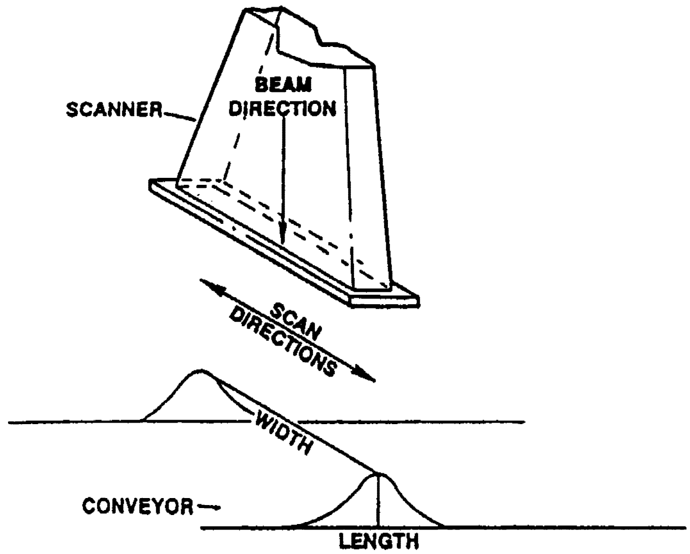

FIG. 1 Diagram Showing Beam Length and Width for a Scanned Beam Using a Conveyor Material Handling System

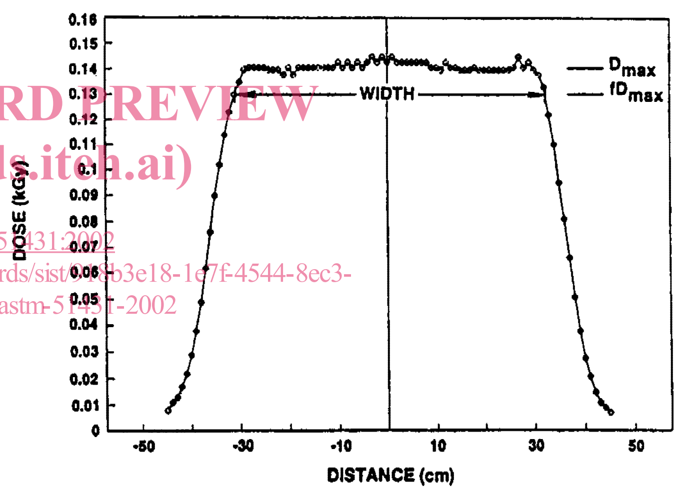

FIG. 2 Example of Electron-beam Dose Distribution Along the Beam Width[4] with the Width Noted at Some Defined Fractional Level *f* of the Average Maximum Dose D_{max}

3.1.4 *bremsstrahlung*—broad-spectrum electromagnetic radiation emitted when an energetic electron is influenced by a strong electric field such as that in the vicinity of an atomic nucleus. Practically, 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 **(1, 2)**.[5]

3.1.5 *compensating dummy*—simulated product used during routine production runs in process loads that contain less

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

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

product than specified in the documented product loading configuration, or simulated product used at the beginning or end of a production run, to compensate for the absence of product.

3.1.5.1 *Discussion*—Simulated product or phantom material may be used during irradiator characterization as a substitute for the actual product, material or substance to be irradiated.

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

3.1.7 *dose uniformity ratio*—ratio of the maximum to the minimum absorbed dose within the process load. The concept is also referred to as the max/min dose ratio.

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 energy spectrum*—particle fluence distribution of electrons as a function of energy.

3.1.10 *electron range*—penetration distance in a specific, totally absorbing material along the beam axis of the electrons incident on the material (equivalent to practical electron range, R_p).

3.1.10.1 *Discussion*—See Fig. 3—R_p can be measured from experimental depth-dose distributions in a given material. Other forms of electron range are found in the dosimetry literature, eg., extrapolated range derived from depth-dose data and the continuous-slowing-down-approximation range (the calculated pathlength traversed by an electron in a material in the course of completely slowing down). Electron range is usually expressed in terms of mass per unit area ($kg \cdot m^{-2}$), but sometimes in terms of unit thickness (m) for a specified material.

3.1.11 *half-value depth (*R_{50})—depth in homogeneous material at which the absorbed dose has decreased to 50 percent of its maximum value.

3.1.11.1 *Discussion*—See Fig. 3—The half-value depth usually applies to electrons.

3.1.12 *optimum thickness (*R_{opt})—depth in homogeneous material at which the absorbed dose equals the absorbed dose at the surface where the electron beam enters.

3.1.12.1 *Discussion*—See Fig. 3.

3.1.13 *practical electron range (*R_p)—distance from the incident surface of a homogeneous material where the electron beam enters to the point where the tangent at the steepest point (the inflection point) on the almost straight descending portion of the depth-dose distribution curve meets the depth axis.

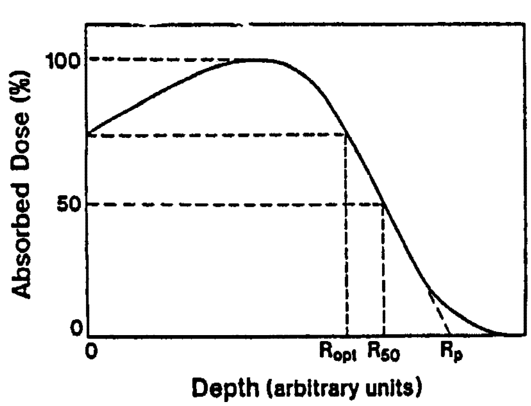

FIG. 3 A Typical Depth Dose Distribution for an Electron Beam

3.1.13.1 *Discussion*—See Fig. 3.

3.1.14 *process load*—a volume of material with a specified loading configuration irradiated as a single entity.

3.1.15 *production run*—a series of process loads consisting of materials, or products having similar radiation-absorption characteristics, that are irradiated sequentially to a specified range of absorbed dose.

3.1.16 *reference material*—homogeneous material of known radiation absorption and scattering properties used to establish characteristics of the irradiation process, such as scan uniformity, depth-dose distribution, throughput rate, and reproducibility.

3.1.17 *reference plane*—a selected plane in the radiation zone that is perpendicular to the electron beam axis.

3.2 Definitions of other terms used in this standard that pertain to radiation measurement and dosimetry may be found in ASTM Terminology E 170. Definitions in ASTM E 170 are compatible with ICRU 60; that document, therefore, may be used as an alternative reference.

4. Significance and Use

4.1 Food products may be processed with accelerator-generated radiation (electrons and bremsstrahlung) to derive public health or economic benefits, or both. Examples include parasite and pathogen control, insect disinfestation, growth and maturation inhibition, and extension of shelf-life. Food irradiation specifications usually include an upper and lower limit of absorbed-dose, and may also include an upper limit on overall average. For a given application, one or both of these values may be prescribed by regulations that have been established on the basis of available scientific data. Therefore, it is necessary to determine the capability of an irradiation facility to process within these absorbed-dose limits prior to the irradiation of the food product. Once this capability is established, it is necessary to monitor and document the maximum and minimum absorbed dose in the irradiated product for each production run to verify compliance with the process specifications with an acceptable level of confidence.

NOTE 4—The Codex Alimentarius Commission **(9)** uses the term "overall average absorbed dose" in discussing broad concepts such as the wholesomeness of foods irradiated to an overall average absorbed dose of less than 10 kGy. The overall average dose should not, however, be used in place of minimum or maximum absorbed doses for specific applications. The CAC confirms this in the following statement from CAC/RCP 19-1979, Annex A: "(T)he design of the facility and the operational parameters have to take into account minimum and maximum dose values required by the process."

NOTE 5—In addition to regulations specifying minimum and maximum absorbed dose limits for a food, some countries have regulations requiring that an overall average dose should not exceed a specified value, which is the mean of the specified minimum and maximum limits. The overall average dose absorbed by the food is the mean value of the measured minimum and maximum absorbed dose values.

4.2 Some food products are processed in the chilled or frozen state. Therefore, it is necessary to confirm that the dosimeters used for routine monitoring are useable at low temperature and that the dosimeter temperature during irradiation is sufficiently stable to allow correction for temperature effects on the dosimeter response.

4.3 For more detailed discussions of radiation processing of foods, see ASTM Guides F 1355, F 1356 and F 1736.

4.4 Regulations in some countries limit the maximum electron energy to 10 MeV and photon energy to 5 MeV for the purpose of food irradiation to avoid induced radioactivity in the food.

4.5 To ensure that products are irradiated with reproducible doses, routine process control requires documented product handling procedures before, during, and after the irradiation, consistent orientation of the products during irradiation, monitoring of critical process parameters, routine product dosimetry, and documentation of the required activities and functions.

4.6 Accelerator-generated radiation can be in the form of electrons or photons (bremsstrahlung) produced by the electrons. Penetration into the product required to accomplish the intended effect is one of the factors affecting the decision to use electrons or photons. Penetration of 5-MeV bremsstrahlung radiation in water or plastic materials is slightly greater than that of Co-60 gamma rays **(1-4)**.

NOTE 6—More detailed discussion of food irradiation processing may be found in Refs **5-10**.

5. Radiation Source Characteristics

5.1 *Electron Facilities*:

5.1.1 Radiation sources for electrons with energies greater than 300 keV considered in this practice are either direct action (potential-drop) or indirect-action (microwave-powered) accelerators. The radiation fields depend on the characteristics and the design of the accelerators. Included among these characteristics are the electron beam parameters, that is, the electron energy spectrum, average electron beam current and beam current distribution on the product surface.

5.1.2 These aspects are further discussed in ISO/ASTM Practice 51649.

5.2 *Bremsstrahlung Facilities*:

5.2.1 A high-energy X-ray (bremsstrahlung) generator emits short-wavelength electromagnetic radiation, which is analogous to gamma radiation from radioactive isotopic sources. Although their effects on irradiated materials are generally similar, these kinds of radiation differ in their energy spectra, angular distribution, and dose rates.

5.2.2 The physical characteristics of the X-ray field depend on the design of the X-ray converter and the parameters of the electron beam striking the target, that is, the electron energy spectrum, average electron beam current, and beam current distribution on the target.

5.2.3 The physical characteristics of an X-ray source and its suitability for radiation processing are further discussed in ISO/ASTM Practice 51608.

6. Irradiation Facilities

6.1 *Facility Components*:

6.1.1 Electron and bremsstrahlung irradiation facilities include the electron beam accelerator system; material handling systems; a radiation shield with personnel safety system; product staging, loading, and storage areas; auxiliary equipment for power, cooling, ventilation, etc.; equipment control room; a laboratory for dosimetry and product testing; and personnel offices. Bremsstrahlung facilities also include an X-ray converter (see ISO/ASTM Practice 51608). The electron beam accelerator system consists of the radiation source (see ISO/ASTM Practice 51649), equipment to disperse the beam on product and associated equipment **(11)**.

6.2 *Process Parameters*:

6.2.1 There are various process parameters that play essential roles in determining and controlling the absorbed dose in radiation processing at an irradiation facility. They should, therefore, be considered when performing the absorbed-dose measurements required in Sections 8, 9, and 10.

6.2.2 Process parameters include process load characteristics (for example, size, bulk density, and heterogeneity), irradiation conditions (for example, processing geometry, multi-sided exposure and number of passes through the beam), and operating parameters. (see Fig. 4).

6.2.3 Process parameters that will achieve the absorbed dose within the specified limits are established during process qualification (see Section 9).

6.2.4 During routine product processing (see Section 10), the facility operating parameters are controlled and monitored to maintain all values that were set during process qualification.

6.3 *Operating Parameters*:

6.3.1 Operating parameters include beam characteristics (controlled by accelerator parameters: for example, energy, average beam current, and pulse rate); conveyor speed and performance characteristics of material handling; and beam dispersion parameters (for example, beam width and frequency at which scanned beam is swept across product). Operating parameters are measurable, and their values depend on the

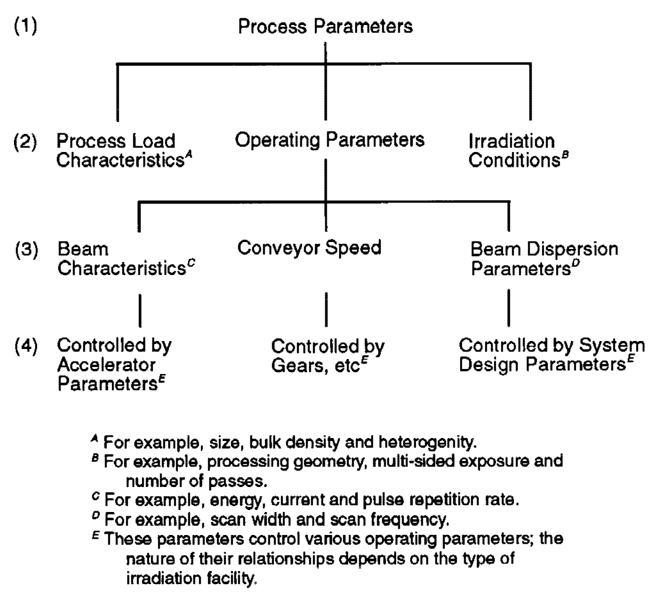

FIG. 4 A Diagram of the Parameter Relationships for an Electron or Bremsstrahlung Facility

facility controlling parameters (see row (4) in Fig. 2). During installation qualification (see 8), absorbed dose characteristics over the expected range of the operating parameters are established for a reference material.

6.3.2 *Beam Characteristics*:

6.3.2.1 The three principal beam characteristics that affect dosimetry are the electron energy spectrum, average beam current, and pulse beam current. The electron energy spectrum affects the depth-dose distribution within the product (see ISO/ASTM Practice 51649). The average and pulse beam currents, in addition to several other operating parameters, affect the average and peak dose rates, respectively.

NOTE 7—If the accelerator does not have an energy analyzing system (for example, an analyzing magnet), the electron energy spectrum of the beam can be specified in a practical way by two parameters: the average electron energy (E_a) and the most probable electron energy (E_p). The values of these two parameters at the surface of water-equivalent product may be measured experimentally (see ISO/ASTM Practice 51649).

6.3.3 *Beam Dispersion*:

6.3.3.1 Dispersion of the electron beam to produce a beam width adequate to cover the processing zone may be achieved by various techniques. These include electromagnetic scanning of a pencil beam or use of defocussing elements or scattering foils.

6.3.3.2 The beam width, in addition to several other operating parameters, affects the dose rate. Scanning of a pencil beam can produce pulsed dose at points along the beam width. This can influence the dosimeters' performance when they are sensitive to dose rate variations.

6.3.3.3 See ISO/ASTM Practice 51649 for determination of beam width and dose uniformity across the beam width.

6.3.3.4 Pay special attention to the dose distribution near the front surface and also near other surfaces of the process load.

NOTE 8—The front surface dose increases with the angle of incidence of the electron beam, that is, near the edge of the scanned beam (See Fig. X1.9 in ISO/ASTM Practice 51649). Also, scattering out of electrons can depress the dose near other surfaces. These phenomena will also affect the depth-dose distribution.

6.3.3.5 For bremsstrahlung irradiators, absorbed dose rate depends on the angular distribution of the bremsstrahlung beam, in addition to the electron energy spectrum and average beam current. Photon energy and angular distribution depend on the design and composition of the converter and on the electron energy **(3,12)**.

6.3.4 *Conveyor Speed*—For facilities utilizing continuously-moving conveyors to transport product through the irradiation zone, conveyor speed determines the irradiation time. Therefore, when other operating parameters are held constant, conveyor speed governs the absorbed dose in the product.

NOTE 9—The conveyor speed and the beam current may be linked for some types of accelerators so that a variation in one causes a corresponding change in the other to maintain a constant value of the absorbed dose (also see Note 13).

6.4 *Product Handling System*:

6.4.1 The absorbed dose distribution within the food product being irradiated may be affected by the configuration of material handling.

6.4.2 *Bremsstrahlung Facilities*—The penetrating quality of high-energy X rays permits the treatment of large containers or full pallet loads of products. The container size for optimum photon power utilization and dose uniformity depends on the maximum energy and product density. The narrow angular distribution of the radiation favors the use of continuously moving conveyors rather than shuffle-dwell systems to enhance dose uniformity.

6.4.3 *Electron Facilities*—Two different configurations commonly used are:

Conveyors or Carriers—Boxes, with thickness comparable to the electron range, containing food products are placed upon carriers or conveyors for passage through the electron beam. The speed of the conveyor or carriers is controlled in conjunction with the electron beam current and beam width so that the required dose is delivered.

Bulk-flow System—For irradiation of liquids or particulate materials like grain, bulk-flow transport through the irradiation zone may be used. Because the flow of fluids and particulate materials through the irradiation zone may be turbulent and the path and the velocity of individual elements are not controllable, an average dose may be derived from average velocity and dose field in the irradiation zone in order that the required dose is applied. In case where adherence to minimum and maximum dose is required more sophisticated dosimetry techniques should be applied (see Ref **(13)** and also 9.2.4).

7. Dosimetry Systems

7.1 Dosimetry systems are used to measure absorbed dose. They consist of the dosimeters, measurement instruments and their associated reference standards, and procedures for the system's use.

NOTE 10—For a comprehensive discussion of various dosimetry methods applicable to the radiation types and energies discussed in this practice, see ICRU Reports 14, 34, 35, and 37.

7.2 *Description of Dosimeter Classes*—Dosimeters may be divided into four basic classes according to the accuracy of the dosimetry systems and areas of application: primary standard, reference standard, transfer standard, and routine dosimeters. ISO/ASTM Guide 51261 provides detailed information about the selection of dosimetry systems for different applications.

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

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

7.2.3 *Transfer Standard Dosimeters*—Transfer standard dosimeters are specially selected dosimeters used for transferring absorbed-dose information from an accredited or national