INTERNATIONAL STANDARD

ISO 15567

First edition
1998-12-15

Practice for dosimetry in an X-ray (bremsstrahlung) facility for radiation processing

Pratique de la dosimétrie dans une installation de traitement de produits alimentaires par des rayons X (Bremsstrahlung)

Reference number
ISO 15567:1998(E)

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.

International Standard ISO 15567 was prepared by the American Society for Testing and Materials (ASTM) Subcommittee E10.01 (as E 1608-94) and was adopted, under a special "fast-track procedure", by Technical Committee ISO/TC 85, *Nuclear energy*, in parallel with its approval by the ISO member bodies.

A new ISO/TC 85 Working Group WG 3, *High-level dosimetry for radiation processing*, was formed to review the voting comments from the ISO "Fast-track procedure" and to maintain these standards. The USA holds the convenership of this working group.

International Standard ISO 15567 is one of 20 standards developed and published by ASTM. The 20 fast-tracked standards and their associated ASTM designations are listed below:

ISO Designation	ASTM Designation	Title
15554	E 1204-93	*Practice for dosimetry in gamma irradiation facilities for food processing*
15555	E 1205-93	*Practice for use of a ceric-cerous sulfate dosimetry system*
15556	E 1261-94	*Guide for selection and calibration of dosimetry systems for radiation processing*
15557	E 1275-93	*Practice for use of a radiochromic film dosimetry system*
15558	E 1276-96	*Practice for use of a polymethylmethacrylate dosimetry system*
15559	E 1310-94	*Practice for use of a radiochromic optical waveguide dosimetry system*
15560	E 1400-95a	*Practice for characterization and performance of a high-dose radiation dosimetry calibration laboratory*
15561	E 1401-96	*Practice for use of a dichromate dosimetry system*

International Organization for Standardization
Case postale 56 • CH-1211 Genève 20 • Switzerland
Internet iso@iso.ch

Printed in Switzerland

15562	E 1431-91	*Practice for dosimetry in electron and bremsstrahlung irradiation facilities for food processing*
15563	E 1538-93	*Practice for use of the ethanol-chlorobenzene dosimetry system*
15564	E 1539-93	*Guide for use of radiation-sensitive indicators*
15565	E 1540-93	*Practice for use of a radiochromic liquid dosimetry system*
15566	E 1607-94	*Practice for use of the alanine-EPR dosimetry system*
15567	E 1608-94	*Practice for dosimetry in an X-ray (bremsstrahlung) facility for radiation processing*
15568	E 1631-96	*Practice for use of calorimetric dosimetry systems for electron beam dose measurements and dosimeter calibrations*
15569	E 1649-94	*Practice for dosimetry in an electron-beam facility for radiation processing at energies between 300 keV and 25 MeV*
15570	E 1650-94	*Practice for use of cellulose acetate dosimetry system*
15571	E 1702-95	*Practice for dosimetry in a gamma irradiation facility for radiation processing*
15572	E 1707-95	*Guide for estimating uncertainties in dosimetry for radiation processing*
15573	E 1818-96	*Practice for dosimetry in an electron-beam facility for radiation processing at energies between 80 keV and 300 keV*

For the purposes of this International Standard, the following amendments to the ASTM text apply.

Page 1, subclause 1.3

Replace subclause 1.3 by the following.

> 1.3 Dosimetry is only one component of a total quality assurance program for an irradiation facility. Other controls besides dosimetry may be required for specific applications such as medical device sterilization and food preservation.
>
> 1.4 For the irradiation of food and the radiation sterilization of health care products, other specific ISO standards exist. For food irradiation, see ISO 15562:1998, *Practice for dosimetry in electron and bremsstrahlung irradiation facilities for food processing* (ASTM Practice E 1431). For the radiation sterilization of health care products, see ISO 11137:1995, *Sterilization of health care products — Requirements for validation and routine control — Radiation sterilization*. In those areas covered by ISO 11137, that standard takes precedence.

Page 1, subclause 1.4

Renumber this subclause as 1.5.

Designation: E 1608 – 94

AMERICAN SOCIETY FOR TESTING AND MATERIALS
1916 Race St. Philadelphia, Pa 19103
Reprinted from the Annual Book of ASTM Standards. Copyright ASTM
If not listed in the current combined index, will appear in the next edition.

Standard Practice for Dosimetry in an X-Ray (Bremsstrahlung) Facility for Radiation Processing[1]

This standard is issued under the fixed designation E 1608; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This practice covers dosimetric procedures to be followed in facility characterization, process qualification, and routine processing using X-rays (bremsstrahlung) to ensure that the entire product has been treated within an acceptable range of absorbed doses. Other procedures related to facility characterization, process qualification, and routine processing that may influence absorbed dose in the product are also discussed. The establishment of effective or regulatory dose and X-ray energy limits are not within the scope of this practice.

1.2 In contrast to monoenergetic gamma rays, the bremsstrahlung energy spectrum extends from low values up to the maximum energy of the electrons incident on the X-ray target (see Section 5 and the Appendix).

1.3 Dosimetry is only one component of a total quality assurance program for an irradiation facility. Other controls besides dosimetry may be required for specific applications such as medical device sterilization and food preservation (see Sections 8, 9, and 10 and Note 8).

NOTE 1—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 2.1 and 2.2.

NOTE 2—Bremsstrahlung characteristics are similar to gamma rays from radioactive isotopes. See Practice E 1204 for the applications of dosimetry in the characterization and operation of gamma-ray irradiation facilities. For information concerning electron beam irradiation technology and dosimetry, see Practice E 1431.

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

E 1204 Practice for Dosimetry in Gamma Irradiation Facilities for Food Processing[2]

E 1205 Practice for Use of a Ceric-Cerous Sulfate Dosimetry System[2]

E 1261 Guide for the Selection and Application of Dosimetry Systems for Radiation Processing of Food[2]

E 1275 Practice for Use of a Radiochromic Film Dosimetry System[2]

E 1276 Practice for Use of a Polymethylmethacrylate Dosimetry System[2]

E 1310 Practice for Use of a Radiochromic Optical Waveguide Dosimetry System[2]

E 1400 Practice for Characterization and Performance of a High-Dose Gamma-Radiation Dosimetry Calibration Laboratory[2]

E 1401 Practice for Use of a Dichromate Dosimetry System[2]

E 1431 Practice for Dosimetry in Electron and Bremsstrahlung Irradiation Facilities for Food Processing[2]

E 1538 Practice for Use of the Ethanol-Chlorobenzene Dosimetry System[2]

E 1539 Guide for Use of Radiation-Sensitive Indicators[2]

E 1540 Practice for Use of a Radiochromic Liquid Dosimetry System[2]

E 1607 Practice for Use of the Alanine-EPR Dosimetry System[2]

2.2 *ICRU Reports:*[3]

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

Report 33 Radiation Quantities and Units

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

Report 37 Stopping Powers for Electrons and Positrons

3. Terminology

3.1 *Definitions*—Definitions of terms used in this practice may be found in Terminology E 170 and ICRU Report 33.

3.2 *Descriptions of Terms Specific to This Standard*—Definitions of some terms specific to this practice are listed below.

3.2.1 *absorbed dose, D*—the quotient of de by dm, where de is the mean energy imparted by ionizing radiation to matter of mass dm (see ICRU Report 33):

$$D = de/dm$$

The special name of the unit for absorbed dose in the International System of Units (SI) is the gray (Gy).

---

[1] This practice is under the jurisdiction of ASTM Committee E-10 on Nuclear Technology and Applications and is the direct responsibility of Subcommittee E10.01 on Dosimetry for Radiation Processing.

Current edition approved April 15, 1994. Published August 1994.

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

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

$$1\ Gy = 1\ J\ kg^{-1}$$

3.2.1.1 *Discussion*—The special unit for absorbed dose was formerly the rad.

$$1\ rad = 10^{-2}\ J\ kg^{-1}$$

$$1\ rad = 10^{-2}\ Gy$$

$$1\ Mrad = 10\ kGy$$

3.2.2 *absorbed dose enhancement*—the increase (decrease) in the absorbed dose, as compared to the equilibrium dose, at a point in the material of interest. This will occur near an interface between materials with different atomic numbers.

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

3.2.3.1 *Discussion*—When a beta particle (electron) passes close to a nucleus, the strong attractive coulomb force causes the beta particle to deviate sharply from its original path. The change in direction is due to radial acceleration, and in accordance with classical theory the beta particle loses energy by electromagnetic radiation at a rate proportional to the square of the acceleration. This means that the bremsstrahlung photons have a continuous energy distribution that ranges downward from a theoretical maximum equal to the kinetic energy of the beta particle. Practically, bremsstrahlung is produced when an electron beam strikes any material (converter). The bremsstrahlung spectrum depends on the electron energy, converter material, and its thickness.

3.2.4 *calibration curve*—the graphical or mathematical relationship between the response of a dosimeter and the absorbed dose for a given dosimetry system. This is also referred to as the dosimetry system response function.

3.2.5 *dose uniformity ratio*—the ratio of the maximum to minimum absorbed dose within an irradiation container.

3.2.5.1 *Discussion*—It is a measure of the degree of uniformity of the absorbed dose. This concept is also referred to as the max/min dose ratio.

3.2.6 *dosimeter (dose meter)*—a device for measuring radiation-induced signals that can be related to absorbed dose (or energy deposited) by radiation in materials and is calibrated in terms of the appropriate quantities and units.

3.2.7 *dosimetry system*—a system used for determining absorbed dose, consisting of dosimeters, measurement instrumentation, the calibration curve, reference standards, and procedures for the system's use.

3.2.8 *electron energy*—the kinetic energy of an electron that is usually given in units of electron volts (eV), kiloelectron volts (keV), or megaelectron volts (MeV).

3.2.9 *electron energy spectrum*—the frequency distribution of electrons as a function of energy. The energy spectrum of the electrons incident on the converter depends on the type of electron accelerator and the beam dispersion system being used.

3.2.10 *equilibrium absorbed dose*—the absorbed dose value that exists in a material at a minimum distance from any interface with another material, with this distance being greater than the range of the maximum energy electrons generated by the incident photons.

3.2.11 *measurement quality assurance plan*—a documented program for the measurement process that quantifies the total uncertainty of the measurements (both random and systematic error components). This plan shall demonstrate traceability to national standards and shall show that the total uncertainty meets the requirements of the specific application.

3.2.12 *traceability*—an unbroken chain of calibrations leading to documented assurance that the dose reading of a dosimeter system has been derived from a certified reference material, national or international standard.

3.2.13 *X rays*—the common name for the short-wavelength electromagnetic radiation emitted by high-energy electrons when they are accelerated, decelerated, or deflected by strong electric or magnetic fields. The term includes both bremsstrahlung from nuclear collisions and the characteristic monoenergetic radiation emitted when atomic electrons make transitions to more tightly bound states.

3.2.14 *X-ray converter*—a device for generating X rays (bremsstrahlung) from an electron beam, consisting of a target, means for cooling the target, and a supporting structure.

3.2.15 *X-ray target*—the X-ray converter that is struck by the electron beam. It is usually made of metal with a high atomic number, high melting temperature, and high thermal conductivity.

4. Significance and Use

4.1 A variety of products and materials may be irradiated with X rays to modify their characteristics and improve the economic value. Examples are single-use medical devices (sterilization), agricultural commodities (preservation), and various polymeric products (material modification). Dosimetry requirements for X-ray processing may vary depending on the type and end use of the product.

NOTE 3—Dosimetry is required for regulated irradiation processes, such as the sterilization of medical devices and the preservation of food, because the results may affect the health of the consumer. It is less important for other industrial processes, such as polymer modification, which can be evaluated by changes in the physical properties of the irradiated materials. Nevertheless, routine dosimetry may be used to monitor the reproducibility of the treatment process.

4.2 As a means of (quality) control of an irradiation process, dosimeters are used to relate their calibrated response to radiation exposure to the absorbed dose in the material or product being irradiated (see Section 7).

4.3 Radiation processing specifications usually include a pair of absorbed-dose limits: a minimum value to ensure the intended beneficial effect and a maximum value to avoid product degradation. For a given application, one or both of these values may be prescribed by process specifications or regulations. Knowledge of the dose distribution within the irradiated material is essential to meet these requirements.

4.4 Several critical parameters must be controlled to obtain reproducible dose distributions in the processed materials. The processing rate and dose distribution depend on the X-ray intensity, photon energy spectrum, spatial distribution of the radiation field, conveyor speed, and product configuration (see Sections 5 and 10 and the Appendix).

4.5 Before an irradiation process can be used, it must be qualified to determine its effectiveness in delivering known, controllable doses. This involves testing the process equipment, calibrating the measuring instruments and dosimetry system, and demonstrating the ability of the process to deliver the desired dose distributions in a reliable and reproducible manner (see Sections 8 and 9).

4.6 To ensure consistent dose delivery in a qualified irradiation process, routine process control requires procedures for product handling before and after the treatment, prescribed orientation of the products during irradiation, monitoring of critical process parameters, routine product dosimetry, and documentation of the required activities and functions (see Sections 10 and 11).

5. Radiation Source Characteristics

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

5.2 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.

5.3 These aspects of an X-ray source and its suitability for radiation processing are reviewed in more detail in the Appendix.

6. Irradiation Facilities

6.1 *Facility Components*—An X-ray irradiation facility includes a high-energy, high-power electron accelerator with X-ray converter, product conveyor, radiation shield with personnel safety system, product staging, loading and storage areas, auxiliary equipment for power, cooling, ventilation, etc., an equipment control room, laboratory for dosimetry, and product testing, and personnel offices. The design shall conform to applicable regulations and guidelines (see Refs **1** and **2**).

6.2 *Product Handling System*—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.

6.3 *Irradiation System*—The configuration of the X-ray converter, the beam current distribution on the target, and the penetrating quality of the radiation, and the size, shape, and density of the product load affect the dose uniformity ratio (see Refs **3–5**).

7. Dosimetry Systems

7.1 *Dosimeter Selection*—The ASTM and ICRU documents listed in 2.1 and 2.2 provide detailed information on the selection and use of high-dose dosimeter systems for gamma-ray (photon) and electron-beam irradiation facilities. Many of these dosimetry systems are also applicable for high-energy X rays since their radiation responses are relatively insensitive to the photon or electron energies (see Practices E 1026, E 1204, E 1205, E 1275, E 1276, E 1310, E 1400, E 1401, E 1431, E 1538, E 1540, and E 1607, Guides E 1261 and E 1539, and ICRU Reports 14, 33, 35, and 37).

NOTE 4—Dosimeters consisting mainly of water or hydrocarbon materials are suitable for both gamma rays and high-energy X rays. Some exceptions are dosimeters containing substantial amounts of material with high atomic numbers. These may be especially sensitive to the low-energy photons in the bremsstrahlung spectrum.

NOTE 5—The X-ray dose rate may be higher than that of gamma rays used for radiation processing, especially in products passing near the X-ray converter. The dose-rate dependence of the dosimeters should be considered in their calibration procedure (see Refs **6** and **7**).

7.2 *Dosimeter Calibration:*

7.2.1 A dosimetry system shall be calibrated prior to use in accordance with a documented procedure that specifies details of the calibration process and quality assurance requirements. The system shall also be calibrated at periodic intervals to ensure that the accuracy of the absorbed-dose measurement is maintained within required limits.

7.2.2 The instruments used in the analysis of the dosimeters shall be calibrated at periodic intervals using appropriate standards traceable to national standards.

7.2.3 Each batch of dosimeters shall be calibrated by an irradiation facility that has an absorbed dose rate traceable to national standards and comparable to the dose rate in the production facility. The irradiation facility should meet the requirements specified in Practice E 1400. Alternatively, each batch may be calibrated against a standard dosimeter under the actual conditions of use in the production irradiation facility.

8. Installation Qualification

8.1 The purpose of dosimetry in qualifying an X-ray facility is to establish baseline data for monitoring the effectiveness, predictability, and reproducibility of the irradiation process throughout a typical range of operating parameters. Dosimetry shall be used for the following purposes:

8.1.1 To establish relationships between absorbed dose in a reproducible geometry and operating parameters.

8.1.2 To characterize the stability of dose when these parameters fluctuate statistically and through normal operations.

8.1.3 To measure absorbed dose distributions in reference materials.

8.2 *Equipment Documentation*—Documentation shall exist describing the equipment, any modifications, and its operation. This information shall be retained for the life of the facility. It shall include the following:

8.2.1 The layout of the facility showing the locations of the major components;

8.2.2 The descriptions, specifications, and characteristics of the electron accelerator, the X-ray converter, the product conveyor, the control system, and all other auxiliary equipment and instrumentation;

8.2.3 The testing, calibrating, and operating procedures for all of the equipment and instrumentation, including the dosimetry system;

8.2.4 Identification of the instrumentation used to control, monitor, and record the critical process parameters that affect the absorbed dose in the irradiated products.

8.3 *Equipment Testing and Calibration*—The first phase of qualifying an irradiation facility is to determine that the processing equipment performs according to its specifications. This includes the accelerator and X-ray converter, product conveyor, control system and its software, and other auxiliary equipment and instrumentation. Calibration of the equipment, instrumentation, and dosimetry system is also essential. Special emphasis must be given to the critical parameters that affect the dose distribution in the irradiated products. These include the electron energy, electron beam current, beam scanning amplitude, and conveyor speed.

8.4 *Irradiator Characterization*—The second phase is to show that the irradiation process can be accomplished within the specified tolerances under prescribed operating conditions and that the results are reproducible. Reference material of product can be used for this purpose. The dose distribution within the reference material or product should be determined by detailed dose mapping. The effects of small variations in the critical process parameters should be assessed and recorded.

8.5 *Measurement Quality Assurance Plan*—Proper measurement procedures, with appropriate statistical controls and documentation, shall be used to ensure that the equipment works properly and that the treatment process delivers the required doses according to specifications.

9. Process Qualification

9.1 *Process Parameters*—For each product to be treated in the irradiation facility, there will usually be a minimum dose to obtain the desired effect and a maximum dose that the product can tolerate without degradation in quality. These dose limits may have to be determined experimentally. The equipment parameters to achieve the required doses must also be determined.

9.2 *Absorbed Dose Mapping*—The dose distribution within the product package and throughout the product container or pallet load must be measured to find the locations of the minimum and maximum doses. The relationship of these doses to that obtained at a conveniently accessible point on the outside of the product or container may also be determined for use in routine processing. The reproducibility of these doses at the minimum, maximum, and monitoring points should be evaluated. The effects of variations in the critical process parameters must also be evaluated.

NOTE 6—Monitoring of operating parameters alone may not be adequate for some radiation processes (for example, sterilization of medical products and preservation of food). Dosimetry is required during routine product processing for these situations.

NOTE 7—In conjunction with dose distribution measurements, it is usually necessary to conduct testing of the product materials to ensure compatibility with the X-ray treatment. It is recommended that this testing be performed at doses larger than the maximum absorbed dose attained during routine processing.

10. Routine Processing

10.1 *Process Monitoring*—All critical process parameters that can affect the absorbed dose distribution must be controlled and monitored during all routine processing. The tolerance limits on these parameters must be determined and the treatment process aborted if excessive variations occur. Measurements of these critical parameters should be made and also recorded at regular intervals to prove the continuity of the process (see 4.4).

10.2 *Routine Dosimetry*—It is not necessary to have dosimeters on every product unit, but they should be placed at the beginning and the end of a production run to confirm the validity of the irradiation process. For long runs, dosimeters should also be placed near the middle of the run and at other intervals as appropriate.

11. Certification

11.1 *Process Control*—All equipment functions and personnel activities that ensure the effectiveness of the irradiation process are components of the process control program. These include product handling procedures before and after irradiation, proper loading of the product conveyor, monitoring of the critical process parameters, and routine product dosimetry.

11.2 *Documentation*—All aspects of the irradiation process that can affect its validity should be covered by written procedures. Installation qualification and process qualification should be accomplished according to plan and all of the results recorded. Routine operations and dosimetry data should be recorded and correlated with product records.

11.3 Documentation should be reviewed by authorized personnel and maintained for inspection.

12. Precision and Bias

12.1 Records and reports should include estimates of the measurement uncertainty of absorbed dose that include both precision and bias at a specified confidence level (see Guide E 1261).

12.2 The critical parameters for the irradiation process should take into account the level of uncertainty of the dosimetry system to ensure delivery of the required dose.

12.3 The calibration of the dosimeters should be traceable to national standards and should be conducted at regular intervals (see Guide E 1261).

NOTE 8—Additional information on regulations and guidelines for radiation processing can be found in Refs **8–20**.

13. Keywords

13.1 absorbed dose; bremsstrahlung; dose distribution; dose mapping; dosimeter; dosimetric procedures; dosimetry; electron accelerator; electron beam; facility characterization; ionizing radiation; irradiator characterization; photon; radiation; radiation dosimetry; radiation facility; radiation processing; X ray; X-ray processing; X-ray target; X-ray utilization

APPENDIX

Nonmandatory Information

X1. X-RAY (BREMSSTRAHLUNG) CHARACTERISTICS

X1.1 *X-Ray Processing*—The physical properties of X rays (bremsstrahlung) are well known, and the use of this type of radiation for material processing has been studied extensively **(21)**. Some important characteristics of this technology are described below, and more detailed information can be obtained from the selected references listed at the end of the appendix. Some of this knowledge has been obtained by dosimetry, but much is based on theoretical analyses using the Monte Carlo methods listed in Ref **22** and the data sources in Refs **23–27**.

X1.2 *Electron Accelerators:*

X1.2.1 Since bremsstrahlung is produced by high-energy electrons, an electron accelerator is essential for generating this kind of radiation. Various types of accelerators can be used, including both direct-action and indirect-action machines. High-power technologies appropriate for X-ray processing have been reviewed in Refs **28–30**.

X1.2.2 *Direct Action Accelerators*—Machines of this type employ dc or pulsed high-voltage generators to create strong electric fields. The electrons are accelerated by these fields through evacuated, single-gap or multiple-gap beam tubes from a thermionic cathode at high negative potential to a grounded anode. The most powerful systems use cascaded rectifier circuits to convert low-voltage ac to high-voltage dc power. Direct action accelerators can now produce electron energies up to 5 MeV and electron beam powers up to 200 kW **(5, 31–34)**.

X1.2.3 *Indirect-Action Accelerators*—Machines of this type use microwave or very high frequency (vhf) ac power to accelerate electrons within evacuated metallic waveguides or resonant cavities, which are at ground potential. The electrons gain energy by moving in phase with the electromagnetic wave. The final energy is determined by the field strength and length of the beam trajectory. Microwave accelerators can now produce electron energies in the 5 to 15 MeV range with average beam powers up to 50 kW at 10 MeV **(35–39)**. Linear induction accelerators may be applicable in the future **(28, 30, 40, 41)**.

X1.3 *Converter Design:*

X1.3.1 The X-ray conversion efficiency (electron power to X-ray power emitted in the forward direction) increases with the electron energy and atomic number of the target material. For example, tantalum, tungsten, or gold are suitable materials because of their high densities and melting temperatures. Theoretical analyses with Monte Carlo codes have shown that conversion efficiencies of approximately 7 to 8 % at 5 MeV and 14 to 16 % at 10 MeV can be obtained with optimum thicknesses of tantalum or tungsten converters (approximately 40 % of the maximum electron range) supported by a copper channel cooled with water **(1, 42–49)**.

X1.3.2 Most of the electron beam power is dissipated as heat in the target assembly and must be removed by a cooling system **(1, 45)**. The total thickness of the target assembly plus the cooling channel should be slightly greater than the maximum electron range in order to avoid irradiating the products with primary electrons.

X1.4 *Converter and Beam Configurations:*

X1.4.1 In contrast to radiographic and therapeutic X-ray machines, which use small-diameter electron beams to make well-collimated X-ray beams, radiation processing equipment must use electron beams with large cross sections and targets with large areas to dissipate the beam power. The electron beams may be dispersed by scanning magnets, defocussing magnetic lenses, or beam-scattering foils.

X1.4.2 For irradiating products on a moving conveyor, it is convenient to use beam scanning to uniformly cover an elongated target that is oriented across the conveyor. This configuration increases the width of the radiation field and facilitates the treatment of large volumes of material (see Fig. X1.1) **(1, 39, 44–46, 50–57)**.

X1.5 *Bremsstrahlung Properties:*

X1.5.1 In the energy range from 5 to 10 MeV, the X-ray power P_x emitted by an optimum converter is proportional to the electron beam current I times the square of the electron energy E **(4, 42, 43, 45, 48, 49, 51, 54, 58)**. With constant electron beam power $P_e = I\,E$, the emitted X-ray power increases linearly with the electron energy. This means that the electron beam to X-ray power conversion efficiency n increases linearly with the electron energy as follows:

$$P_x = f\,I\,E^2 = f\,P_e\,E$$

$$n = P_x/P_e = f\,E$$

f = a proportionality factor.

X1.5.2 Unlike gamma rays from radioactive nuclei, high-energy X rays are not emitted isotropically, but are concentrated in the electron beam direction (see Figs. X1.2 and X1.3)**(43, 45, 56–58)**. The angular dispersion decreases as

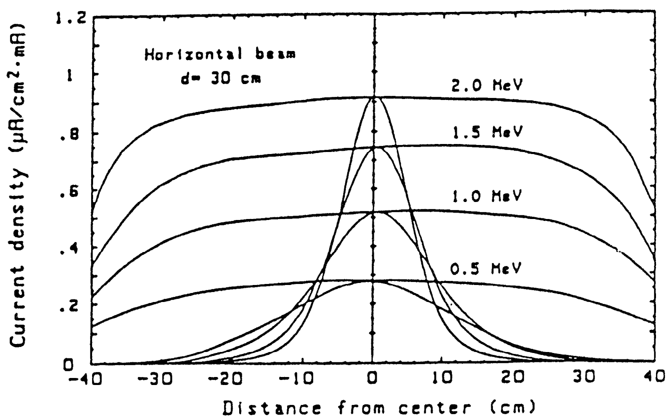


FIG. X1.1 Beam Current Density Distributions in the X and Y Directions of No. 1 Accelerator of JAERI Takasaki (Fig. 2.1 from Ref 45)

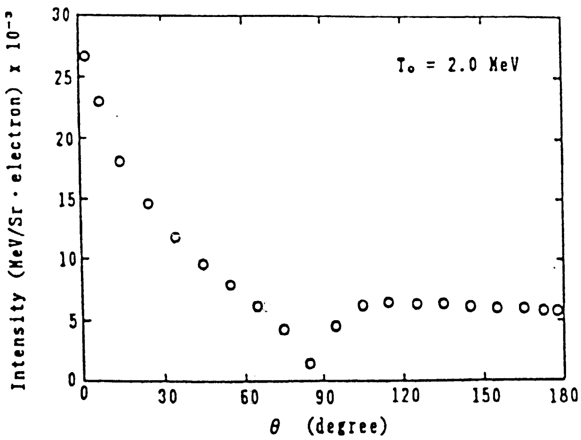


FIG. X1.2 X-ray Intensity per Incident 2 MeV Electron Incident Perpendicularly on a Tantalum Target with Thickness of One Continuous Slowing Down Approximation (CSDA) Range as a Function of Emitting Angle Calculated by ETRAN Code (Fig. 3.3 from Ref 45)

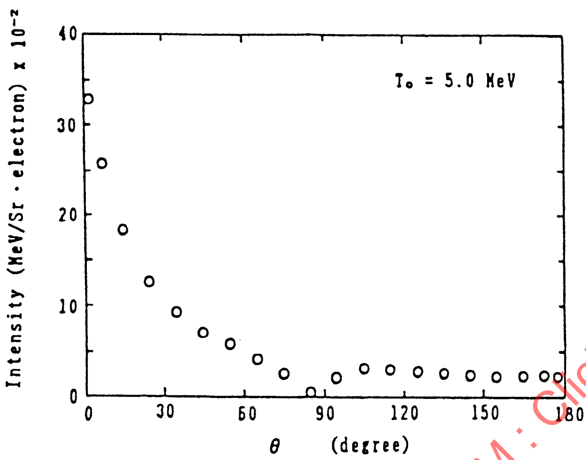
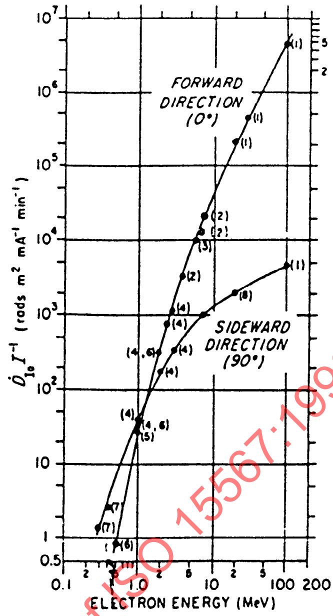


FIG. X1.3 X-ray Intensity per Incident 5 MeV Electron Incident Perpendicularly on a Tantalum Target with Thickness of One CSDA Range as a Function of Emitting Angle Calculated by ETRAN Code (Fig. 3.4 from Ref 45)

the energy of the electrons increases. For example, the ratios of X-ray intensities in the forward and sideward (slightly backward) directions with small-diameter electron beams on thick, high-density targets are approximately 4/1 at 3 MeV, 10/1 at 5 MeV, and 40/1 at 10 MeV (see Fig. X1.4) (**59**).

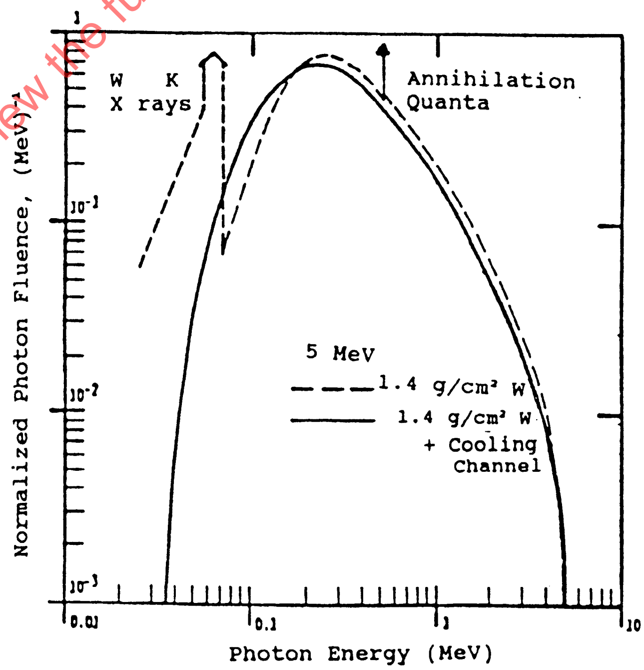
X1.5.3 The forward concentration increases the radiation intensity and reduces the size of the irradiation zone in comparison to a large-area gamma-ray source of equivalent power and throughput capacity. These effects reduce the treatment time and volume of products within the treatment room. This facilitates the transition from one type of product to another in a continuing irradiation process.

X1.5.4 The continuous energy spectrum of bremsstrahlung emitted through the target assembly extends from approximately 35 keV up to the maximum energy of the electrons incident on the converter. The differential energy spectrum (number of photons per unit energy interval) increases as the photon energy decreases (see Figs. X1.5 and X1.6) (**43, 46, 58, 60**). For example, the numerical average photon energy produced by 5 MeV electrons in a tantalum or tungsten target with optimum thickness is only approximately 0.75 MeV.



NOTE—The numbers along the curves identify papers cited in Ref **59**.

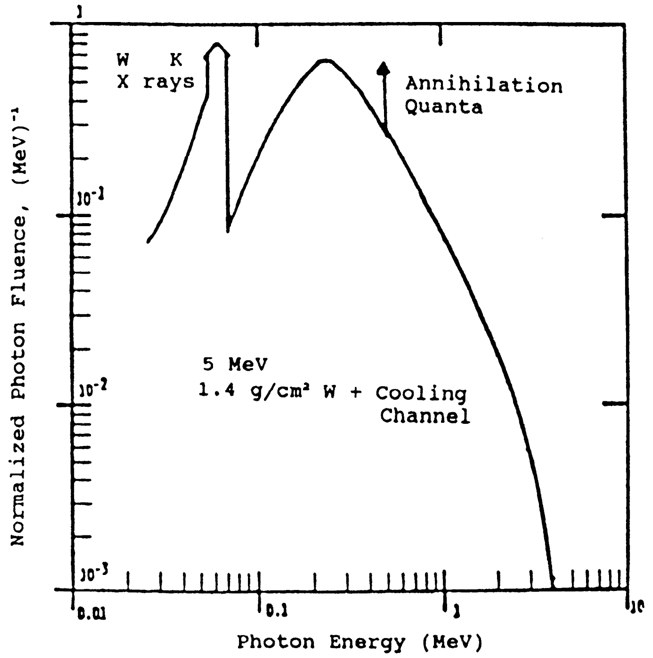
FIG. X1.4 X-Ray Emission Rates from High-Z Targets (Fig. E 1 from Ref 59)



NOTE—Results are given for transmission both by the converter plate only and by the converter plate plus cooling channel.

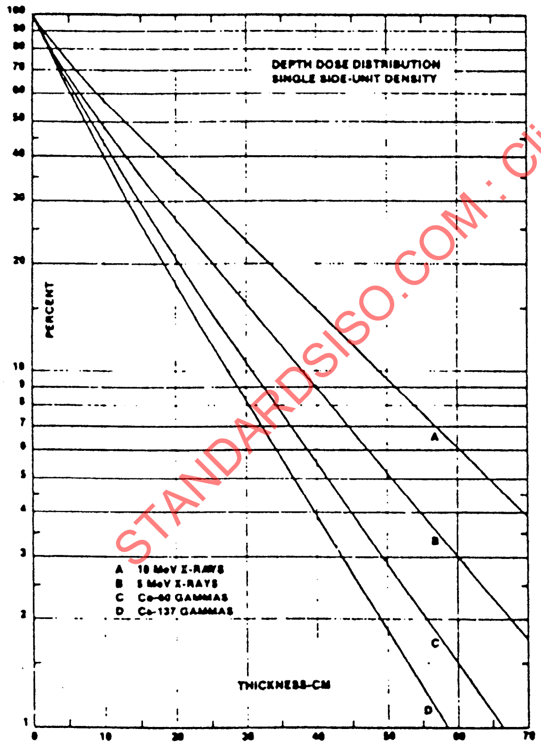
FIG. X1.5 Spectrum of Transmitted Photons (Fig. 2 a from Ref 43)

X1.5.5 Even though the average photon energy is low in comparison to the maximum energy, the penetration of broad-beam 5 MeV X rays in absorbers with low atomic numbers is still greater than that of gamma rays from Co-60, which have an average photon energy of 1.25 MeV (see Fig. X1.7). This is due to the higher energy components and



NOTE—Results pertain to reflection by total target. Spectra of photons emergent from target incorporating 1.4 g/cm² W converter. The results are for a 5 MeV incident electron beam energy and include all photons regardless of emergent angle.

FIG. X1.6 Spectrum of Reflected Photons (Fig. 2 b from Ref 43)



NOTE—Percentage depth-dose distribution in water or unit-density materials for single-sided irradiation: (*A*) 10 MeV X-rays; (*B*) 5 MeV X-rays; (*C*) ^{60}Co gamma rays; and (*D*) ^{137}Cs gamma rays.

FIG. X1.7 Depth Dose Distribution (Fig. 1 from Ref 4)

forward concentration of bremsstrahlung versus the isotropic emission of gamma rays from large area sources **(1, 4, 28, 41, 46, 48, 49, 56, 57)**.

X1.6 *Absorbed Dose Distributions:*

X1.6.1 With large-volume absorbers and a single-track conveyor, the longitudinal dose distributions (parallel to the direction of conveyor motion) are nearly uniform, except for slight increases on the leading and trailing edges of the absorbers. On the other hand, the latitudinal dose distributions (orthogonal to the conveyor motion) decrease at both sides of the absorber, even when the X-ray target extends beyond the sides of the conveyor (see Fig. X1.8) **(1, 2, 46, 57)**.

X1.6.2 The depth dose distributions (dose attenuation curves) obtained by irradiating low-atomic-number materials (for example, water, plastic, or cardboard) with 5 MeV X rays are essentially exponential. However, the slope of the curve tends to decrease slightly as the thickness increases, due to hardening of the X-ray spectrum, that is, the greater attenuation of lower-energy photons (see Fig. X1.9) **(1, 2, 43, 46, 56, 57)**.

X1.6.3 With elongated targets, large area absorbers, and a moving product conveyor, the surface dose on the side facing the target is quite near the exponential depth-dose curve (see Fig. X1.10) **(1, 2, 56–57)**. Thus, the dose buildup effect near the surface, which is seen with collimated beams of high-energy X rays or gamma rays and stationary absorbers, is not significant in a broad-beam X-ray irradiation process **(61–63)**.

X1.6.4 The max/min dose ratio and the photon power utilization both depend on the size and density of the irradiated material as well as the method of conveying the material through the radiation field **(1, 53, 54, 57)**. By using dual-track conveyor systems with two-sided irradiation and multiple layers of material, it is theoretically possible to achieve low max/min dose ratios (for example, 1.1 to 1.2) and high photon power utilization (for example, 50 to 60 %)

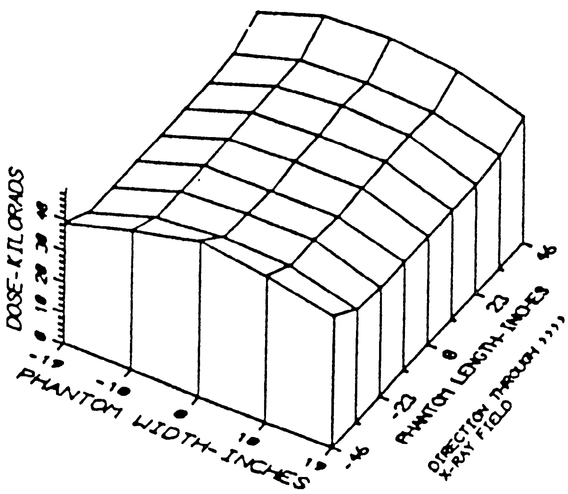


FIG. X1.8 Dose Contour Map, Moving Exposure (Fig. 3 from Ref 46)

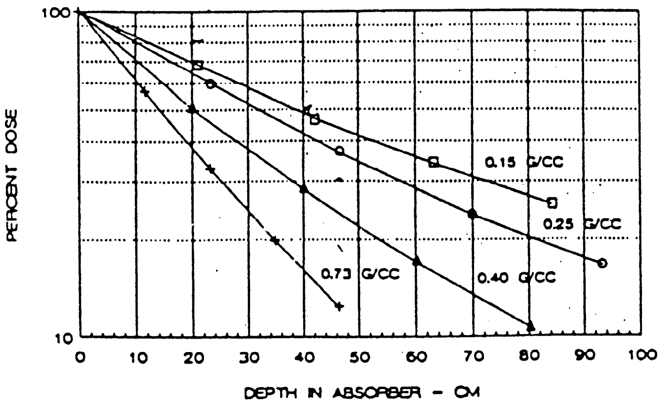


FIG. X1.9 Attenuation Curve for 5 MeV X-Rays in Absorbers of Various Densities, with Moving Conveyor and Scanning Beam (Fig. 5 from Ref 1)

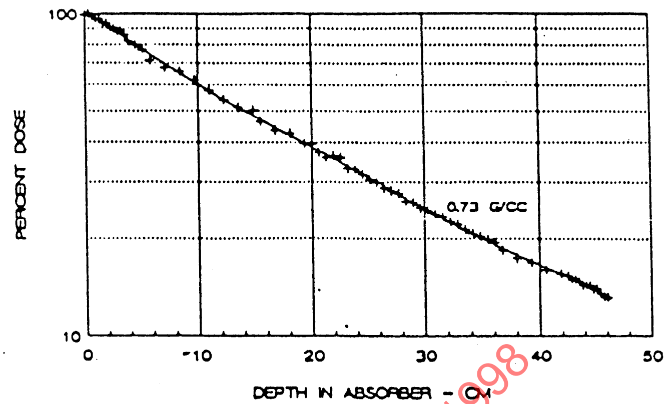


FIG. X1.10 A High-Resolution Attenuation Curve for 5 MeV X-Rays in the Heaviest Absorber, with Moving Conveyor and Scanning (Fig. 6 from Ref 1)

in large volumes of absorbing material with low atomic number and low density (for example 0.3 g/cm^3) (**3, 64, 65**).

X1.7 *Chemical and Biological Effects:*

X1.7.1 Studies on the radiation degradation of polypropylene with gamma rays, X rays, and electrons have shown that X-ray effects are intermediate between gamma rays and electrons. This is attributed to the differences in dose rates. Higher dose rates deplete the available oxygen in the material faster than it can be replenished by diffusion and reduce the degradation of physical properties accordingly (**66**).

X1.7.2 The biological effectiveness of gamma rays, X rays, and electrons is essentially the same for microorganisms (spores) irradiated in air. However, some differences have been observed in other media. The oxygen depletion effect reduces the effectiveness of the radiation as the dose rate increases. X rays have been found to be intermediate between gamma rays and electrons in such conditions (**67–69**).

REFERENCES

(1) Cleland, M. R., Thompson, C. C., Kato, H., Odera, M., Morrissey, R. F., Herring, C. M., O'Neill, M. T., Wilcott, T. R., Masefield, J., Hansen, J. M., Saylor, M. C., and Sloan, D. P., "Evaluation of a New X-Ray Processing Facility," *Nuclear Instruments and Methods in Physics Research*, B56/57, 1991, pp. 1242–1245.

(2) Takehisa, M., Saito, T., Takahashi, T., Sato, Y., and Sato, T., "Characteristics of a Contract Electron Beam and Bremsstrahlung (X Ray) Irradiation Facility of Radia Industry," *Radiation Physics and Chemistry*, Vol 42, Nos. 1–3, 1993, pp. 495–498.

(3) Tanaka, S., Agematsu, K., Sunaga, H., Tanaka, R., Taniguchi, S., and Kashiwagi, M., "High-Power X-Ray Irradiation Facility for Industrial Application. (I) Irradiation Method," *Proceedings 23rd Annual Meeting on Radioisotopes in the Physical Sciences and Industry*, 1986, p. 36.

(4) Cleland, M. R., and Pageau, G. M., "Comparisons of X-Ray and Gamma-Ray Sources for Industrial Irradiation Processes," *Nuclear Instruments and Methods in Physics Research*, B24/25, 1987, pp. 967–972.

(5) Thompson, C. C., and Cleland, M. R., "High-Power Dynamitron Accelerators for X-Ray Processing," *Nuclear Instruments and Methods in Physics Research*, B40/41, 1989, pp. 1137–1141.

(6) Sato, T., Takahashi, T., Saito, T., Takehisa, M., and Miller, A., "Application of Calorimeters for 5 MeV EB and Bremsstrahlung Dosimetry," *Radiation Physics and Chemistry*, Vol 42, Nos. 4–6, 1993, pp. 789–792.

(7) Sunaga, H., Tachibana, H., Tanaka, R., Okamoto, J., Terai, H., and Saito, T., "Study on Dosimetry of Bremsstrahlung Radiation Processing," *Radiation Physics and Chemistry*, Vol 42, Nos. 4–6, 1993, pp. 749–752.

(8) *Manual of Food Irradiation Dosimetry*, Technical Reports Series No. 178, Chadwick, K. H., Ehlermann, D. A. E., and McLaughlin, W. L., IAEA, Vienna, 1977.[4]

(9) *Irradiation in the Production, Processing and Handling of Food, Federal Register*, Vol 50, No. 140, 1985, p. 29658, amending 21 CFR Part 179.[5]

(10) *Irradiation of Pork for Control of Trichinella Spiralis, Federal Register*, Vol 51, No. 10, 1986, pp. 1769–1771, amending 9 CFR Part 318.[5]

(11) *Response to Comments; Irradiation of Pork for Control of Trichinella Spiralis, Federal Register*, Vol 51, No. 234, 1986, pp. 43872–43875, amending 9 CFR Part 318.[5]

(12) *Food Additives; Irradiation in the Production, Processing and Handling of Animal Feed and Pet Food; Ionizing Radiation for Treatment of Laboratory Animal Diets, Federal Register*, Vol 51, No. 33, 1986, pp. 5992–5993, amending 21 CFR Parts 570 and 579.[5]

(13) *Irradiation in the Production, Processing and Handling of Food, Federal Register*, Vol 51, No. 75, 1986, pp. 13376–13399, amending 21 CFR Part 179.[5]

(14) *Use of Irradiation as a Quarantine Treatment for Fresh Fruits of Papaya from Hawaii, Federal Register*, Vol 54, No. 4, 1989, pp. 387–393, amending 7 CFR Part 318.[5]

(15) *Irradiation in the Production, Processing and Handling of Foods, Federal Register*, Vol 54, No. 33, 1989, pp. 7404–7405, amending 21 CFR Part 179.[5]

[4] Available from IAEA, Wagramerstrasse 5, P.O. Box 100, A-1400 Vienna, Austria.

[5] Available from Standardization Documents Order Desk, Bldg. 4 Section D, 700 Robbins Ave., Philadelphia, PA 19111-5094, Attn: NPODS.