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Practice for dosimetry in an electron-beam facility for radiation processing at energies between 80 keV and 300 keV

Pratique de la dosimétrie de faisceaux d'électrons pour irradiations à des énergies comprises entre 80 keV et 300 keV

Reference number
ISO 15573:1998(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 15573 was prepared by the American Society for Testing and Materials (ASTM) Subcommittee E10.01 (as E 1818-96) 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 15573 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*

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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*

3.2.9 *depth-dose distribution, n*—variation of absorbed dose with depth from the incident surface of a material exposed to a given radiation (see Fig. 1 for calculated values).

3.2.10 *dose uniformity ratio, n*—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.

3.2.11 *dosimeter, n*—a device that, when irradiated, exhibits a quantifiable change in some property of the device which can be related to absorbed dose in a given material using appropriate analytical instrumentation and techniques.

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

3.2.13 *electron energy, n*—kinetic energy of the accelerated electron beam (units—eV (electron volts)). Often, acceleration voltage in kV is used to characterize beam energy in keV. The maximum energy of the beam inside the accelerator is equal to the acceleration voltage but expressed in keV units. The beam energy at the product surface is less than the maximum energy inside the accelerator due to losses in the beam path, such as the window and the air gap.

3.2.14 *traceability, n*—the documentation demonstrating by means of an unbroken chain of comparisons that a measurement is in agreement within acceptable limits of uncertainty with comparable nationally or internationally recognized standards.

3.2.15 *practical electron range, n*—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.

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

3.2.17 *production run, n—continuous-flow irradiation*, 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.

3.2.18 *product plane, n*—the plane corresponding to the top surface of the product being irradiated.

3.2.19 *self-shielded accelerator, n*—an electron beam source that is integrally designed with radiation shielding, product transport system, and irradiation chamber.

3.2.20 *single-gap accelerator, n*—an electron beam source consisting of a vacuum tube and a high voltage power supply that can accelerate a dispersed beam of electrons from a high voltage potential to ground potential in one stage.

3.2.21 *surface area rate coefficient (K), n*—a quantity relating area irradiated per unit time to beam current and absorbed dose. Typically this value is expressed in kGy meters^2 per milliampere minute, or Megarad feet^2 per milliampere minute. Calculated values using Monte Carlo simulation are shown in Table 1. In the literature, this processing rate concept is sometimes called the processing coefficient.

3.2.22 *uncertainty, n*—a parameter associated with the result of a measurement that characterizes the dispersion of the values that could reasonably be attributed to the measurand or derived quantity (see Guide E 1707).

4. Significance and Use

4.1 A variety of processes use low energy electron beam accelerators to modify product characteristics. Dosimetry requirements, the number and frequency of measurements, and record keeping requirements will vary depending on the type and end use of the products being processed. In many cases dosimetry may be used in conjunction with physical, chemical, or biological testing of the product. In many cases reference standards may be developed, comparing dosimetry results with other quantitative product testing; for example, sterility, gel fraction, melt flow, modulus, molecular weight distribution, or cure analysis tests can be used to determine radiation dose in specific relevant materials. Wherever possible, the results of quantitative physical testing should be used in conjunction with dosimetry in commercial radiation processing applications.

4.2 Radiation processing specifications usually include a

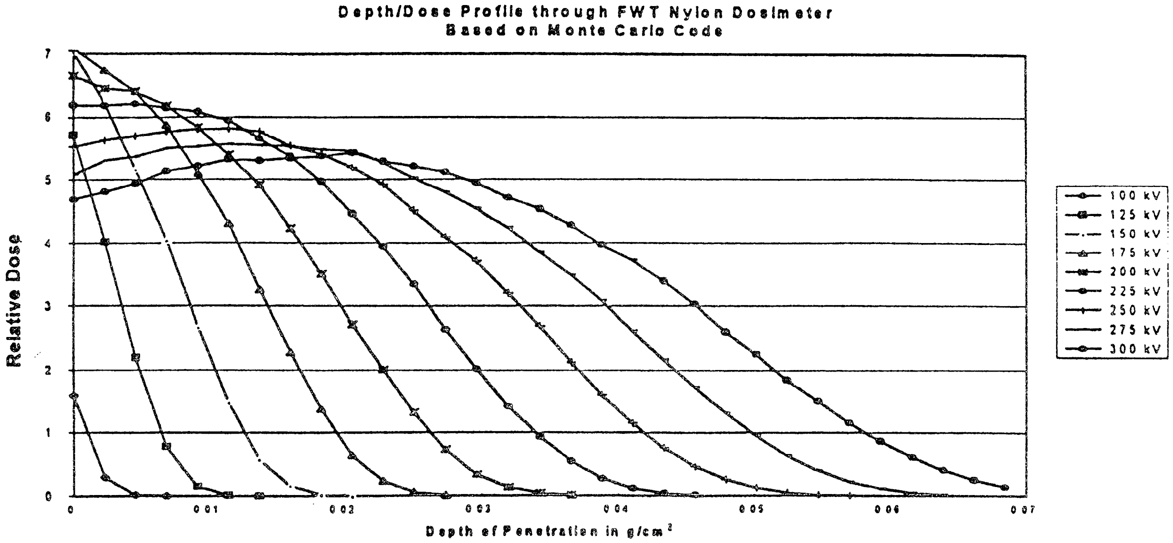

FIG. 1 Depth Dose Curves (0.5 mil Ti Window, 0.5 in. Air Gap)

TABLE 1 Calculated *K* Values at the Product Surface

Electron Beam Acceleration Voltage	Kilogray Metres²/ Milliampere Minute (*K*)[A]	Megarad Feet²/Milliampere Minute (*K*)[A]
100 kV	6.0	6.5
125 kV	14.9	16.0
150 kV	24.3	25.1
175 kV	23.4	25.2
200 kV	23.3	25.1
225 kV	22.7	24.4
250 kV	21.4	23.0
275 kV	18.7	20.1
300 kV	18.5	19.9

[A] Based on Monte Carlo Integrated Tiger Series simulation, assuming Far West (FWT 60-00) film dosimeters and 12.7 mm (0.5 in.) air gap.

minimum or maximum absorbed dose limit, or both. For a given application these limits may be set by government regulation or by limits inherent to the product itself.

4.3 Critical process parameters must be controlled to obtain reproducible dose distribution in processed materials. The electron beam energy (in eV), beam current (in mA), spatial distribution of the beam, and exposure time or process line speed all affect absorbed dose (see Section 5). In some liquid-to-solid polymerization applications (often referred to as radiation curing), the residual oxygen level during irradiation must be controlled to achieve consistent results. A high level of residual oxygen can affect product performance in these curing applications, but it will not affect the absorbed dose.

4.4 Before any radiation process can be utilized, it must be validated to determine its effectiveness. This involves testing of the process equipment, calibrating the measuring instruments, and demonstrating the ability to deliver the desired dose within the desired dose range in a reliable and reproducible manner. The desired improvements, as well as any undesirable effects due to radiation damage to a specific product, should be understood.

5. Dosimetry System

5.1 The documents listed in Section 2 provide detailed information on the selection and use of appropriate dosimetry systems for gamma-ray and electron beam irradiation. Due to the limited depth of penetration of low energy electron beams and the narrow air gaps that are inherent in self-shielded equipment, thin film dosimeters are usually preferred over thicker systems (see Refs **1**, **2**, and **3**,[6] Practices E 1275 and E 1650, and Guide E 1261).

6. Installation Qualification and Testing

6.1 *Equipment Testing*—The first phase of qualifying an irradiation facility is to determine that the processing equipment performs in accordance with design specifications. The process should include mechanical and electrical testing of the electron beam accelerator and related processing equipment, and should include, but not be limited to, the following:

6.1.1 Operation of all safety interlocks,

6.1.2 Operation of all system interlocks,

6.1.3 An extended demonstration of system performance at specified ratings,

6.1.4 Operation of the system over the full range of voltage and beam current,

6.1.5 Radiation survey at maximum operating voltage and current,

6.1.6 Mechanical inspection of the system,

6.1.7 Electrical inspection of the system,

6.1.8 Performance of the inert gas system, if applicable,

6.1.9 Performance of the ozone exhaust system, if applicable, and

6.1.10 Testing and calibration of product handling system over the full performance range.

6.2 The second phase of qualifying an irradiation facility is to characterize the performance of the equipment using dosimetry. The purpose of these measurements is to qualify the dose delivering characteristics of the equipment for performance acceptance and for future reference. The process should include, but not be limited to, the following:

6.2.1 *Surface Area Rate Measurements*—minimum of five measurements over the voltage range of interest with at least five dosimeters equally spaced across the width of the beam at the product plane at a nominal dose level. The surface area rate measurement should be repeated at a typical operating voltage level at several different beam current levels to establish and test the linearity between beam current and surface dose (see Appendix X1).

6.2.2 *Beam Uniformity Measurements*—minimum of one dosimeter per 2.5 cm over full width. Three measurements should be made at the product plane (see Appendix X1).

6.2.3 *Depth-dose Measurements*—A minimum of three measurements should be made at each voltage covering the voltage range of interest measured with the dosimetry stack at the product plane (see Appendix X1).

7. Frequency of Dosimetric Measurements

7.1 Initial facility performance evaluation dosimetry should be conducted in accordance with Section 6.

7.2 *Product Validation*—Surface area rate measurements should be made during product validation to compare with the results of product testing.

NOTE 1—Absorbed dose distribution measurements may be required for regulated processing applications.

7.3 *After Routine Maintenance*—After routine maintenance such as window changes, a minimum number of three surface area rate measurements should be made.

7.4 *After Major System Maintenance*—After major system maintenance such as cathode or insulator bushing replacement, a minimum number of three surface area rate and beam uniformity measurements should be made.

7.5 *Routine Process Control*—Surface area rate measurements can be made during a production run. In some applications process control dosimetry may be required by regulation or may be desirable for quality control record keeping.

8. Throughput Calculations

8.1 *Mass Processing Rate*—The beam power of an electron beam machine can be expressed in watts, which is the product of the beam voltage (kV) and the beam current (mA). An absorbed dose of 10 kGy (1 Mrad) corresponds to

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[6] The boldface numbers in parentheses refer to a list of references at the end of this practice.

the uniform absorption of 10 kilowatt seconds of energy in 1 kilogram of product assuming 100 % utilization efficiency. For a machine having an output of 1 kilowatt, this translates to a bulk processing rate of 360 kg (794 lbs) of product per h to an absorbed dose of 10 kGy (1 Mrad) assuming 100 % beam power utilization.

8.1.1 Actual beam power utilization is lower than 100 %, so in order to utilize this concept for a given situation the efficiency of radiation absorption in the product must be known. This concept is typically expressed by the simple equation:

$$\text{Mass processing rate} = \frac{C_{cap} \cdot P \cdot f}{D} \qquad (2)$$

where:

C_{cap} = 3600 kGy kg/kW h or 794 Mrad lbs/kW h,
P = beam power in kW,
f = beam power efficiency, and
D = dose in kGy or Mrad.

NOTE 2—The beam power efficiency factor, f, is the fraction of the beam power absorbed in the product. The dose, D, in this formula is the average dose throughout the product.

8.2 *Area Processing Rate*—It is often convenient to calculate the area processing rate using the surface area rate (K). This method involves a simple formula based on the Surface Area Rate or Processing Coefficient (K) which takes into account the electron energy, absorption efficiency, beam current, spatial dispersion, and process line speed. In this case the surface area processing rate can be expressed by the simple equation:

$$\text{Area processing rate} = W_b \cdot V_1 = \frac{K \cdot I}{D} \qquad (3)$$

where:

K = surface area rate in kGy m^2/mA min or Mrad ft^2/mA min,
D = dose in kGy or Mrad,
W_b = beam width in m or ft,
V_1 = line speed in m/min or ft/min, and
I = beam current in mA.

See Table 1 for calculated K values at specific acceleration voltages.

9. Certification

9.1 *Documentation:*

9.1.1 Establish a record and documentation system that documents all dosimetry data from facility installation and testing procedures, process validation, machine maintenance and change history.

9.1.1.1 Record the measurements of performance that qualify the dose delivering characteristics of the equipment. The Irradiation Control Record must have the date, time, critical process parameters, and the name of the machine operator (see 4.3).

9.1.1.2 When appropriate, record dosimetry results and the values of the processing parameters affecting absorbed dose together with sufficient information identifying these parameters with specific production runs.

9.1.1.3 Record or reference the calibration and maintenance of equipment and instrumentation used to control or measure the absorbed dose delivered to the product (see Guide E 1261).

9.1.2 *Facility Records:*

9.1.2.1 Record the dates and times of any facility maintenance, including specific components replaced. Record all equipment failures, the nature of the problem that caused the failure, and any corrective action taken.

9.2 *Review and Approval:*

9.2.1 Review and approve all dosimetry records in accordance with an established quality control program.

9.2.2 Audit all documentation periodically to ensure that records are accurate and complete.

9.3 *Retention of Records:*

9.3.1 Retain all records at the facility and have them available for inspection as needed. Keep the files for a period of time specified by relevant authorities (see 4.1).

10. Measurement Uncertainty

10.1 To be meaningful, a measurement of dose shall be accompanied by an estimate of uncertainty. Components of uncertainty shall be identified as either Type A or Type B according to their method of evaluation. Type A evaluation of standard uncertainty is based on the statistical analysis of a series of observations, and Type B is based on all other methods of analysis. Additional information is given in Guide E 1707 and Refs **4** and **5**. In addition to Type A and Type B classifications, other classifications may be useful.

NOTE 3—This standard uses the methodology adopted in 1993 by the International Standardization Organization (ISO) for estimating uncertainty. This is different from the way the uncertainty has been traditionally expressed in terms of "precision" and "bias" where precision is a measure of the extent to which replicate measurements made under specified conditions are in agreement, and bias is the systematic error (see Practices E 170, E 177, and E 456). The new method for treatment of uncertainties is in conformance with current internationally accepted practices.

10.2 The components of uncertainty involved in measuring absorbed dose using this dosimetry system shall be estimated or determined. The overall uncertainty in absorbed dose may be estimated from a combination of these components, and the procedure for combining these components should be specifically stated or referenced in all results.

11. Keywords

11.1 absorbed dose; dosimeter; dosimetry system; electron beam; electron beam accelerator; ionizing radiation; radiation processing; radiation crosslinking; radiation curing

APPENDIX

(Nonmandatory Information)

X1. METHOD FOR MEASURING SURFACE AREA RATE COEFFICIENT (*K*), DOSE DEPTH, AND DOSE UNIFORMITY

X1.1 This appendix describes methods for measuring surface area rate coefficient (*K*), dose depth, and dose uniformity.

X1.2 *Method for Measuring the Surface Area Rate Coefficient (K):*

X1.2.1 The surface area rate is a measure of the electron beam efficiency at the surface of the product. This coefficient is determined by measurement of the surface dose at a moderate beam current or the dose of interest over the dynamic operating voltage range.

X1.2.2 It is important to determine the value of *K* over a range of voltages because the value of *K* can vary widely with voltage as shown in Table X1.1. In general, *K* will be highest at voltages of about 175 kV and will be lower in value at voltages either lower or higher than 175 kV. At lower voltages, the variation in *K* is the result of the increased attenuation of the dose caused by the energy loss in the window and the air gap. At higher voltages, the reduction in *K* is a result of the energy deposition peak moving beyond the plane of the dosimeter as shown in Fig. X1.1.

X1.2.3 The value of *K* is determined from dosimeter measurements at different voltages using the simple equation given in 8.2.

X1.2.4 The first step in determining *K* is to prepare a series of index cards, each with a minimum of five dosimeters. The dosimeters should be located adjacent to one another in a row across the center of the card. The dosimeters should be taped to the card at the edges of the dosimeter. When taping the dosimeters to the cards, care must be taken not to cover the center portion of the dosimeter where the reading will be taken.

X1.2.5 In characterizing the machine, it is important to eliminate any backscatter from the beam stop from interfering with the measurement of *K* since the value of *K* should be directly related to machine output rather than processing conditions. Therefore, a thickness of two index cards should be used to prevent backscatter from the beam stop from affecting the dose measurements.

TABLE X1.1 Example of Depth Dose Distribution at 300 kV (Air Gap 2.5 cm, 13 µm Titanium Foil Window)

Layer	Individual Thickness, µm	Plotting Depth, µm	Dose, kGy	Depth (mg/cm^2)	Normalized Percent Dose
1	50	50	32.5	5.7	100 %
2	50	100	33.7	11.4	104 %
3	50	150	35.2	17.1	108 %
4	50	200	34.4	22.8	106 %
5	50	250	34.2	28.5	105 %
6	50	300	32.0	34.2	98 %
7	50	350	27.3	39.9	84 %
8	50	400	23.2	45.6	71 %
9	50	450	17.8	51.3	55 %
10	50	500	12.3	57	38 %
11	50	550	7.4	62.7	23 %
12	50	600	3.6	68.4	11 %
13	50	650	1.5	74.1	2 %
14	50	700	0	79.8	0 %

X1.2.6 A commonly used dosimeter for this type of measurement is thin film radiochromic dosimeters (see Practice E 1275).

X1.2.7 Care must be exercised in preparing the dosimeters on the cards so as to minimize the exposure of the dosimeters to ambient light as UV energy may also cause a change in optical density of most radiochromic dosimeters. Proper handling and reading instructions for a given dosimeter can be obtained from the manufacturer of the dosimeter.

X1.2.8 Once the dosimeter cards have been prepared, they can be taped onto a moving web to convey them through the electron beam. It is recommended that the beam current and web speed be set at a moderate level so as not to exceed the limits of accuracy for the particular dosimeter chosen and not to exceed the range at which they are calibrated.

X1.2.9 Once the beam current and web speed have been set for the selected beam voltage, the dosimeter card is passed through the electron beam. If the dosimeters are left uncovered during their exposure, care must be exercised to avoid errors due to UV light exposure, exposure to humidity, and contamination. If a thin covering material is used to protect the dosimeter, a correction factor for the *K* value should be applied to compensate for the attenuation of the covering material.

X1.2.10 A minimum and a maximum voltage and several intermediate voltages should be selected to provide for a sufficient number of measurements to accurately determine the *K* values in the voltage region of interest.

X1.2.11 Record the average dose at each voltage. These data along with the web speed, current and beam width will define the *K* value. See formula in Section 8.2.

X1.3 *Method for Measuring Depth-Dose Distribution:*

X1.3.1 Electron beam treatment of homogeneous materials produces absorbed dose distributions that vary with depth within the material. The shape of the depth-dose curve is determined by collisions of primary and secondary electrons with atomic electrons and nuclei in the absorbing material. So, the shape is dependent on the atomic composition of the material and the electron energy. The depth of penetration (electron range) is proportional to the electron energy. This can be seen in the family of depth-dose distribution curves shown in Fig. 1.

X1.3.2 The depth-dose distribution curves are usually plotted in normalized units. Penetration is expressed in mass per unit area or thickness multiplied by density.

X1.3.3 The first step in measuring and plotting the depth-dose distribution of a machine is to prepare a dosimeter stack. The thickness of the dosimeter stack must be