INTERNATIONAL STANDARD

ISO/ASTM 51818

Second edition
2009-06-15

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

Pratique de la dosimétrie dans une installation de traitement par irradiation utilisant un faisceau d'électrons d'énergies comprises entre 80 keV et 300 keV

Reference number
ISO/ASTM 51818:2009(E)

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Published in the United States

Contents

Page

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75% of the member bodies casting a vote.

ASTM International is one of the world's largest voluntary standards development organizations with global participation from affected stakeholders. ASTM technical committees follow rigorous due process balloting procedures.

A project between ISO and ASTM International has been formed to develop and maintain a group of ISO/ASTM radiation processing dosimetry standards. Under this project, ASTM Subcommittee E10.01, Radiation Processing: Dosimetry and Applications, is responsible for the development and maintenance of these dosimetry standards with unrestricted participation and input from appropriate ISO member bodies.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. Neither ISO nor ASTM International shall be held responsible for identifying any or all such patent rights.

International Standard ISO/ASTM 51818 was developed by ASTM Committee E10, Nuclear Technology and Applications, through Subcommittee E10.01, and by Technical Committee ISO/TC 85, Nuclear energy.

This second edition cancels and replaces the first edition (ISO/ASTM 51818:2002), which has been technically revised.

Standard Practice for Dosimetry in an Electron Beam Facility for Radiation Processing at Energies Between 80 and 300 keV[1]

This standard is issued under the fixed designation ISO/ASTM 51818; 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 covers dosimetric procedures to be followed to determine the performance of low energy (300 keV or less) single-gap electron beam radiation processing facilities. Other practices and procedures related to facility characterization, process qualification, and routine processing are also discussed.

1.2 The electron-energy range covered in this practice is from 80 keV to 300 keV. Such electron beams can be generated by single-gap self-contained thermal filament or plasma source accelerators.

1.3 *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:*[2]

E 170 Terminology Relating to Radiation Measurements and Dosimetry

E 2232 Guide for Selection and Use of Mathematical Methods for Calculating Absorbed Dose in Radiation Processing Applications

E 2303 Guide for Absorbed-Dose Mapping in Radiation Processing Facilities

2.2 *ISO/ASTM Standards:*[2]

51261 Guide for Selection and Calibration of Dosimetry Systems for Radiation Processing

51275 Practice for Use of a Radiochromic Film Dosimetry System

51400 Practice for Characterization and Performance of a High-Dose Radiation Dosimetry Calibration Laboratory

51607 Practice for Use of the Alanine-EPR Dosimetry System

51649 Practice for Dosimetry in an Electron Beam Facility for Radiation Processing at Energies Betweeen 300 keV and 25 MeV

51650 Practice for Use of a Cellulose Acetate Dosimetry System

51707 Guide for Estimating Uncertainties in Dosimetry for Radiation Processing

2.3 *International Commission on Radiation Units and Measurements (ICRU) Report:*[3]

ICRU Report 60 Fundamental Quantities and Units for Ionizing Radiation

2.4 *Monte Carlo Codes for Calculating Absorbed Dose and Dose Distribution:*[4]

ZTRAN

PENELOPE

Integrated Tiger Series (ITS)

Monte Carlo Neutron Proton (MCNP)

Electron Gamma Shower (EGS4)

Energy Deposition in Multiple Layers (EDMULT)

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 $d\bar{\varepsilon}$ by dm, where $d\bar{\varepsilon}$ is the mean incremental energy imparted by ionizing radiation to matter of incremental mass dm.

$$D = \frac{d\bar{\varepsilon}}{dm} \quad (1)$$

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

[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 Radiation Processing: Dosimetry and Applications, and is also under the jurisdiction of ISO/TC 85/WG 3.

Current edition approved June 18, 2008. Published June 2009. Originally published as ASTM E 1818–96. Last previous ASTM edition E 1818–96 $^{\varepsilon 1}$. ASTM E 1818–96 $^{\varepsilon 1}$ was adopted in 1998 with the intermediate designation ISO 15573:1998(E). The present International Standard ISO/ASTM 51818:2008(E) replaces ISO 15573 and is a major revision of the last previous edition ISO/ASTM 51818:2002(E).

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

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

[4] Available in the USA from the Radiation Safety Information Computational Center (RSICC), Oak Ridge National Laboratory (ORNL), P.O. Box 2008, Oak Ridge, TN 37831, Tel: 865-574-6176, Fax: 865-574-6182, Web Address: www-rsicc.ornl.gov. Available in Europe from CERN or web address www.cern.ch/geant4, OECD Nuclear Energy Agency, Le Seine Saint-Germain, 12 boulevard des Iles, 92130 Issy-les-Moulineaux, France. Tel: +33 (0) 1 4524 8200, Fax: +33 (0) 1 4524 1110, Web address: www.nea.fr.

3.1.2 *average beam current*—time-averaged electron beam current delivered from the accelerator.

3.1.3 *beam length*—dimension of the irradiation zone along the direction of product movement, at a specified distance from the accelerator window.

3.1.3.1 *Discussion*—For graphic illustration, see ISO/ASTM Practice 51649. *(1)* This term usually applies to electron irradiation. *(2)* Beam length is therefore perpendicular to beam width and to the electron beam axis. *(3)* In case of product that is stationary during irradiation, *beam length* and *beam width* may be interchangeable.

3.1.4 *beam power*—product of the average electron beam energy and the average beam current (unit kW).

3.1.5 *beam uniformity*—dose variation distributed across the beam width.

3.1.6 *beam width*—dimension of the irradiation zone perpendicular to the direction of product movement, at a specified distance from the accelerator window.

3.1.6.1 *Discussion*—For graphic illustration, see ISO/ASTM Practice 51649. *(1)* This term usually applies to electron irradiation. *(2)* Beam width is therefore perpendicular to beam length and to the electron beam axis. *(3)* In case of a low-energy, single-gap electron accelerator, beam width is equal to the active length of the cathode assembly in vacuum. *(4)* In the case of product that is stationary during irradiation, *beam width* and *beam length* may be interchangeable. *(5)* Beam width may be quantified as the distance between two points along the dose profile, which are at a defined fraction of the maximum dose value in the profile. *(6)* Various techniques may be employed to produce an electron beam width adequate to cover the processing zone, for example, use of electromagnetic scanning of a pencil beam (in which case beam width is also referred to as scan width), defocusing elements, and scattering foils.

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

3.1.7.1 *Discussion*—See Fig. 1 for calculated values for electron energies from 100 to 300 keV.

3.1.8 *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.

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

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

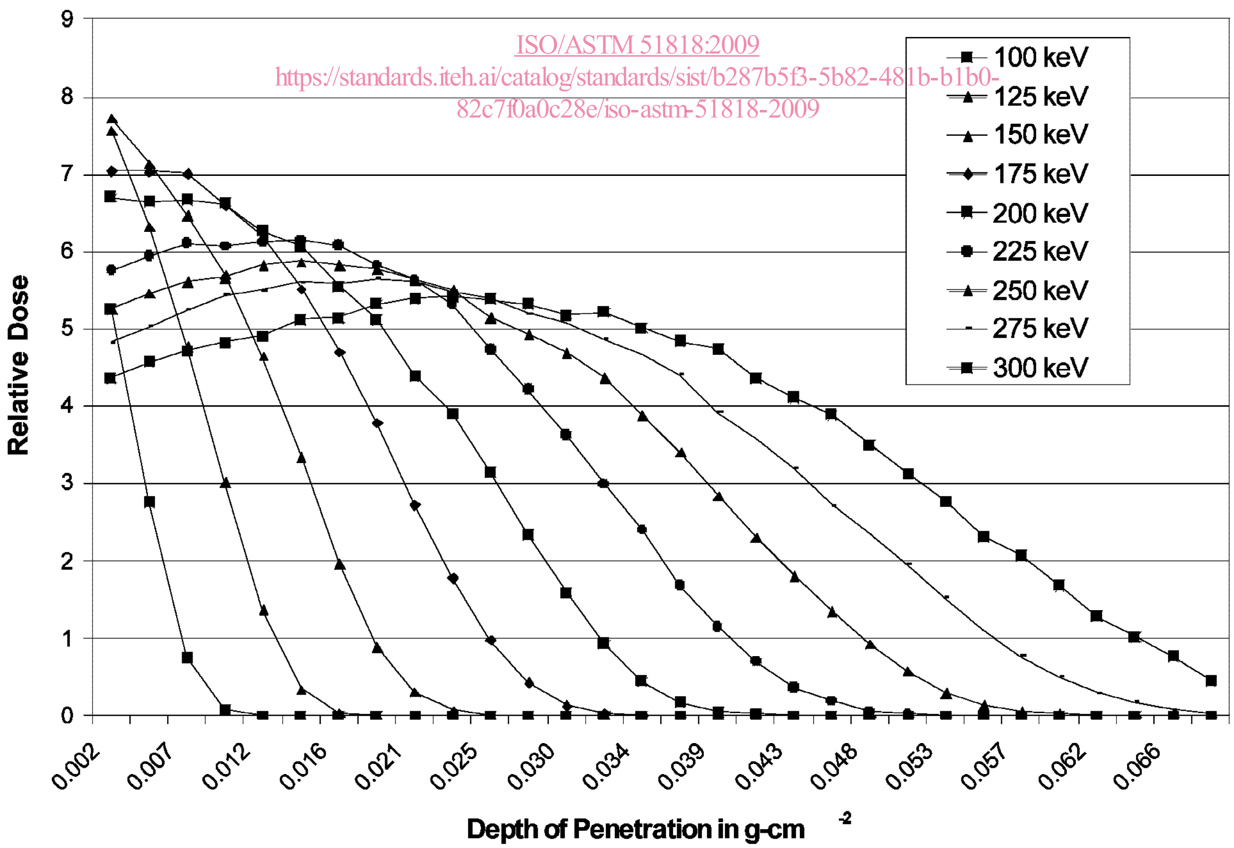

FIG. 1 Depth dose curves calculated from Monte Carlo Code (ITS) for acceleration voltages ranging 100 to 300 keV in 25 keV increments. The curves show only depth-dose in a unit density substrate passing under the beam path (13-µm titanium window, 20-mm air gap).

3.1.11 *electron beam energy*—average kinetic energy of the accelerated electrons in the beam (units—eV (electron volts)).

3.1.11.1 *Discussion*—Often, the numeric value of the 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.

3.1.12 *practical electron range* R_p—depth in homogeneous material 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 extrapolated X-ray background.

3.1.12.1 *Discussion*—For graphic illustration, see ISO/ASTM Practice 51649.

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

3.1.14 *production run (for continuous-flow and shuffle-dwell irradiation)*—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.

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

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

3.1.17 *uncertainty*—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 ISO/ASTM Guide 51707).

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *air gap*—distance between the product plane and the electron beam window.

3.2.2 *electron processor*—electron beam accelerator and associated equipment.

3.2.3 *linear rate coefficient* (K_L)—quantity relating the product length irradiated per unit time to beam current and absorbed dose.

3.2.3.1 *Discussion*—Typically, this value is expressed in kilogray meters per milliampere minute, or megarad feet per milliampere minute. Theoretical values can be calculated from the surface area rate coefficients given in Table 1 for particular beam widths. This quantity is sometimes called the linear processing coefficient (see 9.3) In this standard the terms "rad" or "megarad (Mrad)" are included in addition to the SI units for the convenience of some industry users.

3.2.4 *mass processing rate*—mass throughput rate based on the output power (expressed in watts) of the electron beam, the mass of the irradiated material and the dose.

3.2.4.1 *Discussion*—Typically this value is expressed in kilogray kilograms per kilowatt hour or megarad pounds per kilowatt hour. In this standard the terms "rad" or "megarad (Mrad)" are included in addition to the SI units for the convenience of some industry users.

3.2.5 *product plane*—plane corresponding to the top surface of the product being irradiated.

3.2.6 *single-gap accelerator*—electron beam source consisting of a vacuum chamber 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.

3.2.7 *surface area rate coefficient* (K_A)—quantity relating the product area irradiated per unit time to beam current and absorbed dose.

3.2.7.1 *Discussion*—Typically this value is expressed in kilogray square meter per milliampere minute, or megarad square foot per milliampere minute. Example values are shown in Table 1. This quantity is sometimes called the area processing coefficient. In this standard the terms "rad" or "megarad (Mrad)" are included in addition to the SI units for the convenience of some industry users.

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

TABLE 1 Measured dose at surface, $K_A f_i$, dose from calculated K_A, and derived values of f_i at specific acceleration voltages (13-µm Titanium window, 20-mm air gap, 30-cm wide processor running at 25 cm sec^{-1} with a beam current of 10 mA)

Electron Beam Acceleration Voltage	Dosimetry kGy (Mrad)	kGy Meter^2/Milliampere second ($K_A \cdot f_i$)^A	Mrad Foot^2/Milliampere minute ($K_A \cdot f_i$)^A	Monte Carlo TIGER Result kGy (Mrad)^B	Beam Current Utilization Efficiency (f_i)
100 kV	9.37 (0.937)	0.0722	4.69	13.6 (1.36)	0.69
125 kV	34.3 (3.43)	0.265	17.2	51.4 (5.14)	0.67
150 kV	46.2 (4.62)	0.355	23.1	66.8 (6.68)	0.69
175 kV	49.5 (4.95)	0.382	24.8	69.5 (6.95)	0.71
200 kV	47.3 (4.73)	0.365	23.7	66.1 (6.61)	0.72
225 kV	45.1 (4.51)	0.348	22.6	61.7 (6.17)	0.73
250 kV	41.2 (4.12)	0.317	20.6	55.8 (5.58)	0.74
275 kV	39.6 (3.96)	0.305	19.8	50.7 (5.07)	0.78
300 kV	35.8 (3.58)	0.275	17.9	46.7 (4.67)	0.77

^{A} Calculations based on dosimetry **(8)**. The beam current utilization efficiency factor (f_i) is an integral part of the calculation.
^{B} The 1-D Monte Carlo TIGER calculation does not include the beam current utilization efficiency factor (f_i). When the calculation is compared with dosimetry, the beam current utilization efficiency factor (f_i) is thus derived for each voltage. (See Note 7 in 9.2 for discussion.)

4. Significance and use

4.1 A variety of irradiation or treatment processes use low energy electron processors 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. Dosimetry measurements are often used in conjunction with physical, chemical, or biological testing of the product, to help verify specific treatment parameters.

NOTE 1—In many cases reference data may be developed, comparing dosimetry results with other quantitative product testing; for example, gel fraction, melt flow, modulus, molecular weight distribution, or cure analysis tests can be used to estimate radiation dose in specific relevant materials.

4.2 Radiation processing specifications usually include a 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 or keV), beam current (in mA), spatial distribution of the beam, and exposure time or process line speed all affect absorbed dose.

NOTE 2—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 does not affect the absorbed dose. However, oxygen effects on the response function of the dosimeter used in the measurement of dose should be taken into account.

4.4 Before any radiation process system 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.

5. Dosimetry systems

5.1 *Description of Dosimeter Classes*:

5.1.1 Dosimeters may be divided into four basic classes according to their relative quality and areas of application: primary-standard, reference-standard, transfer-standard, and routine dosimeters. ISO/ASTM Guide 51261 provides information about the selection of dosimetry systems for different applications. All classes of dosimeters, except the primary standards, require calibration before their use.

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

5.1.1.2 *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 ISO/ASTM Guide 51261.

5.1.1.3 *Transfer-Standard Dosimeters*—Transfer-standard dosimeters are specially selected dosimeters used for transferring absorbed-dose information from an accredited or national standards laboratory to an irradiation facility in order to establish traceability for that facility. These dosimeters should be carefully used under conditions that are specified by the issuing laboratory. Transfer-standard dosimeters may be selected from either reference-standard dosimeters or routine dosimeters taking into consideration the criteria listed in ISO/ASTM Guide 51261.

5.1.1.4 *Routine Dosimeters*—Routine dosimeters may be used for radiation process quality control, dose monitoring and dose mapping. Proper dosimetric techniques, including calibration, shall be employed to ensure that measurements are reliable and accurate. Examples of routine dosimeters, along with their useful dose ranges, are given in ISO/ASTM Guide 51261.

5.2 The documents listed in Section 2 provide detailed information on the selection and use of appropriate dosimetry systems for 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 **1-6**,[5] ISO/ASTM Practices 51275, 51607 and 51650, and ISO/ASTM Guide 51261).

NOTE 3—Dosimetry systems are available that provide the option of using either a single point measurement dosimeter method or a continuous scan area readout technique for use with film strips or segments of film.

6. Calibration of the dosimetry system

6.1 A dosimetry system shall be calibrated prior to use and at intervals thereafter in accordance with the user's documented procedure that specifies details of the calibration process and quality assurance requirements. Calibration methods are given in ISO/ASTM Guide 51261.

6.2 *Calibration Irradiation*—Irradiation is a critical component of the calibration of the dosimetry system. Acceptable ways of performing the calibration irradiation depend on whether the dosimeter is used as a reference-standard, transfer-standard or routine dosimeter.

6.2.1 *Reference- or Transfer-Standard Dosimeters*—Calibration irradiations shall be performed at a national or accredited laboratory using criteria specified in ISO/ASTM Practice 51400.

6.2.2 *Routine Dosimeters*—The calibration irradiation may be performed by irradiating the dosimeters at *(a)* a national or accredited laboratory using criteria specified in ISO/ASTM Practice 51400, *(b)* an in-house calibration facility that provides an absorbed dose (or an absorbed-dose rate) having measurement traceability to nationally or internationally recognized standards, or *(c)* a production irradiator under actual production irradiation conditions, together with reference- or

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

transfer-standard dosimeters that have measurement traceability to nationally or internationally recognized standards. In case of option *(a)* or *(b)*, the resulting calibration curve shall be verified for the actual conditions of use (see ISO/ASTM Guide 51261).

NOTE 4—While 6.2.2 is valid for most dosimeter calibrations, it must be recognized that the irradiation of many dosimeters with low energy electrons (less than 300 keV) will lead to dose gradients through the thickness of the dosimeter. When the dosimeter is measured, this will lead to an apparent dose that is related to the dose distribution. For a given set of irradiation conditions, the apparent dose will depend on the thickness of the dosimeter, ie., different thickness dosimeters will measure different apparent doses **(7)**. One solution to overcome this problem might be to suggest that all dose measurements are specified as dose to water in the first micrometer of the absorbing material. This is given the symbol D_{μ} and is independent of dosimeter thickness.

The relationship between D_{μ} and the apparent dose strongly depends on dosimeter response function, dosimeter thickness, dose, radiation energy, accelerator window material and thickness, distance window to dosimeter, and temperature of air between window and dosimeter. The relationship must be calculated for each set of irradiation conditions. The relationship must be applied for calibrations that are carried out by comparison between two different dosimeter systems (ISO/ASTM Guide 51261).

6.3 *Measurement Instrument Calibration and Performance Verification*—For the calibration of the instruments, and for the verification of instrument performance between calibrations, see ISO/ASTM Guide 51261, the corresponding ISO/ASTM or ASTM standard for the dosimetry system, and/or instrument-specific operating manuals.

7. Installation and operational qualification

7.1 Installation qualification is carried out to determine that the processing equipment performs in accordance with the 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:

7.1.1 Operation of all radiation monitors,

7.1.2 Operation of all system interlocks,

7.1.3 An extended demonstration of electron beam system performance at specified ratings,

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

7.1.5 Radiation survey at maximum operating voltage and current,

7.1.6 Mechanical inspection of the system,

7.1.7 Electrical inspection of the system,

7.1.8 Performance of the inert gas system, if applicable,

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

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

7.2 Operational qualification is carried out to characterize the performance of the equipment using dosimetry. The purpose of these measurements is to qualify the dose delivery characteristics of the equipment for performance acceptance and for future reference. The process should include, but not be limited to, the following:

7.2.1 *Surface Area Rate Coefficient Measurements*—Use a minimum of five measurements over the voltage range of interest with at least five dosimeters or dose measurements 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 Annex A1).

7.2.2 *Beam Uniformity Measurements*—Use a minimum of one dosimeter or dose measurement per 2.5 cm over full beam width (see Annex A1).

7.2.3 *Depth-dose Measurements*—Depth-dose measurements shall be made to cover the voltage range of interest. A minimum of three measurements shall be made at each voltage selected for testing. A practical method to accomplish this is to measure depth-dose with a stack of dosimeters, at the product surface (see Annex A1).

8. Performance qualification

8.1 Initial process system performance qualification shall be conducted in accordance with Section 7 to establish a base-line of performance for the specific facility.

NOTE 5—Absorbed dose distribution measurements may be required for regulated processing applications. For radiation process system and product dose mapping guidance, see Guide E 2303.

8.2 Surface area rate measurements shall be made during product validation to compare with the results of product testing.

8.3 *Frequency of Dosimetric Measurements*:

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

8.3.2 *Major System Maintenance*—After major system maintenance such as cathode or insulator bushing replacement, a minimum number of three surface area rate coefficient and beam uniformity measurements should be made to ensure that beam optics have not been compromised.

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

9. Throughput calculations

9.1 *Mass Processing Rate*—The beam power of an electron processor can be expressed in watts (W), which is the product of the average acceleration voltage in kilovolts (kV) and the average beam current in milliamperes (mA), or in kilowatts (kW), which is the product of megavolts (MV) and milliamperes (mA). An absorbed dose of 10 kGy (1 Mrad) corresponds to the uniform absorption of 10 kilowatt seconds (10 kilojoules) of energy in 1 kilogram of product. For a machine having an output of 1 kilowatt, this translates to a mass