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Guide for estimating uncertainties in dosimetry for radiation processing

Guide pour l'estimation des incertitudes en dosimétrie pour le traitement par irradiation

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Foreword

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

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

International Standard ISO 15572 was prepared by the American Society for Testing and Materials (ASTM) Subcommittee E10.01 (as E 1707-95) 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 15572 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*

Designation: E 1707 – 95

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Standard Guide for Estimating Uncertainties in Dosimetry for Radiation Processing[1]

This standard is issued under the fixed designation E 1707; 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 guide defines possible sources of error in dosimetry performed in gamma, x-ray (bremsstrahlung) and electron irradiation facilities and offers procedures for estimating the resulting magnitude of the uncertainties in the measurement results. Basic concepts of measurement, estimate of the measured value of a quantity, "true" value, error and uncertainty are defined and discussed. Components of uncertainty are discussed and methods are given for evaluating and estimating their values. How these contribute to the standard uncertainty in the reported values of absorbed dose are considered and methods are given for calculating the combined standard uncertainty and an estimate of overall (expanded) uncertainty. The methodology for evaluating components of uncertainty follows ISO procedures (see 2.3). The traditional concepts of precision and bias are not used. Examples are given in five appendixes.

1.2 This guide assumes a working knowledge of statistics. Several statistical texts are included in the references (**1**, **2**, **3**, **4**).[2]

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:*

E 170 Terminology Relating to Radiation Measurements and Dosimetry[3]

E 177 Practice for Use of the Terms Precision and Accuracy as Applied to Measurement of a Property of a Material[3]

E 178 Practice for Dealing With Outlying Observations[3]

E 456 Terminology Relating to Quality and Statistics[4]

E 666 Practice for Calculating Absorbed Dose from Gamma or X Radiation[3]

E 876 Practice for Use of Statistics In the Evaluation of Spectrometric Data[5]

E 1026 Practice for Using the Fricke Reference Standard Dosimetry System[3]

E 1204 Practice for Dosimetry in Gamma Irradiation Facilities for Food Processing[3]

E 1205 Practice for Use of a Ceric-Cerous Sulfate Dosimetry System[3]

E 1249 Practice for Minimizing Dosimetry Errors in Radiation Hardness Testing of Silicon Electronic Devices Using Co-60 Sources[3]

E 1261 Guide for Selection and Calibration of Dosimetry Systems for Radiation Processing[3]

E 1275 Practice for Use of a Radiochromic Film Dosimetry System[3]

E 1276 Practice for Use of a Polymethylmethacrylate Dosimetry System[3]

E 1310 Practice for the Use of a Radiochromic Optical Waveguide Dosimetry System[3]

E 1401 Practice for Use of a Dichromate Dosimetry System[3]

E 1431 Practice for Dosimetry in Electron and Bremsstrahlung Irradiation Facilities for Food Processing[3]

E 1607 Practice for Use of the Alanine-EPR Dosimetry System[3]

2.2 *ICRU Reports:*[6]

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

ICRU Report 17 Radiation Dosimetry: X-Rays Generated at Potentials of 5 to 150 kV

ICRU Report 33 Radiation Quantities and Units

ICRU Report 34 The Dosimetry of Pulsed Radiation

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

ICRU Report 37 Stopping Powers for Electrons and Positrons

2.3

3. Terminology

3.1 *Definitions:*

3.1.1 *absorbed dose, D*—quantity of radiation energy imparted per unit mass of a specified material. The unit of absorbed dose is the gray (Gy) where 1 gray is equivalent to the absorption of 1 joule per kilogram (= 100 rad). The mathematical relationship is the quotient of $d\bar{\epsilon}$ by dm, where $d\bar{\epsilon}$ is the mean energy imparted by ionizing radiation to matter of mass dm (see ICRU 33).

[1] This guide 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.

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

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

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

[5] *Annual Book of ASTM Standards*, Vol 03.06.

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

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

3.1.2 *accuracy of measurement*—closeness of the agreement between the result of a measurement and the true value of the measurand.

3.1.3 *calibration curve*—graphical representation of the relationship between dosimeter response and absorbed dose for a given dosimetry system. For a mathematical representation, see **response function.**

3.1.4 *coefficient of variation*—sample standard deviation expressed as a percentage of sample mean value (see 3.37 and 3.38).

$$(CV) = S_{n-1}/\bar{x} \times 100\ \%$$

3.1.5 *combined standard uncertainty*—standard uncertainty of the result of a measurement when that result is obtained from the values of a number of other quantities, equal to the positive square root of a sum of terms, the terms being the variances or covariances of these other quantities weighted according to how the measurement result varies with changes in these quantities.

3.1.6 *confidence interval*—an interval estimate that contains the mean value of a parameter with a given probability.

3.1.7 *confidence level*—the probability that a confidence interval estimate contains the value of a parameter.

3.1.8 *corrected result*—result of a measurement after correction for the best estimate of systematic error.

3.1.9 *correction*—value that, added algebraically to the uncorrected result of a measurement, compensates for systematic error.

DISCUSSION—The correction is equal to the negative of the systematic error. Some systematic errors may be estimated and compensated by applying appropriate corrections. However, since the systematic error cannot be known perfectly, the compensation cannot be complete.

3.1.10 *correction factor*—numerical factor by which the uncorrected result of a measurement is multiplied to compensate for a systematic error.

DISCUSSION—Since the systematic error cannot be known perfectly, the compensation cannot be complete.

3.1.11 *coverage factor*—numerical factor used as a multiplier of the combined standard uncertainty in order to obtain an overall uncertainty.

DISCUSSION—A coverage factor, k, is typically in the range of 2 to 3 (see 8.3).

3.1.12 *dosimeter batch*—quantity of dosimeters made from a specific mass of material with uniform composition, fabricated in a single production run under controlled, consistent conditions and having a unique identification code.

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

3.1.14 *error (of measurement)*—result of a measurement minus a true value of the measurand.

DISCUSSION—Since a true value cannot be determined, in practice a conventional true value is used. The quantity is sometimes called "absolute error of measurement" when it is necessary to distinguish it from relative error. If the result of a measurement depends on the values of quantities other than the measurand, the errors of the measured values of these quantities contribute to the error of the result of the measurement.

3.1.15 *expected value*—sum of possible values of a variable weighted by the probability of the value occurring. It is found from the expression:

$$E(v) = \Sigma_i\ P_i V_i$$

where:
V_i = i^{th} value, and
P_i = probability of i^{th} value.

3.1.16 *influence quantity*—quantity that is not included in the specification of the measurand but that nonetheless affects the result of the measurement.

DISCUSSION—This quantity is understood to include values associated with measurement reference standards, reference materials, and reference data upon which the result of the measurement may depend, as well as phenomena such as short-term instrument fluctuations and parameters such as temperature, time, and humidity.

3.1.17 *(measurable) quantity*—attribute of a phenomenon, body or substance that may be distinguished qualitatively and determined quantitatively; for example, the specific quantity of interest in this guide is absorbed dose.

3.1.18 *measurand*—specific quantity subject to measurement.

DISCUSSION—A specification of a measurand may include statements about other quantities such as time, humidity, or temperature. For example, equilibrium absorbed dose in water at 25°C.

3.1.19 *measurement*—set of operations having the object of determining a value of a quantity.

3.1.20 *measurement procedure*—set of operations, in specific terms, used in the performance of particular measurements according to a given method.

3.1.21 *measurement system*—system used for evaluating the measurand.

3.1.22 *measurement traceability*—The ability to demonstrate and document on a continuing basis that the measurement results from a particular measurement system are in agreement with comparable measurement results obtained with a national standard (or some identifiable and accepted standard) to a specified uncertainty.

3.1.23 *method of measurement*—logical sequence of operations used in the performance of measurements according to a given principle.

DISCUSSION—Methods of measurement may be qualified in various ways such as: substitution method, differential method, and null method.

3.1.24 *outlier*—a measurement result that deviates markedly from others within a set of measurement results.

3.1.25 *overall uncertainty*—quantity defining the interval about the result of a measurement within which the values that could reasonably be attributed to the measurand may be expected to lie with a high level of confidence.

DISCUSSION—Overall uncertainty is referred to as "expanded uncertainty" (see Guide to the Expression of Uncertainty in Measurement) (5).[7] To associate a specific level of confidence with the interval defined by the overall uncertainty requires explicit or implicit assumptions regarding the probability distribution characterized by the measurement result and its combined standard uncertainty. The level of confidence that may be attributed to this interval can be known only to the extent to which such assumptions may be justified.

[7] Available from International Organization for Standardization, Case Postal 56, CH-1211 Geneva 20 Switzerland.

3.1.26 *primary standard dosimeter*—a dosimeter of the highest metrological quality, established and maintained as an absorbed dose standard by a national or international standards organization.

3.1.27 *principle of measurement*—scientific basis of a method of measurement.

3.1.28 *quadrature*—a method of estimating overall uncertainty from independent sources by taking the square root of the sum of the squares of individual components of uncertainty (for example, coefficient of variation).

3.1.29 *random error*—result of a measurement minus the mean result of a large number of measurements of the same measurand that are made under repeatable or reproducible conditions (see 3.32 and 3.33).

DISCUSSION—In these definitions (and that for systematic error), the term "mean result of a large number of measurements of the same measurand" is understood to mean "the expected value or mean of all possible measured values of the measurand obtained under conditions of repeatability or reproducibility". This ensures that the definition cannot be misinterpreted to imply that for a series of observations, the random error of an individual observation is known and can be eliminated by applying a correction. The view of this guide is that error is an idealized concept and that errors cannot be known exactly.

3.1.30 *reference standard dosimeter*—a dosimeter of high metrological quality, used as a standard to provide measurements traceable to and consistent with measurements made using primary standard dosimeters.

3.1.31 *reference value (of a quantity)*—value attributed to a specific quantity and accepted, sometimes by convention, as having an uncertainty appropriate for a given purpose; for example, the value assigned to the quantity realized by a reference standard.

DISCUSSION—This is sometimes called "assigned value", or "assigned reference value".

3.1.32 *relative error (of measurement)*—error of measurement divided by a true value of the measurand.

DISCUSSION—Since a true value cannot be determined, in practice a reference value is used.

3.1.33 *repeatability (of results of measurements)*—closeness of the agreement between the results of successive measurements of the same measurand carried out subject to all of the following conditions: the same measurement procedure, the same observer, the same measuring instrument, used under the same conditions, the same location, and repetition over a short period of time.

DISCUSSION—These conditions are called "repeatability conditions." Repeatability may be expressed quantitatively in terms of the dispersion characteristics of the results.

3.1.34 *reproducibility (of results of measurements)*—closeness of agreement between the results of measurements of the same measurand, where the measurements are carried out under changed conditions such as differing: principle or method of measurement, observer, measuring instrument, location, conditions of use, and time.

DISCUSSION—A valid statement of reproducibility requires specification of the conditions changed. Reproducibility may be expressed quantitatively in terms of the dispersion characteristics of the results. In this context, results of measurement are understood to be corrected results.

3.1.35 *response function*—mathematical representation of the relationship between dosimeter response and absorbed dose for a given dosimetry system.

3.1.36 *result of a measurement*—value attributed to a measurand, obtained by measurement.

DISCUSSION—When the term "result of a measurement" is used, it should be made clear whether it refers to: the indication, the uncorrected result, the corrected result, and whether several values are averaged. A complete statement of the result of the measurement includes information about the uncertainty of the measurement.

3.1.37 *routine dosimeter*—dosimeter calibrated against a primary-, reference-, or transfer-standard dosimeter and used for routine dosimetry measurement.

3.1.38 *sample mean*—a measure of the average value of a data set which is representative of the population. It is determined by summing all the values in the data set and dividing by the number of items (n) in the data set. It is found from the expression:

$$\bar{x} = \frac{1}{n} \sum_i x_i,\ i = 1, 2, 3 \ldots n$$

3.1.39 *sample standard deviation*, S_{n-1}—measure of dispersion of values expressed as the positive square root of the sample variance.

3.1.40 *sample variance*—the sum of the squared deviations from the sample mean divided by $(n-1)$, given by the expression:

$$S^2_{n-1} = \frac{\Sigma (x_i - \bar{x})^2}{(n-1)}$$

where:

x_i = individual value of parameter with $i = 1, 2 \ldots n$, and

$\bar{x}$ = mean of n values of parameter (see 3.37).

3.1.41 *standard uncertainty*—uncertainty of the results of a measurement expressed as a standard deviation.

3.1.42 *systematic error*—mean result of a large number of repeated measurements of the same measurand minus a true value of the measurand.

DISCUSSION—The repeated measurements are carried out under the conditions of the term "repeatability". Like true value, systematic error and its causes cannot be completely known. The error of the result of a measurement may often be considered as arising from a number of random and systematic effects that contribute individual components of error to the error of the result (see E 170, E 177, and E 456).

3.1.43 *traceability*—see **measurement traceability**.

3.1.44 *transfer standard dosimeter*—a dosimeter, often a reference standard dosimeter, suitable for transport between different locations for use as an intermediary to compare absorbed dose measurements.

3.1.45 *true value*—value of measurand that would be obtained by a perfect measurement.

DISCUSSION—True values are by nature indeterminate and only an idealized concept. In this guide the terms "true value of a measurand" and "value of a measurand" are viewed as equivalent (see 5.1.1).

3.1.46 *Type A evaluation (of standard uncertainty)*—method of evaluation of a standard uncertainty by the statistical analysis of a series of observations.

3.1.47 *Type B evaluation (of standard uncertainty)*—method of evaluation of a standard uncertainty by means other than the statistical analysis of a series of observations.

3.1.48 *uncertainty (of measurement)*—a parameter, associated with a measurand or derived quantity, that characterizes the distribution of the values that could reasonably be attributed to the measurand or derived quantity.

DISCUSSION—For example, uncertainty may be a standard deviation (or a given multiple of it), or the width of a confidence interval. Uncertainty of measurement comprises, in general, many components. Some of these components may be evaluated from the statistical distribution of the results of series of measurements and can be characterized by experimental standard deviations. The other components, which can also be characterized by standard deviations, are evaluated from assumed probability distributions based on experience or other information. It is understood that all components of uncertainty contribute to the distribution.

3.1.49 *uncorrected result*—result of a measurement before correction for the assumed systematic error.

3.1.50 *value (of a quantity)*—magnitude of a specific quantity generally expressed as a number with a unit of measurement, for example, 25 kGy.

4. Significance and Use

4.1 Gamma, electron and x-ray (bremsstrahlung) facilities routinely irradiate a variety of products such as food, medical devices, aseptic packaging and commodities (see Practices E 1204 and E 1431). Process parameters for the products must be carefully controlled to ensure that these products are processed within specifications (see ANSI/AAMI ST31-1990, ANSI/AAMI ST32-1991 and ISO 11137 **(6, 7, 8)**.[8] Accurate dosimetry is essential in process control (see Guide E 1261). For absorbed dose measurements to be meaningful, the overall uncertainty associated with these measurements must be estimated and its magnitude quantified.

NOTE 1—For a comprehensive discussion of various dosimetry methods applicable to the radiation types and energies discussed in this guide, see ICRU Reports 14, 17, 34, 35 and Reference **(9)**.

4.2 This standard guide uses the methodology adopted by the International Organization for Standardization for estimating uncertainties in dosimetry for radiation processing (see 2.3). The ASTM traditionally expresses uncertainty 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 a systematic error (see Practice E 170, E 177 and E 456). As seen from this standard, sources of uncertainty are evaluated as either Type A or Type B rather than in terms of precision and bias. Both random and systematic error clearly are differentiated from components of uncertainty. The methodology for treatment of uncertainties is in conformance with current internationally accepted practice. (See Guide to the Expression of Uncertainty in Measurement **(5)**.)

4.3 Although this guide provides a framework for assessing uncertainty, it cannot substitute for critical thinking, intellectual honesty, and professional skill. The evaluation of uncertainty is neither a routine task nor a purely mathematical one; it depends on detailed knowledge of the nature of the measurand and of the measurement method and procedure used. The quality and utility of the uncertainty quoted for the result of a measurement therefore ultimately depends on the understanding, critical analysis, and integrity of those who contribute to the assignment of its value.

[8] Available from Association for the Advancement of Medical Instrumentation, 3330 Washington Boulevard, Suite 400, Arlington, VA 22201-4598.

5. Basic Concepts—Components of Uncertainty

5.1 *Measurement:*

5.1.1 The objective of a measurement is to determine the value of the measurand, that is, the value of the specific quantity to be measured. A measurement therefore begins with an appropriate specification of the measurand, the method of measurement, and the measurement procedure.

5.1.2 In general, the result of a measurement is only an approximation or estimate of the value of the measurand and thus is complete only when accompanied by a statement of the uncertainty of that estimate.

5.1.3 In practice, the specification or definition of the measurand depends on the required accuracy of the measurement. The measurand should be defined with sufficient exactness relative to the required accuracy so that for all practical purposes the measurand value is unique.

NOTE 2—Incomplete definition of the measurand can give rise to a component of uncertainty sufficiently large that it must be included in the evaluation of the uncertainty of the measurement result.

5.1.3.1 Although a measurand should be defined in sufficient detail that any uncertainty arising from its incomplete definition is negligible in comparison with the required accuracy of the measurement, it must be recognized that this may not always be practicable. The definition may, for example, be incomplete because it does not specify parameters that may have been assumed, unjustifiably, to have negligible effect; or it may imply conditions that can never fully be met and whose imperfect realization is difficult to take into account.

5.1.4 In many cases, the result of a measurement is determined on the basis of repeated observations. Variations in repeated observations are assumed to arise from not being able to hold completely constant each influence quantity that can affect the measurement result.

5.1.5 The mathematical model of the measurement procedure that transforms the set of repeated observations into the measurement result is of critical importance since, in addition to the observations, it generally includes various influence quantities that are inexactly known. This lack of knowledge contributes to the uncertainty of the measurement result along with the variations of the repeated observations and any uncertainty associated with the mathematical model itself.

5.2 *Errors, Effects, and Corrections:*

5.2.1 In general, a measurement procedure has imperfections that give rise to an error in the measurement result. Traditionally, an error is viewed as having two components, namely, a random component and a systematic component.

5.2.2 Random error presumably arises from unpredictable or stochastic temporal and spatial variations of influence quantities. The effects of such variations, hereafter referred to as random effects, give rise to variations in repeated observations of the measurand. The random error of a measurement result cannot be compensated by correction but it can usually be reduced by increasing the number of observations; its expectation or expected value is zero.

NOTE 3—The experimental standard deviation of the arithmetic mean or average of a series of observations is not the random error of the mean, although it is so referred to in some publications on uncertainty. It is instead a measure of the uncertainty of the mean due to random effects. The exact value of the error in the mean arising from these effects cannot be known. In this guide great care is taken to distinguish between the terms "error" and "uncertainty"; they are not synonyms but represent completely different concepts; they should not be confused with one another or misused.

5.2.3 Systematic error, like random error, cannot be eliminated but it too can often be reduced. If a systematic error arises from a recognized effect of an influence quantity on a measurement result, hereafter referred to as a systematic effect, the effect can be quantified and, if significant in size relative to the required accuracy of the measurement, an estimated correction or correction factor can be applied. It is assumed that after correction, the expectation or expected value of the error arising from a systematic effect is zero.

NOTE 4—The uncertainty of an estimated correction applied to a measurement result to compensate for a systematic effect is not the systematic error. It is instead a measure of the uncertainty of the result due to incomplete knowledge of the value of the correction. In general, the error arising from imperfect compensation of a systematic effect cannot be exactly known.

5.2.4 It is assumed that the result of a measurement has been corrected for all recognized significant systematic effects.

NOTE 5—Often, measuring instruments and systems are adjusted or calibrated using measurement reference standards to eliminate systematic effects; however, the uncertainties associated with these standards must still be taken into account.

5.3 *Uncertainty:*

5.3.1 The uncertainty of the result of a measurement reflects the lack of exact knowledge of the value of the measurand. The result of a measurement after correction for recognized systematic effects is still only an estimate of the value of the measurand because of the uncertainty arising from random effects and from imperfect correction of the result for systematic effects.

NOTE 6—The result of a measurement (after correction) can unknowingly be very close to the value of the measurand (and hence have a negligible error) even though it may have a large uncertainty. Thus the uncertainty of the result of a measurement should not be interpreted as representing the remaining unknown error.

5.3.2 In practice there are many possible sources of uncertainty in a measurement, including:

5.3.2.1 incomplete definition of the measurand;

5.3.2.2 imperfect realization of the definition of the measurand;

5.3.2.3 sampling—the sample measured may not represent the defined measurand;

5.3.2.4 inadequate knowledge of the effects of environmental conditions on the measurement procedure or imperfect measurement of environmental conditions;

5.3.2.5 personal bias in reading analog instruments;

5.3.2.6 instrument resolution or discrimination threshold;

5.3.2.7 values assigned to measurement standards;

5.3.2.8 values of constants and other parameters obtained from external sources and used in the data reduction algorithm;

5.3.2.9 approximations and assumptions incorporated in the measurement method and procedure; and

5.3.2.10 variations in repeated observations of the measurand under apparently identical conditions.

NOTE 7—These sources are not necessarily independent and some may contribute to 5.3.2.10. Of course, an unrecognized systematic effect cannot be taken into account in the evaluation of the uncertainty of the result of a measurement but contributes to its error.

5.3.3 Uncertainty components are classified into two categories based on their method of evaluation, "Type A" and "Type B" (see Section 3). These categories apply to uncertainty and are not substitutes for the words "random" and "systematic". The uncertainty of a correction for a known systematic effect may be obtained by either a Type A or Type B evaluation, as may be the uncertainty characterizing a random effect.

5.3.4 The purpose of the Type A and Type B classification is to indicate the two different ways of evaluating uncertainty components. Both types of evaluation are based on probability distributions and the uncertainty components resulting from each type are quantified by a standard deviation or a variance.

5.3.5 The population variance u^2 characterizing an uncertainty component obtained from a Type A evaluation is estimated from a series of repeated observations. The best estimate of u^2 is the sample variance s^2 (see 3.39). The population standard deviation u, the positive square root of u^2, is thus estimated by s and for convenience is sometimes referred to as a Type A standard uncertainty. For an uncertainty component obtained from a Type B evaluation, the population variance u^2 is evaluated using available knowledge and the estimated standard deviation u is sometimes referred to as a Type B standard uncertainty.

5.3.5.1 Thus a Type A standard uncertainty is obtained from a probability density function derived from an observed frequency distribution, while a Type B standard uncertainty is obtained from an assumed probability density function based on the degree of belief that an event will occur. The two approaches are both valid interpretations of probability.

NOTE 8—A Type B evaluation of an uncertainty component is often based on a pool of comparatively reliable information.

5.3.6 The total uncertainty of the result of a measurement, termed combined standard uncertainty and denoted by u_c, is an estimated standard deviation equal to the positive square root of the total variance obtained by summing all variance and covariance components, however evaluated, using the law of propagation of uncertainty (see Appendix X5).

5.3.7 To meet the needs of some industrial and commercial applications, as well as requirements in the areas of health and safety, an overall uncertainty U, whose purpose is to provide an interval about the result of a measurement within which the values that could reasonably be attributed to the measurand may be expected to lie with a high level of confidence, is obtained by multiplying the combined standard uncertainty u_c by a coverage factor k (see 8.3).

NOTE 9—The coverage factor k is always to be stated so that the standard uncertainty of the measured quantity can be recovered for use in calculating the overall standard uncertainty of other measurement results that may depend on that quantity.

5.4 *Practical Considerations:*

5.4.1 By varying all parameters on which the result of a measurement depends, its uncertainty could be evaluated by statistical means. However, because this is rarely possible in practice due to limited time and resources, the uncertainty is usually evaluated using a mathematical model of the measurement procedure and the law of propagation of uncertainty. Thus implicit in this guide is the assumption that a measurement procedure can be modeled mathematically to the degree imposed by the required accuracy of the measurement.

5.4.2 Because the mathematical model may be incomplete, all parameters should be varied to the fullest practicable extent so that the evaluation of uncertainty is based as much as possible on observed data. Whenever feasible, the use of empirical models of the measurement procedure founded on long-term quantitative data, and the use of check standards and control charts that can indicate if a measurement procedure is under statistical control, should be part of the effort to obtain reliable evaluations of uncertainty. A well-designed experiment can greatly facilitate such efforts and is an important part of the art of measurement.

5.4.3 In order to decide if a measurement system is functioning properly, the experimentally observed variability of its output values is often compared with the variability predicted by combining the appropriate uncertainty components that characterize its constituent parts. When calculating the predicted standard deviation of the distribution of experimentally observed output values, only those components (whether obtained from Type A or Type B evaluations) that could contribute to the observed variability of these values should be considered.

NOTE 10—Such an analysis may be facilitated by gathering those components that contribute to the variability and those that do not into two separate and appropriately labeled groups. The evaluation of overall uncertainty must take both groups into consideration.

5.4.4 An apparent outlier (see 3.23) in a set of measurement results may be merely an extreme manifestation of the random variability inherent in the data. If this is true, then the value should be retained and processed in the same manner as the other measurements in the set. On the other hand, the outlying measurement may be the result of gross deviation from prescribed experimental procedure or an error in calculating or recording the numerical value. In subsequent data analysis the outlier will be recognized as unlikely to be from the same population as that of the others in the measurement set. An investigation shall be undertaken to determine the reason for the aberrant value and whether it should be rejected (see Practice E 178 for methods of testing for outliers).

5.5 *Graphical Representation of Concepts:*

5.5.1 Figure 1 depicts some of the ideas discussed in this Section. It illustrates why the focus of this guide is uncertainty and not error. The exact error of a result of a measurement is, in general, unknown and unknowable. All one can do is estimate the values of input quantities, including corrections for recognized systematic effects, together with their standard uncertainties (estimated standard deviations), either from unknown probability distributions that are sampled by means of repeated observations, or from subjective or *a priori* distributions based on the pool of available information; and then calculate the measurement result from the estimated values of the input quantities and the combined standard uncertainty of that result from the standard uncertainties of those estimated values. Only if there is a sound basis for believing that all of this has been done properly, with no significant systematic effects having been overlooked, can one assume that the measurement result is a reliable estimate of the value of the measurand and that its combined standard uncertainty is a reliable measure of its possible error.[9]

6. Evaluation of Standard Uncertainty

6.1 *Measurement Procedure:*

6.1.1 The measurand Y (absorbed dose) is generally not measurable directly, but depends on N other measurable quantities $X_1, X_2, \ldots, X_N$ through a functional relationship f:

$$Y = f(X_1, X_2, \ldots, X_N) \quad (1)$$

6.1.1.1 The input quantities $X_1, X_2, \ldots, X_N$ and their associated uncertainties may be determined directly in the current measurement process by means of repeated observations and may involve corrections for influence quantities such as temperature or humidity. They may also involve uncertainties such as calibration of routine dosimeter response under conditions that differ from actual irradiator facility conditions (different dose rates, temperature cycle, etc.). Other quantities that may be involved are those due to use of reference or transfer standard dosimeters and their associated uncertainties.

6.1.2 The Type A component of uncertainty that is due to non-repeatability or non-reproducibility of irradiation conditions during calibration and non-reproducibility or non-repeatability of dose measurements at the production irradiator facility will cause a random error in the measurements. Sources of these Type A standard uncertainty components are discussed in Section 7. Estimates of the magnitude of these components can be made by performing replicate repeated measurements under the same conditions.

6.1.3 The Type B component of uncertainty that has not been obtained by repeated observations can be evaluated by using all relevant information on the possible variability of the input quantities X_i. This pool of information may include previous measurement data, documented performance characteristics of the dosimetry system, and uncertainties assigned to reference or transfer standard dosimeters. Sources of these Type B standard uncertainty components are discussed in Section 7.

6.2 *Type A Evaluation of Standard Uncertainty:*

6.2.1 The best estimate of the expected value of a quantity is obtained by n independent measurements made under the same conditions of measurement (see 3.37) and is given by the arithmetic mean, x, or average of those measurements. The sample standard deviation, s_{n-1}, of these observations characterizes the variability of the observed values or their dispersion about their mean. For example, at a production irradiator facility, repeated measurements of dose at the

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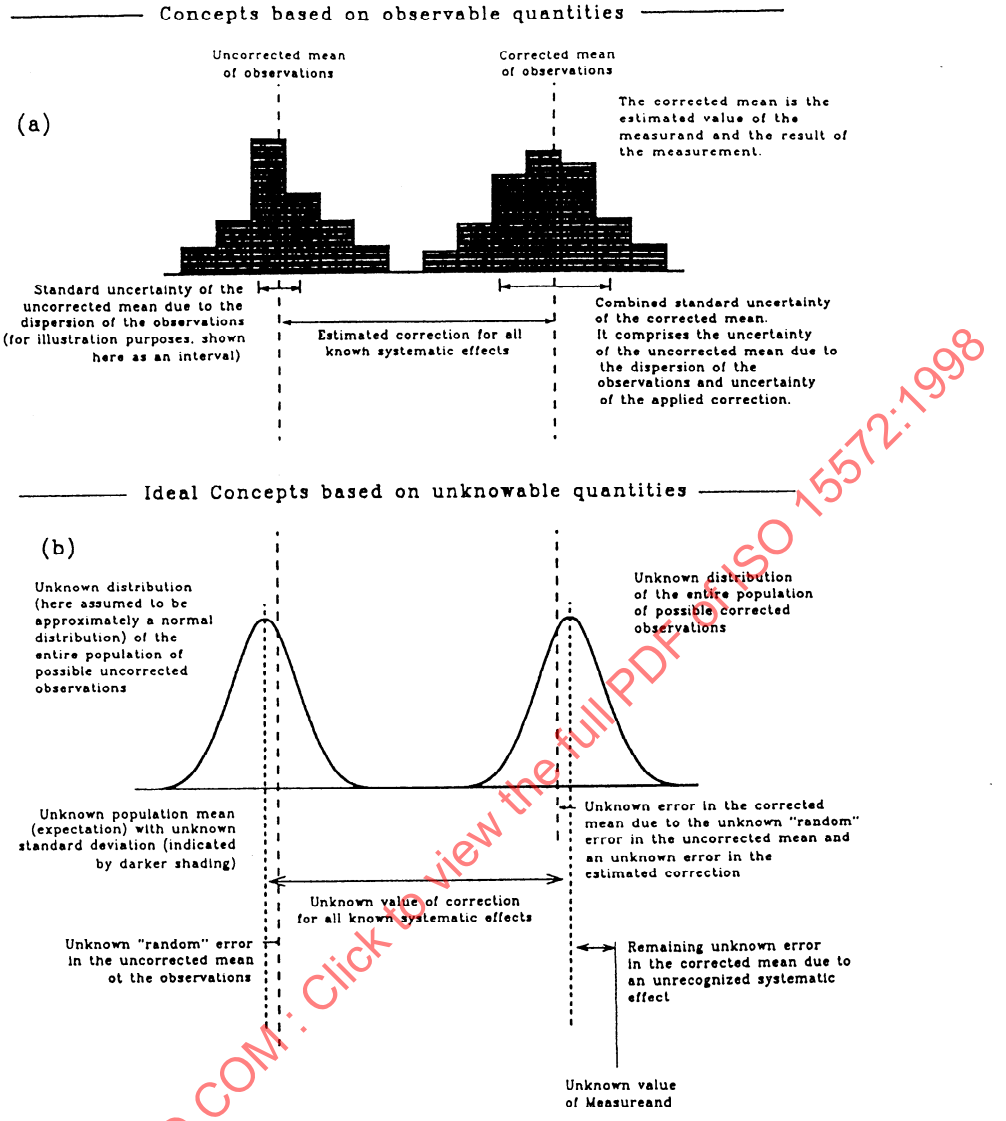

FIG. 1 Graphical Illustration of Value, Error, and Uncertainty

same location within product of the same density, radiation absorption properties, and geometry, for the same nominal dose and environmental conditions would provide an estimate of the random error in the dosimetry system. The sample standard deviation, s_{n-1}, can be referred to as a Type A standard uncertainty, u_A.

6.2.1.1 The random component of uncertainty may also be estimated from the separate sources that contribute to the Type A uncertainty. This may be desirable when the total random uncertainty is unacceptably large and the major source of the uncertainty must be identified.

6.2.1.2 Individual Type A components can be identified by using an experimental program of repeated measurements that controls all other components of uncertainty. For example, the uncertainty contributed by variations in dosimeter thickness within a batch can be estimated by measuring the thickness of a large number of randomly selected dosimeters while controlling all other variables such as humidity and temperature.

6.2.2 For well-characterized measurement procedures under a state of statistical control, a combined or pooled variance s_P^2 or pooled sample standard deviation s_P may be available (see Practice E 876). In such cases the variance of the mean of n independent repeated measurements is s_P^2/n and the Type A standard uncertainty is $u_A = s_P/\sqrt{n}$.

6.2.3 For Type A components of uncertainty, increasing the degrees of freedom of u_A, equal to $n - 1$ for the case where s_{n-1} is calculated from n independent measurements, will improve the quality of the estimate of uncertainty.

6.3 *Type B Evaluation of Standard Uncertainty:*

6.3.1 For an estimate of the input dose value X_i that has not been obtained from repeated measurements, the estimated variance u_B^2 or standard uncertainty u_B is evaluated by judgment using all relevant information on the possible variability of X_i. As mentioned in 6.1.3, this pool of information may include previous measurement data, general knowledge on the behavior characteristics of the dosimetry system, and uncertainties associated with reference or transfer standard dosimeters employed. The uncertainty u_B estimated in this way is referred to as a Type B

standard uncertainty.

6.3.2 Several methods may be used to develop estimates of the magnitude of Type B uncertainty components. One method is to estimate reasonable maximum magnitudes of each component based on the known operating conditions of the calibration and production irradiator facilities and the documented uncertainty characteristics of the dosimetry system. Another method estimates the magnitude of each component as a function of these facilities' operations.

6.3.3 The first method estimates the maximum magnitude likely to be observed for each component. For example, if the response of the dosimetry system is known to vary with temperature, then the maximum uncertainty for the operational temperature range is used as the uncertainty component due to temperature effects. If there is no specific knowledge about the possible values of X_i within its estimated bounds of a_- to a_+, it is assumed that it is equally probable for X_i to take on any value within those bounds (that is a rectangular distribution, see Fig. 2(*a*)). As shown in Fig. 2(*a*) the sample standard deviation is $a/\sqrt{3}$. In some cases it is more realistic to expect that values near the bounds are less likely than those near the midpoint. It is then reasonable to replace the rectangular distribution with a symmetric triangular distribution with a base width of $a_- - a_+ = 2a$, see Fig. 2(*b*). Assuming such a triangular distribution for X_i, the expectation value of X_i is $(a_- + a_+)/2$ and its variance is $u_B^2 = a^2/6$. Thus, the Type B standard uncertainty is $u_B = a/\sqrt{6}$.

6.3.4 A second method of evaluating Type B uncertainties defines the component as a function of the operating characteristics of the irradiation facility. The functional relationship may be known or unknown.

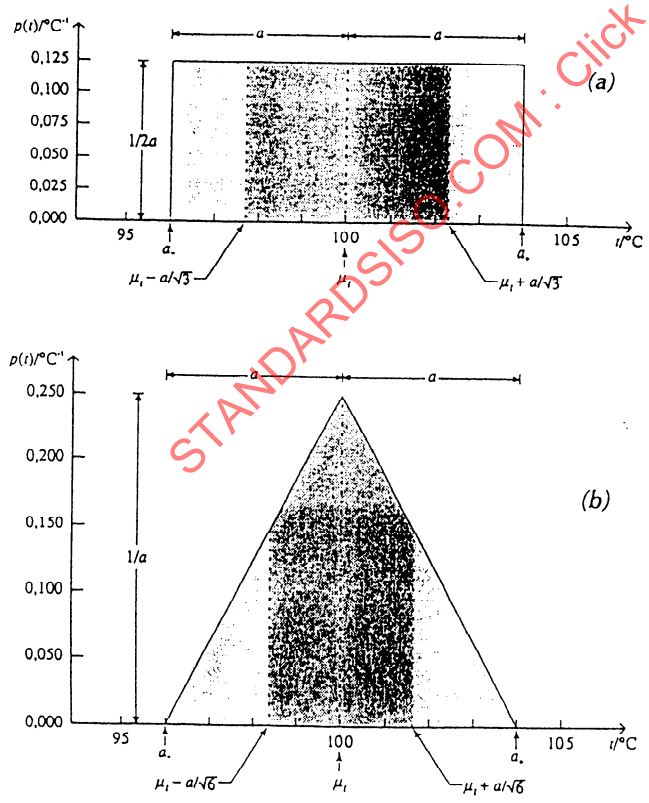

FIG. 2 Graphical Illustration of Evaluating Type B Standard Uncertainty

6.3.4.1 For example, for a known relationship, where the response of the dosimetry system to a given dose varies with the temperature, then the uncertainty may be estimated as a function of the temperature at which each fraction of dose was received. The function which describes the relationship between dose, uncertainty, and temperature requires detailed knowledge of the temperature regimen during irradiation.

6.3.4.2 For an unknown relationship, a random function may be used to describe the relationship between uncertainty and environmental characteristics. For example, the relationship may be realized by a random distribution function relating duration of exposure of the dosimetry system to a temperature during irradiation. The expected uncertainty due to temperature variations is the weighted sum of duration at a temperature weighted by the probability of the duration occurring.

6.3.5 For the case where a reference or transfer standard dosimeter is employed, and the uncertainty quoted by the supplier is given as a multiple of a standard deviation, the Type B standard uncertainty, u_B, may be taken as equal to the quoted value divided by the multiplier. If the uncertainty is given as a confidence interval, such as 95 % or 99 %, then it may be assumed that the multipliers are approximately 2 and 3, respectively (see 8.3). The value for u_B is obtained by dividing the given confidence interval by the appropriate factor.

7. Sources of Uncertainty

7.1 Contributions to the combined uncertainty in the experimental value for the measurement of absorbed dose by a dosimetry system include the following:

7.1.1 Uncertainty in the absorbed dose received by the dosimeters during system calibration,

7.1.2 Analysis of dosimeter response,

7.1.3 Fit of dosimetry data to a calibration curve, and

7.1.4 Routine use of dosimeters in a production irradiation facility.

7.2 Examples of these contributions to combined uncertainty are given in Appendixes X1 through X4.

7.3 Each source of uncertainty usually consists of several components of both Type A and Type B. Components of uncertainty from each source are combined first by type, that is, the Type A components together and Type B components together. Then the Type A contributions are combined with the Type B contributions to give a combined standard uncertainty, u_c. Methods for combining uncertainties are discussed in Section 8.

7.4 Some components that may contribute to the first source of uncertainty are listed in Table 1. Clearly all components may not apply to a given class of dosimeter or method of calibration.

NOTE 11—For each of the quantities in Tables 1 to 4, the first subscript denotes the source of uncertainty and the second subscript denotes the component of uncertainty. A zero means there is no assignable component and a prime signifies the component is estimated by Type B evaluation.

7.4.1 Routine dosimetry systems can be calibrated by irradiation at a high dose radiation dosimetry calibration laboratory, an in-house calibration facility whose dose rates

TABLE 1 Examples of Uncertainty in Absorbed Dose Administered by a Gamma Ray Calibration Facility

Component of Uncertainty	Type A	Type B
Response of Primary or Reference Standard	u_{cs}	u'_{cs}
Irradiation Time	u_{ct}	u'_{ct}
Decay Corrections	u_{cd}	u'_{cd}
Non-Uniformities in Standard Radiation Field	u_{cf}	u'_{cf}
Corrections for Attenuation and Geometry	0	u'_{ca}
Conversion of Absorbed Dose to Reference Material	0	u'_{cc}

TABLE 2 Examples of Uncertainty in Dosimeter Readings

Component of Uncertainty	Type A	Type B
Intrinsic Variation in Dosimeter Response	u_{sl}	0
Variation in Thickness of Individual Dosimeters	u_{st}	u'_{st}
Measurement of Thickness of Individual Dosimeters	u_{sx}	u'_{sx}
Variations in Readout Equipment	u_{sq}	u'_{sq}

TABLE 3 Examples of Uncertainty in Calibration Curve

Component of Uncertainty	Type A	Type B
Variation in Response of Dosimeters	u_{fm}	u'_{fm}
Analytical Function Used in Fit	0	u'_{fa}

TABLE 4 Examples of Uncertainty Due to Routine Use

Component of Uncertainty	Type A	Type B
Deviations in Environment from Calibration Conditions	u_{re}	u'_{re}
Influence of Adjacent Product on Dosimeter	u_{rp}	u'_{rp}
Reproducibility in Placement of Dosimeter Within Product Unit	u_{rr}	u'_{rr}
Orientation of Dosimeters to Source of Radiation	u_{ro}	u'_{ro}

have been demonstrated to be traceable to appropriate national standards, or irradiation of reference or transfer standard dosimeters with routine dosimeters in the production irradiator facility. In all cases, components of uncertainty that are delineated in Table 1 need to be estimated and these components subsequently combined to find an estimate of total combined standard uncertainty.

7.4.2 The calibration laboratory or facility normally presents the user with a single number for uncertainty that is given at a 95 % to 99 % confidence level. The standard uncertainty is obtained by dividing this number by the appropriate multiplying factor, for example, 2 for a 95 % confidence interval and 3 for a 99 % confidence level (see 6.3.5 and 8.3). The standard uncertainty is typically combined in quadrature with other components of uncertainty to obtain an estimate of combined uncertainty in absorbed dose.

7.5 Some components of uncertainty that are traceable to analysis of dosimeter response are given in Table 2.

7.5.1 Variation in the absorbance of several dosimeters that are irradiated under the same conditions can be used to estimate the Type A components of uncertainty in Table 2. Sets of dosimeters used in calibration of a batch of dosimeters or irradiated under the same conditions at an irradiator can be used for this purpose.

7.5.2 The measurement equipment may introduce Type B components of uncertainty in the determination of dosimeter response. For example, some types of dosimetry systems require knowledge of dosimeter thickness in the calculation of absorbed dose. Possible uncertainties associated with the thickness gage may need to be taken into account. If thickness of individual dosimeters is not measured, that is, an average thickness for the lot or manufacturers specification is used, uncertainty associated with variations in thickness of individual dosimeters may need to be taken into account. In those cases where a spectrophotometer serves as the readout equipment, a source of uncertainty could be introduced if the wavelength setting differs from the reference value.

7.6 Dosimetry calibration data must be fitted to an analytical form, for example, linear, exponential or polynomial, that provides a good fit to the measurement data. The uncertainty in absorbed dose associated with the uncertainty in the calibration curve depends on the data used in the fit and the type of analytical function that is used to fit the data. These components of uncertainty are given in Table 3.

7.6.1 Dependent on the dosimetry system and range in absorbed dose over which the fit occurs, different analytical forms may be selected to fit the data. Selection and application of the type of fit should be guided by the following five considerations.

7.6.1.1 If the response of the dosimeter obeys a known physical relationship, for example, logarithmic, that function should be used.

7.6.1.2 Otherwise, the data should be plotted and inspected to ascertain if a particular relationship provides a good fit to the data. This exercise also can reveal the presence of possible outliers (3).

NOTE 12—In plotting the data, absorbed dose normally is selected as the independent variable, x-axis. An exchange of the independent and dependent variables can lead to a small error in the values of absorbed dose that are predicted by the calibration curve. The magnitude of this source of uncertainty depends on what is known about the random errors.

7.6.1.3 The simplest function, for example, linear, that gives a good fit to the data should be used.

7.6.1.4 If the response of the dosimeters is best fitted using a polynomial, the order of the polynomial should be no greater than necessary to give an acceptable fit.

7.6.1.5 The fit should not be used to predict values of absorbed dose that exceed the range of calibration.

7.7 The use of dosimeters in routine production introduces uncertainties due to the differences in environmental conditions from conditions during calibration. Furthermore, production systems may not be able to control the temperature, product density, product orientation and other variables during product irradiation. As a result, each aspect of the production irradiation environment introduces another element of uncertainty into the estimation of the delivered dose. To the extent that these sources cannot be controlled, the uncertainties they introduce should be bounded through knowledge of the sensitivity of the dosimetry system to production conditions. Some components that may contribute to this source of uncertainty are given in Table 4.

NOTE 13—A dosimeter used in routine production may be placed in a position within or on product which is not a maximum or minimum absorbed-dose position (that is, a reference position). An additional source of uncertainty is introduced when converting the dose measurement at the reference position to a maximum or minimum absorbed dose. This source of uncertainty is not due to the absorbed-dose measurement; rather, it is a source of uncertainty in the calculation of maximum or minimum absorbed dose.

8. Combining Uncertainties—Statement of Uncertainty

8.1 For sources of uncertainty that are independent (not correlated), the combined uncertainty is obtained by combining all Type A standard uncertainties and all Type B standard uncertainties in quadrature. If a functional relationship between variables is known to exist, use the procedures of Appendix X5 to determine the combined standard uncertainty. This combined standard uncertainty is designated as u_c (**10**).

8.2 For sources of uncertainty that are related, the effects of those correlations must be taken into account in determining the combined standard uncertainty. Full treatment of correlation effects is beyond the scope of this guide; however, in the special case where all estimates of input quantities are correlated, the combined standard uncertainty is the linear sum of the Type A and Type B standard uncertainties. This has the effect of giving a maximum limit to the estimate of the combined uncertainty.

8.3 Although u_c can be used as the final expression of uncertainty of a measurement result, it is often necessary to give the uncertainty in terms of an interval about the measurement result within which the values that could reasonably be attributed to the measurand may be expected to lie with a high level of confidence. This additional measure of uncertainty that provides such a confidence interval is termed overall uncertainty and denoted as U. The overall uncertainty U is obtained by multiplying the combined standard uncertainty u_c by a coverage factor k:

$$U = ku_c \tag{2}$$

8.3.1 The choice of a coverage factor that corresponds to an exact level of confidence is difficult to achieve in practice. This is true because it requires the full knowledge of the probability distribution of the measurand. However, for a large number of measurements and a probability distribution that is approximately normal, coverage factors of 2 and 3 correspond approximately to confidence levels of 95 % and 99 %, respectively.

8.3.1.1 To obtain a better approximation of the coverage factor than that assumed above, it is necessary to determine the factor by means of the Student's t distribution. For small number degrees of freedom (small number of measurements), it may be necessary to calculate the effective degrees of freedom by use of the Welch-Satterwaite formula (see Ref **4** and ISO Guide to the Expression of Uncertainty in Measurement (**5**)).

9. Information Provided by Uncertainty

9.1 Appendixes X1 through X4 provide several examples of estimates of uncertainty associated with measurement of absorbed dose. Estimates of components of uncertainty and overall uncertainty are given. This information serves several useful purposes.

9.1.1 Listing of all known components of uncertainty, as shown for example in Tables X1.1, X1.2 and X1.3, lessens the chance that the measurand will be influenced in an unknown way by a component of error that could significantly affect the accuracy of the reported value.

9.1.2 The estimate of overall uncertainty can be compared to limits that are given in standard practices for use of individual dosimetry systems to determine if the measurement procedure is under statistical control. For example, the estimates of overall uncertainty in Tables X1.6 and X1.7 are less than ±6 % at a 95 % confidence level. Comparison of these numbers to the recommended limit of ±6 % in Practice E 1276 suggest these processes are under statistical control.

9.1.3 Components of uncertainty that affect the experimentally observed variability of the measurand, for example the data in Table X2.1 and X2.2, can be used to assess the measurement system. If a value of absorbed dose falls outside the 95 % confidence band, it may be suspect and indicative of a problem with the measurement system. The confidence interval that is found from these measureable quantities also can be used in setting process parameters to ensure all measurements of absorbed dose fall within protocol limits. Adjustment for these uncertainties is sometimes referred to as the target dose concept (see Ref **13** and ISO 11137 (**8**)).

9.1.4 The overall uncertainty including all Type A components and Type B components may be considered in setting process parameters. The value of this approach and ramifications on processing specifications are outside the scope of this guide.

10. Keywords

10.1 absorbed dose; accuracy; bias; dosimeter; dosimetry; electron beams; error; gamma radiation; radiation processing; Type A evaluation; Type B evaluation; uncertainty; x-ray

APPENDIXES

(Nonmandatory Information)

X1. EXAMPLES OF UNCERTAINTY FROM CALIBRATION OF DOSIMETERS

X1.1 The methods described in Section 6 were used in evaluating Type A and Type B components. Components of uncertainty are combined in their simplest form, that is, they are assumed to be uncorrelated and are added in quadrature (see 8.1 and 8.2). Examples of uncertainty associated with specification of absorbed dose at a calibration facility are given in Tables X1.1, X1.2 and X1.3. The values of individual components of uncertainty are based on actual numbers that were found from published literature or experimental estimates.

X1.2 The example in Tables X1.1 and X1.2 are for high dose radiation dosimetry calibration laboratories. These facilities serve as a site for calibration of routine dosimeters and as a source of transfer dosimeters for use at irradiators.

TABLE X1.1 Example of Uncertainties in Absorbed Dose Values for a Pool Type Gamma Facility

Component of Uncertainty	Type A, %	Type B, %
Response of Primary Standard	...[A]	0.14
Irradiation Time	0.23	...[A]
Decay Corrections	0.02	0.01
Non-Uniformities in Standard Radiation	0.25	...[A]
Corrections for Attenuation and Geometry	...[A]	1.00
Conversion of Absorbed Dose to Reference Material	...[A]	0.30
Type A and Type B Components Combined in Quadrature Separately	0.34	1.05
Both Components Combined in Quadrature, u_c	1.11	

[A] In this example, these components were considered insignificant.

TABLE X1.2 Example of Uncertainties in Absorbed Dose Values for Electron Beam Facility

Component of Uncertainty	Type A, %	Type B, %
Response of Primary Standard	...[A]	0.80
Stability after Irradiation	0.50	...[A]
Influence of Irradiation Conditions (Non-Uniformities and Attenuation)	0.50	1.00
Conversion of Absorbed Dose to Reference Material	...[A]	1.00
Type A and Type B Components Combined in Quadrature Separately	0.71	1.62
Both Components Combined in Quadrature, u_c	1.77	

[A] In this example, these components were considered insignificant.

TABLE X1.3 Example of Uncertainties in Absorbed Dose Values for Irradiation of Ceric-Cerous Dosimeters in a Gammacell 220 Irradiator Calibrated by Fricke Dosimetry

Component of Uncertainty	Type A, %	Type B, %
Response of Fricke Dosimeters	...[A]	1.75
Irradiation Time	0.08	...[A]
Decay Corrections	0.01	0.03
Non-Uniformities in Standard Radiation	0.25	...[A]
Type A and Type B Components Combined in Quadrature Separately	0.26	1.75
Both Components Combined in Quadrature, u_c	1.77	

[A] In this example, these components were considered insignificant.

In each case the primary standard that was used in the calibration of the facility was a calorimeter or ionization chamber (see Guide E 1261).

X1.3 The example in Table X1.3 is for an in-house calibration facility whose dose rates have been demonstrated to be traceable to appropriate national standards. The Fricke system, which is a widely used reference standard, was used to calibrate the Gammacell[10] (see Practice E 1026).

X1.4 The estimates of uncertainty that are given in Tables X1.1, X1.2 and X1.3 do not take into account contributions from analysis of dosimeter response, fit of dosimetry data to a calibration curve, and routine use. Examples of these contributions to the overall uncertainty are given in following sections of this appendix.

X1.5 Difference in the environment between calibration and use represents a potentially significant source of uncertainty in measurement of absorbed dose with routine dosimeters in the irradiator facility. Collocation of transfer standard dosimeters with the routine dosimeters during irradiation in the irradiator facility offers one method for estimating the magnitude of systematic error in the measurements. In-plant calibration can be used to assess the effects of environment on dosimeter response. An example of an estimate of uncertainty associated with this approach to calibration is given in Tables X1.4, X1.5 and X1.6. In this example the ceric-cerous system was used as the transfer standard. The dichromate and alanine systems represent two other examples of reference standards that may serve as transfer standards (see Practices E 1401 and E 1607).

X1.6 The components of uncertainty in Table X1.4 take into account response of the dosimeters and fit of the calibration data to an analytical function, that is, polynomial fit (see X2 and X3). In Table X1.5 uncertainties due to differences in environment between the Gammacell and production facility are taken into account. Additional components of uncertainty that result from use of a routine dosimetry system are considered in Table X1.6. It is assumed that routine use of the analytical instrumentation, irradiation temperature, and time after irradiation for analysis of the

TABLE X1.4 Example of Uncertainties in Calibration of Ceric-Cerous Transfer Standard Dosimetry System

Component of Uncertainty	Type A, %	Type B, %
Absorbed Dose Values (Table X1.3)	0.26	1.75
Response of Sets of Five Ceric-Cerous Dosimeters	0.31	...[A]
Polynomial Fit for Calibration Curve	1.00	...[A]
Type A and Type B Components Combined in Quadrature Separately	1.08	1.75
Both Components Combined in Quadrature, u_c	2.06	

[A] In this example, these components were considered insignificant.

TABLE X1.5 Example of Uncertainties in Absorbed Dose Values Measured in a Production Irradiator Using Sets of Two Ceric-Cerous Dosimeters

Component of Uncertainty	Type A, %	Type B, %
Ceric-Cerous Dosimetry System Calibration (Table X1.4)	1.08	1.75
Ceric-Cerous Dosimeter Response (Set of Two Dosimeters)	0.49	...[A]
Temperature Correction	...[A]	0.50
Effects Due to Differences in Photon Energy Spectra of Sources	...[A]	0.50
Type A and Type B Components Combined in Quadrature Separately	1.19	1.89
Both Components Combined in Quadrature, u_c	2.23	

[A] In this example, these components were considered insignificant.

TABLE X1.6 Example of Uncertainties in Calibration of Harwell Red 4034 Perspex Dosimeters in Production Irradiator Using Ceric-Cerous Transfer Standard Dosimeters

Component of Uncertainty	Type A, %	Type B, %
Response of Set of Two Ceric-Cerous Dosimeters (Table X1.5)	1.19	1.89
Non-Uniformities in Irradiation	1.00	...[A]
Red Perspex Dosimeter Response (Set of Three Dosimeters)	0.80	...[A]
Polynomial Fit for Calibration Curve	1.00	...[A]
Type A and Type B Components Combined in Quadrature Separately	2.01	1.89
Both Components Combined in Quadrature, u_c	2.76	

[A] In this example, these components were considered insignificant.

[10] The Gammacell Model 220, available from Nordion International, Inc., 447 March Rd., P.O. Box 13500, Kanata, Ontario, Canada K2K 1XB, has been found suitable for this purpose.

TABLE X1.7 Example of Overall Uncertainty for Calibration and Use of Red Perspex Dosimeters

Component of Uncertainty	Type A, %	Type B, %
Standard Laboratory Estimate of Reference Dosimeter Uncertainties	0.90	0.60
Temperature Correction of Reference Dosimeters	...[A]	0.20
Timing of Reference Dosimeter Irradiations	...[A]	0.10
Decay Correction	...[A]	0.10
Reproducibility of Dose Rates	0.10	...[A]
System Calibration, Type A and Type B Components Combined in Quadrature Separately	0.91	0.65
Timing of Routine Dosimeter Irradiations	...[A]	0.10
Measurement of Specific Absorbance (Mean of Four Dosimeters)	0.41	0.22
Thickness of Dosimeters	...[A]	0.10
Specific Absorbance of Dosimeter	1.39	0.22
Analysis, Type A and Type B Components Combined in Quadrature Separately	1.45	0.34
Conversion to Polynomial Form	...[A]	0.50
Mathematical Use of Polynomial	...[A]	0.10
Fit to Calibration Curve, Type B Components Combined in Quadrature	...[A]	0.51
Type A and Type B Components Combined in Quadrature Separately	1.71	0.89
Both Components Combined in Quadrature, u_c	1.93	

[A] In this example, these components were considered insignificant.

Red Perspex[11] dosimeters (a type of polymethylmethacrylate dosimeter) are similar to those used in the calibration run. If any of these differ, it may be necessary to consider additional sources of uncertainty (see X4.1). Also, the component of uncertainty due to response of the routine dosimeters will depend on the number of dosimeters that are used at each dose point.

X1.7 Table X1.7 provides an example of an actual estimate of the overall uncertainty associated with calibration and use of a batch of Red Perspex[11] dosimeters. Individual components of uncertainty are summed in quadrature. The estimate of uncertainty does not take into account possible components of uncertainty that may result from differences in environmental conditions, energy spectrum, or dose rate between the calibration laboratory and a production irradiator (**11**).

[11] Red Perspex, available from Irradiation and Dosimetry Service, AEA Technology, Building 0.30, Harwell Laboratory, Oxfordshire OX 11 ORA, England.

X2. EXAMPLES OF UNCERTAINTY ASSOCIATED WITH MEASUREMENT OF DOSIMETER RESPONSE

X2.1 The data in Table X2.1 were derived from actual measurements of absorbance of thin film radiochromic dosimeters that were used in the calibration of a batch of dosimeters. These measurements were made under conditions of repeatability. Five replicate measurements of net absorbance were made at each value of absorbed dose. The values in Table X2.1 represent averages of the five measurements. All of the net absorbances were normalized to a single dosimeter thickness. By pooling the sets of absorbance data, a single value for uncertainty was found.

NOTE X2.1—Pooling increases the degrees of freedom and improves the quality of the estimate (see Practice E 876). This approach is valid only if each set of analysis was obtained under similar or identical conditions with samples of similar composition and history.

X2.1.1 The pooled estimate for the coefficient of variation that is given in Table X2.1 was found from the expression (see Practice E 876),

TABLE X2.1 An Example of Type A Uncertainty in Specific Absorbance (Pooled Estimate)

Absorbed Dose, kGy	$\overline{\Delta A}_i$	$S_{i-1} \times 10^{-3}$	$S^2_{i-1}/\overline{\Delta A}^2_i \times 10^{-4}$
8.0	0.073	1.3	3.2
10.0	0.087	1.3	2.2
15.2	0.126	1.3	1.1
20.0	0.169	0.8	0.2
25.0	0.208	1.6	0.6
30.0	0.241	1.3	0.3
40.0	0.308	1.8	0.3

$$CV\ \% = \sqrt{\frac{4(3.2 + 2.2 + 1.1 + 0.2 + 0.6 + 0.3 + 0.3) \times 10^{-4}}{28}} \times 100\ \%$$

$$CV\ \% = 1.1\ \%$$

$$CV\ \% = \sqrt{\frac{\Sigma_i\,(n_i - 1)S^2_{i-1}/\overline{\Delta A}^2_i}{\Sigma_i\,(n_i - 1)}} \times 100\ \% \qquad \text{(X2.1)}$$

where:

S_{i-1} = sample standard deviation for i^{th} set of absorbance data,
$(n_i - 1)$ = degrees of freedom for i^{th} set of data,
$\overline{\Delta A}_i$ = average value absorbance for i^{th} set of data, and
n_i = number of replicate measurements for i^{th} set of data.

The coefficient of variation at a confidence level of 95 % or 99 % can be found through multiplication of the value in Table X2.1 by 2 or 3 respectively. In the cited example these overall uncertainties are 2.2 % and 3.3 % respectively.

X2.2 The data in Table X2.2 show the variability in absorbance of thin film radiochromic dosimeters that were irradiated under conditions of reproducibility at an irradiator facility. Over a period of several days, different sets of three dosimeters were irradiated to the same nominal dose. Possible sources of random errors could include intrinsic variation in dosimeter response and day-to-day variations in the physical environment, for example, temperature, positioning of dosimeters within the irradiator, and shielding.

X2.2.1 A standard deviation, $S_{\text{dosimeter}}$, for dosimeters is computed by pooling the standard deviations from each day,

$$S_i = \left\{\frac{1}{2}\sum_{j=1}^{3}(x_{i,j} - \bar{x}_i)^2\right\}^{1/2} \qquad \text{(X2.2)}$$

over the nine days;

$$S_{\text{dosimeter}} = \left\{\frac{1}{9}\sum_{i=1}^{9} S_i^2\right\}^{1/2} \qquad \text{(X2.3)}$$

TABLE X2.2 Measured Absorbance of Radiochromic Dosimeters Irradiated Under Reproducible Conditions

Dosimeter Set	Absorbance
1	0.282
	0.274
	0.276
2	0.294
	0.274
	0.284
3	0.300
	0.284
	0.292
4	0.290
	0.300
	0.286
5	0.296
	0.294
	0.302
6	0.290
	0.278
	0.284
7	0.290
	0.290
	0.290
8	0.278
	0.288
	0.286
9	0.284
	0.292
	0.292

where:
$x_{i,j}$ = individual value of absorbance, i = 1–9; j = 1–3, and
$\bar{x}_i$ = average absorbance for a given day.

X2.2.2 A total standard deviation is computed from the daily averages by

$$S_t = \left\{ \frac{1}{8} \sum_{i=1}^{9} (\bar{x}_i - \bar{\bar{x}})^2 \right\}^{1/2} \quad \text{(X2.4)}$$

where:
$\bar{\bar{x}}$ = grand mean of all values of absorbance.

X2.2.3 The standard deviation for days is computed by subtraction to be

$$S_{day} = \left\{ S_t^2 - \frac{1}{3} S_{dosimeter}^2 \right\}^{1/2} \quad \text{(X2.5)}$$

X2.2.4 The standard deviation for a single measurement of absorbance on a given day is

$$S = \{ S_{day}^2 + S_{dosimeter}^2 \}^{1/2} \quad \text{(X2.6)}$$

X2.2.4.1 Computations of the individual standard deviations taken from the data in Table X2.2 are given in Table X2.3. Based on the data in Table X2.3, the coefficient of variation is ±2.7 % or ±5.4 % at 95 % confidence level.

X2.3 An example of the effect of shift in wavelength setting on the measurement of absorbance by a spectrophotometer is illustrated in Fig. X2.1. The reference wavelength for the Red Perspex dosimeters that are used in this example is 640 nm.

X2.3.1 As an example, assume that the uncertainty in setting the wavelength is ±1 nanometer from the reference wavelength and the probability distribution of settings within these bounds is uniform, that is, any value is equally probable. A change of ±1 nanometer in the reference wavelength introduces a ±1 % change in specific absorbance which results in a coefficient of variation of ±1 %/$\sqrt{3}$. At a 95 % confidence level the overall uncertainty is ±2 %/$\sqrt{3}$ = ±1.2 %.

TABLE X2.3 Standard Deviations from Measurement of Absorbance

Day	Individual Measurements of Absorbance			Mean	Standard Deviation	Degrees of Freedom
1	0.282	0.274	0.276	0.27733	0.00416	2
2	0.294	0.274	0.284	0.28400	0.01000	2
3	0.300	0.284	0.292	0.29200	0.00800	2
4	0.290	0.300	0.292	0.29200	0.00721	2
5	0.296	0.294	0.297	0.29733	0.00416	2
6	0.290	0.278	0.284	0.28400	0.00600	2
7	0.290	0.290	0.290	0.29000	0.00000	2
8	0.278	0.288	0.286	0.28400	0.00529	2
9	0.284	0.292	0.292	0.28933	0.00462	2
Pooled standard deviation, $S_{dosimeter}$					0.00611	18
Grand mean, $\bar{\bar{x}}$					0.28778	
Total standard deviation, s_t					0.00598	8
Standard deviation for days, s_{day}					0.00483	
Standard deviation, s (measurement on a single dosimeter)					0.00779	

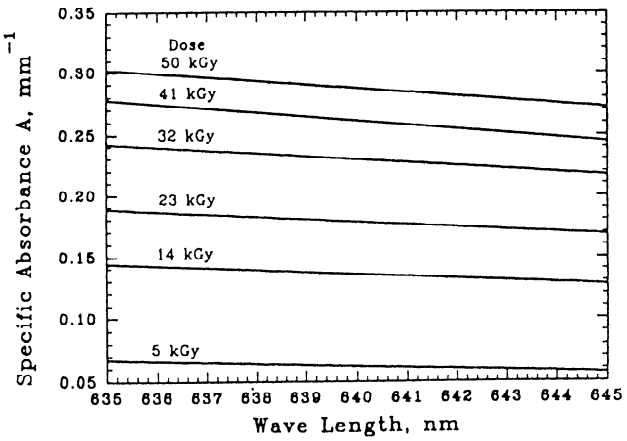

FIG. X2.1 Measured Specific Absorbance versus Wavelength for Red Perspex Dosimetry System

X3. EXAMPLES OF UNCERTAINTY ASSOCIATED WITH CURVE FITTING

X3.1 Several examples of curve fits to actual dosimetry calibration data are given in this section. The 95 % confidence interval about the fit is used to estimate the component of uncertainty in absorbed dose from fit of the calibration data to an analytical function.

X3.2 *Linear Fit*—The radiochromic optical wave guide dosimeter is a routine dosimeter that provides a means of measuring absorbed dose in materials (see Practice E 1310). It is particularly useful for measuring absorbed dose in food products. Net absorbance can be related to absorbed dose by the relationship:

$$\Delta A_{i,j} = a + bD_j \quad \text{(X3.1)}$$

where:

$\Delta A_{i,j}$ = change is absorbance of irradiated sample,
i = 1, 2 . . . n (number identifying dosimeters at each absorbed dose level),
j = 1, 2 . . . m (number identifying absorbed dose levels),
D_j = absorbed dose,
a = intercept of the plot determined by a least-squares linear regression fit of the data, and
b = slope of the plot determined by regression analysis.

X3.2.1 The data in Table X3.1 were fitted with a linear function and plotted in Fig. X3.1. Eight replicate measurements of net absorbance are given for each value of absorbed dose. The ±95 % confidence bands for the fit also are plotted in Fig. X3.1. These bands were determined by plotting the confidence intervals at various dose point values (12). The confidence interval at the dose point D_x is given by:

$$\pm \sqrt{2F_\alpha(2, N-2)}\, S_{N-2} \left[\frac{1}{N} + \frac{(D_x - \bar{D})^2}{\sum_i (D_i - \bar{D})^2}\right]^{1/2} \quad \text{(X3.2)}$$

where:
$F_\alpha(2, N-2)$ = upper α percent point of the F distribution (in this example the F value at 95 % confidence is 3.2),
S_{N-2} = sample standard deviation of the residual values where residual value is the difference between the measured net absorbance and the value calculated from the curve fit,
N = total number of response points = nm,
$\bar{D}$ = average dose value, and
D_i = individual dose point.

NOTE X3.1—The confidence interval given by Eq X3.2 is for the fitted curve. As more response points, N, are used in the curve fit, these limits become tighter. Individual values of response may fall outside the confidence interval for the fitted curve. Examples of uncertainty associated with measurements of dosimeter response are given in Appendix X2.

X3.2.2 The variations in values of net absorbance about the curve at a 95 % confidence level are given in Table X3.2. As seen from the data in this table, the maximum uncertainty occurs at the low dose end of the curve and the minimum uncertainty is found at the midpoint of the curve.

TABLE X3.1 Example of Dosimeter Response as a Function of Absorbed Dose for a Radiochromic Optical Waveguide Dosimetry System

Absorbed Dose, kGy	Net Absorbance	Absorbed Dose, kGy	Net Absorbance
0.25	0.236	0.75	0.651
0.25	0.242	0.75	0.667
0.25	0.230	0.75	0.663
0.25	0.237	0.75	0.667
0.25	0.238	1.00	0.891
0.25	0.241	1.00	0.886
0.25	0.249	1.00	0.870
0.25	0.243	1.00	0.860
0.50	0.459	1.00	0.882
0.50	0.452	1.00	0.875
0.50	0.457	1.00	0.874
0.50	0.451	1.00	0.870
0.50	0.447	1.25	1.100
0.50	0.445	1.25	1.115
0.50	0.445	1.25	1.101
0.50	0.448	1.25	1.078
0.75	0.671	1.25	1.085
0.75	0.667	1.25	1.100
0.75	0.651	1.25	1.107
0.75	0.667	1.25	1.090

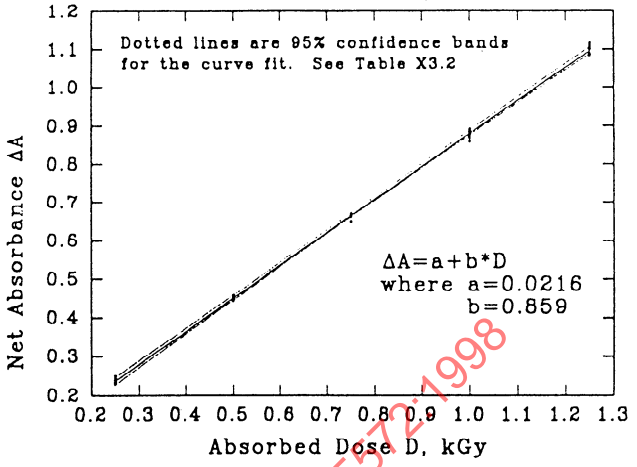

FIG. X3.1 Response Curve for Optichromic Dosimetry System

TABLE X3.2 Curve Fit Data for Linear Fit to Radiochromic Optical Waveguide Dosimetry System

Dose, kGy	Net Absorbance Curve Fit	95 % Confidence Interval
0.25	0.237	±0.006
0.35	0.323	±0.005
0.45	0.409	±0.005
0.55	0.495	±0.004
0.65	0.581	±0.004
0.75	0.667	±0.004
0.85	0.753	±0.004
0.95	0.839	±0.004
1.05	0.925	±0.005
1.15	1.011	±0.005
1.25	1.097	±0.006

X3.2.3 The uncertainty in absorbed dose due to the fit can be found from substitution of the 95 % confidence level values of net absorbance into Eq X3.1. The resultant overall uncertainties in absorbed dose have values of +3.1 % and −2.5 % at the low dose point on the curve and values of +0.8 % and −0.4 % over the midrange doses.

X3.3 *Power Model*—The thin film radiochromic dosimeter is used as a routine dosimeter for measurement of absorbed dose (see Practice E 1275). Over a limited range of absorbed dose the response of this dosimeter exhibits linear behavior under logarithmic transformation. Net absorbance $\Delta A_{i,j}$ is related to absorbed dose D_j by the relationship:

$$\Delta A_{i,j} = aD_j^b \quad \text{(X3.3)}$$

which under logarithmic transformations becomes,

$$ln(\Delta A_{i,j}) = ln(a) + b ln(D_j) \quad \text{(X3.4)}$$

where ln, a, and b are the intercept and slope, respectively, for the straight line. Both parameters are determined by linear regression analysis.

X3.3.1 As an example, a logarithmically transformed linear fit was applied to the data shown in Table X3.3. Results of the fit are shown in Fig. X3.2. The variations in values of net specific absorbance about the curve at a 95 % confidence level are given in Table X3.4.

X3.3.2 The uncertainty in absorbed dose due to the fit can be found from substitution of the 95 % confidence level values of net specific absorbance into Eq X3.3 and solving

TABLE X3.3 Dosimeter Response as a Function of Absorbed Dose for a Thin Film Radiochromic Dosimetry System

Absorbed Dose, kGy	Net Specific Absorbance	Absorbed Dose, kGy	Net Specific Absorbance
6.00	9.438	20.00	27.093
6.00	9.512	20.00	26.623
6.00	9.580	20.00	27.839
6.00	9.576	20.00	26.556
6.00	9.670	20.00	27.435
8.00	12.006	25.00	32.960
8.00	12.226	25.00	32.884
8.00	12.116	25.00	32.881
8.00	12.100	25.00	32.596
8.00	12.345	25.00	33.598
10.00	15.057	30.00	40.034
10.00	14.778	30.00	37.443
10.00	14.955	30.00	39.517
10.00	14.837	30.00	37.768
10.00	14.884	30.00	39.445
15.00	21.232	35.00	44.687
15.00	21.183	35.00	45.489
15.00	21.273	35.00	43.827
15.00	21.559	35.00	45.587
15.00	21.526	35.00	45.626
		40.00	50.190
		40.00	50.064
		40.00	48.957
		40.00	47.862
		40.00	47.959

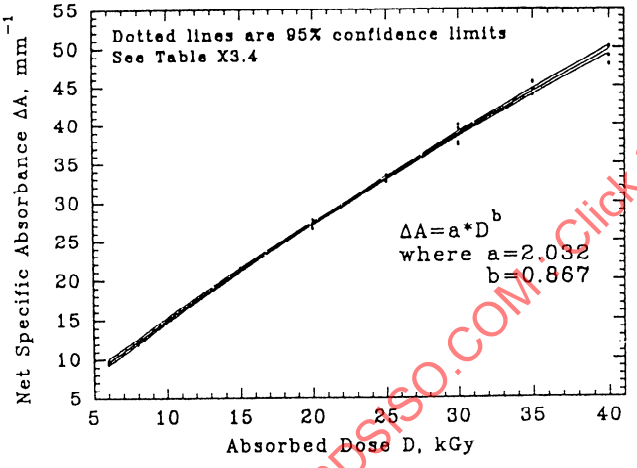

FIG. X3.2 Response Curve for Thin Film Radiochromic Dosimetry System

for absorbed dose. In this example, an overall uncertainty of ±5.0 % occurs at the 6 kGy dose point, and an overall uncertainty of ±1.0 % is found over the midrange portion of the calibration curve.

X3.4 Logarithmic Fit-Polymethylmethacrylate, typically in the form of small chips, is used as a routine dosimeter (see Practice E 1276). The response data for this type of dosimeter can be fitted to a logarithmic function. Net absorbance $\Delta A_{i,j}$ is related to absorbed dose D_j by the expression:

$$\Delta A_{i,j} = a + b\log(D_j + c) \quad \text{(X3.5)}$$

where a, b, and c are constants to be found from linear regression fit of the data.

X3.4.1 The data in Table X3.5 for Red Perspex were fitted to a logarithmic expression which is shown in Fig. X3.3. The variations in values of specific absorbance about the curve at a 95 % confidence level, are given in Table X3.6.

TABLE X3.4 Logarithmic Transformed Linear Curve Fit Data for Thin Film Radiochromic System

Dose, kGy	Net Specific Absorbance Curve Fit	95 % Confidence Limits
6	9.607	±0.423
8	12.328	±0.388
10	14.960	±0.356
14	20.027	±0.302
18	24.903	±0.267
22	29.635	±0.259
26	34.254	±0.281
30	38.778	±0.327
34	43.223	±0.388
38	47.599	±0.459
40	49.763	±0.496

TABLE X3.5 Dosimeter Response As a Function of Absorbed Dose for Red Perspex System

Absorbed Dose, D, kGy	Specific Absorbance	Absorbed Dose, D, kGy	Specific Absorbance
5.00	0.615	25.00	2.019
5.00	0.623	25.00	2.020
5.00	0.625	25.00	2.025
5.00	0.623	25.00	2.009
5.00	0.636	25.00	2.019
10.00	1.069	30.00	2.288
10.00	1.069	30.00	2.271
10.00	1.066	30.00	2.280
10.00	1.067	30.00	2.267
10.00	1.062	30.00	2.270
15.00	1.439	35.00	2.478
15.00	1.432	35.00	2.463
15.00	1.453	35.00	2.465
15.00	1.441	35.00	2.463
15.00	1.477	35.00	2.455
20.00	1.757	40.00	2.650
20.00	1.756	40.00	2.636
20.00	1.740	40.00	2.645
20.00	1.742	40.00	2.652
20.00	1.757	40.00	2.663
		45.00	2.834
		45.00	2.820
		45.00	2.826
		45.00	2.814
		45.00	2.826

X3.4.2 The uncertainty in absorbed dose from the fit is found from substitution of the data in Table X3.6 into Eq X3.5. A maximum overall uncertainty in absorbed dose of ±1.6 %, occurs at the 5 kGy dose point, and an overall uncertainty of ±0.2 % is found over the midrange portion of the calibration curve.

X3.5 *Polynomial Fit*—Polynomials provide a generic method for fitting calibration data to an analytical function. Response as a function of absorbed dose can be approximated by a polynomial function of the form:

$$Y = \sum_{n=0}^{P} A_n X^n \quad \text{(X3.6)}$$

where X normally represents absorbed dose, Y, dosimeter response, and P is the order of the polynomial. The coefficients A_n are estimated by standard least-square procedures.

X3.5.1 The Red Perspex data in Table X3.5 were fitted to second, third and fourth order polynomials. The respective fits and 95 % confidence bands are shown in Figs. X3.4,

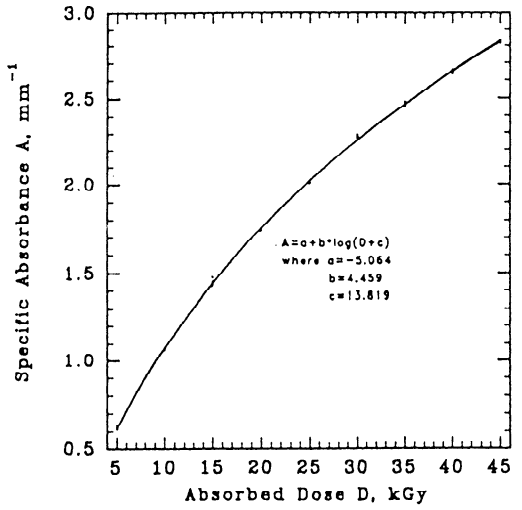

FIG. X3.3 Response Curve for Red Perspex Dosimetry System—Logarithmic

TABLE X3.6 Logarithmic Curve Fit Data for Red Perspex System

Dose, kGy	Specific Absorbance Curve Fit	95 % Confidence Interval
5	0.619	±0.008
10	1.076	±0.007
15	1.445	±0.006
20	1.755	±0.005
25	2.022	±0.004
30	2.256	±0.005
35	2.465	±0.006
40	2.654	±0.007
45	2.826	±0.008

X3.5, and X3.6. The goodness-of-fit can be evaluated by several parameters that are obtained as part of the fitting process. Two such parameters are the coefficient of determination, r^2 (often called the correlation coefficient), and the F-value (or F-statistic). The r^2 value always increases as more terms are added to the polynomial. Values for these

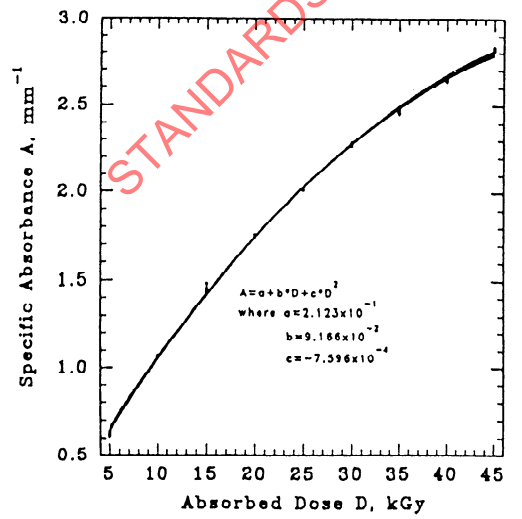

FIG. X3.4 Response Curve for Red Perspex Dosimetry System—2nd Order Polynomial

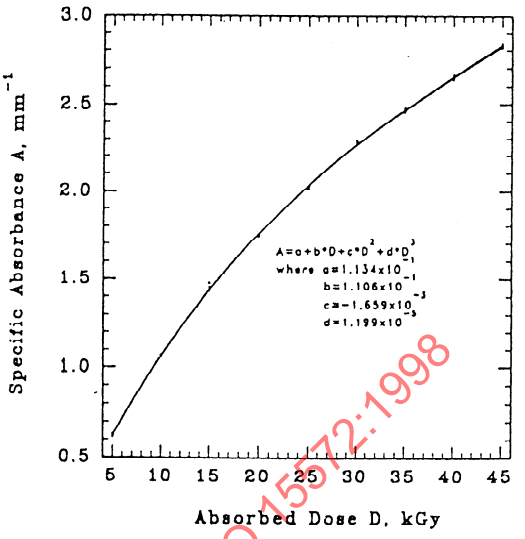

FIG. X3.5 Response Curve for Red Perspex Dosimetry System—3rd Order Polynomial

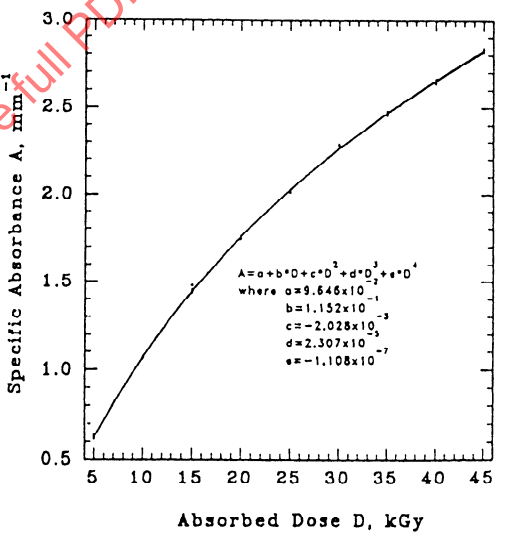

FIG. X3.6 Response Curve for Red Perspex Dosimetry System—4th Order Polynomial

two parameters for the three polynomials fitted are given in Table X3.7.

NOTE X3.2—Commercial computer software that can provide the polynomial (and other functions) fits and the resultant statistical parameters such as r^2 and F-values is widely available.

X3.5.2 The criterion for evaluating the values of the r^2 test is that a good fit is indicated by values close to 1. Larger F-values indicate better fit to the data with the largest F-value indicating the best fit. Since the r^2 values for degrees

TABLE X3.7 Polynomial Fit Test Parameters

Degree of Polynomial	r^2	F-Value
2	0.99904	21 909
3	0.99976	57 766
4	0.99977	43 437

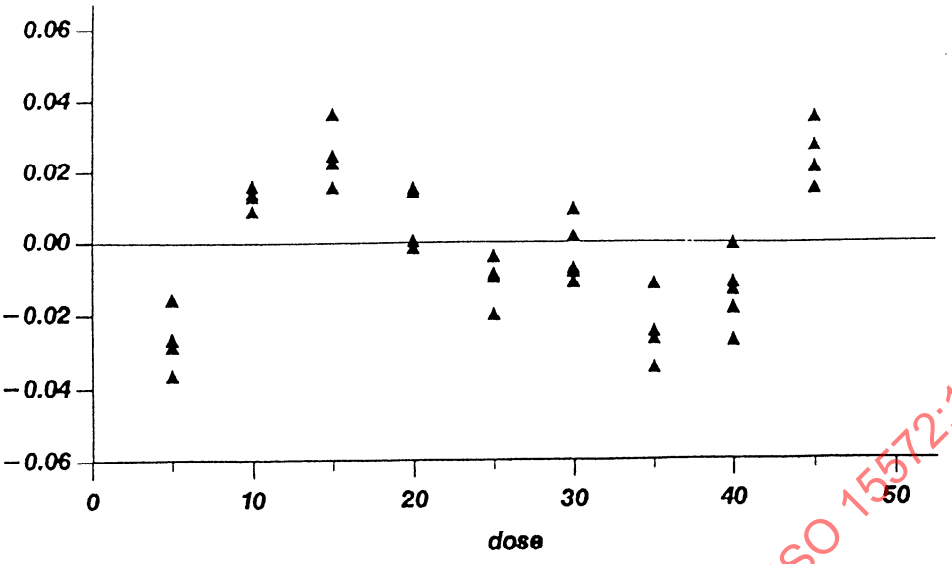

FIG. X3.7 Residuals for Red Perspex Dosimetry System—2nd Order Polynomial

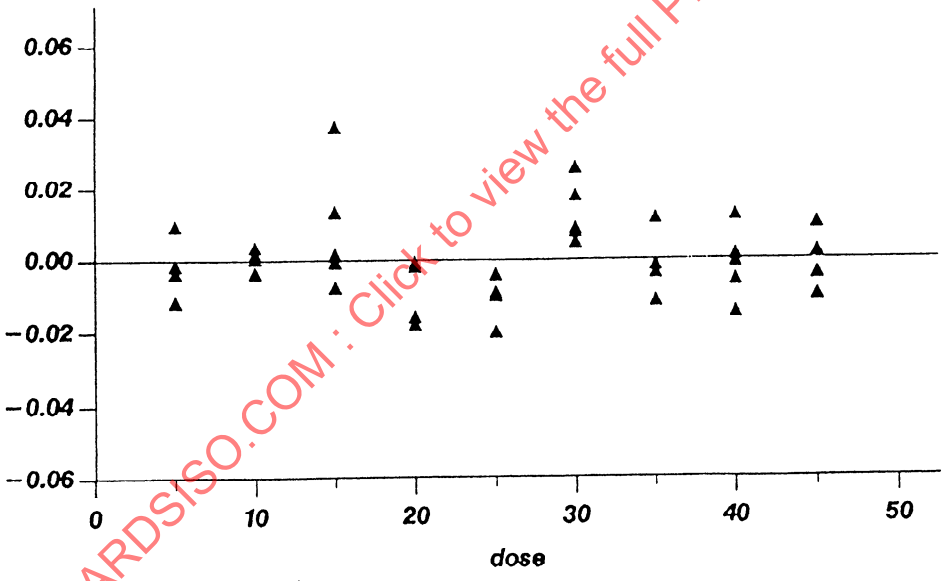

FIG. X3.8 Residuals for Red Perspex Dosimetry System—3rd Order Polynomial

3 and 4 indicate essentially equally good fits, it can be seen that the *F*-value test is much more sensitive than the r^2 test and generally would be the test of choice.

X3.5.3 Examination of residuals also can be used to test for goodness of fit. Small percentage differences between the actual values of net absorbance and those predicted by the curve are indicative of a good fit. This point is illustrated in Figs. X3.7 and X3.8 which show residuals for the second and third order polynomial fits. The residuals are more equally distributed for third order, therefore indicating that a third order polynomial offers a better fit than a second order polynomial.

X3.5.4 The degree of the polynomial selected should be the lowest order that gives a good fit to the data set. Selection of higher orders can introduce oscillatory behavior into the fit, resulting in a curve that may not accurately relate to the physical response of the dosimetry system.

X4. UNCERTAINTY ASSOCIATED WITH ROUTINE USE

X4.1 Dependent on the source of radiation, type of irradiator and products being processed, some components in Table 4 (see 7.6) could significantly contribute to the total uncertainty in reported values of absorbed dose or alternately could be ignored. For example, variability in orientation of dosimeters to an electron beam could significantly contribute to the estimate of uncertainty in absorbed dose. Whereas, orientation of dosimeters may have little effect in the value of absorbed dose in large panoramic gamma irradiators (**13**). Rather than cite examples for all of the components of uncertainty in Table 4, only those components that may significantly contribute to total uncertainty regardless of the source of radiation, type of irradiator or product are considered here. The user of this guide, however, is alerted to the importance of the remaining components of uncertainty in Table 4 and possible need to take them into account.

X4.2 Change in the environment during routine use from calibration conditions represents a potentially significant source of uncertainty in measurements of absorbed dose at the irradiator facility. This component of uncertainty usually appears as a systematic error in the measurement. By proper packaging, dosimeters can be isolated from certain environments, for example, ultraviolet radiation and humidity; however, the effect on response of other environmental factors such as temperature, dose rate, and energy spectrum must be taken into account (see Practice E 1249 and Refs **14, 15, 16** and **17**). For this reason, calibration conditions should approximate those for routine use when possible. In addition, selection of a dosimetry system that is insensitive to variation in environment will reduce systematic errors in the measurements. Irradiation of this type of dosimeter with the routine system offers one method of correcting for systematic errors. Unfortunately, the ideal dosimeter does not exist and corrections for environmental factors with estimates of systematic error may be required.

X4.2.1 Information on the temperature dependence of dosimetry systems is usually available from the manufacturer and published literature (**14, 15** and **16**). Figure X4.1 provides an example of the temperature response for two types of dosimetry systems (see Practices E 1205 and E 1275 and Refs **14** and **16**). Both curves, which are normalized to a response of one at 20°C, were generated at given dose levels and dose rates. As seen from this figure, a correction of several percent in dosimeter response would be required if the temperature of irradiation deviates significantly from 20°C.

X4.2.2 Dose rates during irradiation of product may differ significantly from the calibration conditions. Even at a single irradiator facility, dose rate may vary by a factor of ten

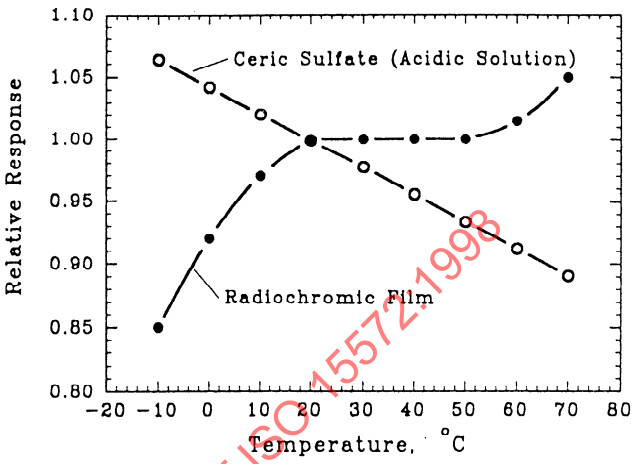

FIG. X4.1 Irradiation Temperature Dependence

or more during the irradiation cycle. Fortunately, dosimeters routinely used to monitor dose at irradiators are relatively insensitive to dose rate effects. Even so, corrections in response of several percent may be necessary. Calibration of dosimeters at the dose rate extremes of the irradiator can be used to bracket the effect of dose rate on response. Co-location of dose rate independent dosimeters with the routine dosimeters also can be used to estimate the systematic error in the response of the routine system.

X4.2.3 For x-ray and gamma sources, correction for the spectral dependence of dosimeters can be assessed through the use of cavity theory (**18**). At the extremes of "thin" and "thick" dosimeter, the correction factor that relates absorbed dose in dosimeter to the medium of interest is given by the ratio of mass collision stopping powers and mass energy absorption coefficients respectively (see Guide E 1261). This approach has been used to estimate the correction factor that should be applied to various types of dosimeters when they are exposed to different photon spectra (**17**). Knowledge of the response functions of the dosimeter and photon spectrum at the irradiator are required for calculation of the correction factor (see Practice E 1249). If the response is not corrected for energy dependence, a systematic error of several percent is possible.

X4.2.4 For electron beam irradiators, the variation of mass collision stopping powers over dosimeter thickness may in practice introduce uncertainties depending on the beam energy, scatter conditions, and the depth of measurement (see ICRU Reports 35 and 37). For these reasons, dosimeters must be thin and the ratio of mass collision stopping powers (material/dosimeter) must be essentially constant over the range of secondary electron energies.