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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.
Current edition approved May 15, 1995. Published July 1995.
[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:

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

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.

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.

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

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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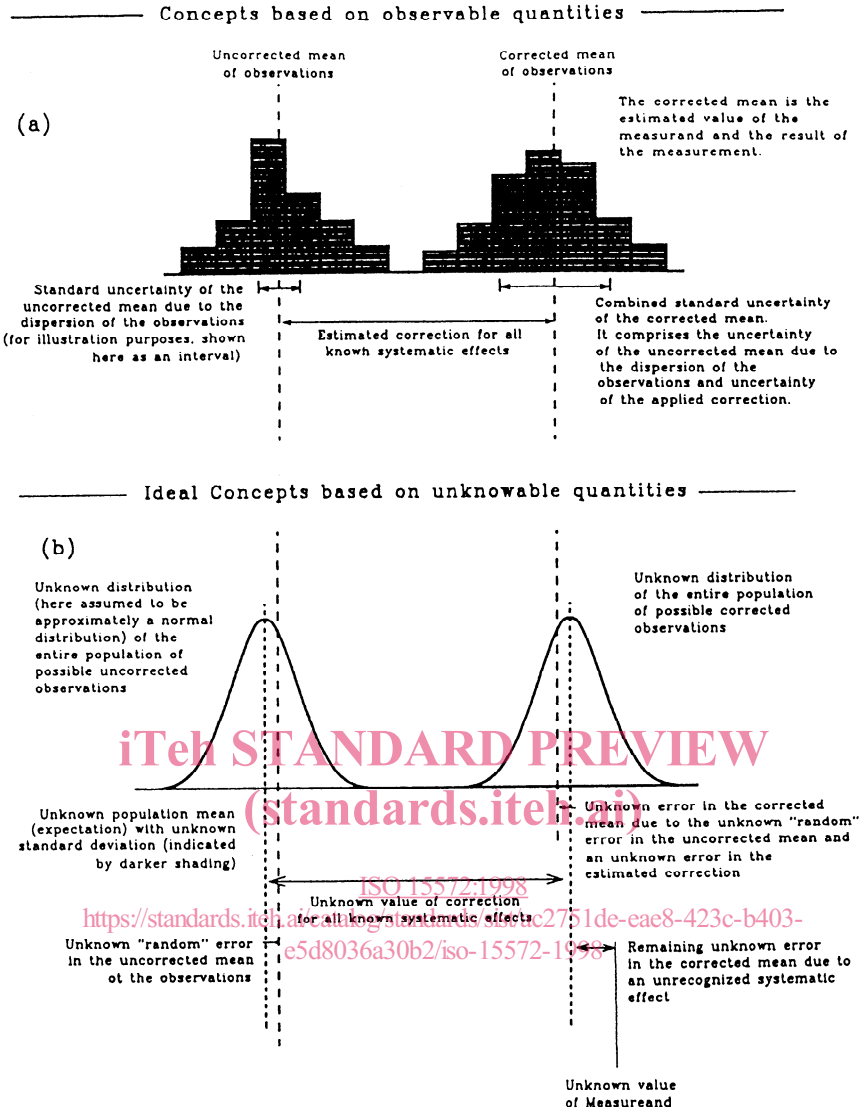

FIG. 1 Graphical Illustration of Value, Error, and Uncertainty

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