Designation: E3376 – 23

Standard Practice for Calibration and Usage of Germanium Detectors in Radiation Metrology for Reactor Dosimetry[1]

This standard is issued under the fixed designation E3376; 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 standard establishes techniques for calibration, usage, and performance testing of germanium detectors for the measurement of gamma-ray emission rates of radionuclides in radiation metrology for reactor dosimetry. The practice is applicable only to samples of small size, approximating to point sources. It covers the energy and full-energy peak efficiency calibration as well as the determination of gamma-ray energies in the 0.06 MeV to 2 MeV energy region and is designed to yield gamma-ray emission rates with an uncertainty of ±3 % (see Note 1). This technique applies to measurements that do not involve overlapping peaks, and in which peak-to-continuum considerations are not important.

NOTE 1—Uncertainty U is given at the 68 % confidence level; that is, $U=\sqrt{\Sigma\sigma_i^2+1/3\Sigma\delta_i^2}$ where δ_i are the estimated maximum systematic uncertainties, and σ_i are the random uncertainties at the 68 % confidence level. Other techniques of error analysis are in use (**1, 2**).[2]

1.2 Additional information on the setup, calibration, and quality control for radiometric detectors and measurements is given in IEEE/ANSI N42.14 and in Guide C1402 and Practice D7282.

1.3 The values stated in SI units are generally to be regarded as standard. The rad is an exception.

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.5 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[3]

C1402 Guide for High-Resolution Gamma-Ray Spectrometry of Soil Samples

D7282 Practice for Setup, Calibration, and Quality Control of Instruments Used for Radioactivity Measurements

E170 Terminology Relating to Radiation Measurements and Dosimetry

2.2 *IEEE/ANSI Standard:*[4]

N42.14 Calibration and Usage of Germanium Detectors Spectrometers for Measurement of Gamma-Ray Emission Rates of Radionuclides

3. Terminology

3.1 *Definitions:*

3.1.1 *certified radioactivity standard source*—a calibrated radioactive source, with stated uncertainties, whose calibration is certified by the source supplier as traceable to an international or national standards laboratory.

3.1.2 *check source*—a radioactivity source, not necessarily calibrated, that is used to confirm the continuing satisfactory operation of an instrument.

3.1.3 *correlated photon summing*—the simultaneous detection of two or more photons originating from a single nuclear disintegration.

3.1.4 *dead time*—the time after a triggering pulse during which the system is unable to retrigger.

3.1.5 *FWHM*—(full width at half maximum) the full width of a gamma-ray peak distribution measured at half the maximum ordinate above the continuum.

3.1.6 *FWTM*—(full width at tenth maximum) the full width of a gamma-ray peak distribution measured at one tenth of the maximum ordinate above the continuum.

[1] This practice is under the jurisdiction of ASTM Committee E10 on Nuclear Technology and Applications and is the direct responsibility of Subcommittee E10.05 on Nuclear Radiation Metrology.

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

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

[4] Available from Institute of Electrical and Electronics Engineers, Inc. (IEEE), 445 Hoes Ln., Piscataway, NJ 08854-4141, http://www.ieee.org.

3.1.7 *national radioactivity standard source*—a calibrated radioactive source prepared and distributed as a standard reference material by an international or national standards laboratory.

3.1.7.1 *Discussion*—In the United States, the national standards laboratory is the U.S. National Institute of Standards and Technology (NIST).

3.1.8 *resolution, gamma ray*—the measured FWHM, after background subtraction, of a gamma-ray peak distribution, expressed in units of energy.

3.2 *Acronyms:*

3.2.1 *GUM*—the GUM, Guide to the Expression of Uncertainty in Measurement (**2**).

3.2.2 *ROI*—region of interest.

3.3 For other relevant terms, see Terminology E170.

NOTE 2—The terms "standard source" and "radioactivity standard" are general terms used to refer to the sources and standards of National Radioactivity Standard Source and Certified Radioactivity Standard Source.

4. Summary of Practice

4.1 This practice describes the calibration and usage of germanium detectors for measurement of gamma-ray emission rates of radionuclides in radiation metrology for nuclear reactors. The practice is intended for use by knowledgeable persons who are responsible for the development of correct procedures for the calibration and usage of germanium detectors.

4.2 A source emission rate for a gamma ray of a selected energy is determined from the counting rate in a full-energy peak of a spectrum, together with the measured efficiency of the spectrometry system for that energy and source location. It is usually not possible to measure the efficiency directly with emission rate standards at all desired energies. Therefore, a curve or function is constructed to permit interpolation between available calibration points.

5. Significance and Use

5.1 High-purity germanium detectors are used for precise gamma-ray spectroscopy for the purpose of determining radioactivity in materials. Typical applications include monitoring, mapping, and characterization of neutron energy spectra in nuclear reactors or isotopic fission sources.

6. Apparatus

6.1 A typical gamma-ray spectrometry system used in reactor dosimetry consists of a germanium crystal, cooling system (cryogenic or electronic), power supply, and either digital or analog signal processing. When gamma rays interact with the detector, they produce pulses which must be analyzed and counted. Digital processing is often integrated into the detector system with fast analog-to-digital converter, mathematical shaping, signal, and amplification followed by the binning of the pulses. In analog systems, signal processing takes place in individual modules. In both cases, the resultant channelized data are collected and stored electronically for further analysis.

7. Preparation of Apparatus

7.1 Follow the manufacturer's instructions for setting up and preliminary testing of the equipment. Observe all of the manufacturer's limitations and cautions. All tests described in Section 12 should be performed before starting the calibrations, and all corrections made when required. A check source may be used to check the stability of the system at least before and after the calibration. In cases where electronic settings are adjustable by the user, it is essential that all the settings be the same for calibration and subsequent use.

8. Calibration Procedure

8.1 *Energy Calibration*—Determine the energy calibration (channel number versus gamma-ray energy) of the detector system at a fixed gain by determining the channel numbers corresponding to full-energy peak centroids from gamma rays emitted over the full-energy range of interest from multipeaked or multinuclide radioactivity sources, or both. Determine nonlinearity correction factors as necessary (**3**).

8.1.1 Using suitable gamma-ray compilations (**4, 5**), plot or fit to an appropriate mathematical function the values for peak centroid (in channels) versus gamma energy.

8.2 *Efficiency Calibration:*

8.2.1 Accumulate an energy spectrum using calibrated radioactivity standards at a desired and reproducible source-to-detector distance. Set the ROI for each peak of interest to include at least all channels within the FWTM of the peak. At least 20 000 net counts should be accumulated in each full-energy gamma-ray peak of interest using National or Certified Radioactivity Standard Sources, or both (see 12.1, 12.5, and 12.6).

8.2.2 For each standard source, obtain the net count rate (total count rate of region of interest minus the Compton continuum count rate and, if applicable, the ambient background count rate within the same region) in the full-energy gamma-ray peak, or peaks, using a method that provides consistent results (see 12.2, 12.3, and 12.4).

8.2.3 Correct the standard source emission rate for decay to the date and time of the count in 8.2.2.

8.2.4 Calculate the full-energy peak efficiency, E_f, as follows:

$$E_f = \frac{N_p}{N_\gamma} \tag{1}$$

where:

E_f = full-energy peak efficiency (counts per gamma ray emitted),

N_p = net gamma-ray count in the full-energy peak (counts per second live time) (Note 3) (see 8.2.2), and

N_γ = gamma-ray emission rate (gamma rays per second).

NOTE 3—Any other unit of time is acceptable provided it is used consistently throughout.

8.2.5 There are many ways of calculating the net gamma-ray count. This practice specifies a valid, common technique, applicable when there are no interferences from photo peaks within an energy range at least equal to the FWTM adjacent to the peak of interest.

8.2.5.1 Other net peak area calculation techniques used for single peaks when there is interference from adjacent peaks are not considered in this practice. Other techniques are acceptable, if they are used in a consistent manner and have been verified to provide accurate results.

8.2.5.2 Using a simple model, the net peak area for a single peak can be calculated as follows:

$$N_A = G_s - B - I \quad (2)$$

where:

G_s = gross count in the peak region of interest (ROI) in the sample spectrum,
B = continuum, and
I = number of background counts in the region of interest (if there is no background peak, or if a background subtraction is not performed, $I = 0$).

8.2.5.3 The net gamma-ray count, N_p, is related to the net peak area as follows:

$$N_p = N_A / T_s \quad (3)$$

where:

T_s = spectrum live time.

8.2.5.4 The continuum, B, is calculated from the sample spectrum using the following equation (see Fig. 1):

$$B = \frac{N}{2n}(B_{1s} + B_{2s}) \quad (4)$$

where:

N = number of channels in the peak ROI,
n = number of continuum channels on each side,[5]
B_{1s} = sum of counts in the low-energy continuum region in the sample spectrum, and
B_{2s} = sum of counts in the high-energy continuum region in the sample spectrum.

NOTE 4—These equations assume that the channels that are used to calculate the continuum do not overlap with the peak ROI, and are adjacent to it or have the same size gap between the two regions on both sides. A different equation must be used if the gaps are of a different size.

8.2.5.5 The peak background, I, is calculated from a separate background measurement using the following equation:

$$I = \frac{T_s}{T_b} I_b \quad (5)$$

where:

T_s = live time of the sample spectrum,
T_b = live time of the background spectrum, and
I_b = net background peak area in the background spectrum.

8.2.5.6 If a separate background measurement exists, the net background peak area is calculated from the following equation:

$$I_b = G_b - B_b \quad (6)$$

where:

G_b = sum of gross counts in the background peak region (of the background spectrum), and
B_b = continuum counts in the background peak region (of the background spectrum).

8.2.5.7 The continuum counts in the background spectrum are calculated from the following equation:

$$B_b = \frac{N}{2n}(B_{1b} + B_{2b}) \quad (7)$$

where:

N = number of channels in the background peak ROI,
n = number of continuum channels on each side (assumed to be the same on both sides),
B_{1b} = sum of counts in the low-energy continuum region in the background spectrum, and
B_{2b} = sum of counts in the high-energy continuum region in the background spectrum.

8.2.5.8 If the standard source is calibrated in units of Becquerels, the gamma-ray emission rate is given by:

$$N_\gamma = A P_\gamma \quad (8)$$

where:

A = number of nuclear decays per second, and
P_γ = probability per nuclear decay for the gamma ray (**4**, **5**).

8.2.6 In cases where a calibrated standard source is available for a particular isotope that is also used in an unknown sample, the measured efficiency for that isotope is used directly for the unknown.

8.2.7 Plot, or fit to an appropriate mathematical function, the values for full-energy peak efficiency (determined in 8.2.4) versus gamma-ray energy (see 12.5) (**6-14**).

9. Measurement of Gamma-Ray Emission Rate of the Sample

9.1 Place the sample to be measured at the source-to-detector distance used for efficiency calibration (see 12.6).

9.1.1 Accumulate the gamma-ray spectrum, recording the count duration.

9.1.2 Determine the energy of the gamma rays present by use of the energy calibration obtained under and at the same gain as 8.1.

[5] For simplicity of these calculations, n is assumed to be the same on both sides of the peak. If the continuum is calculated using a different number of channels on the left of the peak than on the right of the peak, different equations must be used.

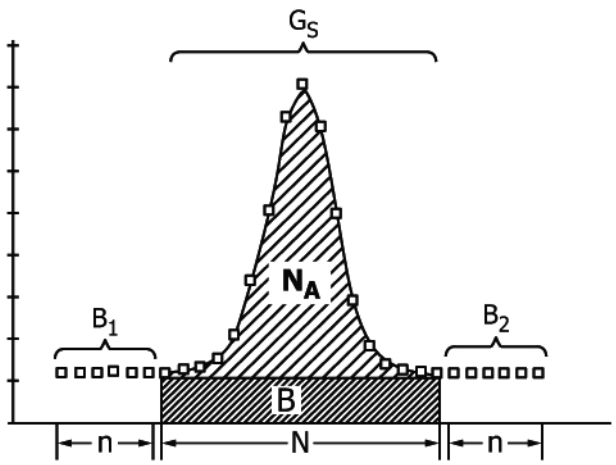

FIG. 1 Typical Spectral Peak with Parameters Used in the Peak Area Determination Indicated

9.1.3 Obtain the net count rate in each full-energy gamma-ray peak of interest as described in 8.2.2 using the same region of interest and continuum regions as were used in the efficiency measurement. In cases where the width of the region of interest varies with energy, use a consistent method for choosing the regions.

9.1.4 Determine the full-energy peak efficiency for each energy of interest from the curve or function obtained in 8.2.5.

9.1.5 Calculate the number of gamma rays emitted per unit live time for each full-energy peak as follows:

$$N_\gamma = \frac{N_p}{E_f} \tag{9}$$

9.1.5.1 When calculating a nuclear transmutation rate from a gamma-ray emission rate determined for a specific radionuclide, a knowledge of the gamma-ray probability per decay is required (**4, 5**), that is,

$$A = \frac{N_\gamma}{P_\gamma} \tag{10}$$

9.1.6 Calculate the net peak area statistical uncertainty as follows:

$$S_{NA} = \sqrt{G_s + \left(\frac{N}{2n}\right)^2 (B_{1s} + B_{2s}) + \left(\frac{T_s}{T_b}\right)^2 (S_{Ib})^2} \tag{11}$$

where:

$$S_{Ib} = \sqrt{G_b + \left(\frac{N}{2n}\right)^2 (B_{1b} + B_{2b})} \tag{12}$$

where:

S_{NA} = net peak area statistical uncertainty (at 1σ confidence level),
G_s = gross counts in the peak ROI of the sample spectrum,
G_b = gross counts in the peak ROI of the background spectrum,
N = number of channels in the peak ROI,
n = number of continuum channels on each side (assumed to be the same on both sides for these equations to be valid),
B_{1s} = continuum counts left of the peak ROI in the sample spectrum,
B_{2s} = continuum counts right of the peak ROI in the sample spectrum,
B_{1b} = continuum counts left of the peak ROI in the background spectrum,
B_{2b} = continuum counts right of the peak ROI in the background spectrum,
T_s = live time of the sample spectrum, and
T_b = live time of the background spectrum.

9.1.6.1 If there is no separate background measurement, or if no background subtract is performed, $S_{Ib} = 0$.

9.1.7 For other sources of uncertainty, see Section 11.

10. Performance Testing

10.1 System tests should be performed on a regularly scheduled basis (or, if infrequently used, preceding the use of the system). The frequency for performing each test will depend on the stability of the particular system as well as on the accuracy and reliability of the required results. Where health or safety is involved, more frequent checking may be appropriate. A range of typical frequencies for noncritical applications is given below for each test.

10.1.1 Check the system energy calibration (typically daily to weekly), using two or more gamma rays whose energies span at least 50 % of the calibration range of interest. Correct the energy calibration, if necessary. Sample counting must be halted or redone if the system energy calibration is found to be inadequate.

10.1.2 Check the system count rate reproducibility (typically weekly to monthly) using at least one long-lived radionuclide. Correct for radioactive decay if significant decay (>1 %) has occurred between checks.

10.1.3 Check the system resolution (typically weekly to monthly) using at least one gamma-ray emitting radionuclide.

10.1.4 Check the efficiency calibration (typically monthly to yearly) using a National or Certified Radioactivity Standard (or Standards) emitting gamma rays with energies spanning the intended range of use.

10.2 Results of all performance checks should be recorded in such a way that deviations from the norm will be readily observable. Appropriate action, which could include confirmation, repair, and recalibration as required, should be taken when the measured values fall outside the predetermined limits.

10.2.1 In addition, the above performance checks (see 10.1) are recommended after an event (such as power failures or repairs) which might lead to potential changes in the system.

11. Sources of Uncertainty

11.1 Other than Poisson distribution uncertainties, the principal sources of uncertainty (and typical magnitudes) in this technique are:

11.1.1 The calibration of the standard source, including uncertainties introduced in using a standard radioactivity solution, or aliquot thereof, to prepare another (working) standard for counting, typically ±1 to 2 % (1S %).

11.1.2 The reproducibility in the determination of net full-energy peak counts, typically ±2 % (1S %).

11.1.3 The reproducibility of the positioning of the source relative to the detector and the source geometry, typically ±1 % (1S %).

11.1.4 The accuracy with which the full-energy peak efficiency at a given energy can be determined from the calibration curve or function, typically ±1.5 % (1S %).

11.1.5 The accuracy of the live-time determinations and pile-up corrections, typically ±1 % (1S %).

12. Precautions and Tests

12.1 *Random Summing and Dead Time:*

12.1.1 *Precaution*—The shape and length of pulses used can cause a reduction in peak areas due to random summing of pulses at rates of over a few hundred per second (**15, 16**). Sample count rates should be low enough to reduce the effect of random summing of gamma rays to a level where it may be neglected, or one should use pile-up rejectors and live-time circuits, or reference pulser techniques of verified accuracy at the required rates (**17-23**).

NOTE 5—Use of percent dead time to indicate whether random summing can be neglected may not be appropriate.

12.1.2 *Test:*

12.1.2.1 Accumulate a ^{60}Co spectrum with a total count rate of less than 1000 counts per second until at least 25 000 counts are collected in the 1.332 MeV and 1.173 MeV full-energy peaks. A mixed isotopic point source may be used. Record the counting live time. The source may be placed at any convenient distance from the detector.

12.1.2.2 Evaluate the activity of ^{60}Co utilizing first the full photon peak area at 1.332 MeV and then the area at 1.173 MeV, including any techniques employed to correct for pile-up and dead time losses.

12.1.2.3 Without moving the ^{60}Co source, introduce a second source, such as ^{57}Co, having no gamma rays emitted with an energy greater than 0.662 MeV. Position the added source so that the highest count rate used for gamma-ray emission rate determinations has been achieved.

12.1.2.4 Erase the first spectrum and accumulate another spectrum for the same length of time as in 12.1.2.1. The same live time may be used, if the use of live time constitutes at least a part of the correction technique.

12.1.2.5 Evaluate the activity of ^{60}Co utilizing first the full photon peak area at 1.332 MeV and then the area at 1.173 MeV, including any techniques employed to correct for pile-up and dead time losses. For the correction technique to be acceptable, the resolution must not have increased beyond the range of the technique and the corrected activity will differ from those in 12.1.2.2 by no more than 2 % 1σ (67 % confidence level).

12.2 *Peak Evaluation:*

12.2.1 *Precaution*—Many techniques (**24-29**) exist for specifying the full-energy peak area and removing the contribution of any continuum under the peak. Within the scope of this standard, various techniques give equivalent results if they are applied consistently to the calibration standards and the sources to be measured, and if they are not sensitive to moderate amounts of underlying continuum. A test of the latter point is a recommended part of this technique.

12.2.2 *Test:*

12.2.2.1 Accumulate a spectrum from a mixed isotopic point source until at least 20 000 net counts are recorded in the peaks of interest lower in energy than 0.662 MeV. The source may be placed at any convenient distance from the detector.

12.2.2.2 Determine the net peak areas of the peaks chosen in 12.2.2.1 with the technique to be tested. Include any calculations employed by the analysis technique to be tested to correct for dead time losses, pile-up, and background contributions.

12.2.2.3 Without moving the mixed isotopic point source, introduce a ^{137}Cs, ^{60}Co, or any other source with no full-energy photons emitted with energies in the range 0.060 MeV to 0.600 MeV so the continuum level of the spectrum in this range is increased 20 times.

12.2.2.4 Erase the first spectrum and accumulate another spectrum for the same live time as in 12.2.2.1, if the use of live time constitutes at least a part of the correction technique.

12.2.2.5 Determine the net peak areas of the same peaks chosen in 12.2.2.1 with the technique to be tested. Include any calculations employed by the analysis technique to be tested to correct for dead time losses, pile-up, and background contributions.

12.2.2.6 Ideally, the deviations of the 12.2.2.5 net peak areas from the 12.2.2.2 values will be no more than 2 % 1σ (67 % confidence level) for the evaluation technique to be acceptable.

12.3 *Correlated Photon Summing Correction:*

12.3.1 Correlated photon summing corrections are not needed when an instrument is calibrated using a standard source of the same radioisotope as the unknown sample.

12.3.2 If an energy-dependent efficiency calibration is performed at a large enough source-detector distance, correlated photon summing corrections may not be needed for sources that produce multiple photons in cascade. In such a case, isotope-specific calibrations can be obtained at closer distances by a ratio method using a check source of each isotope at large and small distance.

12.3.3 When another gamma ray or X-ray is emitted in cascade with the gamma ray being measured, in many cases a multiplicative correlated summing correction, C, must be applied to the net full-energy-peak count rate if the sample-to-detector distance less than 1.5 times the diameter of the detector. The correction factor is expressed as:

$$C = \frac{1}{\Pi_i^n (1 - q_i\, \varepsilon_i)} \tag{13}$$

where:

C = correlated summing correction to be applied to the measured count rate,
n = number of gamma or X-rays in correlation with gamma ray of interest,
i = identification of correlated photon,
q_i = fraction of the gamma ray of interest in correlation with the ith photon, and
ε_i = total detection efficiency of ith correlated photon.

12.3.3.1 Correlated summing correction factors for the primary gamma rays of radionuclides ^{60}Co, ^{88}Y, and ^{46}Sc are approximately 1.09 and 1.03 for a 65 cm^3 detector at 1 cm and at 4 cm sample-to-detector distances, respectively, and approximately 1.01 for a 100 cm^3 detector at a 10 cm sample-to-detector distance. The q_i must be obtained from the nuclear decay scheme, while the ε_i, which are slowly varying functions of the energy, can be measured or calculated (**30-32**).

12.3.4 A similar correction must be applied when a weak gamma ray occurs in a decay scheme as an alternate decay mode to two strong cascade gamma rays with energies that total to that of the weak gamma ray (**33**). The correction is over 5 % for the 0.40 MeV gamma ray of ^{75}Se when a source is counted 10 cm from a 65 cm^3 detector. Other common radionuclides with similar-type decay schemes, however, do not require a correction of this magnitude. For example, ^{47}Ca (1.297 MeV), ^{59}Fe (1.292 MeV), ^{144}Pr (2.186 MeV), ^{187}W (0.686 MeV), and ^{175}Yb (0.396 MeV) require corrections between 0.990 and 0.998 when counted at 4 cm from a 65 cm^3 detector.

12.4 *Correction for Decay During the Counting Period:*

12.4.1 If the value of a full-energy peak counting rate is determined by a measurement that spans a significant fraction of a half-life, and the value is assigned to the beginning of the counting period, a multiplicative correction, F_b, must be applied:

$$F_b = \frac{\lambda t}{1 - e^{-\lambda t}} \quad (14)$$

where:

F_b = decay during count correction (count rate referenced to beginning of counting period),
t = elapsed counting time,
λ = radionuclide decay constant $\left(\frac{\ln 2}{T_{1/2}}\right)$, and
$T_{1/2}$ = radionuclide half-life.

t and $T_{1/2}$ must be in the same units of time (F_b = 1.01 for $t/T_{1/2}$ = 0.03).

12.4.2 If under the same conditions the counting rate is assigned to the midpoint of the counting period, the multiplicative correction F_m will be essentially 1 for $t/T_{1/2}$ = 0.03 and 0.995 for $t/T_{1/2}$ = 0.5. If it need be applied, the correction to be used is:

$$F_m = \frac{\lambda t}{1 - e^{-\lambda t}} e^{-\frac{\lambda t}{2}} \quad (15)$$

12.5 *Efficiency versus Energy Function or Curve*—The expression or curve showing the variation of efficiency with energy (see Fig. 2 for an example) must be determined for a particular detector (**6-14**), and must be checked for changes with time as specified in the standard. If the full energy range covered by this standard is to be used, calibrations should be made at least every 0.1 MeV from 0.06 MeV to 0.30 MeV, about every 0.2 MeV from 0.3 MeV to 1.4 MeV, and at least at one energy between 1.4 MeV and 2 MeV. Radionuclides emitting two or more gamma rays with well-established relative gamma-ray probabilities may be used to better define the form of the calibration curve or function. A calibration with the same radionuclides that are to be measured should be made whenever possible and may provide the only reliable calibration when a radionuclide with cascade gamma rays is measured very close to the detector.

12.6 See mandatory Annex A1 for the fitting method to be used for determination of the energy-dependent function to be used for detector efficiency and for the estimation of the correlation coefficient between efficiencies at pairs of energies.

12.7 *Source Geometry*—A gamma ray undergoing even small-angle scattering is lost from the narrow full-energy peak, making the full-energy peak efficiency sensitive to the source or container thickness and composition. For most accurate results, the source to be measured must duplicate as closely as possible the calibration standards in all aspects (for example, shape, physical and chemical characteristics, etc.). If this is not practicable, appropriate corrections must be determined and applied.

12.7.1 If the source shape and detector distance remain constant, attenuation within the source material is corrected as follows:

$$A_c = A_o \frac{\mu x}{1 - e^{-\mu x}} \quad (16)$$

where:

A_c = corrected number of nuclear decays per second,
A_o = observed number of nuclear decays per second,
μ = cm^2/g = mass attenuation coefficient (**34**), and
x = $g \cdot \frac{1}{cm^3} \cdot cm$ = mass times path length divided by volume.

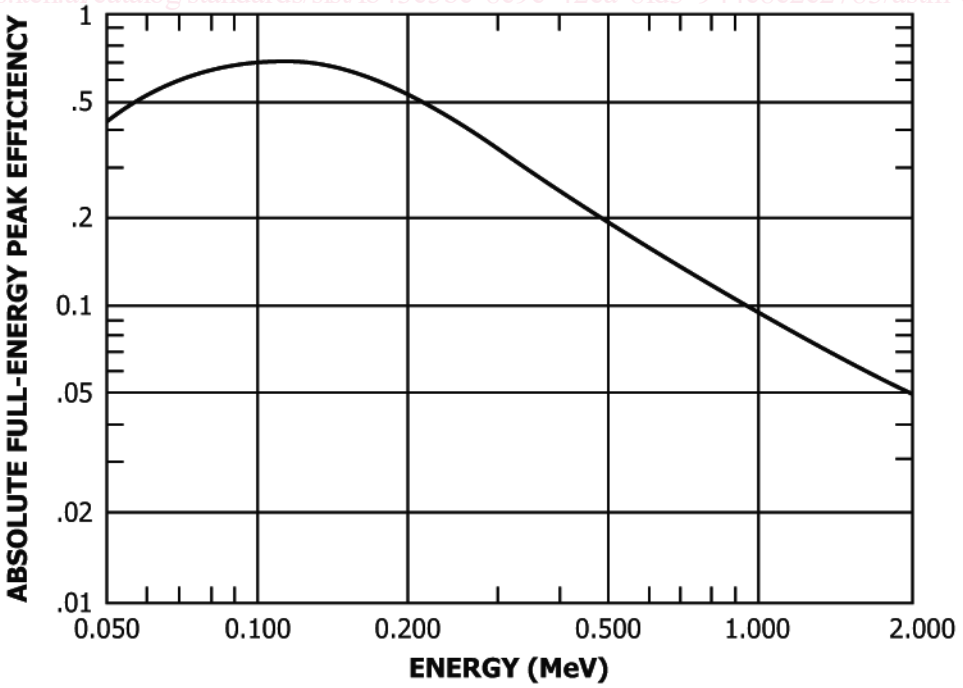

FIG. 2 Typical Efficiency versus Energy for a Germanium Detector

12.7.2 If the source shape, composition, and detector distance remain constant, the attenuation of an interposed absorber are corrected as follows:

$$A_c = A_o \cdot e^{\mu x} \quad (17)$$

13. Precision and Bias

NOTE 6—Measurement uncertainty is described by a precision and bias statement in this standard. Another acceptable approach is to use Type A and Type B uncertainty components (**1, 2**). The Type A/B uncertainty specification is now used in the International Organization for Standardization (ISO) standards and this approach can be expected to play a more prominent role in future uncertainty analyses.

13.1 Tests in individual laboratories have indicated that activities can be determined with a bias of ±3 % (1S %) and with a precision of ±1 % (1S %).

14. Keywords

14.1 calibration of germanium detectors; germanium detectors; radiation metrology; reactor dosimetry; usage of germanium detectors

ANNEX

(Mandatory Information)

A1. FITTING OF ENERGY-DEPENDENT FORMULAE FOR FULL-ENERGY EFFICIENCY OF HPGe DETECTORS

NOTE A1.1—Material in this annex is based on Ref (**35**). General guidance on the linear model for least-squares fitting can be found in Ref (**36**).

A1.1 Overview

A1.1.1 A calibration of the full-energy detection efficiency of gamma spectrometers is performed using multi-element standard sources, or a combination of these together with sources of some isotopes that produce many gamma lines. The sources used do not include all isotopes which the detectors are later used to measure, and therefore the calibration has to include an energy-dependent fitting to obtain the efficiencies at energies other than those in the calibration measurements.

A1.1.2 This fitting process introduces strong correlations between gamma lines of nearby energies.

A1.1.3 Examples are given in this annex of detector calibrations in which the correlations are calculated and propagated through an analysis of measured activities. Methods of calculating the correlations are described in detail, and numerical examples are presented in which strong correlations are present between activities measured for different activation detectors.

NOTE A1.2—Numerical values given in this annex are for illustrative purposes only.

A1.1.4 The effect of uncertainties arising from other causes than source calibration and counting errors is also briefly discussed, so that the results of this work can be placed in context with other errors arising in radiometric dosimetry.

A1.2 Fitting Functions

A1.2.1 Many papers have been published on the topic of efficiency calibration functions for germanium spectrometers. Only a few will be mentioned here.

A1.2.2 McNelles and Campbell (**9**) used a variety of analytical functions, including:

$$\varepsilon = (a_1 / E)^{a_2} + a_3 \exp(-a_4 E) + a_5 \exp(-a_6 E) + a_7 \exp(-a_8 E) \quad (A1.1)$$

A1.2.3 Debertin (**37**) introduced the following class of functions:

$$\varepsilon = a_1 \ln(E) + a_2 \ln(E)/E + a_3 (\ln(E))^2/E + a_4 (\ln(E))^4/E + a_5 (\ln(E))^5/E \quad (A1.2)$$

A1.2.4 Gray and Ahmad (**38**) also selected a linear class of fitting function, defined by:

$$\varepsilon = (a_1 + a_2 \ln(E) + a_3 (\ln(E))^2 + a_4 (\ln(E))^3 + a_5 (\ln(E))^5 + a_6 (\ln(E))^7)/E \quad (A1.3)$$

A1.2.5 Another class of linear fitting functions has been used to fit the logarithm of the measured efficiencies:

$$\ln(\varepsilon) = \sum_i^I a_i \left(\ln\left(\frac{E_c}{E} \right) \right)^{i-1} \quad (A1.4)$$

where E_c is an arbitrary energy chosen near the middle of the energy range (to simplify the problem numerically).

A1.2.5.1 The number of parameters, I, was chosen by Lin et al. (**39**) to be six, for the energy range 300 keV to 9700 keV. Kis et al. (**40**) used up to nine parameters for the range 50 keV to 11 000 keV. Such a large number is not needed for a narrower energy range and may be impractical when the number of measured efficiencies is limited. The number of parameters must always be fewer (ideally many fewer) than the number of measurements. The purpose of fitting a continuous function to the data is so that efficiencies at energies in between those included in the calibration can be determined. Functions that do not sufficiently constrain the values in between the fitted points are useless for this purpose. Eq A1.4, with I chosen as 6, is used in this practice.

A1.3 Least-Squares Model for Linear Fitting Formulae

A1.3.1 Let A represent a column vector of the parameters a_i, for i = 1, I. Then the efficiencies measured for each photon energy of the calibration source can be represented, using Eq A1.4, by:

$$\ln(\varepsilon) = S.A + \delta \quad (A1.5)$$

where $\ln(\varepsilon)$ is a column vector of the measured log values for the efficiencies, S is the design matrix for the model, and δ is