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American National Standard for Calibration of Germanium Detectors for In-Situ Gamma-Ray Measurements

Accredited by the American National Standards Institute

Sponsored by the
National Committee on Radiation Instrumentation, N42

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American National Standard for Calibration of Germanium Detectors for In-Situ Gamma-Ray Measurements

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National Committee on Radiation Instrumentation, N42

Accredited by the

American National Standards Institute

Secretariat

The Institute of Electrical and Electronics Engineers, Inc.

Approved 6 September 2002

American National Standards Institute

Abstract: The need for accurately measuring radioactivity in-situ for a variety of detector characterization techniques requires that performance criteria for efficiency calibration be developed, and such a calibration technique is described in this standard.
Keywords: calibration, gamma-ray, germanium detectors, in-situ

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Introduction

(This introduction is not part of ANSI N42.28-2002, American National Standard for Calibration of Germanium Detectors for In-Situ Gamma-Ray Measurements.)

This standard is the responsibility of the Accredited American Standards Committee on Radiation Instrumentation, N42. Committee N42 delegated the development of this standard to Subcommittee N42.RM. Drafts were reviewed by Committee N42, Subcommittee N42.RM, and other interested parties; and the comments were utilized in producing the standard as finally approved. This standard was approved on N42 letter ballot of 25 September 2002.

Participants

At the time Committee N42 approved this standard, it had the following members:

Louis Costrell, *Chair*
Michael P. Unterweger, *Vice Chair*
Sue Vogel, *Administrative Secretary*

Organization Represented	*Name of Representative*
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At the time this standard was approved, Subcommittee N42.RM had the following members:

Frank X. Masse, *Chair*
J. M. R. Hutchinson, *Secretary*

Robert Ayres	Michael Devine	David McCurdy
Joseph G. Bellian	Roger Ferris	D. M. Montgomery
John D. Buchanan	Robert J. Gehrke	Carl W. Seidel
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Bert M. Coursey	Markku Koskelo	Michael P. Unterweger
	J. L. Lazewatsky	

The balloting committee that approved this standard consisted of all persons listed herein as members of Accredited Standards Committee on Radiation Instrumentation, N42.

At the time this standard was approved, the Working Group had the following members:

P. Shebell, *Co-Chair and Co-Project Leader*
R. J. Gehrke , *Co-Chair and Co-Project Leader*

Frasier Bronson	David Keefer	Ronald Reiman
Scott Faller		Michael P. Unterweger

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American National Standard for Calibration of Germanium Detectors for In-Situ Gamma-Ray Measurements

1. Overview

In-situ gamma-ray spectrometry using portable high-purity germanium (HPGe) detectors, collimated or uncollimated, is a technique for measuring the gamma-ray fluence rate from a gamma-emitting source for the purpose of obtaining or estimating a specific activity or activity concentration. The most common and well-established application of in-situ spectrometry has been the measurements of gamma-emitting radionuclides in surface soils. Recently, the technique is being applied to large extended objects such as walls, pipes, and containers of radioactive material. The impracticality of constructing standards for these geometries precludes the use of traditional approaches to detector calibration. Therefore, those wishing to use the technique have developed alternative approaches that use a combination of measurements and calculations. The growing need for quality assurance for in-situ measurements of radioactivity, along with the variety of calibration techniques, requires that performance tests be developed for assessing the calibration of HPGe detectors for the sources currently being measured.

1.1 Scope and purpose

The purpose of this standard is to specify performance tests for the calibrations of in-situ gamma-ray measurement systems for a range of test configurations. This standard applies to service providers and their customers performing or requiring radioassay of sources using in-situ gamma-ray spectrometry with HPGe detectors (hereafter referred to as “detectors”). It is generally assumed, but not required, that the sources are large (with respect to the detector). It is also assumed that the calibration is performed without the benefit of certified reference materials that are identical, in terms of the radionuclide mix and geometry, to the objects being measured. This standard applies to the calibration of detectors, uncollimated or collimated, for the measurement of the following objects:

— Uniformly contaminated surface soils
— Surficial contamination of flat objects
— Volumetric contamination of cylindrical and rectangular objects
— Containerized homogeneous sources (cylindrical and rectangular containers)
— Attenuated sources

The energy of the gamma-rays addressed in this standard is 60 keV to 3000 keV.

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This standard does not treat the specialized cases of aerial gamma-ray spectrometry, in-situ spectrometry in boreholes. Moreover, this standard does not address in-situ gamma-ray spectrometry measurements for detectors operated in a gross counting mode. Discussions of procedures as they pertain to peak-finding algorithms, peak-position, peak-area measurements, and energy calibration, as well as discussions of performance tests of spectrometry systems and analysis software are beyond the scope of this standard; refer to ANSI N42.14-1999 and IEC 61275-1997-09 for such methods.

CAUTION—While guidance on the application of in-situ gamma-ray spectrometry and the use of in-situ measurement data is beyond the scope of this standard, some general remarks concerning the technique are warranted. As with any measurement technique, one must be aware of assumptions that give rise to limitations on the range of potential applications. In-situ measurements carry specific assumption regarding many measurement parameters. The most notable parameter is the distribution of activity in the source. A detector measures only the gamma-ray fluence from which one can infer an activity concentration. The extent to which the measurement assumptions reflect the actual or true measurement conditions is the extent to which the measurements results will satisfy their intended purpose. For example, a detector that is calibrated to measure sources with uniformly distributed activity will produce inconsistent and misleading results if the source is highly heterogeneous. However, there could be an acceptable degree of heterogeneity that would still allow for useful data. Service providers and their customers should consider using data quality objectives as a guide or a means to evaluate a measurement program that uses or intends to use this technique.

2. References

This standard shall be used in conjunction with the following publications. When the following specifications are superseded by an approved revision, the revision shall apply.

ANSI/ASQC E4-1994, American National Standard Specifications and Guidelines for Quality Systems for Environmental Data Collection and Environmental Technology Programs.[1]

ANSI N42.23-1996, American National Standard Measurement and Associated Instrumentation Quality Assurance for Radioassay Laboratories.

ANSI N42.14-1999, American National Standard for Calibration and Use of Germanium Spectrometers for the Measurement of Gamma-Ray Emission Rates of Radionuclides.

HPS N13.30-1996, Performance Criteria for Radiobioassay.[2]

IEC 61275-1997-09, Radiation protection instrumentation—Measurement of discrete radionuclides in the environment—In-situ photon spectrometry system using a germanium detector.[3]

3. Definitions

The word “shall” denotes a requirement, the word “should” denotes a recommendation, and the word “may” denotes permission. To conform to this standard, in-situ gamma-ray spectrometry measurements (hereafter referred to as in-situ measurements) shall be evaluated according to the requirements of this standard, but not necessarily with its recommendations; however, justification should be documented for deviations from a recommendation.

[1]ANSI publications are available from the Sales Department, American National Standards Institute, 25 West 43rd Street, 4th Floor, New York, NY 10036, USA (http://www.ansi.org/).

[2]HPS standards are available from HPS, 1313 Dolley Madison Blvd., Suite 402, MacLean, VA 22101, USA, Fax 703-790-2672 (http://hps.org/documents/).

[3]IEC publications are available from the Sales Department of the International Electrotechnical Commission, Case Postale 131, 3, rue de Varembé, CH-1211, Genève 20, Switzerland/Suisse (http://www.iec.ch/). IEC publications are also available in the United States from the Sales Department, American National Standards Institute, 25 West 43rd Street, 4th Floor, New York, NY 10036, USA.

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For the purposes of this standard, the following terms and definitions apply:

3.1 absorber: Any material that absorbs or diminishes the gamma-ray fluence from the source.

3.2 activity concentration: The expected number of spontaneous nuclear decays (transformations) per gram, per surface or volume of material in a unit time from a specified energy state (excluding prompt decays from a lower nuclear level) for a given amount of a radionuclide. Its standard unit (SI) is the becquerel (Bq) per mass, volume or surface area, where one Bq equals one decay per second. Activity concentration has often been expressed in curies (Ci), where 3.7×10^{10} Bq equals 1 Ci, exactly.

NOTE—The activity concentration is generally abbreviated to concentration and is sometimes called the *specific activity*.

3.3 attenuated source: A source is attenuated when at least 25% of the gamma rays emitted from the source and in the direction of the detector arrive at the detector having undergone some energy reduction as a result of interactions with absorbers between the source and the detector's encap.

NOTE—The absorbers are generally part of the source, such as a container.

3.4 calibration: The determination of a value that converts a measured number into a desired physical quantity (e.g., pulse height into photon energy, or counts per second into an activity concentration).

NOTE—The calibration refers to a process, procedure, and/or methodology by which one determines an efficiency value.

3.5 coefficient of variation (CV): The standard deviation divided by the average value.

3.6 collimated: Refers to the use of absorbers with transmission holes between the source and the detector to reduce or restrict the detector's field of view.

3.7 combined standard uncertainty (u_c): The uncertainty resulting from combining category A and category B uncertainties, as defined by the Bureau International des Poids et Measures (BIPM), using standard statistical methods. Category A uncertainties are evaluated by applying statistical methods to a series of repeated measurements and are characterized by the estimated standard deviation, σ_A; category B uncertainties are assigned to quantities whose variation is not explicitly observed. Category B uncertainties are determined by estimating from other information an approximation to a corresponding "standard deviation," σ_B, whose existence is assumed. They are combined as if they are all standard deviations.

3.8 containerized source: A radioactive source that is encased or sealed in a specific, regularly shaped container.

3.9 conventional true value: The value attributed to a particular quantity and accepted, sometimes by convention, as having an uncertainty appropriate for a given purpose. *Syn:* **reference value.**

3.10 counting rate: The rate at which detector pulses are being registered in a selected voltage interval. The units are s^{-1}.

3.11 customer: The recipient and user of the in-situ measurement data.

3.12 efficiency: The ratio between the detector response, e.g., the number of selected pulses recorded per unit time to the number of gamma rays emitted by the source per unit time.

NOTE—The efficiency as it is defined above corresponds to what usually is referred to as the *absolute efficiency.*

3.13 field conditions: Environmental and operating conditions under which an in-situ measurement is performed.

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3.14 field of view (FOV): The portion of the source that is bounded by the solid angle subtended by the detector (with respect to the source) in which 90% of photons that are recorded in the full energy photopeak or photopeaks of the spectrum for the energy or energies of interest.

NOTE—The FOV varies with gamma-ray energy, source thickness, composition and density of the source, external attenuation, as well as properties of the detector. The FOV can be expressed in terms of the solid angle or in terms of the linear dimensions of the source.

3.15 full-energy peak: A peak in the spectrum resulting from the complete (total) absorption of gamma rays of a given energy in the active volume of the detector and the collection of all of the resulting charge. *Syn:* **photopeak.**

3.16 high energy: High energy refers to a range of gamma-ray energies. If E is the gamma-ray energy, then a photon is high energy if $100 < E \leq 3000$ keV.

3.17 infinite half-space: A source that subtends a solid angle of 2π steradians and has an infinite thickness.

3.18 in-situ measurement: A measurement that is performed on a source or object in its natural or native condition.

3.19 large source: A source that subtends a solid angle greater than $\pi/2$ but less than 2π steradians.

3.20 linear attenuation coefficient (μ): The linear attenuation coefficient of a material for uncharged ionizing particles is given by the relation

$$\mu = \frac{1}{N}\frac{dN}{dl}$$

where dN/N is the fraction of particles that experience an interaction while traversing a distance dl in a material. The units are cm^{-1}.

3.21 low energy: Refers to a range of gamma-ray energies. If E is the gamma-ray energy, then a photon is low energy if $60 < E \leq 100$ keV.

3.22 mass attenuation coefficient (μ/ρ): The mass attenuation coefficient is the linear attenuation per unit density. The units are $cm^2\ g^{-1}$.

3.23 mass thickness: The mass thickness is mass per unit area (density × thickness). The units are cm^{-2} g.

3.24 mean free path (MFP): The average length a photon will travel before having an interaction. It can be estimated by the reciprocal of the linear attenuation coefficient. The units are cm.

$$MFP \cong 1/\mu$$

3.25 measurements assurance program (MAP): A program that allows manufacturers to verify the accuracy of their measurements through exchange of samples with the National Institute of Standards and Technology (NIST). This involves the analysis of blind samples sent to suppliers by NIST, and NIST measurement of sources certified and provided by the supplier.

3.26 NIST: National Institute of Standards and Technology (formerly U.S. National Bureau of Standards, NBS).

3.27 NSLR: A country's national standardizing laboratory for radioactivity measurements.

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3.28 point source: A source material confined to a volume whose dimensions are small compared with the distance between the source and detector and small compared to the mean free path of the material for its own radiation.

3.29 relative bias (B): The difference between the measurement value and the reference value divided by the reference value.

3.30 relative standard uncertainty [$u_{c,r}(y)$]: The relative standard uncertainty of the measurement result y is the combined standard uncertainty $u_c(y)$ divided by $|y|$.

$$u_{c,r}(y) \equiv \frac{u_c(y)}{|y|} \qquad |y| \neq 0$$

3.31 service provider: The provider of in-situ measurements data.

3.32 small source: A source that subtends a solid angle less than $\pi/2$ steradians.

3.33 soil moisture: The water content in soil expressed as a percentage of mass per unit volume.

3.34 solid angle (Ω): The angular spread at the vertex of a cone measured by the area intercepted by the cone on a unit sphere whose center is at the vertex of the cone. The units are steradians.

3.35 source: An object, typically in solid, that emits gamma rays.

3.36 standard uncertainty (u): A component of the uncertainty that contributes to the uncertainty of a measurement result by an estimated standard deviation. It is equal to the positive square root of the estimated variance.

3.37 standoff distance (d): The distance along the detector's azimuthal axis from the face of the window of the detector housing to the point at which the axis of the detector intersects the plane of the source or its container.

3.38 source thickness (t): The distance between the two boundary surfaces of the source that are aligned along the axis of the detector.

3.39 test conditions: Environmental and operating conditions under which a performance test is executed.

3.40 test value: A value corresponding to a given test configuration that shall be used to demonstrate compliance with this standard.

3.41 thick source: A source is thick if the source thickness is greater than or equal to 1.5 times the mean free path of the gamma ray.

3.42 thin source: A source is thin if the source thickness is less than 1.5 times the mean free path of the gamma ray.

3.43 weighted average ($\bar{y}$): The sum of the products of each value and its weight, divided by the sum of the weights. The weights used in this standard are the measurement uncertainties, σ.

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NOTE—If a series of n measurements are performed measuring values y_i and uncertainties σ_i, then the weighted average is given by

$$\bar{y} = \frac{\sum_{i=1}^{n} (\sigma_i^{-2} y_i)}{\sum_{i=1}^{n} \sigma_i^{-2}}$$

4. General requirements

4.1 Documents and records supplied by the service provider

The service provider shall provide data in the form of documents and records that demonstrate their ability to accurately calibrate a detector for the full range of source-detector geometries set forth in this standard, or to an appropriate subset of geometries that has been agreed to by the customer. The data may apply to a specific detector or to the calibration, in which case the data may apply to a range or class of detectors. In this case, the service provider shall include documentation that demonstrates the calibration to be detector independent; that is, the documentation shall show that those features and/or properties of the range or class of detectors that affect its efficiency for the measurement conditions have been adequately measured and/or modeled.

NOTES

1—A range or class of detectors refers to a collection of detectors that have similar physical properties and are constructed with similar materials. For example, a service provider may have several detectors from a single manufacturer that differ only with respect to the shape and size of the germanium crystal. Such a collection would constitute a range or class of detectors.

2—The features and/or properties of the detector that affect its efficiency include, but are not limited to, its active volume, the shape of the crystal, and materials surrounding the active volume. A service provider wishing to demonstrate that the calibration is detector-independent would have to show that differences or variations in the active volume, crystal shape, and materials surrounding the active volume have been addressed in the calibration.

4.2 Reporting of uncertainty

The service provider shall provide the uncertainty associated with an in-situ measurement. When reporting uncertainty, the service provider shall follow the approach given in Section 7 of NIST Technical Note 1297 [B20]. Specific recommendations on the evaluation of the standard uncertainty and the combined standard uncertainty of an in-situ measurement are given in Clause 8 of this standard, ANSI N42.28-2002.

4.3 Detection limits

The service provider shall furnish estimates of the detection limit for the radionuclides of interest for the techniques used in the measurement. The service provider shall follow the recommendations and practices regarding the use and reporting of detection limits found in A.7 of ANSI N42.23-1996.[4]

[4]Information on references can be found in Clause 2.

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4.4 Quality assurance

The service provider shall have a quality assurance process associated with in-situ measurements. This quality assurance process should be part of an overall quality assurance program. The program should be in compliance with national consensus standards that provide guidance on quality assurance practices such as ANSI N42.23-1996, ANSI/ASQC E4-1994, and ASME NQA-1-1994 [B5].[5] At a minimum, the quality assurance program should address the quality of the following elements:

— Procedures and instruction
— Document control
— Records
— Personnel qualifications
— Quality control of instruments

For guidance on good practices for performing in-situ measurements, as well as calibration methods, this standard recommends ICRU Report 53 [B9].

RECOMMENDATION—An intercomparison between service providers is instrumental for evaluating undetected biases. This standard recommends that, whenever possible, the service provider participate in intercomparison programs for in-situ spectrometric measurements. A description and the results of a previous intercomparison may be found in Miller et al. [B14].

5. General test procedures

5.1 General

The performance tests developed in this standard, ANSI N42.28-2002, are designed to demonstrate the ability of the service provider to calibrate a detector with the accuracy and precision required by this standard for a range of source-detector geometries. The performance shall apply to a specific detector or to the calibration process. In the latter case, the performance can be applied to a range or class of detectors if it can be shown and documented that those features and/or properties of the range or class of detectors that affect its efficiency for the measurement conditions have been adequately measured and/or modeled.

5.2 Test conditions

The test conditions should reasonably simulate the in-situ conditions. If it can be shown that environmental conditions such as temperature, relative humidity, wind, and atmospheric pressure do not influence the result of an in-situ measurement, then they do not need to be simulated in the test.

5.3 Test procedure

The test procedure shall be performed in a manner consistent with the procedures for in-situ measurements. As set forth in 4.4 of this standard, the procedures shall be part of a quality assurance program. It is recommended that any ancillary equipment used in the in-situ measurement that might affect the efficiency, such as analyzer, cables, detector support mechanism, and computer software, also be used in the test.

[5]The numbers in brackets correspond to those of the bibliography in Annex F.

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5.4 Sources

When sources are used for calibration or for performance testing, the sources shall be of either Type 1 or Type 2. The activity of a Type 1 calibration source shall have a traceability to NIST (or to the NSLR in the country in which the source is used). Type 2 calibration sources shall be prepared from radioactive solutions traceable to NIST or purchased from a supplier who has an active Measurements Assurance Program (MAP) with NIST. These sources shall cover the range of geometries and energies for tests specified in 7.3. Where no NIST traceable standard is available, Annex A provides test methods using NIST traceable point sources that will allow the service provider to achieve compliance with this standard. Annex D provides information on characterized sources that have the configurations listed in Table 2.

6. Test configurations, test ranges, and test values

The following geometries are typical of the sources encountered when making in-situ measurements. The test configurations developed in this standard reflect these geometries.

— Short, small diameter cylindrical sources
— Long, small diameter cylindrical sources
— Small area circular or rectangular planar sources
— Large area circular or rectangular planar sources
— Small cylindrical or rectangular volume sources
— Large cylindrical or rectangular volume sources

The test ranges cover two source sizes, two source thicknesses, two energy ranges, source attenuation, and detector collimation. For purposes of testing to establish compliance with this standard, the test values listed in Table 1 shall be met or exceeded.

Table 1—Test values for the test configurations

Test configuration	Test values
Source attenuation	> 63% of the photons have undergone energy reduction
Source size	**Large:** source occupies > 80% of the detector's FOV **Small:** source occupies < 20% of the detector's FOV
Source thickness	**Thick:** > five times the MFP for the gamma-ray energy tested **Thin:** < 1 MFP for the gamma-ray energy measured
Collimation	> factor of five reduction in the signal (e.g., counts or count rate)

NOTES

1—No specific test values for energies are provided, but the test values shall be consistent with the definitions given in Clause 3.

2—The test values for the source sizes are defined in terms of the FOV, which is subsequently defined in terms of the solid angle the source subtends with respect to the detector. For more information on calculating and approximating solid angles, see Annex E.

3—The source thickness reflects the degree of source self-attenuation and is defined in terms of its MFP. The MPF can be approximated in terms of the linear attenuation coefficient (see Clause 3). For a discussion of the linear attenuation coefficient and related quantities, as well as a table for mass attenuation coefficients for the elements and some selected materials, refer to NISTIR 5632 [B8].

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6.1 Partial compliance and limitations on test results

If the service provider is performing a limited range of measurements for a specific application, then at least those configurations that are appropriate for the application in question shall be performance tested. In this case, the service provider will be in, and shall only claim, partial compliance with this standard, assuming that the service provider meets the criteria set forth in Clause 7.

The results of the performance tests are valid indefinitely, unless the measurement conditions, instrument parameters, or aspects of the calibration are modified to the extent that the efficiency is or could be affected.

7. Characterizing the performance

7.1 Performance specification

The performance for a given test shall be passed if the relative bias of the measured value summed with the relative standard uncertainty for the reference value (y_t) and the relative standard uncertainty for the measured value (y_m), is less than or equal to the tolerance level, L, for the test configuration. That is, if

$$|B| + u_{c,r}(y_t) + u_{c,r}(y_m) \leq L \quad (1)$$

The measured value can be the activity, activity concentration, emission rate density, or efficiency.

The relative bias, B, is given by

$$B = (y_m - y_t)/y_t$$

and the relative combined uncertainty $u_{c,r}(y_t)$ of the source is

$$u_{c,r}(y_t) = u_c(y_t)/y_t$$

Similarly, the relative combined uncertainty $u_{c,r}(y_m)$ of the measurement is given by

$$u_{c,r}(y_m) = u_c(y_m)/y_m$$

The relative bias is an indication of the degree to which the calibration will produce detector efficiencies that yield accurate results. The relative standard uncertainty of the reference value is a measure of the precision of the source. Similarly, the relative standard uncertainty of the measured value is an indication of the precision of the measurement value. See Clause 8 for guidance on the evaluation of the combined standard uncertainty associated with the measurement. Table 2 lists the tolerance levels, L, for test configurations.

CAUTION—When computing the relative combined uncertainty of the reference value, attention must be paid to the confidence level of the quoted uncertainty of the reference value. The combined uncertainty assumes a confidence level of approximately 68%. However, some manufacturers or fabricators of certified sources report an expanded uncertainty in which the confidence level is 95% or 99%. For example, Annex D lists sources that may be used to demonstrate compliance; however, the quoted uncertainties are at the 95% confidence level. If compliance is not achieved at the 95% confidence level, it is possible that by adjusting the uncertainty to reflect the 68% confidence level (essentially by dividing the quoted uncertainty by 2), compliance may be achieved.

NOTE—When calculating the activity, activity concentration, emission rate density, or efficiency for radionuclides that emit several gamma rays within an energy range (high or low), the best estimate of the measured value should be calculated using a weighted average, where the weights are the measurement uncertainties (see Clause 3). The relative uncertainty associated with any one gamma-ray energy shall not exceed 0.50.

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RECOMMENDATION—In the event that the reference value is determined by discrete sampling of a large source (see Annex B), then the relative combined uncertainty of the source, $u_{c,r}$, should be replaced by the coefficient of variation, *CV*, in which case Equation (1) becomes

$$|B| + CV + u_{c,r}(y_m) \leq L \quad (1a)$$

where *CV* is given by

$$CV = \sigma(y_t)/y_t$$

The standard deviation, $\sigma(y_t)$, reflects the variation in the results of the sampling data. The reference value is the arithmetic average of the sampling data. The *CV* in this case reflects the degree of variability in the activity concentration of the source.

7.2 Performance analysis

Equation (1) [or Equation (1a)] is used to determine the service provider's performance for a given test configuration. Full compliance with this standard is demonstrated for a detector or class of detectors when a service provider meets the performance specification of 7.1 for all tests listed in Table 2 and meets the other requirements identified in Clause 4 and Clause 5. Partial compliance with this standard is demonstrated for a detector or class of detectors when a service provider meets a the performance specification of 7.1 for a subset of test configuration listed in Table 2 and meets the other requirements identified in Clause 4 and Clause 5 (see 7.1).

7.3 Performance criteria

Table 2 lists performance criteria for the specified test configurations.

Table 2—Performance criteria for the specified test configurations

Tests	Test configurations					Performance criteria
	Attenuation	Size	Thickness	Energy	Collimation	Tolerance level (L)
1a	none	small	thin	low	none	0.35
1b	none	small	thin	high	none	0.25
2a	attenuated	small	thin	low	none	0.35
2b	attenuated	small	thin	high	none	0.25
3a	none	small	thick	low	none	0.35
3b	none	small	thick	high	none	0.25
4a	none	small	thin	low	yes	0.45
4b	none	small	thin	high	yes	0.35
5a	attenuated	small	thin	low	yes	0.45
5b	attenuated	small	thin	high	yes	0.35
6a	none	large	thin	low	none	0.35
6b	none	large	thin	high	none	0.25

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Table 2—Performance criteria for the specified test configurations *(continued)*

Tests	Test configurations					Performance criteria
	Attenuation	Size	Thickness	Energy	Collimation	Tolerance level (L)
7a	attenuated	large	thin	low	none	0.35
7b	attenuated	large	thin	high	none	0.25
8a	none	large	thick	low	none	0.35
8b	none	large	thick	high	none	0.25
9a	none	large	thin	low	yes	0.45
9b	none	large	thin	high	yes	0.35
10a	attenuated	large	thin	low	yes	0.45
10b	attenuated	large	thin	high	yes	0.35

8. Uncertainties and uncertainty propagation

The uncertainty shall be expressed and evaluated following the approach recommended by the International Committee for Weights and Measures (CIPM) and given in the *Guide to the Expression of Uncertainty in Measurements* [B10]. This approach has been adopted by NIST and is summarized in Taylor and Kuyatt [B20]. Basic to CIPM approach is the Type A and Type B evaluation of standard uncertainty, as well as a method for determining combined standard uncertainty. As stated in 4.2, every measurement shall be accompanied by a combined standard uncertainty.

The principle components of combined standard uncertainty for in-situ gamma-ray measurements, not covered in Clause 9 of ANSI N42.14-1999, are associated with differences between the parameters in the calibration standard or calibration model and the actual item to be measured. These parameters typically include but are not limited to

— The distribution of activity
— The mass attenuation coefficients
— The mass thickness associated with the source and external absorbers
— The composition of the source or external absorbers

The standard uncertainties for these parameters require a Type B evaluation. A general discussion of a Type B evaluation of the standard uncertainty may be found in Section 4 of Taylor and Kuyatt [B20]. A Type B evaluation for these parameters involves the use of the following approaches:

a) Evaluation of limiting cases or conditions and their impact on the efficiency or activity. This can be performed experimentally or theoretically. Limiting conditions typically cover the 99% confidence interval.

b) Previous measurement data or concurrent measurement data from other methods.

c) Experience with, or general knowledge of the source distribution and the source matrix.

d) Information from reports and journal articles.

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e) Uncertainties assigned to reference data, such as mass attenuation and density data, taken from handbooks or summarized in tables.

8.1 Evaluation of the standard uncertainty of the source distribution

The uncertainty associated with the distribution of radioactivity within the source is often the most difficult to estimate and often has the greatest impact on the accuracy of the measurement. The estimate of the uncertainty associated with the source distribution shall be from reasonable variations in sample or container. It is not recommended that “worst case” estimates be provided unless specifically required by the customer. As mentioned in the previous section, the service provider shall, when possible, use previous measurement data that can provide information about the distribution and its variation. For example, if the service provider is using in-situ spectrometry to characterize and quantify the extent of contamination associated with the processing of radioactive materials at a particular site, the service provider shall obtain historical site data to evaluate the uncertainty.

8.2 Evaluation of the standard uncertainty in the source matrix and attenuating layers

Uncertainty in the source matrix and attenuating layer arises from an uncertainty in the mass-attenuation coefficient and mass thickness. The uncertainty in the mass-attenuation coefficient reflects an uncertainty in the exact elemental composition in the source matrix, should it differ from the calibration source and calibration model. For higher-energy gamma rays (> 250 keV) the uncertainties associated with mass-attenuation coefficient are small, typically less than 10% (Sowa et al. [B19]). For low energy gamma rays the mass-attenuation coefficient becomes very sensitive to the elemental composition of the source matrix and the corresponding uncertainties can be substantial. In some extreme cases the difference can be an order of magnitude.

The uncertainty in the mass thickness is a function of the uncertainty in the density of the source matrix and the path length of the gamma ray through the source matrix and any external absorbers. Variations in source density caused by fluctuations in temperature are usually insignificant and do not need to be evaluated. Air between the source and the detector is an absorber and should be treated. Variations in air attenuation caused by variations in temperature, density, air pressure, and water content may be significant, especially for combinations of far distances and low energies and high humidity.

For containerized sources where the contents are not known precisely, the service provider must use the methods discussed previously to evaluate the uncertainty.

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Annex A

(normative)

Test methods using point sources

Before simulating the count rate from a line or disk source with points sources, collect a background spectrum. Analyze the spectrum in the same manner as will be done for the performance tests and for any future measurements. If there are any peaks in the background spectrum at the same energies as emitted from the sources to be used in the performance tests, measure the respective background net area count rates in the normal manner (see ANSI N42.14-1999). Store the background net area count rates for subtraction from the respective net peak areas to be determined from the performance test spectra acquired below (especially important for tests in A.2, A.3, and A.4).

A.1 Symmetry over detector polar and azimuthal angles

When simulating line and disk sources with point sources, the detector response over the polar angles, θ, and azimuthal angle, ϕ, (see Figure A.1) should be constant for detectors that have a cylindrical shape. This is especially the case if the polar orientation of the detector is not maintained (e.g., by markings on the detector) during the detector calibration and performance tests.

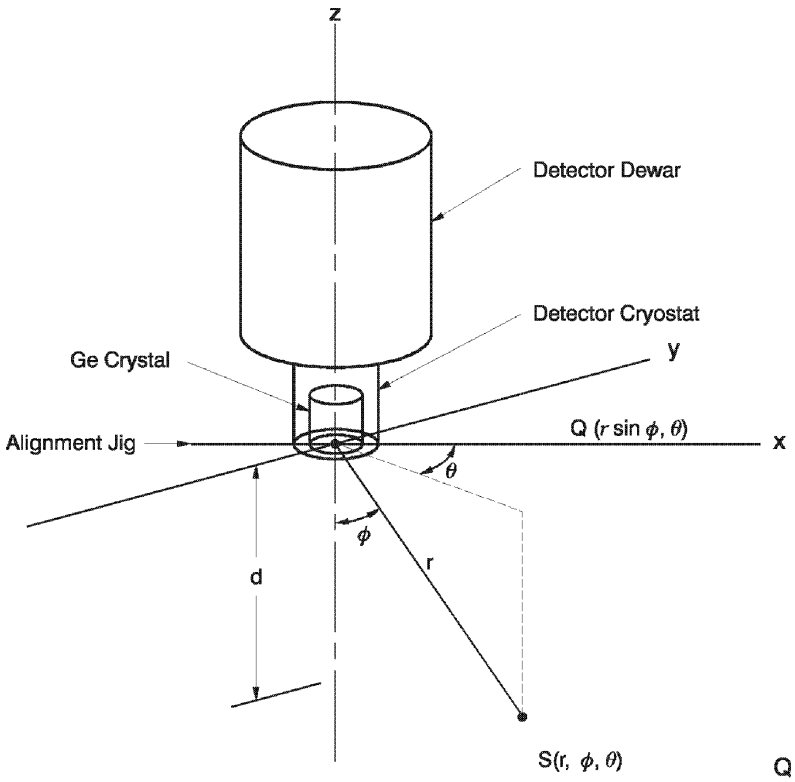


Figure A.1—Drawing of an experimental arrangement

RECOMMENDATION—It is recommended that prior to their calibration or use for in-situ determinations, Ge detectors in compliance with IEC 61275-1997-09 should be measured in accordance with A.1. Any misalignment from polar symmetry shall be corrected either by identifying the true axis of symmetry or by mathematical adjustment.

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The following measurements are designed to detect the presence of any misalignment from polar or azimuthal symmetry. These tests are designed so they can be performed with one radioactive source.

Figure A.1 shows a drawing of an experimental arrangement in which the azimuthal angle φ is defined from the negative *z* axis circling in the clockwise direction rather than from the positive *z* axis in the clockwise direction. The polar angle θ is defined as the angle formed between the positive *x* axis to the projection of the radius in the clockwise direction onto the xy plane. The point S lies on the surface of the ground, with *r* the distance from the center of the exterior surface of the detector housing to the point S.

Although any source may be used, the measurements described in this annex refer to an Eu-152 point source, which can provide a range of gamma-ray energies (122, 244, 344, and 1408 keV). For low energy gamma rays, Am-241 (59.5 keV) is recommended. The use of Y-88 and Th-228 with Eu-152 is recommended when energies above 1200 keV are to be analyzed. The resulting peak count rate obtained by measuring the source or sources should be at least a factor of ten times the background for all gamma-ray peaks to be analyzed. [A point source is one whose source diameter is ≤ 0.5 cm and its covering does not cause any appreciable (i.e., < 1%) absorption of the emitted gamma rays for the energies of interest (e.g., above 60 keV) or a correction for absorption in the source is applied.]

CAUTION—Since Am-241 and Eu-155, a common contaminant in Eu-152 sources, emit 60-keV gamma rays, care must be taken if they are combined into a mixed source, so that the emission rate of each of the lines is well known.

A.1.1 Measurement of polar symmetry (0° ≤ θ ≤ 360°)

Devise a method or build a jig to allow accurate repositioning of a point source with respect to the detector for both position and angle. Devices that accurately position the source-to-detector housing distance with mechanical holders are strongly recommended. The use of a mark to label the side of the cryostat orientation for θ = 0° is recommended.

CAUTION

Do not attempt to place a mark on any detector window consisting of beryllium, carbon fiber, or plastic since that could damage the window.

These measurements should be made to the side of the detector housing at a fixed distance between 8 and 10 cm from the source to the detector housing to detect off-axis alignment. These measurements should lie ~1 cm behind the plane containing the front Ge crystal face (i.e., ~2 cm behind the front face of the cryostat). Distances and angles should be measured fairly accurately (e.g., ± 0.1 cm and ± 3°).

NOTE—An accurate source location is important since small deviations in the distance can result in a few percent difference from the mean count rate.

a) Count a point source of Eu-152 at the preselected distance and at an azimuthal angle of φ = 90° for polar angles of θ = 0°, 90°, 180°, and 270°, respectively, as shown in Figure A.2 for an acquisition time sufficient to obtain a relative uncertainty in the net areas of interest of about 1%. Analyze the low- and high-energy peak areas of interest, subtracting any interfering background net peak counting rates from those of the acquired spectra for this test.

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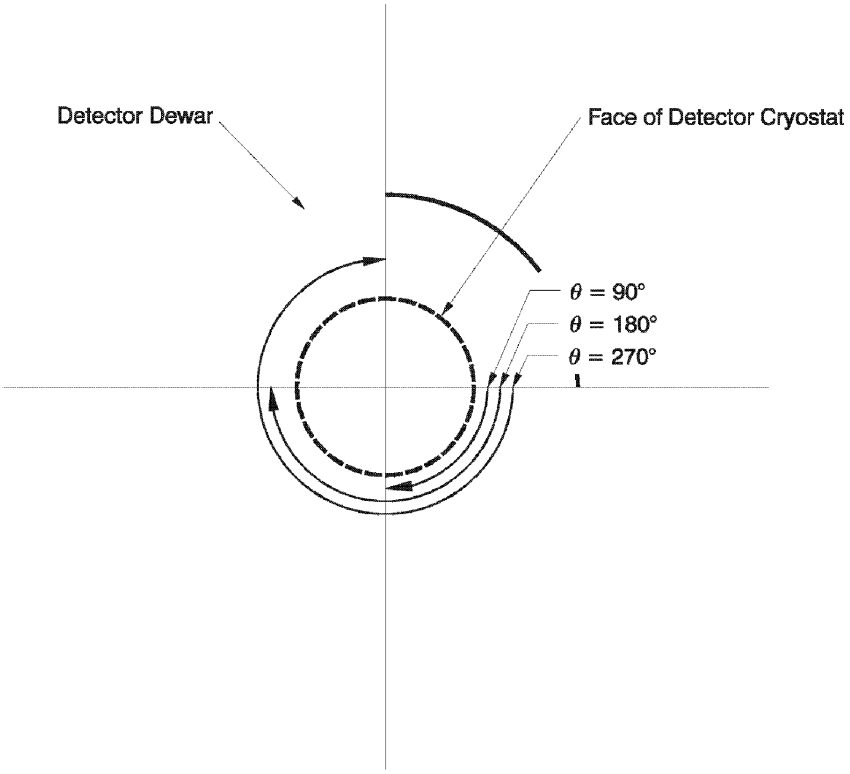


Figure A.2—The coordinate system as seen by looking down at the cryostat face

b) The net peak area counting rate $N_E(\theta)$ for a gamma ray of energy, E, shall be constant for all angles θ to within 5% of the mean counting rate of these four counts. If the counting rates are not constant within this accuracy, determine the offset (from the center of the cryostat face) necessary to achieve this agreement. Estimate the true detector axis from these measurements and convert this offset to the location on the face of the detector housing and mark the "true" axis. Rerun the test with the new axis. If necessary, take additional counts at other polar angles to better locate the symmetry position on the detector cryostat face. Use this location as the origin from which all future measurements are made.

CAUTION—The physical hardware used in the detector crystal mounting mechanisms and dewar housing are often assumed to be symmetric with respect to the detector polar and azimuthal axes. If this is not the case, the detector orientation must be known and maintained from calibration to operation in the field.

A.1.2 Measurement of azimuthal symmetry (90° ≥ φ, and φ ≥ 270°)

a) Count a ^{152}Eu point source at a fixed distance of ≥ 1 meter at azimuthal angles of φ = 0°, 30°, 60°, 90° at a polar angle of θ = 0° and at azimuthal angles of 270°, 300°, and 330°, at a polar angle of θ = 270°, respectively. All angles are to be measured to the polar axis position on the front face of the cryostat. A device to simplify alignment of the source is recommended. Count the point source until the relative uncertainty in the net areas of interest is about 1% and analyze the peak area counting rates of interest in the same manner as described in A.1.1.

b) Verify that the net peak area counting rates at symmetric azimuthal angles, φ, (i.e., 30° and 330°, 60° and 300°, and 90° and θ = 270°) are the same within 5% of the mean count rate. If this is not the case, the dewar and cryostat are not aligned or the method of alignment of the detector is in error (e.g., see Figure A.3). In all cases a change in the detector cryostat orientation should be made to correct the misalignment so that the detector crystal axis is aligned and this test repeated. All

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performance test measurements in A.2 and in-situ measurements should be made with the detector crystal axes aligned (i.e., 0° is along the detector crystal axis).

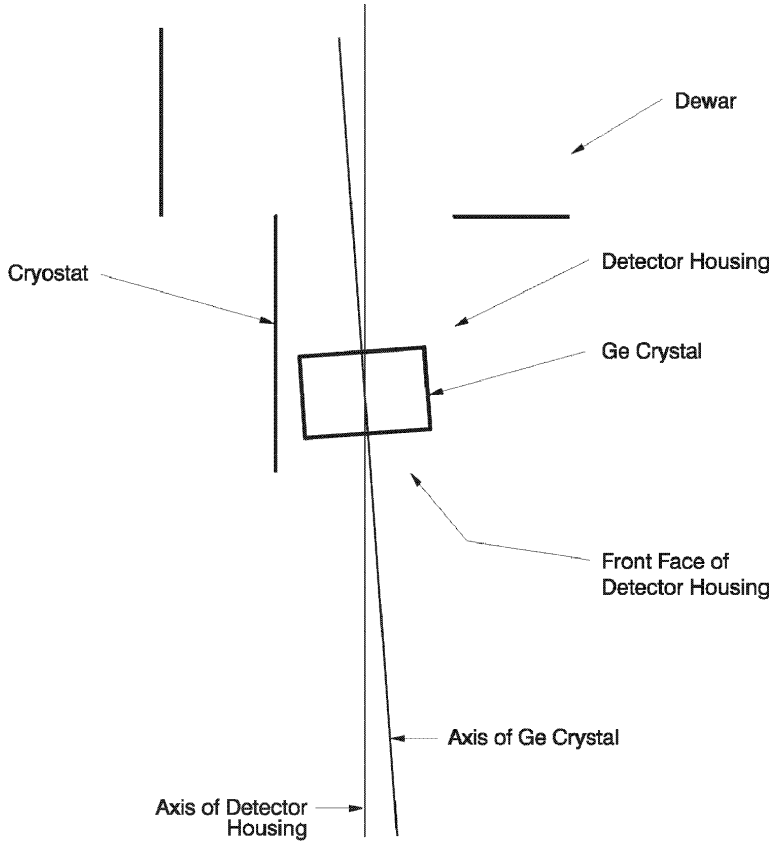


Figure A.3—Example of one potential detector misalignment

A.2 Simulating a finite line or disk source with point sources

A line or a disk source, that is counted with the center of the line or the disk aligned with the axis of the detector at distance d and orthogonal to it (i.e., standoff distance), can be simulated with a series of point-source measurements or a line source consisting of a series of point sources. This is done by dividing the line into a number of segments of length Δx_i or the disk into a set of concentric rings with the width of each ring being Δx_i (the subscript, i, designates the i^{th} segment).

The efficiencies of each segment are calculated and used to determine the efficiency for the line or disk source. The line or disk efficiency can be compared to that being used by the detector for the simulated extended source or used to relate a count rate to an activity concentration. There should be a sufficient number of line or width segments so that each segment or ring can be approximated by a point source located at the position of mean counting rate across the segment length or segment width. The maximum length (width) of each segment shall be kept short enough to avoid changes of more than 25% in counting rate when the point source is moved from the near end of the segment to the far end for azimuthal angles < 65°. The maximum length (width) of each segment shall be kept short enough to avoid changes in counting rate of more than a factor of two across the segment for azimuthal angles of $65° < \varphi < 85°$. No restriction is imposed for azimuthal angles above 85°. This simulation of a line or disk assumes that the source to detector distances are sufficiently large to use the inverse square law for the count rate, $N_{d,E}$, as a function of source distance for positioning the point source in each segment, Δx_i.

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$$N_{d,E} = \frac{K_E}{r^2} = \frac{K_E}{d^2 \cos^2 \varphi} \tag{A.1}$$

where K_E is a constant to be experimentally determined for each of the gamma-ray energies emitted, r is the distance from the front face of the detector cryostat to the point source. Since measurements are made along the length of the line or along the radius of the disk, any small deviations from a $1/r^2$ count rate dependence should not adversely affect the present method (especially for standoff distances ≥ 1 m).

RECOMMENDATION—For standoff distances, d, that are less than 1 m, the distance r is best measured to the position within the detector crystal at which half of the gamma rays of a given energy interact to produce the full-energy peak. Note that this position is a function of energy.

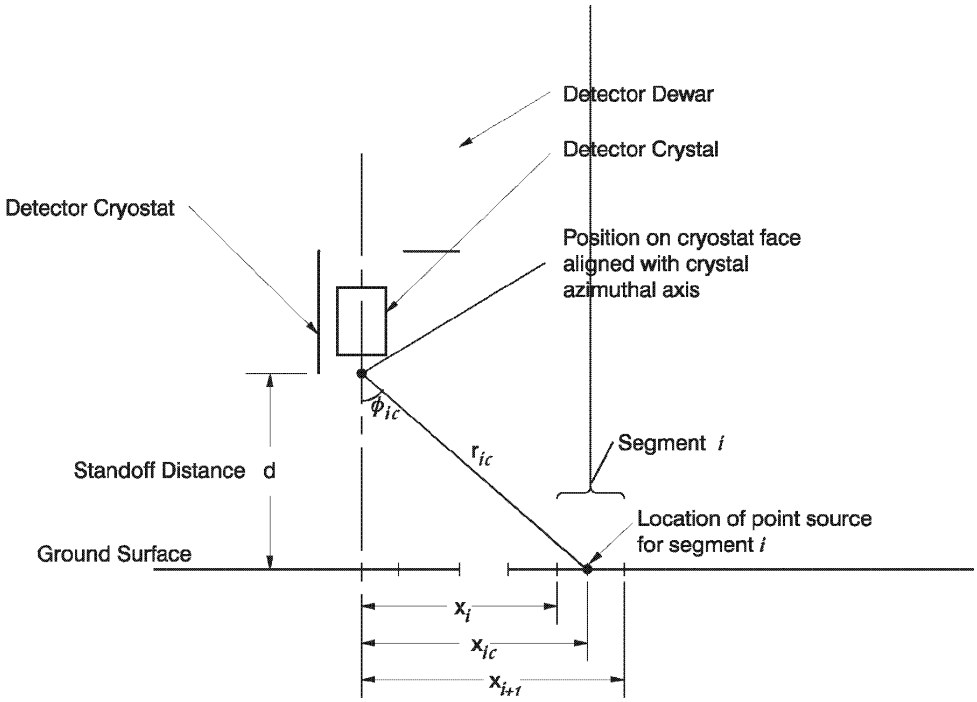


Figure A.4—Geometry of the experiment with labeling of distances and angles

The point source is located at the mean counting rate of the segment as determined by either Equation (A.2) or Equation (A.3) and Figure A.4. The location, x_{ic}, at the average counting rate, n_{ic}, for a segment from x_i to x_{i+1} is different for a line and for a disk-shaped source. For a line source, it is

$$n_{ic} = \frac{\int_{x_i}^{x_{i+1}} \frac{K_E dx}{(d^2 + x^2)}}{\int_{x}^{x_{i+1}} dx} \tag{A.2}$$

For a disk source the average counting rate for a segment from x_i to x_{i+1} is

$$n_{ic} = \frac{\int_0^{2\pi} \int_{x_i}^{x_{i+1}} \frac{K_E x}{(d^2 + x^2)} dx d\theta}{\int_0^{2\pi} \int_{x}^{x_{i+1}} x dx d\theta} \tag{A.3}$$

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The integral is over the horizontal direction x for the line source and over the horizontal distance, x, and the polar angle, θ, for a disk source. Computing the integral for the line source gives Equation (A.4):

$$n_{ic} = \frac{(K_E/d)[\tan^{-1}(x_{i+1}/d) - \tan^{-1}(x_i/d)]}{(x_{i+1} - x_i)} \quad \text{(A.4)}$$

Computing the integral for the disk source gives Equation (A.5):

$$n_{ic} = \frac{(2K_E)[\ln(x_{i+1}^2 + d^2) - \ln(x_i^2 + d^2)]}{(x_{i+1}^2 - x_i^2)} \quad \text{(A.5)}$$

For distances, d, the number of divided segments should be sufficient to attain the accuracy required of this test (see Table 2). The location of x_{ic} in terms of the average count rate n_{ic} is shown in Equation (A.6):

$$x_{ic} = \sqrt{(K_E/n_{ic}) - d^2} \quad \text{(A.6)}$$

To simplify the placement and number of segments for large geometries, we suggest equal angles φ rather than equal segments to divide the line or disk. From the angles, φ, the distances x can be calculated from the relation $x = d\tan\varphi$.

A.2.1 Verification of the full-energy peak efficiency of a finite line or disk source

a) Choose the length, L, of the line source or radius of the disk source for which the detector is calibrated. Position the line so that it is bisected by the detector axis. Divide the line on one side of the detector axis into segments or the disk into concentric rings as described in the above paragraph and as shown in Figure A.4. If the L is small (i.e., within an azimuthal angle of 45°) it may be easiest to divide it into equal segments of length Δx = L/5. If L is long (60° > ϕ > 45°) but not infinite, divide the line into segments of length Δx = L/10. For long lengths (L > 2 m) the Δx segments may best be determined by increments in the azimuthal angle φ from φ_i to φ_{i+1}, where, as shown in Equation (A.7):

$$\Delta x_i = x_{i+1} - x_i = d\,(\tan\varphi_{i+1} - \tan\varphi_i) \quad \text{(A.7)}$$

In this case, the Δx segments are not necessarily of equal length (width). For segments beyond an azimuthal angle of 65°, the delta segments will need to cover many meters when the line or disk is infinite, but the contribution to the counting rate from source at these distances will be a relatively small fraction of the total counting rate and need to be estimated by extrapolation as shown in Figure A.5.

RECOMMENDATION—If the measurements in A.1 show that the polar or azimuthal axes of symmetry coincide with the detector axis, the point sources need to be counted on only one side of the detector/symmetry axis, and the polar axis orientation does not matter. If the detector housing symmetry axis cannot be aligned with the Ge crystal axis, it is suggested that the point sources be counted for 0°< φ < 90° and 360° > φ > 270° for a known polar angle, and this orientation used in future counts. Under these circumstances, the net peak area counting rates of the line segments are summed over the entire length of the line for each gamma ray of energy E, whereas rings comprising a disk source are treated as half rings and the individual counting rates are summed in a similar manner.

b) Place the point source at a standoff distance d and at positions $x_i + \Delta x_{ic}$ cm (i = 0 to m, where $x_o = 0$) from the detector's azimuthal axis and count the source until the relative uncertainty in the net areas of interest is about 1%. The parameter x_{ic} is the position of mean count rate for the segment Δx_i. For segments beyond an azimuthal angle of 45° the relative uncertainty in the net areas of interest needs to be about 3% and beyond 60° only about 5%.

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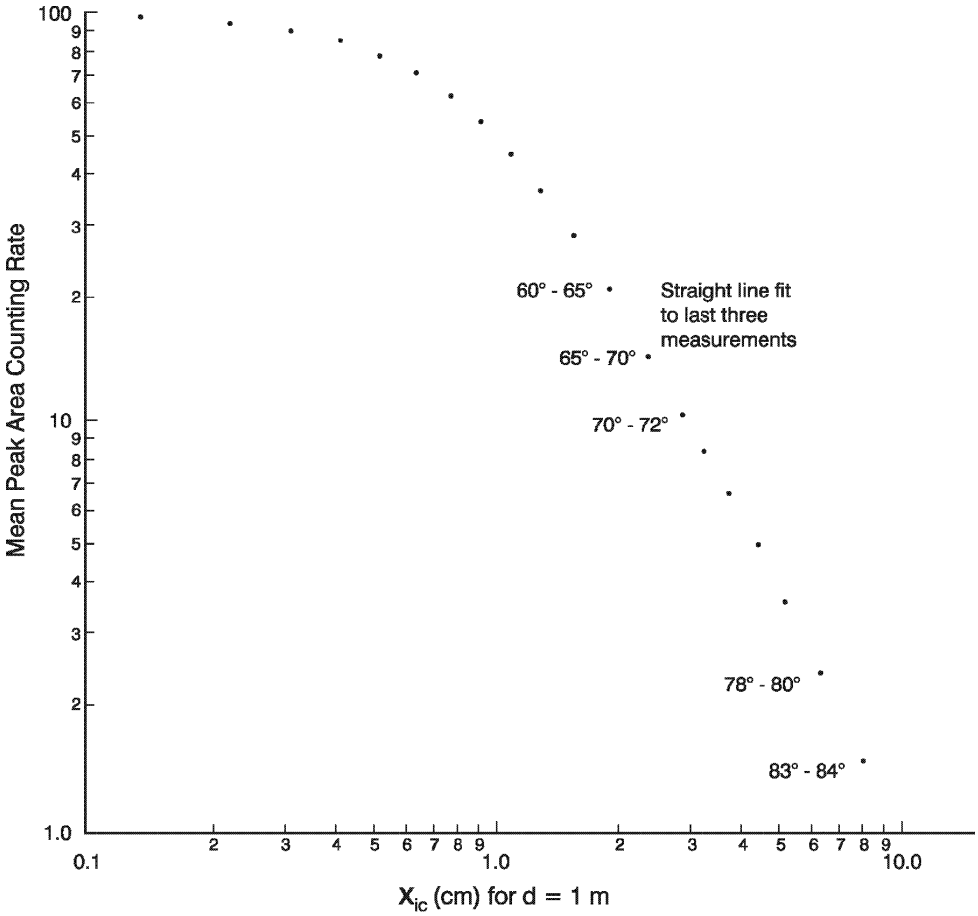


Figure A.5—Extrapolation of average counting rate per segment as a function of horizontal position, x_{ic}, for a line source and for a disk source

RECOMMENDATION—Rather than count the same source for each segment, it is recommended that the total spectrum count rate be approximately maintained over the individual delta segments by using a set of point sources of increasing activity.

c) Count the sources at the positions x_{ic} for every line-source segment, Δx_i, acquiring a spectrum as in step b) until counts in each segment have been acquired. If high-count rates are encountered, correct for peak pile up.

d) Calculate the average efficiencies, $\varepsilon_{E,i}$, for each segment i from Equation (A.8):

$$\varepsilon_{E,i} = n_{E,ic}/R_E(x_{ic}) \quad \text{(A.8)}$$

where $R_E(x_{ic})$ is the gamma-ray emission rate for energy E of the point source located at position x_{ic} of the i^{th} segment, and $n_{E,ic}$ is the mean peak area counting rate for each gamma ray of energy E for the i^{th} segment (see A.2).

e) Sum $\varepsilon_{E,d,i}$ over the segments to obtain the efficiency for the entire line or disk for gamma rays of energy E. For an evenly distributed source with an emission rate density of $\rho_E(x)$ ($\gamma\ s^{-1}\ cm^{-2}$) the efficiency for the entire source is expressed as in Equation (A.9) and Equation (A.10):

$$x_{ic} = \sqrt{(K_E/n_{ic}) - d^2} \quad \text{(A.9)}$$

$$\rho_E(x_{ic}) = R_{E,i}(x_{ic})/a_i \quad \text{(A.10)}$$

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The sums, i, are over m segments. Since the source is evenly distributed, then $\rho_E(x_{ic}) = \rho_E(x'_{ic})$, where $\rho_E(x'_{ic})$ is constant for all segments.

For a line, as shown in Equation (A.11):

$$a_i = 2\Delta x_i \quad \text{(A.11)}$$

Δx_i is the delta length of segment i.

For a ring segment extending for 180° of a disk, as shown in Equation (A.12):

$$a_i = \pi[(x_{i+1} + x_i)/2](\Delta x_i) = (\pi/2)\,(x_{i+1}^2 - x_i^2) \quad \text{(A.12)}$$

If the entire line (or disk) is divided into segments and all segments (i.e., both sides of the detector axis), then Equation (A.7) and Equation (A.8) are divided by 2 with all of the segments integrated in Equation (A.9).

f) If the efficiency for the entire line or disk herein simulated has been previously determined, then this efficiency should be directly compared with that efficiency deduced from Equation (A.9) (see Table 2 for the performance tolerance level for the test to be passed). If the detector efficiencies cannot be compared with the previously measured efficiency, the efficiency from Equation (A.9) will be used to deduce an emission rate for the line or disk geometry being tested. The following steps will allow deduction of the emission rate density from a point-source-collected counting rate.

g) Count a point source on the ground surface and at an azimuthal angle of ~ 45°. Analyze the spectrum to obtain the peak-area counting rates, $N_{t,E}$, for the appropriate gamma-ray energy. The corresponding emission rate density ρ_E, for the source geometry tested is shown in Equation (A.13):

$$\rho_E = R_{t,E}/a_t = [N_{t,E}/a_t]\varepsilon_{t,E} \quad \text{(A.13)}$$

where $N_{t,E}$ is the total peak area counting rate for a peak of energy E, and a_t is the total length or area of the line or disk, as shown in Equation (A.14):

$$a_t = \sum a_i \quad \text{(A.14)}$$

h) Treat the acquired spectrum as if this was an actual in-situ spectrum for the source geometry (i.e., line or disk) being tested. To pass this test, the measured emission rate density $R'_{t,E}/a_t$ should give the value of $[R'_{t,E}/a_t]$ from Equation (A.13) to within the performance tolerance level specified in Table 2.

i) If the simulated emission rate density, $R'_{t,E}/a_t$, deduced from the total count rate, $N_{t,E}$, from the spectral count of the point source in step h) above does not agree with the activity, $R_{t,E}/a_t$, in Equation (A.13), review the experimental measurements and the calculations for errors and repeat the test.

A.3 Simulating an infinite line or disk source with point sources

To simulate the activity of an infinitely long line or extended disk, it is not practical to continue point-source measurements, as in A.2, out to the detector's FOV (i.e., outer edges of sensitivity) to 1500 cm for a surface source. To be detected above background for a source located at 1500 cm the required activities of the point sources quickly reach several millicuries for a typical Ge detector located one meter above the ground surface. It is preferable not to routinely handle sources of this magnitude over extended times. Therefore, beyond 400 cm (for d = 100 cm or φ = 76°) it is acceptable to extrapolate, as shown in Figure A.5, the average count rate for a source as a function of distance x_{ic}. This is done by using regression analysis to estimate the count rate as a function of distance $x = d\tan\varphi$. The additional uncertainty introduced as a result

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of using this approach is small because these counts are a small fraction of the total detected counts for the entire line or disk.

A.3.1 Measurement of the total full-energy peak efficiency of an infinite line or disk source

a) Perform steps a) through d) in A.2.1.

b) Perform a linear regression on the measured data to obtain $n_{E,ic}$ as a function of x_{ic} [e.g., ln ($n_{E,ic}$) = A_E ln (x_{ic}) + B_E, where A_E and B_E are fit coefficients]. This can be also done by plotting $n_{E,ic}$ as a function of x_{ic} on log-log graph paper for the line and for the disk sources.

c) From the plot of $n_{E,ic}$ vs. x_{ic} as shown in Figure A.5 for a line and for a disk source, it is noted that for x_{ic} for an azimuthal angle > 60°, the function is very near a straight line (on a log-log plot). Either from the fitted data or the plot, extrapolate $n_{E,ic}$ out to a value of x_{ic} comparable to φ > 89°.

d) For segments Δx_i above the highest measured segment for x_{ic}, calculate the corresponding value for $n_{E,ic}$ or read it off the plot from the extrapolated line. Do this for φ_i out to 89°. From the $n_{E,ic}$ and x_i and x_{i+1} values, calculate the efficiencies ε_i and sum all segment efficiencies as in Equation (A.9) to obtain $\varepsilon_{t,E}$ as in step e) of A.2.1.

e) Perform steps f) through j) in A.2.1.

A.4 Simulating a line or disk source covered by an absorber of thickness D

This measurement is a repeat of tests in A.1 and A.2 with an absorber covering the source. The absorber should closely approximate the density, elemental composition, and thickness of an absorber typically encountered in the in-situ measurements. One or more building bricks may well simulate the effect of a covering of soil of thickness *d* for energies above 150 keV.

CAUTION—As the distance from the detector azimuthal axis increases, the angle of escape of the gamma rays above the horizontal plane from the brick in the direction of the detector decreases. At these angles the brick or bricks need to be positioned so that all of the radiation passes through the top surface of the brick and not through the side of the brick as shown in Figure A.6. If the radiation can pass through the side of the brick and continue to interact with the detector, it will give an underestimated and inaccurate absorption effect.

A.5 Verification of the accuracy of the detector efficiency for a line or disk source with intervening absorber

These measurements are designed to verify that the algorithms for calculating the gamma-ray emission rate yield results when there is an intervening absorber, other than air, that requires a correction of < 25%.

a) For a finite line or disk source, follow the procedure in A.2.1 with the standoff distance, d, measured to the top surface of the absorber. Calculate the absorber's mass thickness. If necessary, convert g/cm^2 into a density and thickness for soil, SiO_2, or other environmental material.

NOTE—For energies greater than 150 keV, the density is the important parameter; moisture and the elemental composition of the absorber (for an effective Z of the brick ~ 15) has a negligible effect on the absorption.

b) For an infinite line or disk source, perform test A.3.1 with the standoff distance, d, measured to the top surface of the absorber. Follow steps b) through d) to estimate the counting rate contributing to the net peak area counting rate at angles beyond 60°. Complete the steps of test A.3.1.

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A.6 Simulating line and disk sources when using a collimated detector

The difference between simulating extended sources when using a collimated detector is that its peak efficiency changes more rapidly than with an uncollimated detector because the shield attenuates that radiation entering at angles in which a portion of the detector is shielded. Therefore, this region needs to be defined in terms of peak efficiency by the use of a finer division of segments with point-source counts (see A.2, A.3, and A.4) or by use of one or more large plane sources that can be purchased from several commercial vendors (this type of large-area source is included in those discussed in 5.4).

Because few shields in use for in-situ counting are fully opaque above 1 MeV even for 4 cm of lead shielding due to weight and size limitations, a background count should be taken with and without a collimator plug to estimate the leakage as a function of energy. This leakage rate should be kept less than 5%. When the field of view of a collimated detector is relatively small (e.g., < 10 m^2), a line or a plane source comprised of many point source deposits on a tape or film, which is then sealed by covering with a second tape or film, can be prepared or purchased commercially to simulate a line or a plane source large enough to fill the detector's field of view. Although these standardized sources can be expensive, they are preferred to point sources to measure the detector full-energy peak-efficiency curve. Line or plane sources even larger than the prepared standard source can be simulated by multiple counts with the source moved between counts so that the larger area or line is simulated. These individual counts, preferably counted for the same analyzer live time, are then analyzed and the results added. It also may be appropriate to combine the spectra from these multiple counts and analyze them as one spectrum when the same source is used. (In either case the acquisition times should be kept the same, since associated with the combined data is a count time equal to an individual count.)

When the purchase of extended sources is not feasible, the detector efficiency for certain plane geometries can be measured with a set of point sources as described in A.2, A.3, A.4, and A.5 with the one important modification to the procedure required. This modification is to apply a finer division of segments (maybe 1 1/2 or 2 times that used in A.2, A.3, A.4, and A.5) so that the rapidly decreasing sensitivity is properly modeled. Follow the procedures given in the previous subclauses of this annex. The requirements for passing the tests in the text remain the same. See Figure A.6.

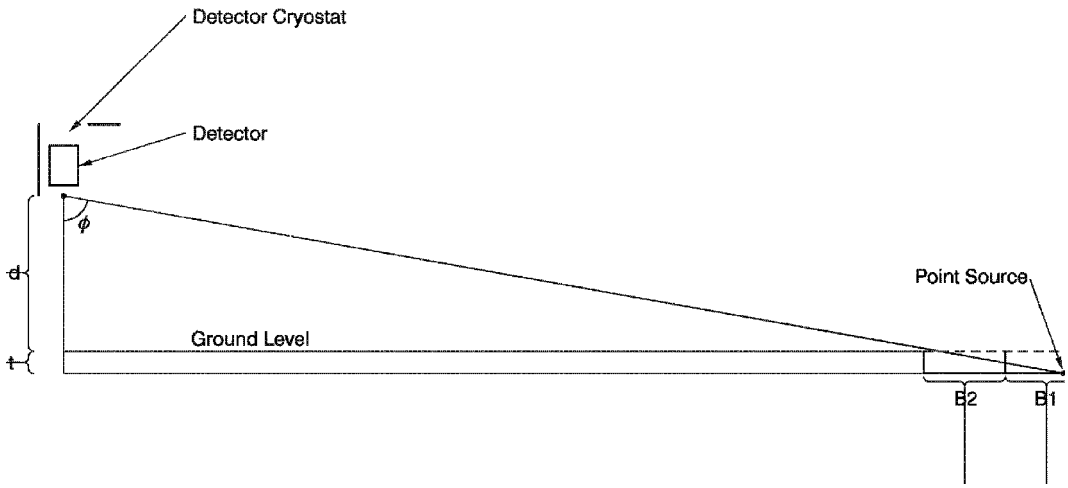


Figure A.6—Geometry of the experiment showing an absorber of thickness *t* covering the point source

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Annex B

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Test methods using gamma emitters in surface soils

B.1 General

This annex describes a method for demonstrating compliance for the test configurations 8a, 8b using naturally occurring gamma-emitting radionuclides in surface soil. The special significance of this configuration is that it corresponds to the measurement of radionuclides in surface soil. The performance will be based on a comparison between discrete soil samples of a test soil volume and an in-situ measurement. This test assumes that the detector calibration is for a uniform distribution of radioactivity, both horizontally and vertically. The following shall apply:

— Smooth soil surface with little or no surface features
— Uniform source matrix, preferably soil, with a known density and elemental composition
— Little or no surface cover
— Infinite diameter and thickness of soil

B.2 Site selection

Follow the guidelines for site selection as described in 7.2.1 of ASTM C998-1990 [B1].

B.2.1 Characteristics

The site used in this test consists of a test soil volume (TSV) and a buffer zone.

The TSV can be an environmental location, such as an open field, or it can be a man-made facility. It should have the following characteristics:

— Surface features that are consistent with the calibration model or the calibration source—typically smooth, flat, and horizontal
— Pedologically uniform (a single soil type within the detector's field of view)—if possible, avoids soils that are sandy, gravelly, or boggy
— No obstacles above or below the soil that could affect the gamma-ray fluence such as trees, tree stumps, shrubs, brush or bushes, rocks, rock outcroppings, boulders, loose aggregate, underground pipes (< 30 cm deep) and groundwater wells
— Surface area and depth large enough to encompass the detector's field of view

Since the properties of the buffer zone do not affect the test measurement, the characteristics of the buffer zone do not have to conform to those of the TSV. However, the buffer should not contain radioactive materials or equipment that could affect the test. Make the buffer zone wide enough to prevent or at least reduce the possibility of persons or objects infringing on the TSV during the test measurement.

RECOMMENDATION—Mark the outside perimeter of the buffer using spray chalk or a water-based spray paint. As an extra precaution, rope off the site for a time as necessary to complete the test.

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CAUTION—There is always the possibility that although a site looks pristine, it is not. The TSV could contain highly variable levels of natural radiation or even radioactive contamination that could disqualify the TSV for use in this test. As a check of radiological uniformity, conduct a scanning survey with a sodium iodide scintillator operated in a gross counting mode. Conduct the scan in manner similar to that described in Section 6.5.4 in NUREG-1507 [B17]. If the TSV is man-made—that is, a large man-made receptacle that will be filled with soil to meet the specifications of Clause 8—then the soil should be checked for uniformity by scanning before being loaded into the receptacle.

B.3 Test method

B.3.1 Test conditions

The test conditions described in 5.2 of this standard apply to this test.

B.3.2 TSV conditions

Unless stated otherwise, the TSV conditions should refer to the condition of the TSV at the time of the test. Clear the TSV of snow, ice, and/or standing water. The ground cover, if any, should be grass or similar vegetation, and not exceed a height of 5 cm unless specifically addressed in the calibration. Clear the TSV of all nonessential personnel and equipment. The soil should not be waterlogged, no standing water/snow should be present, and soil moisture should be uniform throughout the top 15 cm.

RECOMMENDATION—The soil moisture should be measured and should not exceed 15%.

B.3.3 Test configuration and test ranges

The configuration of the test measurement involves the area of the TSV and the standoff distance. With the exception of radon progeny in the air, the detector's field of view should not include any radioactivity that is not within the TSV. Table B.1 lists nuclides and gamma-ray energies that can be used for the test.

Table B.1—Energy ranges, nuclides, and gamma-ray energies for tests

Energy range	Nuclide	Gamma-ray energy (keV)
low	Th-234m	62.9, 94
high	Pb-214	295, 352
	Tl-208	583
	Bi-214	609
	Ac-228	911
	K-40	1460
	Bi-214	1765
	Tl-208	2615

B.4 In-situ measurement protocol

The following procedures shall be used for this test:

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2) Configure the detector with the proper orientation and appropriate standoff distance. The stand-off distance for this test should not be less then than 30 cm or exceed 10 m. In general, all aspects of the set-up and configuration should be consistent with those specified in the calibration.

3) Perform and pass the QA/QC test procedures as outlined in the QA/QC plan.

4) Acquire a spectrum until either (a) 10 000 counts are present in the peak to be analyzed or (b) the uncertainty associated with the counting statistics will not cause the test to fail. For example, suppose one is performing test 8b, in which the tolerance level is 0.25. If it is known that the CV for the soil samples is 0.10, and if after an hour of counting the relative bias is 0.10, and if the uncertainty due to counting for an hour does not cause the relative standard uncertainty to exceed 0.05, then one does not need to count any longer.

5) Record or archive the spectrum, identifying the detector, location, date, and time of measurement.

6) Perform replicates as specified in the QA/QC plan.

RECOMMENDATION—Measure the soil moisture immediately following the test measurement at no less than two locations within the TSV. The soil moisture should be determined using the methods outlined in either ASTM D2974-2000 [B3] or ASTM D3017-1996 [B4].

CAUTION—The method described in ASTM D3017-1996 [B4] uses a neutron source to determine soil moisture. The presence of this source during the test could affect the results.

CAUTION—Portable soil moisture probes and soil moisture meters that measure the dielectric constant of the soil-air-water combination are not measuring the soil moisture as defined in this standard. Typically, they measure the percent holding capacity of the soil. They should not be used.

NOTE—For typical environmental levels of natural radiation, with the possible exception of K-40, and for all but the largest detectors, the requirement of 10 000 counts in a peak in a few hours of data collection is unrealistic. It is therefore recommended that the approach described in Item 3) of B.4 be used. During these performance tests, when not in use store any radioactive sources in well-shielded storage containers away from the TSV and the buffer area.

RECOMMENDATION—If the service provider is restricted to a selection of sites within a facility that has radioactive materials or conducts activities that could produce gamma rays, it is recommended that the site be monitored for a period of 24 hrs before the test, during the test, and 24 hrs after the test measurement. The instrumentation should be able to monitor the dose rate or exposure rate of the site continuously.

B.5 Soil sampling and analysis

B.5.1 Number of samples and sample distribution

Refer to 7.2.2 of ASTM C998-1990 [B1] regarding the number of samples and distribution of samples within the TSV. If the TSV is less than 50 m^2, then collect a minimum of five samples. The maximum number of samples, regardless of the area of the TSV, should not exceed 25. Since the radionuclide distribution is assumed to be uniform within the detector's field of view, the sample distribution should be uniform within the TSV. Some suggested sampling patterns are found in Figure B.1, Figure B.2, and Figure B.3.

NOTE—For nonimpacted and undisturbed areas, it has been shown that there is little improvement in precision when the sample number exceeds 25 (Sowa et al. [B19]).

B.5.2 Sample collection procedure

Collect soil samples immediately following the test measurements for the purposes of determining the radionuclide concentrations.

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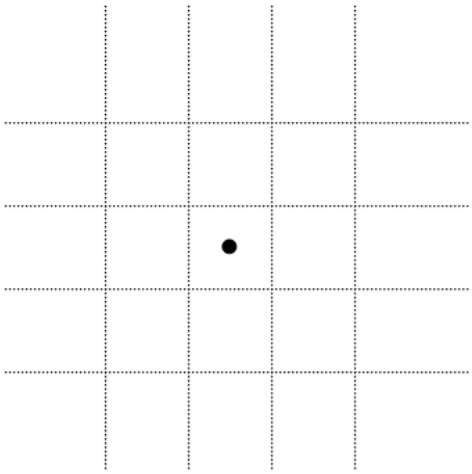


Figure B.1—Square sampling pattern (the dot marks the in-situ measurement location)

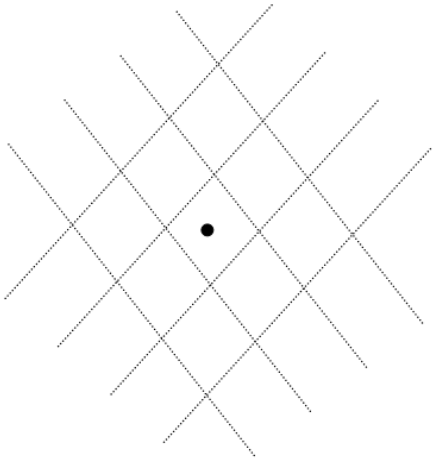


Figure B.2—Triangular sampling pattern (the dot marks the in-situ measurement location)

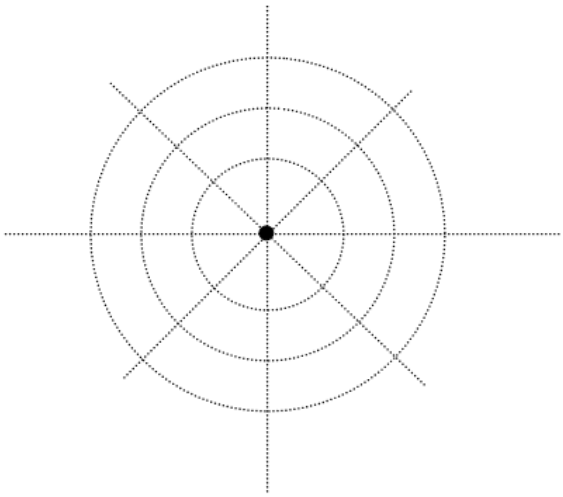


Figure B.3—Radial sampling pattern (the dot marks the in-situ measurement location)

1) Select the sampling locations based on the previous section.
2) At the sampling location or grid point, remove all vegetation to a height of 10 to 20 mm above the soil and save if desired.
3) Insert the sampling tool to a depth of 15 cm below the soil surface and remove the plug.
4) Place the soil plug and residual vegetation and roots in an appropriate container.
5) Repeat the procedure until the appropriate number of cores is collected. Do not composite the cores.
6) Label each container with information such as location, time, date, collector, and depth of core.
7) Clean sampling tools in water and detergent and dry before taking the next sample.

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B.5.3 Sample preparation and analysis

Prepare and analyze the samples for the nuclides used in the test. For example, if the service provider has analyzed their spectrum using Th-234 for the low-energy gamma ray, and Pb-214 and Bi-214 for the high energy ranges, then the soil samples must be analyzed for those nuclides.

The laboratory performing the analysis should process the samples following the practices described in ASTM C999-1990 [B2]. Moreover, the laboratory shall adhere to the practices and follow the recommendations described in ANSI N42.23-1996.

The precision and bias of the soil sample results should meet the requirements of this standard.

NOTE—In some locations it may not be possible to avoid rocky or gravelly soil. It is important for this performance test that the samples reflect the soil, rock, and stones present in TSV. If, after milling and sieving according to ASTM C999-1990 [B2], the weight of the unsieved material—which we are assuming to consist of rocks and stones—is greater than 33% of the weight of the sieved sample, then additional milling may be necessary. Mill the samples until the weight of the unsieved material is less than 33% of the sieved sample.

B.6 Method of comparison and performance criteria

Calculate the mean concentration, standard deviation, and coefficient of variation for the soil samples. Adjust the in-situ measurements to account for the soil moisture using the following relationship:

$$C_{\text{dry}} = \frac{1}{[1 - sm(\%)/100]} \cdot C_{\text{field}}$$

where

C_{dry} is the radionuclide concentration in dry soil,
C_{field} is the in-situ radionuclide concentration,
$sm(\%)$ is the soil moisture expressed as a percentage of wet weight.

Calculate the relative bias and relative standard uncertainty of the measurement. Use Equation (1a) and Table 2 to evaluate the performance.

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Annex C

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Test methods using simulations

Radiation transport programs have been developed that use stochastic or Monte Carlo methods to accurately simulate the transport of radiation through matter. The technique has the advantage of being able to treat complex geometries. Until recently, the inherent complexity of the algorithm typically leads to long execute times on expensive mainframe computers, which limited the applications to weapons and reactor design. With the advent of fast personal computers (PCs), many of the programs have been modified to run on a PC platform. This has allowed the technique to be applied to a much wider range of problems. One such application is the calculation of the efficiency or response function for an HPGe detector (Briesmeister [B6], Kamboj [B11], Moss and Streetman [B15], and Nakamura [B16]). Using this approach, detectors can be calibrated for a variety of applications using models and simulations. Note that the models pertain to the physical objects, such as the source and detector, while the simulation refers to the use of a computer program to duplicate the behavior of individual particles. It must be emphasized that the quality or accuracy of a calibration developed using a simulation is predicated on the quality or accuracy of the transport code and the degree to which the simulation reflects the actual conditions of the measurement. The focus of this annex is to provide a method for validating the models and simulations used for calibrations of the test configurations given in Clause 6.

NOTES

1—A general purpose Monte Carlo transport code called *Monte Carlo Neutron Photon* (MCNP) is a transport code that is well suited for the task of calibrating a detector and performing the procedures outlined in this annex. It was developed at Los Alamos National Laboratory and has been used to calculate many tens of thousands of problems. The large number of applications is significant because it serves as a means of validating the code. MCNP is generally regarded as the gold standard for neutron and very high-energy photon transport calculations (Briesmeister [B6]). It has also been shown to be useful for photons for the energies of interest in this standard, ANSI N42.28-2002. It must be pointed out, however, that the methods detailed in this annex are applicable to valid Monte Carlo transport code, not just MCNP.

2—The documentation available for MCNP on the use of the code and the appropriate parameters for gamma spectroscopy is not very helpful for use in the tests in this standard. Proper use requires the proper selection of code parameters, libraries, and scoring tallies. It also is highly dependent on the exact model of the source, detector, and any intervening absorbers.

3—The proper detector model is not easy to create, since it requires the exact dimensions of components not accessible to the user. Many of the detector features and internal mechanical construction are not reliably known (dead layer, crystal location, radius of rounded corners), or are not supplied to the users (details of internal hardware or proprietary items). Nevertheless, when data from all known components, together with estimates of unknown components, are properly applied, a suitable MCNP model of the detector can usually be obtained.

4—Using MCNP, for example, the detector model can then be combined with a source model of the test configurations. The computed MCNP efficiency is then used as the reference value, along with its computed relative uncertainty for testing the efficiency of the test detector or the test configuration.

C.1 Validating the accuracy of a simulated measurement with a modeled detector and source

The following procedure demonstrates the ability of the service provider to model an HPGe detector:

1) Be sure that the detector, the endcap, and all the other mechanical parts inside the endcap are modeled properly.

2) Obtain NIST-traceable point source.

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3) The source must contain the test energies. Am-241 and Eu-152 are recommended, provided that the Eu-155 content is small or well known.

4) Count the source at a known distance from the detector. The use of a special fixture or jig is recommended.

5) Count the source until there is approximately 1% relative uncertainty in the photopeak area for peaks of interest.

6) Count the source at 0°, 90°, and 135° azimuthal angles.

7) Repeat the 90° measurements at polar angles of 120° and 240° from the first measurement.

8) Compare the three 90° measurements for the polar angles. If any one is greater than 5% from the mean, consider rejecting the detector for this application or compute the radial offset of the detector and use for all future computations and measurements.

9) Create a model of the source, source container, and the air between the source and the detector appropriate to the transport program.

10) Run the transport program to compute the full energy peak efficiency. Run with enough histories to create approximately 1% relative standard deviation uncertainty at each of the test energies.

11) Repeat step 10) for each of three azimuthal angles for which the source was counted (0°, 90°, 135°).

12) Compare the measured efficiency value with the computed value. The relative bias should be within 5% for each test energy and at each location.

NOTE—For the 90° value, use the average of the three radial counts. If multiple test energies exist within the test range, then use the weighted average (see Clause 3).

13) If more than one detector is being tested, repeat steps 1) through 12) for each detector.

C.2 Validating the accuracy of a simulated measurement of an attenuated source

The following procedure demonstrates the ability of the service provider to model a source and absorber to adequately account for gamma-ray attenuation.

1) Obtain a source of suitable activity for the measurements. The source must contain the test energies.

NOTE—The source need not be a NIST-traceable source. Am-241 and Eu-152 are recommended, provided that the Eu-155 content is small or well known.

2) Count the source at a known distance from the simulation. The use of a special fixture or jig is recommended. Count until there is approximately 1% relative uncertainty in the photopeak of interest.

3) Repeat step 2), but interpose an appropriate thickness of absorber such that the attenuation is greater than a factor of 5.

4) Compute the measured attenuation factor for each test energies and for each absorber tested.

5) Simulate or model each of the measurement configurations. Run with enough histories to create approximately 1% relative standard deviation uncertainty at each of the test energies.

6) Compute the attenuation factor as calculated by simulation for each of the test energies for each absorber tested.

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7) Compare the measured attenuation factor with the attenuation factor computed by the simulation. They should be within 5%.

NOTE—Since this is a test of the simulation, it does not need be repeated, as long as the simulation is not changed.

The procedures outlined in C.1 and C.2 should be sufficient to demonstrate the ability of the service to model and simulate a large source, as well as a collimated detector. The service provider should, however, demonstrate that this is true.

C.3 Demonstrating compliance using simulations

The following procedure demonstrates compliance with this standard using simulations. These steps should be done only after the procedures and recommendations described in C.1 and C.2 have been followed.

1) Create a reference value for each of the test configurations.
2) Use the validated detector model for the tests.
3) Use the validated parameters that were used in C.1 and C.2.
4) Create a model for each of the test configurations. Use the appropriate absorber, collimator, thickness, and size of the source to comply with the test conditions. Include air at the proper composition, density, and water content.
5) Run each of the models to compute the efficiency for each test configuration. Run enough histories to generate a relative uncertainty of approximately 1%.
6) Compare each of the reference values with the simulated or test values for each configuration. Compute the test performance according to the method of 7.1 and compare to the tolerance level of 7.3.

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Annex D

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Characterized large area sources

The U.S. Department of Energy and its predecessor agencies have developed facilities at four different locations in the United States that may be suitable for performance testing of in-situ calibrations of germanium detectors. The facilities contain pads and cylindrical configurations that are constructed of concrete with enhanced levels of naturally occurring, gamma-ray emitting radionuclides of known concentration. A list of the pads and configurations appropriate for this standard is provided with their radionuclide contents and other physical characteristics. Use of these facilities is optional. If these facilities can document traceability to NIST, they meet requirements of this standard. The uncertainties given for the radionuclide activities are at the 95% confidence level. No uncertainties have been determined for the dry bulk or partial densities. The information in its entirety is taken from Leino et al. [B13]. Additional information on the parameter assignments of the sources may be found in George et al. [B7].

NOTE—To obtain information about the use of the facilities or the current location of the relocatable calibration pads, contact the D.O.E. Grand Junction Project Office at +1 970 248 6000.

CAUTION—The concentration of Ra-226 is inferred from its progeny Pb-214 and Bi-214. This situation can be problematic when comparing reported values of Ra-226 in these tables to in-situ data because the progeny Pb-214 and Bi-214 occur after Rn-222 in the decay chain of Ra-226. Rn-222 is a noble gas that can escape from the matrix, disrupting the radioactive equilibrium that exists between parent and progeny. The situation can be acute because the half-life of Rn-222 is almost 4 days. Disequilibrium factors for ^{226}Ra depend on the matrix and can be as high as 50% in soil and concrete.

D.1 Grand Junction calibration site, Grand Junction, Colorado

D.1.1 Grand Junction Airport: Walker field pads

Large-area pads are imbedded in an access taxiway at the municipal airport.

Table D.1—Assigned parameters for the Walker Field pads (30 ft by 40 ft)

Pad designation	Concentration (pCi/g)			Dry bulk density ($g.cm^{-3}$)	Partial density H_20 ($g.cm^{-3}$)
	Ra-226	Th-232	K-40		
W1	0.82 ± 1.02	0.67 ± 0.10	12.67 ± 0.72	1.91	0.256
W2	1.92 ± 1.54	0.87 ± 0.12	45.58 ± 1.82	1.99	0.260
W3	1.70 ± 1.38	4.92 ± 0.26	17.07 ± 0.82	1.92	0.208
W4	12.07 ± 5.64	1.04 ± 0.12	17.56 ± 0.98	1.91	0.247
W5	8.36 ± 3.52	1.91 ± 0.16	34.68 ± 1.46	1.97	0.244

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D.1.2 Grand Junction Project Office: cylindrical configurations

Table D.2—Assigned parameters for Grand Junction H pads (48 in. diameter by 20 in. height)

Pad designation	Concentration (pCi/g)			Dry bulk density ($g.cm^{-3}$)	Partial density H_20 ($g.cm^{-3}$)
	Ra-226	Th-232	K-40		
H1	0.84 ± 0.90	0.67 ± 0.10	10.95 ± 0.62	1.86	0.185
H2	0.67 ± 0.90	0.08 ± 0.06	54.00 ± 1.56	1.87	0.142
H3	161.83 ± 20.40	0.66 ± 0.08	11.31 ± 0.86	1.89	0.181
H4	11.03 ± 4.00	67.90 ± 1.24	10.76 ± 1.48	1.92	0.099
H5	102.59 ± 17.42	19.57 ± 0.54	37.75 ± 1.60	1.93	0.143

Table D.3—Assigned parameters for Grand Junction P pads (60 in. diameter by 24 in. height)

Pad designation	Concentration (pCi/g)			Dry bulk density ($g.cm^{-3}$)	Partial density H_20 ($g.cm^{-3}$)
	Ra-226	Th-232	K-40		
PK	1.16 ± 0.78	0.04 ± 0.06	50.96 ± 1.50	1.94	0.145
PL	85.71 ± 14.16	0.64 ± 0.10	15.78 ± 1.02	1.90	0.180
PH	374.36 ± 47.06	0.60 ± 0.10	15.80 ± 1.58	1.92	0.180
PT	6.63 ± 3.06	31.28 ± 0.86	14.92 ± 1.08	1.90	0.162
PB	0.0 ± 0.3	0.0 ± 0.3	0.0 ± 0.1	Not available	Not available

Table D.4—Assigned parameters for Grand Junction E pads (42 in. diameter by 18 in. height)

Pad designation	Concentration (pCi/g)			Dry bulk density ($g.cm^{-3}$)	Partial density H_20 ($g.cm^{-3}$)
	Ra-226	Th-232	K-40		
E1	25.21 ± 6.68	0.67 ± 0.10	13.30 ± 0.72	1.89	0.116
E2	80.34 ± 14.12	0.79 ± 0.10	13.83 ± 0.98	1.84	0.123
E4	395.8 ± 46.92	0.66 ± 0.12	11.43 ± 1.48	1.84	0.143
E5	871.45 ± 97.72	0.75 ± 0.12	14.72 ± 2.18	1.94	0.114

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D.2 Casper Calibration Site, Wyoming: cylindrical configurations

Table D.5—Assigned parameters for Casper E pads (42 in. diameter by 18 in. height)

Pad designation	Concentration (pCi/g)			Dry bulk density ($g.cm^{-3}$)	Partial density H_20 ($g.cm^{-3}$)
	Ra-226	Th-232	K-40		
CE2	281.45 ± 14.42	0.79 ± 0.12	13.63 ± 0.98	1.85	0.135
CE4	409.93 ± 50.90	0.66 ± 0.10	12.29 ± 1.58	1.84	0.162

D.3 Grants Calibration Site, New Mexico: cylindrical configurations

Table D.6—Assigned parameters for Grants P pads (42 in. diameter by 24 in. height)

Pad designation	Concentration (pCi/g)			Dry bulk density ($g.cm^{-3}$)	Partial density H_20 ($g.cm^{-3}$)
	Ra-226	Th-232	K-40		
GPK	0.58 ± 0.82	0.01 ± 0.06	51.53 ± 1.46	1.96	0.127
GPL	87.78 ± 14.32	0.50 ± 0.10	15.58 ± 1.02	1.90	0.165
GPH	375.74 ± 45.14	0.61 ± 0.10	15.93 ± 1.62	1.91	0.142
GPT	6.57 ± 3.14	30.23 ± 0.80	14.94 ± 1.02	1.89	0.146
GPB	0.0 ± 0.3	0.0 ± 0.3	0.0 ± 0.1	Not available	Not available

Table D.7—Assigned parameters for Grants E pads (42 in. diameter by 24 in. height)

Pad designation	Concentration (pCi/g)			Dry bulk density ($g.cm^{-3}$)	Partial density H_20 ($g.cm^{-3}$)
	Ra-226	Th-232	K-40		
GE2	83.13 ± 15.42	0.70 ± 0.10	12.93 ± 1.02	1.85	0.237
GE4	396.66 ± 49.70	0.80 ± 0.12	12.20 ± 1.48	1.84	0.148

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D.4 George West Calibration Site, Texas: cylindrical configurations

Table D.8—Assigned Parameters for George West E pads (42 in. diameter by 18 in. height)

Pad designation	Concentration (pCi/g)			Dry bulk density ($g.cm^{-3}$)	Partial density H_20 ($g.cm^{-3}$)
	Ra-226	Th-232	K-40		
TE2	83.53 ± 15.10	0.66 ± 0.10	3.17 ± 0.98	1.83	0.177
TE4	398.74 ± 50.36	0.51 ± 0.10	11.44 ± 1.58	1.86	0.223

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Annex E

(normative)

Calculation and approximation of solid angles

The general expression, in polar coordinates, for solid angles is given by Equation (E.1):

$$\Omega = \iint \sin\theta d/\theta d/\phi \tag{E.1}$$

While the Equation (E.1) can be difficult to evaluate, for the purposes of identifying the test configurations, it is not necessary to calculate the solid angle precisely.

E.1 Point detector solid angle approximation

Typically, when making in-situ measurements that the dimensions of the source are large in comparison with the dimensions of the crystal, the detector can be approximated by a point. The determination of the solid angle for a point detector simplifies the evaluation of Equation (E.1). The solid angle for a disk of radius *r* and a standoff distance *d* (see Figure E.1) is given by Equation (E.2):

$$\Omega = 2\pi\left[1 - \frac{d}{\sqrt{r^2 + d^2}}\right] \tag{E.2}$$

Note that as the radius gets large, or the standoff distance gets small, the solid angle approaches 2π. Equation (E.2) also can be used to estimate the solid angle for a square by choosing a surrogate disc of radius r' such that the area of the disc is equal to the area of the square. That is, if l is the length of a side of the square, the radius that should be used in Equation (E.2) is

$$r' = l/\sqrt{\pi}$$

For information on calculating the solid angle for other geometrics such as discs and cylinders, see Weast and Selby [B21] and Knoll [B12] and the references contained therein. See Figure E.1.

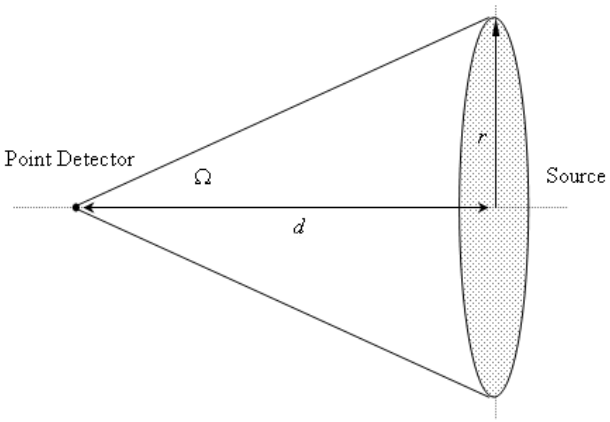


Figure E.1—Solid angle, Ω, subtended by a disk of radius *r* at a standoff distance *d*

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Annex F

(informative)

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