Standard Guide for
Use of Modeling for Passive Gamma Measurements[1]

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1. Scope

1.1 This guide addresses the use of models with passive gamma-ray measurement systems. Mathematical models based on physical principles can be used to assist in calibration of gamma-ray measurement systems and in analysis of measurement data. Some nondestructive assay (NDA) measurement programs involve the assay of a wide variety of item geometries and matrix combinations for which the development of physical standards are not practical. In these situations, modeling may provide a cost-effective means of meeting user's data quality objectives.

1.2 A scientific knowledge of radiation sources and detectors, calibration procedures, geometry and error analysis is needed for users of this standard. This guide assumes that the user has, at a minimum, a basic understanding of these principles and good NDA practices (see Guide C1592), as defined for an NDA professional in Guide C1490. The user of this standard must have at least a basic understanding of the software used for modeling. Instructions or further training on the use of such software is beyond the scope of this standard.

1.3 The focus of this guide is the use of response models for high-purity germanium (HPGe) detector systems for the passive gamma-ray assay of items. Many of the models described in this guide may also be applied to the use of detectors with different resolutions, such as sodium iodide or lanthanum halide. In such cases, an NDA professional should determine the applicability of sections of this guide to the specific application.

1.4 Techniques discussed in this guide are applicable to modeling a variety of radioactive material including contaminated fields, walls, containers and process equipment.

1.5 This guide does not purport to discuss modeling for "infinite plane" in situ measurements. This discussion is best covered in ANSI N42.28.

1.6 This guide does not purport to address the physical concerns of how to make or set up equipment for in situ measurements but only how to select the model for which the in situ measurement data is analyzed.

1.7 The values stated in either SI units or inch-pound units are to be regarded separately as standard. The values stated in each system may not be exact equivalents; therefore, each system shall be used independently of the other. Combining values from the two systems may result in non-conformance with the standard.

1.8 *The values stated in inch-pound units are to be regarded as standard. The values given in parentheses are mathematical conversions to SI units that are provided for information only and are not considered standard.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

C1490 Guide for the Selection, Training and Qualification of Nondestructive Assay (NDA) Personnel

C1592 Guide for Nondestructive Assay Measurements

C1673 Terminology of C26.10 Nondestructive Assay Methods

2.2 *Other Standard:*[3]

ANSI N42.28 Performance Standard for the Calibration of Germanium Detectors for In Situ Gamma-Ray Measurements

3. Terminology

3.1 See Terminology C1673.

4. Summary of Guide

4.1 Passive gamma-ray measurements are applied in conjunction with modeling to nondestructively quantify radioactivity.

4.1.1 Modeling may be used to *(1)* design and plan the measurements, *(2)* establish instrument calibration, *(3)* interpret the data acquired, *(4)* quantify contributions to the measurement uncertainty, *(5)* simulate spectra, and *(6)* evaluate the effectiveness of shielding.

[1] This practice is under the jurisdiction of ASTM Committee C26 on Nuclear Fuel Cycle and is the direct responsibility of Subcommittee C26.10 on Non Destructive Assay.

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

[3] Available from American National Standards Institute (ANSI), 25 W. 43rd St., 4th Floor, New York, NY 10036, http://www.ansi.org.

4.1.2 Various models commonly use analytical, numerical integration and radiation transport approaches. This guide provides a brief review of several approaches to help the user select a suitable method and apply that method appropriately.

4.1.3 Modeling makes use of knowledge of the measurement configuration including the shape, dimensions and materials of the detector, collimator, and measurement item content.

4.1.4 The exact geometry may be approximated in the model. The degree of approximation acceptable is assessed on a case by case basis.

4.1.5 Process knowledge may be required to provide information about inner containers, intervening absorbers, matrix materials or which radionuclides are present.

4.1.6 The models make use of basic physical interaction coefficients. Libraries and data sets must be available.

4.1.7 Models are typically used to: *(1)* account for field of view and geometry effects, *(2)* account for matrix attenuation, *(3)* account for container wall and other absorbers, *(4)* model detectors, *(5)* transfer calibrations from one configuration to another, *(6)* bound the range of assay values due to variations in modeling representation parameters, *(7)* iteratively refine assessments and decision making based on comparisons with observations.

4.1.8 Scans may be performed using low-resolution, portable gamma-ray detectors (for example, NaI) to identify the location of activity and assist with the modeling.

4.1.9 Measurement uncertainties are estimated based on uncertainties of the assumptions of the model.

5. Significance and Use

5.1 The following methods assist in demonstrating regulatory compliance in such areas as safeguards (Special Nuclear Material), inventory control, criticality control, decontamination and decommissioning, waste disposal, holdup and shipping.

5.2 This guide can apply to the assay of radionuclides in containers, whose gamma-ray absorption properties can be measured or estimated, for which representative certified standards are not available. It can be applied to in situ measurements, measurement stations, or to laboratory measurements.

5.3 Some of the modeling techniques described in the guide are suitable for the measurement of fall-out or natural radioactivity homogenously distributed in soil.

5.4 Source-based efficiency calibrations for laboratory geometries may suffer from inaccuracies due to gamma rays being detected in true coincidence. Modeling can be an advantage since it is unaffected by true coincidence summing effects.

6. Procedure

6.1 Modeling may lead to a bias if any of the measurement parameters do not match the physical characteristics of the item. Uncertainties in the item parameters of the following may lead to a bias:

6.1.1 Matrix distribution is homogenous throughout the container,

6.1.2 Hidden containers,

6.1.3 Matrix identification,

6.1.4 Container fill heights,

6.1.5 Mass attenuation coefficients,

6.1.6 Matrix density,

6.1.7 Detector parameters, and

6.1.8 Physical distribution of radioactivity.

6.2 If the quantity of nuclear material is "infinitely thick" to the emitted gamma rays, measurement results will be biased. This hazard is common when measuring items containing large quantities of heavy elements (for example, thorium, uranium, or plutonium) or items with highly attenuating matrices. Alternate NDA assay methods are recommended if this condition exists.

6.3 Self attenuation, commonly present in lumps of actinide material, will bias results low unless lump corrections are computed.

6.4 The Generalized Geometry Holdup Method must be calibrated with the collimator attached to the detector. If the detector recess changes from the calibration position, the results will be biased.

6.5 Absorber foils that are used to reduce count rate must be included in the model.

6.6 Attenuation corrections for very thick items may be somewhat compromised by coherent scattering, which may not be accurately modeled by attenuation calculations.

7. Method Descriptions

Five commonly used methods are described. These include: *(1)* Generalized Geometry Holdup, *(2)* Far-field Approximation, *(3)* Voxel Intrinsic Efficiency, *(4)* Radiation Transport Code, and *(5)* Hybrid Monte Carlo.

7.1 *Generalized Geometry Holdup*—The method represents items as a point, line, or area (**1**).[4] Three method calibrations are obtained from one set of calibration measurements. Point sources of the same material as that to be measured are often used for the calibration. Measurements and calibrations are made with a collimator attached. Additional attenuation correction factors are needed for a complete analysis. The detector calibrations remain the same for all measurements, but attenuation correction factors will vary with the specific measurement. Results are typically reported in units of mass.

7.1.1 *Advantages of this method are:*

7.1.1.1 The detector efficiency is easily determined; three different types of geometry calibrations are performed concurrently.

7.1.1.2 Any cylindrical collimator could be used.

7.1.1.3 Typically, only point sources are used.

7.1.1.4 Additional geometry corrections do not require use of half-life or gamma ray yields.

7.1.2 *Disadvantages of this method are:*

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

7.1.2.1 Some holdup items being measured may not have geometries that simulate points, lines, or areas.[5] However, the errors introduced by these assumptions are often small compared to other errors.

7.1.2.2 The model assumes uniform concentration and distribution of radioactive material. The uncertainties due to these assumptions can be mitigated by taking multiple overlapping measurements (subject to time constraints) and judicial measurement placement.

7.1.2.3 The calibration applies only to the exact detector-collimator configuration used during the calibration.

7.1.2.4 Special nuclear material licenses may be required for the calibration sources.

7.1.3 Typical applications include uranium and plutonium holdup.

7.1.4 *Calibration*—Point sources, representative of the material, m_o, being measured, are positioned in off-axis positions and the peak count rate is determined at each location. The activity of each location can be used to represent the activity/unit area of the area within the concentric ring, a_i. See Fig. 1. This information is integrated to obtain calibration constants for point, line, and area configurations.

7.2 *Far-field Approximation*—This method is used for the calculation of activity in well-defined geometries (**2**). The method assumes that the matrix attenuation correction for the item being measured can be estimated using a far-field matrix correction approximation. Additional correction factors are needed for other types of attenuation and geometry. Templates may be prepared that match parameters of the items being measured and the positioning of the detector during the measurement. Geometry and attenuation correction factors are computed from the information supplied by the templates. This model can be used for many shapes. Usually measurements are made with a collimator to provide detector shielding and directional response. The detector calibration remains the same for all measurements, but attenuation and geometry correction factors will vary with the specific measurement. Results are reported in activity, concentration, or mass units.

7.2.1 *Advantages of this method are:*

7.2.1.1 The detector efficiency is easily determined.

7.2.1.2 The calibration can be applied to any gamma-emitting radionuclide within the energy range of the calibration source and the validity of the correction factors.

7.2.1.3 Models can be constructed for cylinders, boxes, point sources, and disc geometries.

7.2.1.4 Detector collimation is incorporated in the model and does not affect the detector calibration.

7.2.2 *Disadvantages of this method are:*

7.2.2.1 The model does not apply to the analysis of activity in a non-uniform condition (for example, activity in soil in an exponential distribution).

7.2.2.2 The calibration does not apply to close-up geometries, where the far-field approximation for matrix attenuation does not apply, or very large items (for example, infinite planes).

7.2.2.3 Correction factors assume incoming gamma rays are parallel to the detector axis and, therefore, have reduced accuracy for the off-axis portion of activity.

[5] In a gaseous diffusion plant there are many items that contain holdup and cannot be measured as points, lines or areas. Two examples are converters and pipes in pipe galleys. In order to have a large enough standoff for pipes to meet the criteria for lines, several pipes in the galley are usually within the field-of-view. Converters are typically measured from outside cell housings, which places the detector several feet away. Because the converters have a large diameter (from 1.2 m to 2.7 m for the sizes that can be reliably measured by gamma), pulling back far enough to make them line sources would place several converters into the field-of-view, and then they would not be long enough to meet the line source definition. In addition, the internal structure of converters is too complex to model them as point, line, or area.

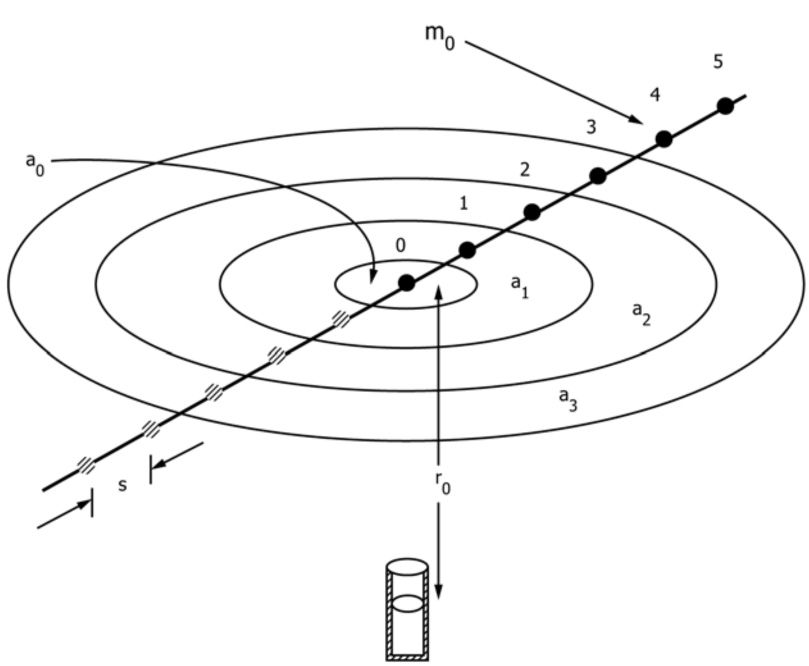

FIG. 1 Detector Position for Calibration

7.2.3 Typical applications include modeling of cylinders, boxes, points and discs with specific dimensions.

7.2.4 *Calibration*—Typically, a radionuclide point source, with activity traceable to national standards, is positioned at a fixed distance from the detector. This source needs to encompass the energy range of gamma-rays that may be used for the analysis. Detector efficiencies are then obtained as a function of energy at the distance used for calibration. Typical calibration distances range from 20 to 40 cm [7.9 to 15.7 in.]. Calibrations are performed with the source on the detector axis so that photons enter only the circular face of the detector.

7.3 *Voxel-Intrinsic Efficiency*—The model (**3**) is typically calibrated with a point source or sources as the far-field method, but the far-field algorithm for matrix attenuation is not used. Instead, the attenuation of each voxel is computed and the overall activity is computed accordingly. The detector is characterized by using information for the detector dead layer, detector can thickness, crystal diameter, crystal length, and side thickness. The intrinsic detector efficiency is computed by not only measuring activity entering the top of the detector but also the side of the detector.

7.3.1 *Advantages of this method are:*

7.3.1.1 The detector efficiency is easily determined.

7.3.1.2 The calibration can be applied to any gamma-emitting radionuclide with gamma rays within the energy range of the calibration source when emission rates are known and correction factors are valid.

7.3.1.3 Models can be constructed from cylinders, boxes, point sources, and disc geometries.

7.3.1.4 Detector position within the collimators can be readjusted to any depth without invalidating the calibration.

7.3.1.5 Gamma-ray penetration into the side of the detector is included in the final algorithm.

7.3.1.6 Accuracy is improved by using detector information.

7.3.1.7 Items can be analyzed close to the detector.

7.3.1.8 Attenuation is accurately computed by following the gamma-ray path through each voxel to the detector.

7.3.2 *Disadvantages of this method are:*

7.3.2.1 Typically, the model does not apply to the analysis of activity in a non-uniform condition (for example, activity in soil in an exponential distribution).

7.3.2.2 Complicated geometries are more difficult to model.

7.3.3 Typical applications include modeling of cylinders, boxes, points and discs with specific dimensions.

7.3.4 *Calibration*—The algorithms take advantage of detector characterization. Initially, full-energy peak intrinsic efficiency is needed for the detector used to make the analysis. To obtain that information, a point-source calibration must be performed at a fixed distance from the face of the detector.

7.4 *Radiation Transport Code Methods*—Radiation transport codes typically use the Monte Carlo method to track the motion of radiation through matter interaction by interaction. Comprehensive Monte Carlo radiation transport codes such as MCNP (**4**), GEANT (**5**), CYLTRAN (**6**), and EGS4 (**7**) allow energy deposition in the sensitive volumes of gamma ray detectors to be computed given the material description and source distribution of the measurement situation. This method of computing efficiencies is absolute in the sense that the cross sections of the primary photons and all subsequent secondary photons are tracked based on detailed calculations of the fundamental physical process taking place. These interaction cross-sections are derived from values stored in a National database. The ultimate accuracy is dependent upon the validity of the transport model for gamma spectroscopy, the proper utilization of the code, accurate cross-sections, and an accurate and detailed model of the detector and the radioactive source. Models are prepared that match parameters of the items being measured and the positioning of the detector during the measurement. The transport code determines the true detection efficiency, which may then be used by automated or manual techniques for activity determination. It is especially helpful for unusually complicated measurement geometries. None of these codes were developed for the purposes of accurate efficiency calibration of gamma spectroscopy detectors. Therefore, the user must be prepared to validate the code and input parameters of the model used to the appropriate levels of accuracy. This will typically require benchmark measurements for the code and geometry-specific model.

7.4.1 *Advantages of this method are:*

7.4.1.1 The computed efficiency can be developed very accurately if all the input parameters are very well known.

7.4.1.2 It can model very complex source-detector geometries, including large sources, off-axis sources, and highly collimated detectors.

7.4.1.3 It is possible to model specific effects such as the full energy absorption of a gamma ray or the partial deposition of energy with subsequent escape. Thereby, the computed energy deposition distribution is a close analog to the observed pulse height spectrum. The net peak areas can be extracted from this energy deposition distribution and provide a direct estimate of the detection efficiency, while the non-peaked areas can be used to estimate the increased background from down-scatter.

7.4.1.4 The full efficiency is determined; no correction factors are needed.

7.4.1.5 Attenuation of thick absorbers is accurately treated, whereas other methods assume a simple slab attenuation correction that has errors due to incomplete treatment of coherent scattering.

7.4.1.6 The simulated spectrum may be analyzed by the gamma spectroscopy software used to analyze experimental spectra.

7.4.1.7 No calibration necessary.

7.4.2 *Disadvantages of this method are:*

7.4.2.1 Typically, all parameters necessary for the model are not well-known.

7.4.2.2 The documentation for gamma spectroscopy applications currently is weak or non-existent; therefore there is an extensive learning effort.

7.4.2.3 The input of the parameters to describe the item and detector geometry is currently not very easy to use and can be time consuming, even for the experienced user.

7.4.2.4 Accurate efficiency computations require detailed description of the active portion of the Ge detector and all other attenuating materials inside the endcap.

7.4.2.5 The time to compute results can be very long (for example, hours, days), especially for low efficiency geometries as are typical for in situ assays.

7.4.2.6 The accuracy of the model depends strongly on the defined physical model.

7.4.3 This method is used to compute activities from a wide range of source configurations. It can be used for modeling simple and complicated geometries for holdup, criticality review, infinite-plane measurements of soil, or other item measurements including items in containers.

7.5 *Hybrid Monte Carlo Transport Approach*—The model (**8**) combines the advantages of Monte Carlo radiation transport codes and minimizes the disadvantages by using a combination of transport codes and ray tracing analyses. The first step is to create an accurate model of the HPGe detector, which includes all items inside the endcap that affect the efficiency (for example, size of the HPGe, dead layer thickness and location, corners, structural hardware, etc.). The accuracy of this model is validated using sources traceable to a national standard covering the expected range of energies, and placed at locations surrounding the detector. Then, a Monte Carlo radiation transport code is used to create a map of the detector efficiency for all locations outside the endcap for all energies of interest. This detector-specific map is then used for subsequent efficiency calibrations for the various source-detector geometries and provided with additional software from the vendor. The detector-specific efficiency map is used in combination with ray tracing analyses to calculate photon attenuation for the given source geometry. Typically, the source geometry is defined by the user with the aid of standard source shape templates. After selecting the appropriate template, the user then enters the relevant dimensions, materials, and densities to describe the item, as well as defining the source-to-detector relationship. In addition, other templates are typically used to define a collimator or housing (or both) that might surround the detector. The software computes the efficiency for the measurement by dividing the source and the detector into voxels. Attenuation factors are computed between all possible source-detector voxel pairs that are then applied to the efficiency for that source voxel, which is derived from the transport code efficiency map for the detector. The overall measurement efficiency will vary with each item type.

7.5.1 *Advantages of this method are:*

7.5.1.1 User input of source-detector model is easier than with radiation transport codes.

7.5.1.2 Very complex source-detector geometries can be modeled including large sources, off-axis sources, and highly collimated detectors.

7.5.1.3 Extensive validation of the process has been performed by the code developer and is supplied to user.

7.5.1.4 The method is reasonably accurate for all distances defined, all azimuthal and polar angles, and a wide range of energies.

7.5.1.5 Computations are faster compared to the Radiation Transport Code Model after completion of the detector-specific efficiency map.

7.5.1.6 The output is a conventional energy-vs.-efficiency matrix suitable for traditional gamma spectroscopy efficiency calibration curve generation.

7.5.1.7 The method is accurate for collimators, including those with small apertures and non-cylindrical openings.

7.5.1.8 The method is accurate for sources both on and off the detector axis.

7.5.1.9 Once the detector is characterized, calibration for most source-detector geometry can be generated within minutes using the vendor software.

7.5.2 *Disadvantages of this method are:*

7.5.2.1 The method requires detailed knowledge of the detector construction and all other materials surrounding the detector to derive the proper detector model, which is proprietary information. The detector presently can be calibrated only at the manufacturer's facility. This makes the method difficult to apply to existing detectors or detectors made by another manufacturer.

7.5.2.2 For highest possible accuracy, the transport code calculations must be done for each individual detector and the result is specific to that detector.

7.5.2.3 The accuracy is limited to the accuracy of the cross-sections, the detector model, and the source description.

7.5.2.4 Because the detector-collimator assembly can be readily changed, the analyst must be aware of the collimator configuration used for measurements.

7.5.3 This method can be used for many shapes including infinite-plane measurements. These include modeling simple and complicated models for holdup, criticality review, or other item measurements.

8. Choosing the Proper Model

8.1 In choosing the appropriate model for a given set of measurements, one must carefully consider multiple factors. A series of questions illustrating these factors are shown below and grouped into seven categories: measurement needs, equipment, calibration, costs, ease of use, availability of technical support, and quality assurance requirements. Not all of these questions may be applicable to a given situation; ultimately, the NDA professional should decide which model to use.

8.1.1 *Measurement Needs:*

8.1.1.1 How is the radioactive source distributed?

8.1.1.2 What type of items is being measured?

8.1.1.3 Can the item be represented by simple approximations?

8.1.1.4 Does the model offer representative shapes of the item?

8.1.1.5 Can the item be measured up close, or can a far-field approximation be applied to the measurements?

8.1.2 *Equipment Needs:*

8.1.2.1 Does the model have specific equipment needs?

8.1.2.2 Can the model be used with existing equipment?

8.1.2.3 Is a special computer required for the model?

8.1.3 *Calibration and Verification:*

8.1.3.1 Is a calibration required?

8.1.3.2 Is verification required?

8.1.3.3 What types of sources are required for model calibration or verification, or both?

8.1.3.4 Is a calibration or a verification source available?

8.1.4 *Costs:*

8.1.4.1 Does software need to be purchased? What are the licensing requirements for the software?

8.1.4.2 Does the equipment require the use a computer for new software?

8.1.4.3 Is it necessary to purchase and maintain new calibration sources?

8.1.4.4 How much time is needed to use the models to analyze the items?

8.1.5 *Ease of Use:*

8.1.5.1 Does calibration require extensive measurements or calculations?

8.1.5.2 Does the model require extensive, complex calculations?

8.1.5.3 If the model requires software, are preloaded templates available?

8.1.5.4 If the model requires software, how complex is the software to use?

8.1.5.5 Are personnel experienced with the modeling technique?

8.1.6 *Availability of Technical Support:*

8.1.6.1 Have there been publications on the development of the model?

8.1.6.2 Have users published results using the model?

8.1.6.3 Are there technical support personnel or further training (or both) available?

8.1.7 *Quality Assurance Requirements:*

8.1.7.1 Does the model require validation by the user?

8.1.7.2 Is the model industry accepted?

8.1.7.3 If software is required, has it been quality tested by the vendor?

8.1.7.4 What is the acceptable measurement uncertainty and which model is most likely to provide an uncertainty estimate within those limits?

8.2 Table 1, located at the end of this guide, presents a brief description of the measurement needs, equipment needs regarding collimators, calibration, and typical uses of each model described in Section 7. This table is presented to assist in the comparison of the models presented.

9. Validation

9.1 Several steps are necessary to validate the measurement process; however, the following steps may not be applicable to every model discussed in this guide.

9.1.1 Software must be validated by the vendor.

9.1.2 Prepare a working standard by placing well-characterized material in a matrix that simulates the measurement item. Care must be taken that the validation matrix reasonably matches the item being modeled.

9.1.2.1 Select a representative shape for the model. Rarely will an exact shape be practical, so simplified shapes are normally used. For example, there may be a pipe shape but the actual pipe being measured may have fittings that are different in size; or the shape may assume a perfectly cylindrical container but the actual container has stiffening rings and closure mechanism. Evaluate these differences between the real and the measured item to assure that the measurement objectives can be met, and to properly assign a total measurement uncertainty to the result.

9.1.2.2 Improve the validation by measuring the item with the detector positioned at several locations (heights angles, slants). If the item can be rotated, then the activity within the item may “appear” to be distributed more homogeneously.

TABLE 1

Model	Ease of Use	Source Geometries	Radionuclide Distribution	Collimator	Calibration	Near-Field Possible	Typical Use
Generalized Geometry Holdup	Easy	Point Line Area	Homogeneous	Fixed Cylindrical	Multi-Point, Gamma-Ray Specific	No	1-2 isotopes in homogeneously distributed matrix
Far-Field Approximation	Moderate	Cylinder Box Point Disc	Homogeneous	Variable Cylindrical	Single-Point, Multi-Line	No	Unknown radionuclide composition in homogeneously distributed matrix
Voxel-Intrinsic Detector Efficiency	Moderate	Cylinder Box Point Disc	Homogeneous	Variable Cylindrical	Single-Point, Multi-Line	Yes	Unknown radionuclide composition in homogeneously distributed matrix
Radiation Transport Code	Difficult	Any	Any	Any	Model Validation	Yes	Unknown radionuclide composition in highly complex measurement situations
Hybrid Monte Carlo	Moderate	Most commonly encountered geometries	Homogeneous within segment, multiple segments can be used	Variable cylindrical, conical, rectangular prism	Detector characterization is performed by manufacturer	Yes	Unknown radionuclide composition in simple to moderately complex measurement situations

9.1.3 Attenuation corrections can be checked by observing the computed activity from several gamma rays of different energies emitted from the same radionuclide. If the attenuation corrections were applied properly, then the same results (within statistical deviation) should be obtained from any of the gamma rays.

9.1.4 Destructive analysis of an item previously measured, if feasible, is an alternative method to validate modeling.

10. Precision and Bias

10.1 Items affecting precision and bias are explained in the Technical Hazard Section. Precision and bias values to an item measurement should be applied on a case by case situation.

11. Keywords

11.1 efficiency calibration; far-field approximation; generalized geometry holdup; infinite plane; nondestructive assay; radiation transport modeling; spectroscopy; voxel-intrinsic efficiency

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