Designation: C1718 – 10 (Reapproved 2019)

Standard Test Method for Nondestructive Assay of Radioactive Material by Tomographic Gamma Scanning[1]

This standard is issued under the fixed designation C1718; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method describes the nondestructive assay (NDA) of gamma ray emitting radionuclides inside containers using tomographic gamma scanning (TGS). High resolution gamma ray spectroscopy is used to detect and quantify the radionuclides of interest. The attenuation of an external gamma ray transmission source is used to correct the measurement of the emission gamma rays from radionuclides to arrive at a quantitative determination of the radionuclides present in the item.

1.2 The TGS technique covered by the test method may be used to assay scrap or waste material in cans or drums in the 1 to 500 litre volume range. Other items may be assayed as well.

1.3 The test method will cover two implementations of the TGS procedure: *(1)* Isotope Specific Calibration that uses standards of known radionuclide masses (or activities) to determine system response in a mass (or activity) versus corrected count rate calibration, that applies to only those specific radionuclides for which it is calibrated, and *(2)* Response Curve Calibration that uses gamma ray standards to determine system response as a function of gamma ray energy and thereby establishes calibration for all gamma emitting radionuclides of interest.

1.4 This test method will also include a technique to extend the range of calibration above and below the extremes of the measured calibration data.

1.5 The assay technique covered by the test method is applicable to a wide range of item sizes, and for a wide range of matrix attenuation. The matrix attenuation is a function of the matrix composition, photon energy, and the matrix density. The matrix types that can be assayed range from light combustibles to cemented sludge or concrete. It is particularly well suited for items that have heterogeneous matrix material and non-uniform radioisotope distributions. Measured transmission values should be available to permit valid attenuation corrections, but are not needed for all volume elements in the container, for example, if interpolation is justified.

1.6 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

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

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

2. Referenced Documents

2.1 *ASTM Standards:*[2]

C1030 Test Method for Determination of Plutonium Isotopic Composition by Gamma-Ray Spectrometry

C1128 Guide for Preparation of Working Reference Materials for Use in Analysis of Nuclear Fuel Cycle Materials

C1156 Guide for Establishing Calibration for a Measurement Method Used to Analyze Nuclear Fuel Cycle Materials

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

C1592/C1592M Guide for Making Quality Nondestructive Assay Measurements (Withdrawn 2018)[3]

C1673 Terminology of C26.10 Nondestructive Assay Methods

[1] This test method 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.

Current edition approved Feb. 1, 2019. Published February 2019. Originally approved in 2010. Last previous edition approved in 2010 as C1718 – 10. DOI: 10.1520/C1718-10R19.

[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] The last approved version of this historical standard is referenced on www.astm.org.

2.2 *ANSI Standards:*[4]

ANSI N15.37 Guide to the Automation of Nondestructive Assay Systems for Nuclear Materials Control

2.3 *Nuclear Regulatory Commission (NRC) Guides*[5]

NRC Guide 5.9 Guidelines for Germanium Spectroscopy Systems for Measurement of Special Nuclear Material, Revision 2, December 1983

NRC Guide 5.53 Qualification, Calibration, and Error Estimation Methods for Nondestructive Assay, Revision 1, February 1984

3. Terminology

3.1 *Definitions:*

3.1.1 Terms shall be defined in accordance with Terminology C1673 except for the following:

3.1.2 *Algebraic Reconstruction Technique (ART), n*—image reconstruction technique typically used in the TGS method to obtain the transmission map as a function of atomic number (Z) and gamma ray energy (**1**).[6]

3.1.3 *aperture, n*—the terminology applies to the width of the detector collimator. In the case of a diamond collimator, the aperture is defined as the distance between the parallel sides of the diamond. In some designs, the detector collimator can be a truncated diamond that consists of flat trim pieces at the left and right corners of the diamond. This type of collimator is usually designed with the distance between the trim pieces set equal to the distance between the parallel surfaces (aperture).

3.1.4 *voxel, n*—volume element; the three-dimensional analog of a two-dimensional pixel. Typically 5 cm on a side for a 208 L drum.

3.1.4.1 *Discussion*—The full container volume will be divided into a number of smaller volume elements (typically 100–2000 or typically 0.1 % of the total container volume), which are not necessarily rectilinear.

3.1.5 *Beers Law, n*—the law states that the fraction of uncollided gamma rays transmitted through layers of equal thickness of an absorber is a constant. Mathematically, Beer's Law can be expressed as follows:

$$T = \frac{I}{I_0} = exp\left\{-\frac{\mu}{\rho}\cdot\rho\cdot t\right\}$$

In the above equation, I_0 is the intensity of a pencil beam of gamma rays incident on a uniform layer of absorber, I is the transmitted intensity through the layer, μ/ρ is the mass attenuation coefficient of the absorber material, ρ is the density of the absorber and t is the thickness of the layer. For a heterogeneous material the exponent would be integrated along the ray path.

3.1.6 *expectation maximization (EM), n*—image reconstruction technique typically used in the TGS method to solve for the emission map as a function of gamma ray energy (**2, 3**).

3.1.7 *grab (or view), n*—a single measurement of the scan, where the scan sequence consists of measurements at various heights, rotational positions, and translation positions of the assay item.

3.1.8 *map (transmission and emission), n*—a voxel by voxel record of the matrix density or linear attenuation coefficient (transmission map) or a voxel by voxel record of radionuclide content (emission map).

3.1.9 *material basis set (or MBS), n*—the method where the linear attenuation coefficient map for a matrix material is determined in terms of 2 or 3 basis elements that span the Z range of interest (**4**).

3.1.10 *non-negative least squares (NNLS), n*—constrained least squares fitting algorithm used in TGS analysis to obtain an initial estimate of the transmission map.

3.1.11 *pre-scan, n*—a preliminary scan of an assay item employed by some TGS implementations to optimize the scan protocol on an item-by-item basis.

3.1.12 *scan, n*—sequence of measurements at various heights, rotational positions, and translation positions of the assay item.

3.1.13 *response function, n*—detector efficiency (absolute or relative) as a function of measurement locus and gamma ray energy.

3.1.14 *tomography, n*—the mathematical method in which gamma ray measurements are used to determine the attenuation and emission characteristics of an item on a voxel-by-voxel basis.

3.1.15 *translation, n*—the relative motion in the horizontal direction of the item to be measured perpendicular to the transmission source-detector axis.

3.1.16 *TGS Number, n*—uncalibrated result of a TGS analysis representing count rate corrected for geometrical efficiency, gamma ray attenuation, and rate loss at a given emission gamma ray energy, proportional to the mass or activity of a specific radionuclide.

3.1.17 *view, n*—see *grab*.

4. Summary of Test Method

4.1 Assay of the radionuclides of interest is accomplished by measuring the intensity of one or more characteristic gamma rays from each radionuclide utilizing TGS techniques. TGS techniques include translating, rotating and vertically scanning the assay item such that a 3-dimensional (3D) image can be reconstructed from the data. Generally two 3D images are constructed; a transmission image and a passive emission image. Corrections are made for count rate-related losses and attenuation by the matrix in which the nuclear material is dispersed. The calibration then provides the relationship between observed gamma ray intensity and radionuclide content.

4.2 Calibration is performed using standards containing the radionuclides to be assayed or using a mixture of radionuclides emitting gamma rays that span the energy range of interest. The activities or masses of the radionuclides and the gamma ray yields are traceable to a national measurement database.

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

[5] Available from U.S. Nuclear Regulatory Commission, Washington, DC 20555-0001, http://nrc.gov.

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

4.2.1 Using a traceable mixed gamma ray standard that spans the energy range of interest will enable the determination of the TGS calibration parameters at any gamma ray energy of interest, not just those that are present in the calibration standard. A calibration curve is generated that parameterizes the variation of the TGS calibration factor as a function of gamma ray energy.

4.3 The assay item is rotated about its vertical axis. Concurrently, the relative position of the assay item and detector are translated. This is repeated for every vertical segment. During this process, a series of measurements (grabs) are taken of gamma rays corresponding to the transmission source and the emission sources. A transmission scan is performed with the transmission source exposed. A separate emission scan is performed with the transmission source shielded.

4.3.1 From the transmission measurements, a 3D map of the average linear attenuation coefficient across of each voxel is determined.

4.3.2 From the emission measurements, a 3D map of the location of the gamma emitting radionuclides is determined. These 3D maps are typically low spatial resolution (for example, approximately 1/10 th the diameter would be a typical characteristic dimension).

4.3.3 Through a voxel by voxel application of Beer's Law, the emission source strength is corrected for the attenuation of the matrix material.

4.4 Count rate-dependent losses from pulse pile-up and analyzer deadtime are monitored and corrected.

4.5 The TGS determines an estimate of the average attenuation coefficient of each voxel in a layer of matrix using an over determined set of transmission measurements.

4.6 A collimator is used in front of the detector to restrict the measurement to a well-defined solid angle.

4.7 The TGS technique assumes the following item characteristics:

4.7.1 The particles containing the radionuclides of interest are small enough to minimize self-absorption of emitted gamma radiation. Corrections to self-attenuation may be applied post TGS analysis, but is outside the scope of this standard.

4.7.2 The mixture of material within each item voxel is sufficiently uniform that an attenuation correction factor, computed from a measurement of gamma ray transmission through the voxel, is appropriate.

4.8 Typically, a single isotope of an element is measured, therefore when the total element mass is required, it is necessary to apply a known or estimated radionuclide/total ratio to the radionuclide assay value to determine the total element content (see Test Method C1030).

5. Significance and Use

5.1 The TGS provides a nondestructive means of mapping the attenuation characteristics and the distribution of the radionuclide content of items on a voxel by voxel basis. Typically in a TGS analysis a vertical layer (or segment) of an item will be divided into a number of voxels. By comparison, a segmented gamma scanner (SGS) can determine matrix attenuation and radionuclide concentrations only on a segment by segment basis.

5.2 It has been successfully used to quantify ^{238}Pu, ^{239}Pu, and ^{235}U. SNM loadings from 0.5 g to 200 g of ^{239}Pu (**5**, **6**), from 1 g to 25 g of ^{235}U (**7**), and from 0.1 to 1 g of ^{238}Pu have been successfully measured. The TGS technique has also been applied to assaying radioactive waste generated by nuclear power plants (NPP). Radioactive waste from NPP is dominated by activation products (for example, ^{54}Mn, ^{58}Co, ^{60}Co, ^{110m}Ag) and fission products (for example, ^{137}Cs, ^{134}Cs). The radionuclide activities measured in NPP waste is in the range from 3.7E+04 Bq to 1.0E+07 Bq. Some results of TGS application to non-SNM radionuclides can be found in the literature (**8**).

5.3 The TGS technique is well suited for assaying items that have heterogeneous matrices and that contain a non-uniform radionuclide distribution.

5.4 Since the analysis results are obtained on a voxel by voxel basis, the TGS technique can in many situations yield more accurate results when compared to other gamma ray techniques such as SGS.

5.5 In determining the radionuclide distribution inside an item, the TGS analysis explicitly takes into account the cross talk between various vertical layers of the item.

5.6 The TGS analysis technique uses a material basis set method that does not require the user to select a mass attenuation curve apriori, provided the transmission source has at least 2 gamma lines that span the energy range of interest.

5.7 A commercially available TGS system consists of building blocks that can easily be configured to operate the system in the SGS mode or in a far-field geometry.

5.8 The TGS provides 3-dimensional maps of gamma ray attenuation and radionuclide concentration within an item that can be used as a diagnostic tool.

5.9 Item preparation is limited to avoiding large quantities of heavily attenuating materials (such as lead shielding) in order to allow sufficient transmission through the container and the matrix.

6. Interferences

6.1 Radionuclides may be present in an item that produce gamma rays with energies the same as or very nearly equal to the gamma rays of the radionuclide to be measured or of the transmission source. There may be instances where emission gamma rays from multiple radionuclides interfere with one another or with a gamma ray present in the background. A few examples are given below:

6.1.1 *Interference with Transmission Gamma Rays:*

6.1.1.1 In TGS systems where an ^{152}Eu source is used as the transmission source, one has to consider the following interferences while assaying plutonium containing waste drums. *(1)* Transmission data from the 121.78 keV gamma ray from ^{152}Eu may be affected by Pu K-Xrays. The interference can be corrected by subtracting the emission background from the