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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.

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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] 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

transmission spectra on a view by view basis. *(2)* Transmission data from the 411.2 keV gamma ray from ^{152}Eu may be affected by the 413.7 keV gamma ray peak from ^{239}Pu. In such cases, the 411.2 keV can be used to calculate transmission only if the emission background has been subtracted. *(3)* Transmission data from the 344.28 keV gamma ray from ^{152}Eu may be affected by the 345.01 keV gamma ray peak from ^{239}Pu. However, the 344.28 keV peak from ^{152}Eu has a relatively high yield and the interference from the ^{239}Pu gamma ray may be negligible. Subtracting the emission background on a view by view basis will eliminate the bias.

6.1.1.2 In the special case of single pass assays (emission and transmission data collected together) of ^{239}Pu waste using ^{75}Se as a transmission source, random coincident summing of the 136.00 and 279.53-keV gamma ray emissions from ^{75}Se produces a low-intensity peak at 415.5-keV that could interfere with the 413.7 keV ^{239}Pu peak. The effects of this sum-peak can be reduced by attenuating the radiation from the transmission source to the lowest intensity required for transmission measurements of acceptable precision. The problem can be avoided entirely by making a two-pass assay, one pass with the transmission shutter open and another pass with the shutter closed.

6.1.2 *Interference among Emission Gamma Rays:*

6.1.2.1 In waste items containing ^{137}Cs and ^{241}Am, the 661.6 keV gamma ray from ^{137} Cs and the 662.4 keV gamma ray from ^{241}Am can interfere with each other. The 721.9 keV gamma ray of ^{241}Am may be useful as an alternative as well as for extracting the 662.4 keV peak area based on branching ratios and detector response. Thereafter, the 661.6 keV peak from ^{137}Cs can be corrected for interference.

6.1.2.2 The 415.8 keV gamma ray from the daughter decay of ^{237}Np can interfere with the 413.7 keV gamma ray of ^{239}Pu. In addition, there are several other gamma rays in the 300–400 keV region. Peaks from these gamma rays could interfere with the 413.7 keV ^{239}Pu peak and several other often-used peaks produced by ^{239}Pu gamma rays. The 129.3 keV gamma ray may be used as a reasonable alternative, if attenuation at this energy will not preclude analysis or substantially decrease precision due to poor counting statistics.

6.1.3 *Interference from Ambient Background:*

6.1.3.1 Peaks may appear at the gamma ray energies used for analysis when there is no item present on the rotating/translating platform. The likely cause is excessive amounts of radioactive sources or waste containers stored in the vicinity of the detector. The preferred solution to this problem is removal of the radioactive sources from the vicinity and restraining the movement of sources close to the system during measurements. If these conditions cannot be met, shielding must be provided to sufficiently eliminate these peaks. Shielding opposite the detector, on the far side of the item to be assayed, will also help reduce the amount of ambient radiation seen by the detector. The ambient background measurement must be taken (following the normal TGS assay protocol) with an item with a representative non-radioactive matrix loaded on to the turntable.

6.1.4 The background contributions can be subtracted during the TGS analysis. The emission background can be subtracted from transmission data, and the ambient background can be subtracted from the emission data. The two types of background subtractions are performed on a view by view basis.

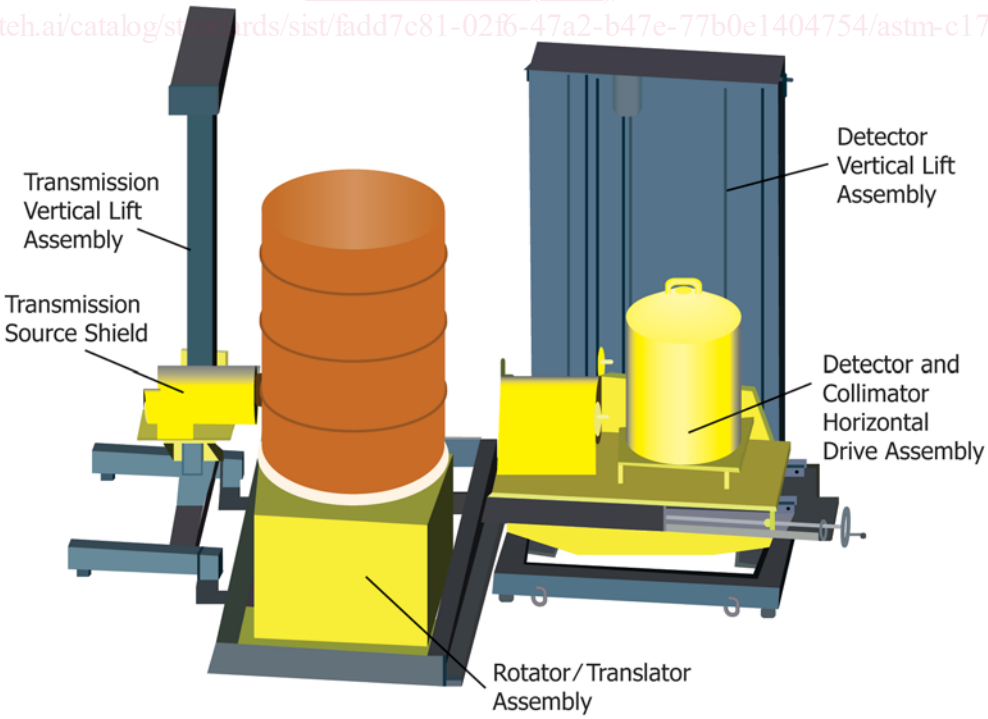

FIG. 1 Example of a Tomographic Gamma Scanning System

7. Apparatus

7.1 In Fig. 1, the detector assembly is on the right hand side and the transmission assembly is to the left. The translating (and rotating) platform with the item loaded on it is shown in the middle. General guidelines for the selection of detectors and signal processing electronics are discussed in relevant operations manuals and NRC Guide 5.9. Data acquisition systems are considered in ANSI N15.37 and NRC Guide 5.9.

7.2 Complete hardware and software systems for TGS, of both large and small items, are commercially available. The specification and procurement of the hardware and software should follow a careful evaluation of the measurement quality objectives, expected materials to be assayed, and associated system costs. This evaluation should be completed by an NDA professional (Guide C1490). The system should have the following components:

7.2.1 *High-resolution, high purity germanium detector*—Detector resolution and efficiency shall be appropriate for the user's specific application and needs as determined by an NDA professional (Guide C1490).

7.2.2 *Detector collimator*—The detector collimator opening shall be a reasonable compromise between spatial resolution and counting statistics, judged against the measurement objective. The count rate per grab of the TGS can be improved by using a wider collimator or a higher efficiency detector.

7.2.3 *External source of gamma rays from a transmission source*—An external source shall be used to interrogate the item and characterize the attenuation properties of matrix. (See Table 1 for suggested sources). The count rate per grab of transmitted gamma rays can be improved by using a transmission source of higher intensity.

7.2.4 *Motorized scanning system*—the items shall be scanned over three axes of motion relative to the detector (usually vertical translation, horizontal translation, and rotation about a vertical axis).

7.2.5 *Tomographic reconstruction algorithms*—TGS reconstruction algorithms shall be employed to determine a three-dimensional map of matrix density and radionuclide distribution.

7.3 *Rate-Loss Correction Source or a Pulser*—A ^{109}Cd source is commonly used as the reference source for performing rate loss corrections. Alternatively, a high precision pulser may be used for the same purpose. When a pulser is used, care needs to be taken in the set-up to avoid spectral distortion.

7.4 *Software*—The system should include one or more software tools for the collection of data, motion control of the system, and analysis of data. The system may include tools for performing isotopic data collection and analysis.

7.5 In two-pass assays, transmission gamma rays can be significantly attenuated by using a shutter made out of a high Z material.

7.6 To attenuate the X-rays from high Z collimator and shield material, the inner walls of the collimator and shield as well as the front face of the detector may be lined with a "graded shield" made of a layer of Sn and a layer of Cu.

TABLE 1 Commonly Used Transmission Source and Assay Radionuclide Combinations

Radionuclide of Interest	Peak Energy (keV)	Transmission Source	Peak Energy (keV)
^{235}U	185.7	^{169}Yb	177.2
			198.0
^{238}Pu	152.7	^{75}Se	136.0
	766.4		400.1
^{238}Pu	152.7	^{152}Eu	121.8
	766.4		244.7
			344.3
			411.1
			778.9
^{239}Pu	129.3	^{75}Se	121.1
	203.6		136.0
	345.0		264.7
	375.1		279.5
	413.7		400.1
^{239}Pu	129.3	^{152}Eu	121.8
	203.6		244.7
	345.0		344.3
	375.1		411.1
	413.7		
^{239}Pu	129.3	^{57}Co	122.1
			136.5
^{137}Cs	661.6	^{152}Eu	411.1
			778.9
^{54}Mn	834.8	^{152}Eu	778.9
			867.4
			964.1
^{60}Co	1173.2	^{152}Eu	964.1
	1332.5		1112.1
			1408.0

8. Preparation of Apparatus

8.1 Perform calibrations using the same procedures and conditions that will be used for the assays of actual items. These include, but are not limited to, electronic components, peak area determination procedures, procedures for the determination of counting losses, voxel sizes, absorber foil combinations, collimator arrangements, and measurement geometries. Changing conditions will change the calibrations. Some commercial systems may allow certain parameters to change (for example, aperture, distance from item surface to detector, etc.) and allow the corresponding calibration factors to be selected.

8.2 Adjust the instrument controls to optimize signal processing and peak analysis functions. Choose the shaping time constant to optimize the trade-off between improved resolution with longer time constants and decreased dead time losses with shorter time constants. Time constants of 4 to 8 μs are commonly used for analog pulse processing electronics. If a digital signal processor is used, select filter settings equivalent to the above-mentioned analog shaping times. Follow the manufacturer's instructions for setting time constants or filter settings.

8.3 Set the conversion gain on the analog-to-digital converter (ADC). Adjust the amplifier gain. Perform pole-zero

cancellation (if a resistive feed-back pre-amplifier is used). Set up a restore rejection veto (reset inhibit) if a transistor reset pre-amplifier is used. Perform an energy and shape calibration of the detector. If a pulser is used for performing rate loss corrections, ensure that the amplitude and frequency of the pulses are set to the appropriate values. A significant advantage in using a pulser as opposed to a rate loss source is that the pulser peak can be placed at an energy where it will not interfere with the gamma ray peaks of interest.

8.4 *Pile-up at high rates*—Pulse pile-up can distort peak shapes and can bias the counts registered in the regions of interest (ROI) in the gamma ray spectra. The TGS technique relies on the counts in the ROIs to determine the transmission and emission maps. It is important to eliminate pulse pile-up. Pile-up rejection circuitry in the amplifier should be enabled to do this.

8.5 Set up the data acquisition and analysis software. Typically, the data acquisition software will interface with mechanism control hardware (stepper motors, DC motors, etc.) in order to ensure that the item is scanned properly. Additionally, the data acquisition software may also have the capability to automatically set an appropriate assay geometry (detector horizontal position, detector collimator aperture, etc.) based on drum dose rate or dead time. In such cases, the parameters for the assay geometry must be entered into the control software. The acquisition software also interfaces with the pulse processing electronics and the system computer to acquire data for a preset time, and store the data.

8.6 Choose collimator sizes that are appropriate to the item type to be assayed.

8.6.1 Collimator aperture must be selected based on *(1)* the distance of the container from the detector, *(2)* the count rate level (or surface dose rate of the container), *(3)* scanning diameter of the assay, and *(4)* the desired voxel grid.

8.6.2 The farther the detector is with respect to the container, the narrower the collimator aperture should be. For TGS systems used in industrial facilities, for a 208 litre drum where the outer surface is at a distance of 500 mm from the detector, a collimator aperture of 60 mm would be typical. If a 208 litre drum is at a distance of 1000 mm from the detector, a collimator aperture of 40 mm would be typical. For TGS systems used in a research facility, for assaying 208 litre drums, the distance from the surface of the drum to the detector is typically 200 mm.

8.6.3 The higher the surface dose rate of the container, the farther the detector should be, and narrower the collimator aperture. This should be done to maintain the spatial resolution, as well as to remain below the upper limit of the dynamic count rate range of the detector.

8.6.4 The collimator aperture is typically set 1 to 1.5 times the length of the voxel, based on sensitivity and precision in a given acquisition time.

8.7 Set up ROIs around gamma ray peak energies of interest for emission as well as transmission scans. For each peak, set up ROIs to cover the peak region and the continuum regions to the left and right of the peak. ROIs around peaks to be used for analysis may be set manually by the operator or semi-automatically by the computer or analyzer, depending on the software package used.

8.8 Set up the number of vertical layers over which the item will be scanned. For a 208 litre or a 300 litre drum, the number of vertical layers to be scanned is normally 16.

8.9 Set up acquisition and analysis software to perform the desired number of data acquisition grabs per scan and the assay time per scan. Also set up the software to analyze the data over the desired voxel grid.

8.10 Typically for a 208 litre drum, for a nominal 1h assay period, about 112 seconds are spent acquiring data at each of the 16 layers in each of the two modes (transmission and emission). Each layer is broken into a 10 × 10 lattice of square voxels (Fig. 2). By convention, based on signal-to-noise and robustness of the analysis arguments, the number of data grabs is set at 1.5 times the number of voxels (that is, roughly π/2 times the number of voxels that fit around the drum perimeter). Therefore for each of the 16 vertical layers, 150 measurements are made in order to mathematically over determine the solution for 88 voxels in the 10 × 10 grid in each layer (assuming all data grabs are valid).

8.10.1 Count time for each view (or grab), should be set based on considerations of counting precision and the overall assay time for the measurement requirement.

8.10.2 The number of views per scan per layer must be greater than the number of voxels in the grid per layer (typically 1.5 times greater, based on sampling theory).

9. Calibration and Reference Materials

9.1 Calibration of a TGS system relies on measurements of well-characterized reference materials containing known amounts of appropriate radionuclides. The radionuclide sources used are calibration standards whose activities or masses are traceable to a national measurements database. The calibration standards are distributed within a container with a well-characterized matrix. Such a configuration is called a reference material in this document. A TGS system calibrated using reference materials can be used to quantify radionuclides in items. A facility may use a “working reference” to calibrate the system if the objective is to track the relative performance of the TGS system for quality assurance purposes. A facility can create a working reference by distributing radionuclide sources, that are not calibration standards, inside a representative container matrix. A TGS system can be calibrated using calibration standards that contain: *(1)* only those radionuclides that are of interest in the item assays (isotope specific calibration), *(2)* radionuclides that are not necessarily of interest in the item assays but consist of gamma lines spanning the energy range of interest, and *(3)* a mixture of radionuclides that are of interest in item assays as well as those that are not expected in item assays. Calibration standards can consist of SNM radionuclides only, non-SNM radionuclides only, or a mixture of SNM and non-SNM radionuclides. Guides C1156 and C1592/C1592M provide additional information useful in developing and executing a calibration plan.

9.2 *Calibration:*