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Segmented Gamma Scanner for Radioactive Waste Assessment: A User Guide

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July 2024

OAK RIDGE National Laboratory

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Nuclear Nonproliferation Division

SEGMENTED GAMMA SCANNER FOR RADIOACTIVE WASTE ASSESSMENT: A USER GUIDE

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ABBREVIATIONS

HPGe	high-purity germanium
NDA	nondestructive assay
QA/QC	quality assurance and quality control
SGS	segmented gamma scanner
SWB	standard waste boxes
TDOP	ten-drum overpacks

EXECUTIVE SUMMARY

Radioactive waste assessment is important for ensuring nuclear material security at various types of facilities, such as enrichment, fuel fabrication, and reprocessing plants. The waste generated at such nuclear facilities is stored in standard containers and is required to be characterized for material-accounting purposes. The segmented gamma scanner system is a popular, nondestructive analysis measurement system used for characterizing nuclear material, including radioactive waste. This document provides guidance on how to achieve effective performance from a segmented gamma scanner system for accurately quantifying fission products, activation products, and transuranic wastes.

1. INTRODUCTION

The objective of radioactive waste assay is to measure waste items, quantify the activities or masses of radionuclides present in the items, and assess the total measurement uncertainties. This assessment allows for the comparison of results with regulatory limits and facilitates the determination of appropriate waste disposal methods. Radioactive waste assessment is equally important for upholding nuclear material security. Waste generated at nuclear facilities is stored in standard containers and requires characterization for material-accounting purposes. This assessment is crucial for the accurate management of nuclear materials, especially in enrichment, fuel fabrication, and reprocessing facilities, where detecting unauthorized access or theft is paramount.

Nondestructive assay (NDA) techniques play an important role in the waste-assessment process, and NDA systems measuring neutron, gamma, or heat signatures emitted by radioactive waste are commonly deployed. The selection of the most suitable NDA system for a waste stream depends on various factors, including the expected radionuclides in the waste stream, data quality objectives, acceptance criteria, fitness for purpose, and cost. This document outlines measurement and analysis steps for performing an NDA of radioactive waste using gamma spectrometry.

NDA systems that use gamma spectrometry have the advantage of providing isotope-specific information. Waste items containing numerous fission products and activation products require an assessment using a gamma-based NDA system, which is capable of identifying the radionuclides and quantifying their activities or masses. In systems measuring only gamma rays emitted by radionuclides (emission only), the geometry correction and container as well as matrix attenuations are determined using a multi-density efficiency calibration.

Some gamma NDA systems use transmission measurements to assess the container and matrix attenuations, which are then applied to the count rates in the full energy peaks in the gamma-ray spectrum. Most gamma-based NDA systems can operate in emission-only mode or emission and transmission mode.

For comprehensive characterization of a waste item, both neutron and gamma measurements are often necessary. Neutron counting determines the ^{235}U mass or $^{240}Pu_{equivalent}$ mass, whereas gamma-ray measurements ascertain the abundances of uranium and plutonium isotopes. The results from neutron and gamma measurements are subsequently combined to provide isotope-specific quantification of uranium or plutonium content in the waste.

Radioactive waste is typically packaged by processing facilities in standard containers. In the United States, the typical container types and their maximum numbers during a transport used for packaging transuranic waste are as follows [1]:

- 55 gal (208 L) drums: 14
- Standard waste boxes (SWBs): 2
- SWBs, each containing one bin: 2
- SWBs, each containing four 55 gal drums: 2
- Ten-drum overpacks (TDOP) containing ten 55 gal drums: 1
- TDOP containing one SWB: 1
- TDOP containing one bin within an SWB: 1
- TDOP containing four 55 gal drums within an SWB: 1

This document will serve as a guide for performing radioactive waste assay using a segmented gamma scanner (SGS) [2]. The SGS is a commonly employed NDA system for the assay of radioactive materials in drums. Typically, a 55-gal drum is used for packaging waste. The measurement steps and practices outlined in this document can be extended to other types of gamma spectrometry–based waste assay systems, such as the box counter and Q2 system.

2. CLASSIFICATION OF RADIOACTIVE WASTE

Radioactive waste is typically classified according to standardized disposal procedures accepted worldwide, though with some variations in terminology among countries. Sections 2.1–2.4 outline the four major categories of radioactive waste.

2.1 REMOTE-HANDLED WASTE

Remote-handled waste is typically defined as waste that has a dose rate of greater than 200 mR/h (2 mSv/h) on its surface. This waste may contain transuranic wastes.

2.2 TRANSURANIC, ALPHA, AND INTERMEDIATE-LEVEL WASTES

Transuranic waste, according to the US Department of Energy's Waste Acceptance Criteria [3], comprises materials contaminated with alpha-emitting transuranic radionuclides with half-lives greater than 20 years and concentrations greater than 100 nCi/g (3,700 Bq/g) at the time of measurement. Internationally, such waste is also called intermediate-level waste.

2.3 LOW-LEVEL WASTE

Low-level waste encompasses waste that is not categorized as transuranic and does not exceed certain concentration limits for specific nuclides. This waste includes items contaminated with radioactive material or that have become radioactive through exposure to neutron radiation, such as protective shoe covers and clothing, wiping rags, mops, filters, reactor water treatment residues, equipment, and tools. The radioactivity level can range from slightly above natural background to very high, such as the levels inside the reactor vessel in a nuclear power plant.

2.4 FREE-RELEASE WASTE

Free-release or very low-level waste criteria vary significantly across countries and undergo frequent changes. Although specific limits and terminology differ, measurement principles remain the same. For example, in Europe, the Basic Safety Standard has set release limit [4], whereas some countries use limits ranging from 0.4 to 50 Bq/g for very low-level waste.

3. RADIOACTIVE WASTE ASSAY USING A SEGMENTED GAMMA SCANNER SYSTEM

The SGS system consists of a collimated and shielded high-purity germanium (HPGe) detector, analog signal processing electronics (or a digital signal processor), and a highly collimated high-activity (several millicuries) transmission source to interrogate the drum matrix. Typically, a long-lived isotope, such as ^{152}Eu, is used as a transmission source and is aligned with the axis of symmetry of the HPGe detector. Between the detector and the transmission source assemblies is a rotating platform on which the waste drum is loaded before an assay. During the assay, the detector and transmission source move in harmonized, discrete steps. The assay item rotates about its vertical axis and is scanned segment by segment along that axis, thereby reducing the effects of nonuniformity in both matrix density and nuclide

distribution. Gamma-ray spectra are collected at each segment, with the transmission shutter open and closed. The system uses a reference pulser or a radioactive source to correct count rate–related losses. Also, correction factors are determined and applied for gamma-ray attenuation within the waste matrix. Subsequently, the appropriate mass or efficiency calibration establishes the relationship between observed gamma-ray intensity and nuclide content. Figure 1 illustrates a typical SGS system [5].

Figure 1. An SGS for assaying radioactive waste in a drum [5].

Two distinct calibration methods can be used for the SGS system:

- Isotope specific calibration: This method provides assay results solely for the radionuclides calibrated within the SGS. Calibration is performed using radionuclide standards, which need to be assayed.

- Efficiency curve calibration: This approach entails determining the system's detection efficiency as a function of gamma-ray energy and matrix density. The calibration curve, known as the multi-density efficiency curve, is used to infer the radionuclide from its gamma energy peaks and then calculating the radionuclide mass from the specific activity and the gamma emission intensity of the radionuclide as well as the corrected count rate and detector efficiency at the peak energy.

The SGS data can be acquired from both transmission and emission scans of the drum. Alternately, an emission-only scan of the drum can also be performed. In the dual mode, in which both transmission and emission data are acquired, the transmission measurements are used to determine the correction factor due to matrix attenuation using the well-known Parker formalism [6]. Many rotations are made per acquisition so that partial turns do not bias the assay when heterogeneous items are measured. In emission-only mode, the multi-density efficiency calibration curve is used to determine the gamma-ray peak efficiency as a function of energy and density.

The corrected gamma-ray count rates for the nuclides of interest are determined on a segment-by-segment basis. The precision of the measured count rate of each gamma ray used for analysis is also estimated on a segment-by-segment basis. At the completion of the measurement of all segments, corrected count rates are summed, and mass values for the nuclides of interest in the entire container are calculated based either on comparisons to appropriate calibration materials or from the gamma emission rates determined from the segment efficiencies determined over the energy range of interest. Based on counting statistics for individual segments, precision values are propagated to obtain the estimated precision of the analysis.

American Society for Testing and Materials Standard C1133 [7] is a good reference for applying the SGS method for waste assay.

4. MEASUREMENT PROCEDURE

Many of the procedural steps provided herein may be easily adapted to other types of gamma-based waste assay systems (such as the box counter).

4.1 SETTING UP AND OPTIMIZING MEASUREMENT PARAMETERS

Typically, a gamma spectrometry system consists of the following components: the detector, the high-voltage power supply, the preamplifier, the amplifier, the analog-to-digital converter, the multichannel analyzer, and an oscilloscope. A schematic of a typical gamma spectrometry system is provided in Figure 2.

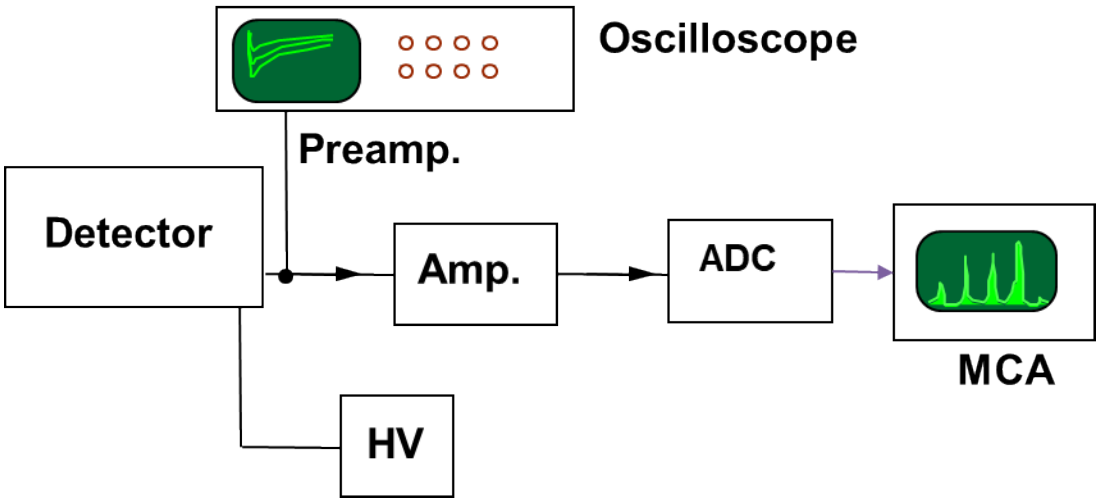

Figure 2. Components of a gamma spectrometer [8].

The pulse-processing electronics can be an analog or digital system. Digital signal processors are being increasingly used because of their portability and ease of set up. Except for the detector, all of the components shown in Figure 2 are available in one single integrated portable unit, with an operation and functionality that can be controlled by embedded software and firmware.

Follow these steps to set up and optimize the measurement parameters of the SGS:

1. Connect the gamma-ray detector and the electronic components used for pulse processing (Figure 2).

2. Adjust the instrument controls to optimize signal processing and peak analysis functions. Choose the shaping time constant or filter parameter to optimize the trade-off between improved resolution with longer time constants and decreased dead time losses with shorter time constants.

3. Set up the conversion gain of the analog-to-digital converter to an appropriate value so that enough channels will be included in the peak and the peaks that are closely spaced in energy will be resolved.

4. Adjust the system gain so that the gamma-ray peaks in the energy range of interest are present within the total number of multichannel analyzer channels selected.

5. Perform the pole-zero adjustment with an oscilloscope. Some of the modern digital multichannel analyzers have built in oscilloscopes that can be used conveniently for pole-zero adjustment. Perform the pole-zero adjustment until the output pulse from the amplifier (or the digital signal processor) neither undershoots nor overshoots the baseline. The pole-zero adjustment must be performed at a pulse height that corresponds to a channel number in the upper one-third of the spectrum. Proper adjustment of pole zero is necessary for good energy resolution, avoiding an increased dead time and maintaining the linearity of the pulse height spectrum. Figure 3 illustrates the scenarios of proper and improper adjustment of pole zero.

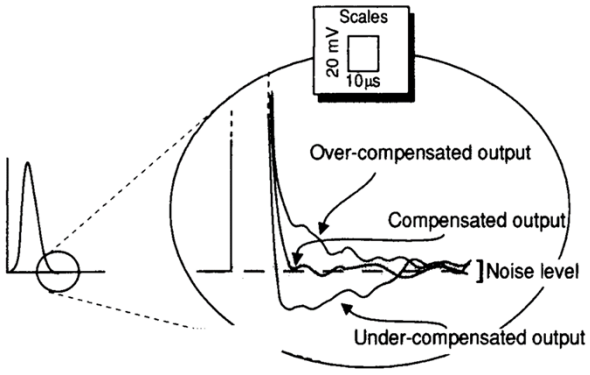

Figure 3. Pole-zero compensation [8].

6. Count rate losses due to pulse pileup must be corrected using a radioactive source or an electronic pulser. Use an electronic pulser because the reference peak can be adjusted to an energy in which there is no interference with gamma-ray peaks from the assay.

7. If a radioactive source is to be used as a reference for correcting count rate losses, then select a source whose gamma-ray peak does not interfere with the gamma-ray peaks from the assay. The reference source must be replaced when more than three half-lives have elapsed since its installation or at a more frequent interval if it is deemed necessary. Cadmium-109 is an example of a reference source used in many gamma-based waste assay systems. At the time of the assay, the source activity must be decay corrected when establishing the reference rate.

8. A two-point energy gain stabilization is preferable if such an option is available in the employed pulse-processing electronics.

9. To eliminate electronic noise interference, ensure that the cables that connect the detector and pulse-processing unit are sufficiently separated from other cables that connect to the electrical motors that enable mechanical movements of system components.

10. After the system set up is complete, perform an energy calibration using one or more radioactive sources that emit gamma rays that span the energy range of interest. For assaying waste, an energy range up to 3 MeV is recommended.

4.2 DETECTOR SHIELD AND COLLIMATOR

A gamma-based NDA system used in waste assay applications will typically be shielded and collimated. To attenuate lead or tungsten x-rays fluoresced from the collimator and shielding material, graded shielding is recommended. Liners made from tin and copper are used on the inner surfaces of the shield

and the collimator. The user should choose collimator sizes that are appropriate to the item type to be assayed. For example, for measuring waste in a 55 gal drum using an SGS system or a Q2 NDA system, a lead collimator with a thickness of 5.08 cm, and with dimensions (width × height × depth) of 25.4 cm × 10.16 cm × 20.32 cm is appropriate.

4.3 SEGMENTATION AND SCANNING

The following includes key notes about the segmentation and scanning process:

- To minimize the biases caused by matrix heterogeneity and nonuniformity of source distribution, a cylindrical item such as a 55 gal drum is rotated and scanned at several vertical segments.

- The user should choose scanning segment sizes that match the item and collimator sizes. In an SGS, the segment sizes are typically set to a value between the height of the collimator aperture and half the height of the collimator aperture.

- Box-shaped items are scanned horizontally, and the assay is performed at points along the length of the box. The number of horizontal segments and the number of collimated HPGe detectors required to adequately cover the entire volume of a large box, such as a B-25 or an SWB, depend on the length of the box. For assaying large items, more than one HPGe detector might be required to adequately cover the entire volume of the item and mitigate the bias due to nonuniformities. Figure 4 shows a gamma box counter system with two HPGe detectors on the side of a B-25 box [9].

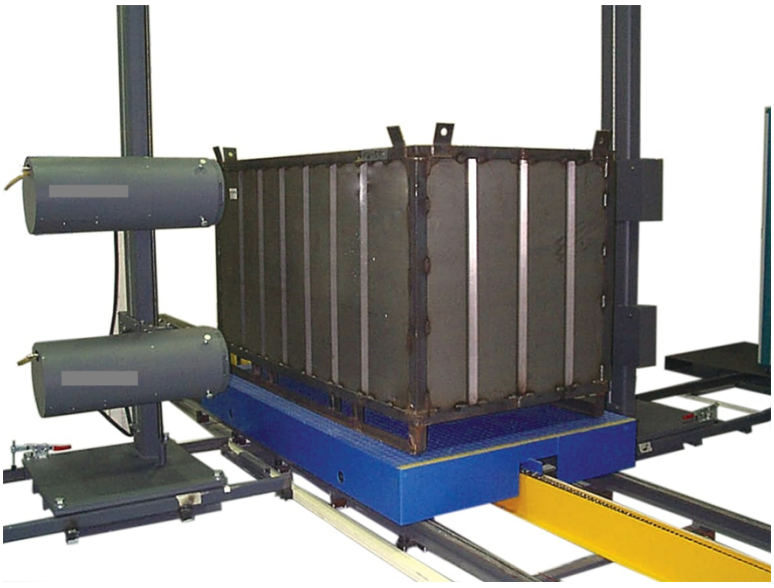

Figure 4. Gamma box counter for assaying a B-25 box [9].

- For drum scanning systems, such as the SGS system, the vertical scan at each segment is performed in two passes: (1) with the transmission source exposed and (2) an emission only scan with the transmission source shuttered.

4.4 TRANSMISSION SOURCE

Users should be aware of the following information about the transmission source:

- The transmission source strength is selected so the gamma rays penetrate the measurement item and provide reasonable counting precision. Consequently, it is typically considerably stronger than the count rate correction source to perform effectively.

- For assaying waste in 55 gal drums using an SGS, a source strength of 10–50 mCi is typically sufficient if the density of the item to be assayed is approximately 1 g/cm^3 or less. If items with higher densities are expected to be assayed (e.g., up to 2 g/cm^3), then the transmission source activity must be higher (e.g., 300 mCi). A higher activity source will entail increased shielding to mitigate the radiological hazard.

- Transmission source shields reduce radiation exposure to workers and collimate the radiation from the transmission source to a narrow region containing the detector.

- If an assay system is to be calibrated for multiple radionuclides, select a transmission source that has multiple gamma-ray energies (with appropriate relative intensities) and use a suitable method to determine transmissions at the radionuclide analysis energies. For waste assay systems, ^{152}Eu and ^{133}Ba are good choices for a transmission source because they emit gamma rays at multiple energies and are relatively long-lived.

- The count rate of a new source may be attenuated by collimation, absorbers directly in front of the source, source-to-detector spacing, or some combination thereof.

- In assays where gamma-ray peaks from the transmission source interfere with determination of the area of the gamma-ray peak used for nuclide analysis, peak-fitting software may be able to resolve the overlap.

- As a safety consideration, design shutters so that in the event of a power failure the shutters will automatically shield the radiation beam from the transmission source.

5. CALIBRATION

In addition to the energy calibration, a waste assay system requires a few other types of calibrations to generate the desired assay results:

- Reference peak calibration
- Transmission calibration
- Efficiency calibration

More guidance on these calibrations is provided in Sections 5.1–5.3.

5.1 REFERENCE PEAK CALIBRATION

Follow these steps to complete the reference peak calibration:

1. Acquire a spectrum with only the rate loss source, either the radioactive source or an electronic pulser (i.e., without other gamma-ray sources in the vicinity of the detector). With the acquisition and analysis software, establish the reference count rate at the appropriate energy.

2. The reference correction is performed during an assay. Compare the ratio of the decay-corrected reference peak rate during the assay to the reference rate established during calibration. Note that

decay correction is needed only if a radioactive source is used as a reference source; it is not needed for an electronic pulser.

5.2 TRANSMISSION CALIBRATION

Transmission calibration is performed by either using an empty container (with no radioactive sources and matrix) located between the transmission source and the detector or, alternatively, with the transmission source directly exposed to the detector. In the former case, the container attenuation is factored into the transmission calibration, and the correction factor is only to account for matrix attenuation. In the latter case, the transmission calibration does not include container attenuation. Either method can be selected.

It is good practice to perform transmission calibration measurements at three different vertical positions of the drum: (1) at one-quarter the height of the drum, (2) at the mid-height of the drum, and (3) at three-quarters the height of the drum. The net peak areas at specific energies can be averaged, and the uncertainties in the average can be determined.

Follow these steps to complete the transmission calibration:

1. Position the detector and transmission lifts at one-quarter the height of the 55 gal drum. Expose the transmission source, and acquire data for a sufficient length of time so that a precision of ±1.0% or better is achieved for the gamma-ray peaks of interest. Repeat the measurement at the one-half of the height and at three-fourths of the height.

2. Determine the net peak areas and their uncertainties at each transmission gamma-ray energy. Determine the average of the net peak areas from the three trials (at the three different heights), and the uncertainties in the average net peak area.

3. Perform the measurements at three different heights and average the net peak areas to mitigate biases due to any variation in container wall thickness and any misalignments in the detector–transmission assembly.

During an assay, the transmission through the drum matrix will be determined based on the ratio of the empty drum transmission calibration (or with respect to the no-container calibration). The matrix transmission is used to perform attenuation correction. An example of transmission through a drum matrix is illustrated in Figure 5.

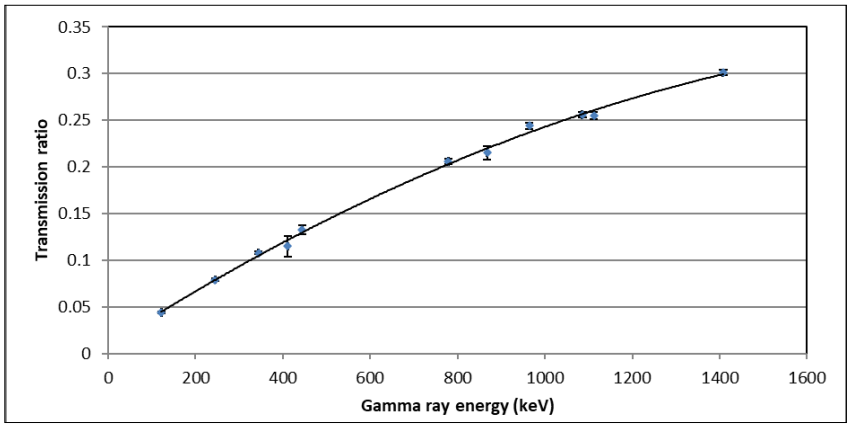

Figure 5. Transmission ratios measured for a representative drum matrix [5].

5.3 EFFICIENCY CALIBRATION

Follow these steps to complete the efficiency calibration:

1. Empty container efficiency calibration: The count rates at gamma-ray peaks of interest from a waste item must be corrected not only for rate loss and matrix attenuation but also for source-to-detector geometry. Typically, a calibration count is performed by locating many multiline or multinuclide sources at designated locations within an empty container so that a volume-weighted average of the detector response can be established with no matrix attenuation. This empty container efficiency calibration will be factored in during analysis so that the geometry correction is considered in the assay results. For the SGS, four mixed nuclide line source standards (^{241}Am, ^{133}Ba, ^{137}Cs, and ^{60}Co) are located at designated radial positions inside an empty 55 gal drum. The radial locations start from the center of the matrix and spiral toward the edge of the drum. Then, when the drum is rotated, a uniform volume-weighted average response is generated. Figure 6 shows a schematic drawing of a 55 gal drum with holes at designated radial locations to accommodate calibration sources. The smaller diameter holes are used to locate the mixed-nuclide line source standards.

Figure 6. A 55 gal drum with holes to accommodate calibration standards [5].

2. Multi-density efficiency calibration: The multi-density calibration is applied to the count rates recorded during the emission scan of the assay and corrects for source-to-detector geometry as well as matrix attenuation. It is a very useful alternative method to generate assay results, especially at higher matrix densities, in which transmission-based results might yield large uncertainties.
   a. Calibration drums, typically five in number, with a uniform matrix and with matrix densities ranging from 0.03 to 1.5 g-cm^{-3} are used. Each drum has holes drilled at the predesignated radial locations and can accommodate the line source standards. During calibration, the drum is rotated. Measurements are performed in the emission-only mode, and the transmission source is not exposed.
   b. The composition of matrix material in each calibration drum consists of materials such as foam, softboard, particleboard, sand, and so on (i.e., low Z materials). The effective Z of the matrices is approximately the same for all the drums. Therefore, the variation in efficiency is effectively only because of the average density of the matrix.
   c. Figure 6 shows the geometry of the calibration drum.
   d. Acquire data (emission only) at each of the vertical segments.
   e. For calibration, the total count times typically range from 1 h for the empty drum to 8 h for the heaviest drum. These somewhat-long counting times are necessary to ensure good counting statistics (approximately 1%–2%) for the segment counts.
   f. Create a certificate file using the activities specified by the source manufacturer and store it in the system.

g. Using the decay-corrected gamma emission rates at each gamma line from source standard and the corresponding net peak count rates at the gamma-ray energies, determine the peak efficiency of the detector.
h. Perform the multi-density efficiency calibration for each segment of each matrix density. Also, perform the summed spectrum efficiency calibration for each matrix density.
i. Using the acquisition and analysis software, generate a multi-density calibration. Using this, the efficiency for any energy and any density within the range of calibration can be obtained by interpolation. During item assay, the density of the "unknown" matrix is input by user. The software then interpolates the efficiency using the multi-density calibration curves. Figure 7 illustrates an example multi-density calibration for a 55 gal drum matrix.

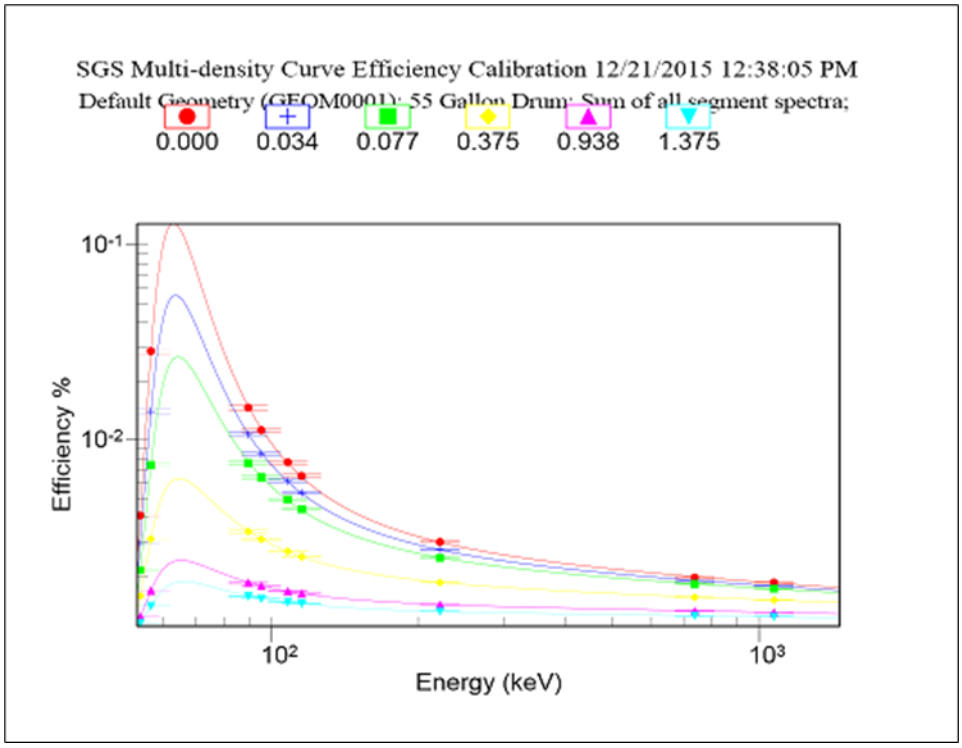

Figure 7. SGS Multi-density efficiency calibration curves for summed spectra from all segments [5].

3. Calibrate mathematical efficiency: Mathematical efficiency calibration methods such as the In Situ Object Counting System (ISOCS) [9] or ISOTOPIC [11] can be applied as an alternative to the empirical calibration method. Mathematical methods offer the advantage of avoiding the practical difficulties of manufacturing calibration standards for large items such as 55 gal drums or a B-25 box. However, as a matter of good practice, mathematical calibration (or any calibration) must be independently validated by the user before being deployed to measure waste items.

6. ASSAY AN UNKNOWN WASTE ITEM

Once the calibration has been completed, the SGS is ready to assay unknown source distributions inside a 55 gal drum. The activity of the unknown source can be determined by using data acquired in the transmission and emission modes. In this case, the emission count rate from a drum segment is correct for matrix attenuation that uses the transmission data. The empty drum's (no matrix) efficiency calibration is used to correct for geometry.

In Equation 1, $\dot{C}_{\text{net}}$ is the net peak count rate registered at a given gamma-ray energy emitted by the source or sources inside the drum, Γ is the gamma-ray yield (number of gammas per decay), $\varepsilon_{\text{empty}}$ is the empty drum efficiency, which corrects for the geometry effects. The correction factors (*CF*) for rate loss and matrix attenuation that are given by Equations 2 and 3. If a radioactive source is used, the reference rate must be decay corrected to the assay date and time.

$$A_{\text{unknown}} = \frac{\overset{*}{C}_{\text{net}}}{\varepsilon_{\text{empty}} \cdot \Gamma} \cdot CF_{\text{rate\_loss}} \cdot CF_{\text{matrix}} \tag{1}$$

$$CF_{\text{rate\_loss}} = \frac{\text{Pulser\_rate(reference)}}{\text{Pulser\_rate(assay)}} \tag{2}$$

$$CF_{\text{Matrix}} = \frac{-\kappa \cdot ln(T)}{1 - T^{\kappa}} \tag{3}$$

The equation for matrix attenuation (Equation 3) follows from the discussion by Jack Parker [6]. In the equation, *T* is the transmission through the matrix only at an emission energy of interest, and κ is the geometrical factor by which the diameter of the drum matrix is multiplied to obtain the mean path length of the emerging photons out of the plane of the uniform disk.

A second analysis type is to apply the efficiency correction based on the multidensity efficiency curve to the emission count rate. This analysis can be done on each segment as well as on the summed spectra from all segments. In this case, the activity of the unknown source inside the drum is given by the following equation:

$$A_{\text{unknown}} = \frac{\overset{*}{C}_{\text{net}}}{\varepsilon(E,\rho) \cdot \Gamma} \cdot CF_{\text{rate\_loss}} \cdot \tag{4}$$

In Equation 4, the quantity ε(*E*,ρ) is the peak efficiency at the gamma-ray energy *E* for a matrix density of ρ. This is obtained by interpolation from the multidensity efficiency calibration. The multidensity calibration can be applied to the data acquired in each segment, thus determining the activity on a segment-by-segment basis. Alternatively, the multidensity calibration can be applied to the counts from the summed spectra.

7. ASSAYING WASTE ITEMS

Follow these steps to assay a waste item:

1. Assay items are measured at each vertical segment using either a two-pass (transmission and emission) or a one-pass (emission only) scan. For a two-pass assay, the transmission through the matrix (and the container) is determined based on the transmission calibration and the net count rates at the gamma-ray peaks from the transmission source. The transmission at the emission energy of interest is obtained by interpolation.

2. From the emission scan, the net peak count rates at the gamma-ray energies emitted by nuclear material present in the waste item are determined at each vertical segment.

3. Using the gamma-ray spectra acquired at the segment and the summed spectra from all segments, a gamma-ray spectral analysis is performed. The gamma spectral analysis typically consists of the following steps:
   a. Locate the peaks

b. Fit the peaks (analysis), which also involve subtracting the continuum counts under the peaks
c. Subtract the background
d. Correct the efficiency
e. Identify the nuclide with interference correction and activity (or mass) quantification
f. Generate a report

4. The radionuclide activity (or mass) variation from segment to segment—above and beyond statistical variations—is a measure of the heterogeneity of the matrix and the nonuniformity of the source distribution.

5. The results from the summed spectrum analysis yield the best sensitivities.

8. SAFETY PRECAUTIONS

The following key precautions should be kept in mind:

- The SGS consists of many moving parts, such as the rotator, detector lift, and transmission lift. Mechanical motion of one or more parts of the system is indicated by an amber lamp. When the system components are in motion, maintain a safe distance away from the system to avoid any injury.

- The system consists of yellow tape switches. If these are contacted when the system components are in motion, then an emergency stop is activated. All motion stops to prevent injuries to personnel.

- The SGS has several emergency stops (red button). In an emergency, press an E-stop button to stop all motion, thus preventing injury to personnel or damage to equipment.

- The transmission source is a high-activity source (typically 10 mCi). When the transmission shutter is open (as indicated by a red lamp switched on) and the transmission source is exposed, do not get in front of the beam. Always adhere to the ALARA principle.

9. MEASUREMENT CONTROL

Follow these steps to limit errors and to promote repeatability as a part of measurement control:

1. The facility or NDA practitioner should establish a measurement program under and in conjunction with the quality assurance program for the site and then perform measurements and record the results according to the defined program.

2. Before performing item assays in each shift (8 h shift), complete the quality assurance and quality check (QA/QC) to ensure that the measurement system is operating under established tolerances.
   a. Typically, this entails a QA/QC measurement using a check source (e.g., ^{57}Co or ^{137}Cs) and recording the full width at half maximum, peak centroid position, and net peak area.
   b. If the QA/QC data collected over several days show that the measured parameters are within the expected statistical variations, then the system is functioning normally. However, if the dataset shows a uniformly increasing or decreasing trend or variations that are inconsistent with expected statistical variations, then it indicates a possible problem in the system operations. Item assays must be stopped, and the problem must be investigated and resolved.

3. One of the calibration drums, with the mixed gamma standard rod sources configured in them, can be measured daily to verify that the system is operating within established QA/QC thresholds.

10. QUALITY MEASUREMENT: IMPORTANT CONSIDERATIONS

The following are important considerations [12] that affect the quality of gamma-based NDA of waste items:

- Radial or axial nonuniformity of the radioactive source material in the item
- Matrix heterogeneity or source geometry (e.g., lumps) causing self-absorption
- Nonrepresentative calibration standards
- Attenuation
- Shielding and collimation, as appropriate
- Graded shielding to minimize interference of x-rays from higher *Z* shielding materials
- Low signal-to-noise ratio
- Signal distortion (e.g., tailing, pulse pileup or random coincidence summing, true coincidence summing)
- Dead time correction
- Measurement geometry
- Item size (physical dimensions)
- Container packaging and matrix attenuation
- Background radiation
- Interfering radiation
- Decay of radioactive sources used to routinely test the stability or functionality of a measurement system, transmission sources, and rate-based correction sources

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