A Mobile Automated Tomographic Gamma Scanning System – 13231

J. M. Kirkpatrick, P.J. LeBlanc, D. Nakazawa, D. L. Petroka, S. Kane Smith, R. Venkataraman, and M. Villani
Canberra Industries, Inc. 800 Research Parkway, Meriden CT 06450 USA

ABSTRACT

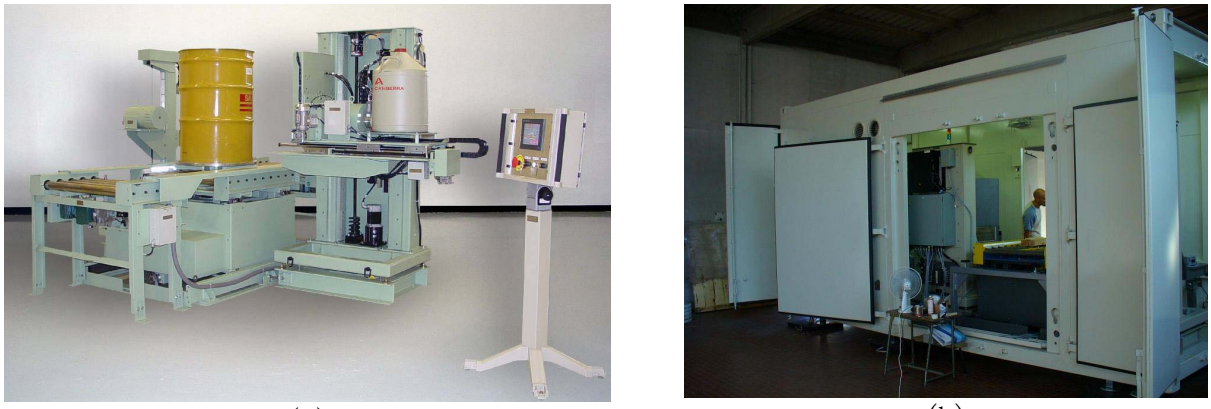
Canberra Industries have recently designed and built a new automated Tomographic Gamma Scanning (TGS) system for mobile deployment. The TGS technique combines high-resolution gamma spectroscopy with low spatial resolution 3-dimensional image reconstruction to provide increased accuracy over traditional approaches for the assay of non-uniform source distributions in low-to medium-density, non-heterogeneous matrices. Originally pioneered by R. Estep at Los Alamos National Laboratory (LANL), the TGS method has been further developed and commercialized by Canberra Industries in recent years. The present system advances the state of the art on several fronts: it is designed to be housed in a standard cargo transport container for ease of transport, allowing waste characterization at multiple facilities under the purview of a single operator. Conveyor feed, drum rotator, and detector and collimator positioning mechanisms operated by programmable logic control (PLC) allow automated batch mode operation. The variable geometry settings can accommodate a wide range of waste packaging, including but not limited to standard 220 liter drums, 380 liter overpack drums, and smaller 20 liter cans. A 20 mCi Eu-152 transmission source provides attenuation corrections for drum matrices up to 1 g/cm^3 in TGS mode; the system can be operated in Segmented Gamma Scanning (SGS) mode to measure higher density drums. To support TGS assays at higher densities, the source shield is sufficient to house an alternate Co-60 transmission source of higher activity, up to 250 mCi. An automated shutter and attenuator assembly is provided for operating the system with a dual intensity transmission source. The system's 1500kg capacity rotator turntable can handle heavy containers such as concrete lined 380 liter overpack drums. Finally, data acquisition utilizes Canberra's Broad Energy Germanium (BEGE) detector and Lynx MCA, with 32k channels, providing better than 0.1 keV/channel resolution to support both isotopic analysis with the MGA/MGAU software and a wide 3 MeV dynamic range. The calibration and verification of the system is discussed, and quantitative results are presented for a variety of drum types and matrices.

INTRODUCTION

The Tomographic Gamma Scanning system or TGS [1] is a Non-Destructive Assay (NDA) technique that combines High Resolution Gamma Spectrometry (HRGS) with three dimensional, low spatial resolution attenuation (transmission) and emission imaging in order to provide improved assay accuracy over traditional gamma ray waste assay methods. The TGS technique has been fully described previously, so only a brief overview is presented here. Readers interested in more detailed presentation of the methodology can find it in the references [1, 2, 3]. The TGS transmission and emission images are generated by scanning the waste drum to be assayed with three degrees of freedom (rotation, translation, and elevation), rather than with the two dimensional scanning protocol used in traditional Segmented Gamma Scanners (SGSs). The TGS emission image is a map of activity onto the three dimensional grid of discrete volume elements or

"voxels" representing the waste container. The transmission images provide a corresponding map of matrix density, and are used to correct the emission imaging response matrix for sample specific attenuation losses. Because it corrects for non-uniform matrix distribution and non-homogeneous nuclide distributions using the measured spatial distributions, the TGS method is more accurate than traditional non-imaging methods when dense heterogeneous wastes with non-uniform activity distributions are assayed. The primary objective of the TGS method is not the generation of high quality images familiar to the medical or non-destructive examination communities; nevertheless, the low resolution images which are its by-product can be a powerful, if qualitative, visual record that can be used during technical review to add assurance to process-based, or other, knowledge. Typically the TGS technique is applicable to drums with densities up to 1 g/cc; for higher densities the system can also be operated in SGS mode.

Because it was designed to support waste remediation efforts at multiple sites, all of the instrument's primary subsystems are housed and operated within a modified standard shipping container for ease of transportation. Figure 1 shows the typical TGS subassemblies (a) and the mobile system housed in its shipping container (b). The system was also designed to allow batch mode processing with little or no operator intervention required after initial setup, and to permit the assay of containers larger, heavier, or more dense than the standard 55 gallon or 220 liter waste drum. Smaller container sizes can also be accommodated.



(a) (b)

Figure 1: (a) A standard TGS system showing the basic system components; (b) Automated TGS housed in transport container.

SYSTEM COMPONENTS

The TGS system consists of three primary mechanical subassemblies – the detector system, the transmission source system, and the drum rotator/translation turntable system – in addition to computer, data acquisition, and control electronics. In operation, a conveyor system loads and unloads drums to and from the turntable assembly; at the turntable the drum is automatically weighed to determine overall density. During the assay the drum is simultaneously rotated and

translated horizontally, perpendicular to the detector, while the HPGe detector and transmission source assemblies are moved vertically in unison to each of the segment positions.

Detector Assembly

The core of the TGS detector subassembly is a Canberra BE5030 Broad Energy Germanium (BEGe) detector mounted on a motorized lift platform. The BEGe is a planar HPGe detector that provides both high resolution and efficiency for low- and high-energy gamma rays, allowing both the quantitative analysis of any special nuclear material content and the determination of the relative isotopic abundances using a single detector. The planar geometry is ideal for this application since the large diameter of the crystal fills the collimator opening for the TGS mode. The BE5030 detector has a front surface area of 60 cm^2 and a thickness of 2 cm, with a nominal efficiency of 50%. It typically provides resolution of 750 eV at 122 keV (0.61%) and 2,200 eV at 1,332 keV (0.17%). The performance of the BEGe detector relative to a coaxial detector is shown in Figure 2.

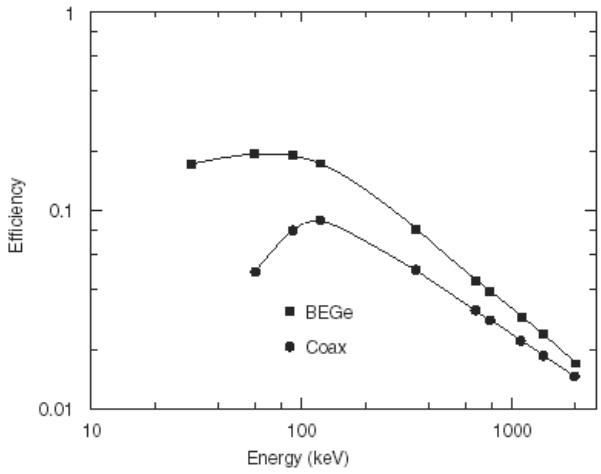


Figure 2 Absolute Efficiency of BE5030 compared to a Coaxial of 60mm diameter by 80mm length for a source measuring 74mm diameter by 21mm located on the endcap. Both detectors have 50% Relative Efficiency for Co-60 point source at 25cm.

The detector itself is housed in a 254mm thick lead shield to minimize the impact of background gamma radiation, with tin and copper inner liners to minimize the effects of the Lead X-rays. An automated variable collimator allows optimization of the spatial resolution for the measurement conditions and technique utilized. The variable collimating aperture is formed by interweaved layers of sintered tungsten lined with tin to reduce tungsten x-ray emission. These layers can be opened and closed either to change the spatial resolution of the TGS measurement or to switch to an SGS measurement mode. Closing the tungsten leaves forms a diamond shaped aperture with flat-to-flat openings between 12.7mm to approximately 60mm. For SGS mode, the aperture opens to a height of approximately 95mm and width of 400mm. The width of the opening is

controlled via the system PLC and operating software. Figure 3 shows the minimum and maximum collimator apertures.

Figure 3. The TGS variable collimator showing minimum (left) and maximum (right) apertures.

For measuring drums with very high activities (in excess of 2mSv/hr), the system also includes the automated detector attenuation assembly to protect the High Purity Germanium (HPGe) detector, and a detector-positioning slide mechanism that allows ± 35cm adjustment of the source-to-detector distance.

The automated geometry, consisting of detector position, collimator opening, and attenuators, is set by Programmable Logic Controller (PLC) based upon the measurement of a dosimeter mounted on the side of the detector vertical lift at the beginning of each assay. The detector platform's vertical drive stepper-motor will raise and lower the HPGe detector, variable collimator, and dosimeter together over a vertical range of 100cm. The unit supports operational weights up to 680kg (1500lb).

Source Assembly

A 20 mCi Eu-152 transmission source was provided with the system to allow reliable density mapping of waste drums with matrix densities up to 1 g/cc. Above this density, the statistics of the transmission gamma-ray peaks are too poor to be used in the TGS analysis, and the SGS analysis is normally used. Because this system is anticipates both 220L and 380L drums with densities up to 2.3g/cc, a Dual Range Transmission Assembly was also installed to provide an alternative option to use the TGS technique at higher densities. Dual Range Transmission Correction[1] (also known as the Hi Beam/Lo Beam method) requires a 50mCi Co-60 transmission source and employs a second set of automated attenuating shutters, located in front of the transmission source module, to prevent saturation of the HPGe during the measurement of low-density waste. The smaller transmission-attenuating shutter, referred to as the attenuator, is dropped in place lowering the transmission source count rate. Figure 4 displays pictures of the attenuator and shutter assembly.

[1] U.S. Patent # 7,541,590 B2, "Extending the Dynamic Range of the TGS through the use of a Dual Intensity Transmission Beam", issued 2 June 2009.

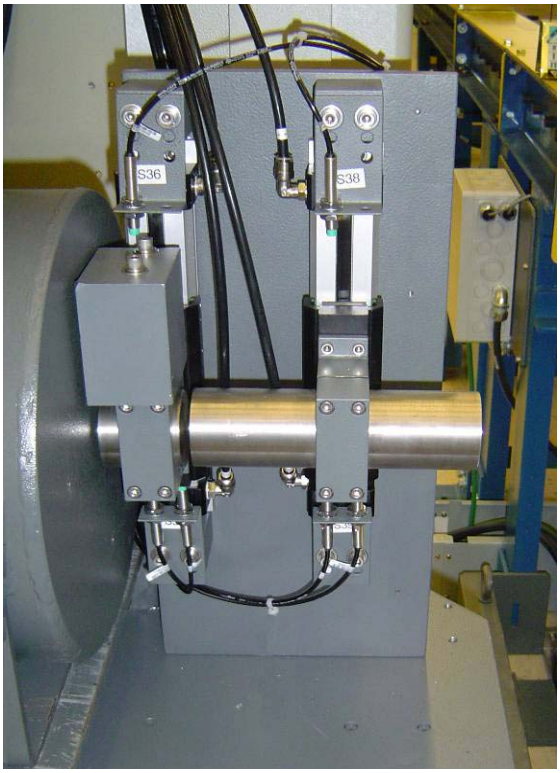


Figure 4 Transmission Source Assembly for the Dual Range Transmission Source Correction

When used with the TGS measurement technique, a three-pass assay protocol is required. The three-pass assay protocol includes one emission pass, one low-intensity transmission pass (with attenuator down and shutter up), and one high-intensity transmission pass (both attenuator and shutter up). The additional transmission pass adds at least 30 minutes to the total measurement time and requires an application specific version of Canberra's NDA 2000 software that includes the Hybrid TGS analysis.

The transmission source shield thickness is increased from 10.16cm, typically used in a standard TGS system, to ~14cm of Pb to accommodate a transmission source as large as 250mCi of Co-60. Because of the greater weight of the transmission source shield, a higher-capacity vertical lift was required, similar to that used for the transmission source assembly.

Rotator Turntable Assembly

To integrate the TGS system into a line of conveyors, a conveyor/rotator module is provided that can interface with the overall conveyor system. The rotator includes a series of powered rollers that move the drum from the conveyor to turntable located at the center of the platform. The 700mm turntable has a 1500kg capacity. The rotator is fitted with a four load cell weigh scale system so that calculations involving drum weight can be performed. The load cell accuracy is tailored to meet the expected weight range. Multiple (four) load cells are used to ensure accuracy is maintained even when the center of mass is not over the center of rotation.

Data Acquisition Electronics

The raw signal from the HPGe detector is amplified by a Transistor Reset Preamplifier (TRP), which ensures good energy resolution even at high-count rates. Data acquisition will be performed through the LYNX Digital Signal Analyzer and the NDA 2000 software package. A Model 1654 Reference Pulser is added to the data acquisition train to provide accurate dead-time correction for the TGS measurement technique.

The LYNX Digital Signal Analyzer is a 32K-channel integrated signal analyzer based on advanced digital signal processing (DSP) techniques. The LYNX operates in pulse height analysis (PHA), multichannel scaling (MCS), dual channel loss free counting (LFC), multispectral scaling (MSS) and time-stamped list modes, and offers excellent count rate and temperature stability. It provides dual memory capability to permit the TGS application to collect a spectrum in one memory region while transferring the data in the other memory region, thereby eliminating any counting and/or time losses in the TGS operating mode. The LYNX is mounted directly on the detector lift platform to optimize the signal processing, communicating back to the control cabinet through wired Ethernet. Benefits include higher throughput with superior resolution, greater count rate stability, improved temperature stability, and reduced ballistic deficit effects.

The Canberra Model 1654 Quad Reference Pulser is provided for dead-time correction. The 1654 Quad Pulser provides a consistent reference peak for dead-time correction by adding the pulser peak directly into the pulse processing circuit, at pulse rates from 50 to 1000 Hz. The 1654 also includes independent selectable x1 or x3 (internal jumper) pulse output amplitude boost for each pulser channel to adjust the pulser rate and peak location in the gamma spectrum based on the application requirements.

Software

The Automated TGS uses Canberra's NDA 2000 Non-Destructive Assay (NDA 2000) software for operations and analysis. The NDA 2000 integrated approach to Non-Destructive assay allows the software to switch quickly and easily between SGS and TGS scanning and analysis modes. The following additional software provides supplemental analysis or support:

- The ISOCS (*In Situ* Object Counting System) Calibration Software is used for the efficiency calibration of the SGS measurement mode.

- The Multi-Group Analysis (MGA) software add-ons to Genie 2000 are also provided with the system and can be used with NDA 2000. MGA uses a sophisticated peak fitting and deconvolution algorithm, which provides a higher accuracy quantification of special nuclear materials compared to the traditional peak analysis. S508C MGA is specifically for the identification and quantification of plutonium isotopes. S507C MGAU is specifically for the identification and quantification of uranium isotopes.

- Multi-Group Analysis for Uranium (MGAU) was designed to improve the accuracy of measurements of uranium-bearing samples over traditional methods while simplifying or eliminating the setup and calibration steps necessary with other methodologies.

PERFORMANCE ESTIMATES

A properly calibrated and operated TGS is one of the most accurate NDA techniques available for the assay of Pu-239, U-235 and other gamma emitting radionuclides [4]. The error budget (contributions to the Total Measurement Uncertainty, TMU) is the combination of many influences. The precision of the TGS result is directly affected by the counting statistics of the transmission and emission data, the mechanical reproducibility of the geometry, the stability of the digital signal processing chain, and the environmental background. Bias of the TGS results is a result of lumps of radionuclides in the matrix, electronic noise, partial volume effects, calibration uncertainty, and geometry error. All of these influences are included in the TMU, and further information can be found in the TGS ASTM standard[5].

Measurement accuracy is generally within 5 – 10% [6] for a measurement time of 60 minutes, for most low-density waste matrices (<0.5 g/cc), in a 208L drum for gamma-ray energies of a few hundred keV and greater. A complete TMU Analysis has been performed and requires a number of assumptions about the waste drums to be assayed. Some deviation from the predicted TMU values is expected.

The following two tables present a summary of the expected accuracy of the TGS. Note that TGS data for drums with densities greater than 1g/cc is very limited; the figures shown here are based on high-density measurements performed with a high-density automated TGS [7].

Error Source	Matrix Density (g/cc)						
	0.25	**0.50**	**0.75**	**1.0**	**1.25**	**2.0**	**3.0**
Counting Statistics	5%	5%	5%	5%	5%	5%	5%
Matrix Non-Homogeneity	5%	5%	5%	5%	5%	5%	5%
Matrix Source Distribution	2%	4%	6%	9%	11%	17%	26%
Calibration Error	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%
TMU (1 sigma)	8%	9%	10%	11%	13%	21%[2]	31%

Table 1 TGS Mode Total Measurement Uncertainties for Cs-137 in various matrix drum types assuming only Cs-137 contamination present. (Errors at 1-sigma confidence level).

TGS CALIBRATION

The response of a TGS system at any gamma ray energy of interest is given in terms of a quantity called the "TGS Number". The TGS number is the emission count rate at a given energy, summed over all voxels (volume elements) inside the container, and multiplied by a normaliza-

[2] TGS data for drums with densities greater than 1g/cc is very limited. These accuracies are based on high-density measurements performed with a high-density automated TGS. The results are published in:

tion factor; it is proportional to the activity, or the mass, of a given nuclide. This is formalized in Equation (1).

$$\text{TGS\#} = N \times \sum_i s_i \,, \tag{1}$$

In Equation (1), s_j is the emission image in voxel i that has been corrected for geometry, rate loss, and attenuation. The factor N is the normalization. The normalization factor ensures that the total number of counts projected from the reconstructed image equals the sum of counts in the experimental view (raw counts from Regions of Interest) vector. The normalization factor will vary between assays depending upon the three-dimensional analysis and counting statistics.

The TGS calibration factor each gamma ray energy of interest is simply the inverse of the TGS number per unit activity (or per unit mass), such that.

$$A = CF \times TGS\# \,, \tag{2}$$

In equation (2), CF is the TGS calibration factor in units of either μCi / TGS# or gram of a given nuclide / TGS Number. The assay result A will be reported according to the units of the calibration factor.

To calibrate the TGS, a series of one hour TGS assays were performed using a set of six line-source reference standards, containing Am-241, Ba-133, Cs-137, and Co-60, and a set of 220 liter and 380 liter calibration drums, provided by the customer, with matrices of varied material and densities. The significant emission lines of these nuclides span the range of energies required for quantification of nuclides of interest to the end user. For each gamma ray line of interest in the calibration set, the measured TGS number is combined with source certificate data to calculate the efficiency ε in units of TGS number per gamma per second.

Two duplicate assays were made in each of the different matrices, and all efficiency data points obtained for a given gamma energy were combined to yield a weighted mean efficiency value for that energy. This helps to average out any bias that may be related to matrix density, or source position relative to the TGS voxel boundaries. In principle, the TGS method corrects for matrix density, but some small residual bias is not unexpected.

The calibration drum set consisted of three 220 liter drums with matrices of high-density wood (0.76 g/cc), low-density wood (0.41 g/cc), and heterogeneous PVC in 8 aluminum cans (0.12 g/cc); two steel-lined 380 liter overpack drums with matrices of neoprene (0.40 g/cc) and wood (0.49 g/cc). The calibration drums were provided to Canberra by the end user as representative of the containers expected to be assayed by the system in operation.

The efficiency data are fitted with a function of the form

$$\varepsilon \equiv \frac{\text{TGS\#}}{\gamma\text{ps}} = \frac{A}{E} + \frac{B}{E^3} + e^{-E}\left\{\frac{C}{E^2} + \frac{D}{E^3}\right\}, \tag{3}$$

using the standard linear least squares method. The fit is performed such that the reduced chi-squared of the result is normalized to unity. This is achieved by doing the fit twice: the first fit gives a raw reduced chi-squared value, then the data errors are multiplied by the square root of the reduced chi-squared and the fit is repeated. This helps to account for non-statistical sources

of uncertainty that may be overlooked in the reported uncertainty in the TGS number, and results in a more realistic final error on values calculated from the calibration function. Once the parameters have been determined, the calibration factors *CF* for the lines of other nuclides, beyond those of the calibration set of, may be calculated using this efficiency function. Thus to obtain the assay result in microcuries for line *j*:

$$CF_j = \frac{1}{\varepsilon Y_j} \times \frac{1}{37,000}, \tag{4}$$

where Y_j is the gamma ray yield or intensity for the j^{th} line.

A listing of the calibration lines used, source emission rates, weighted mean TGS number results, and calculated efficiencies for the 220 liter drums is given in Table 2. The least squares fit of the calibration equation (3) to the data is shown in Figure 5. The calibration data and resulting fit for the 380 liter drums are given in Table 3and Figure 6, respectively.

Nuclide	Energy	W.M. TGS#	W.M. Error	Source GPS	GPS Error	TGS#/GPS	Error
Am-241	0.05956	2.706	0.0984	828269	10144	3.267e-6	0.125e-6
Ba-133	0.08121	11.199	0.1084	2031814	24885	5.512e-6	0.086e-6
	0.27648	1.226	0.0102	424834	5203	2.885e-6	0.043e-6
	0.30289	2.882	0.0124	1095948	13423	2.630e-6	0.034e-6
	0.35608	8.436	0.0202	3694207	45245	2.284e-6	0.028e-6
	0.38373	1.134	0.0074	535660	6560	2.117e-6	0.029e-6
Cs-137	0.66185	1.180	0.0072	931203	11405	1.268e-6	0.017e-6
Co-60	1.17364	0.797	0.0049	934032	11440	0.854e-6	0.012e-6
	1.33269	0.731	0.0042	934032	11440	0.783e-6	0.011e-6

Table 2 TGS efficiency calibration data for 220L drum geometry

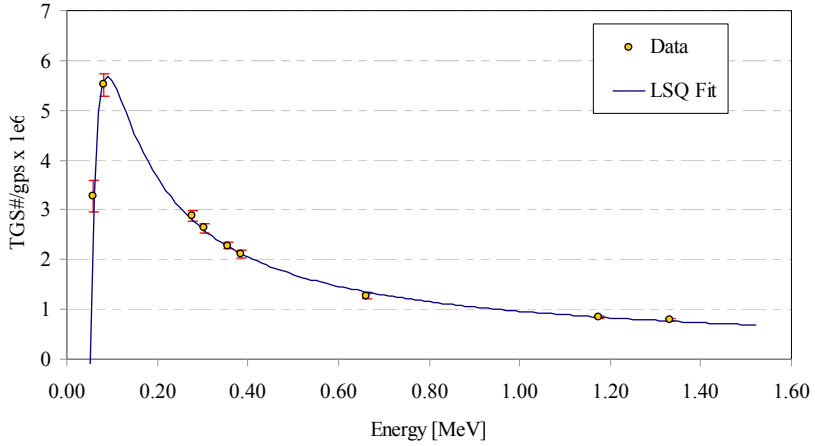


Figure 5 TGS efficiency calibration for the 220L Drum Geometry

Nuclide	Energy	W.M. TGS#	W.M. Error	GPS	GPS Error	TGS/GPS	Error
Am-241	0.05956	0.909	0.3169	828269	10144	1.097e-6	0.383e-6
Ba-133	0.08121	12.940	0.5969	2031814	24885	6.368e-6	0.304e-6
	0.27648	1.170	0.0286	424834	5203	2.755e-6	0.075e-6
	0.30289	2.843	0.0449	1095948	13423	2.594e-6	0.052e-6
	0.35608	8.481	0.0654	3694207	45245	2.296e-6	0.033e-6
	0.38373	1.155	0.0204	535660	6560	2.157e-6	0.046e-6
Cs-137	0.66185	1.174	0.0157	931203	11405	1.261e-6	0.023e-6
Co-60	1.17364	0.774	0.0086	934032	11440	0.829e-6	0.014e-6
	1.33269	0.724	0.0074	934032	11440	0.775e-6	0.012e-6

Table 3 TGS efficiency calibration data for 380L drum geometry

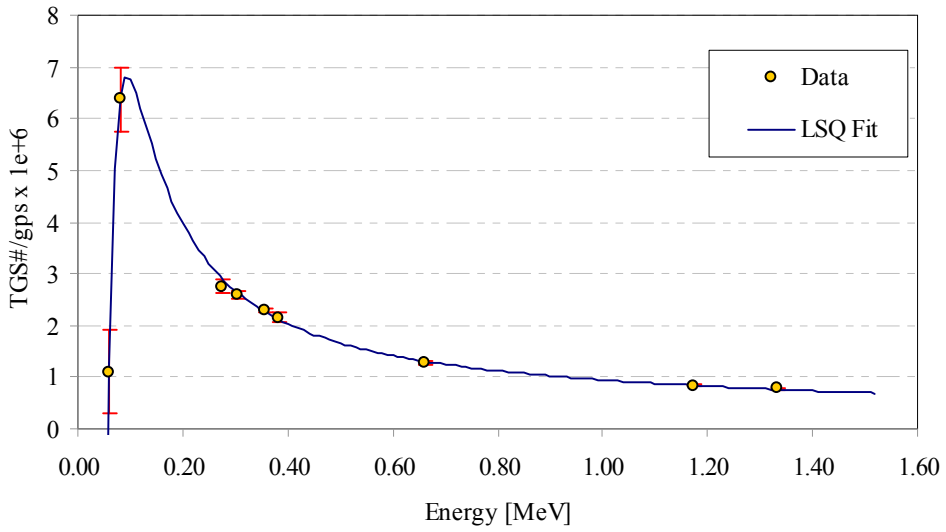


Figure 6 TGS efficiency calibration for the 380L drums geometry

Verification Measurements

The 220L calibration is verified by re-measuring the calibration rod set in a different set of calibration drums. A set of US 55 gallon drums, owned by Canberra and used for standard system calibrations, and having different matrix materials, densities, and holes for rod placement than the original calibration drums provided by the end user, were used for this purpose. The verification set consisted of three drums, with uniform matrices of foam (0.07 g/cc), Homasote (a cellulose fiber wallboard, 0.51g/cc) and particle board (0.75g/cc). The calibration rods were inserted into each drum and assayed for one hour. Activity values are determined for each gamma line using the TGS number and the Correction Factor determined from the efficiency calibration function. Recovery percentages were determined by comparing the weighted mean line activities

for Ba-133, Cs-137, and Co-60 against compared the decay corrected certificate activities for the rod sources. Am-241 is not compared because, although the 59 keV line is used to constrain the low end of the efficiency fit during calibration, this energy is below the recommended range for TGS assay. The recovery results for each nuclide in all verification assays are shown in Figure 7. In all cases, the recovery was found to be within a range of roughly 95% -- 105%.

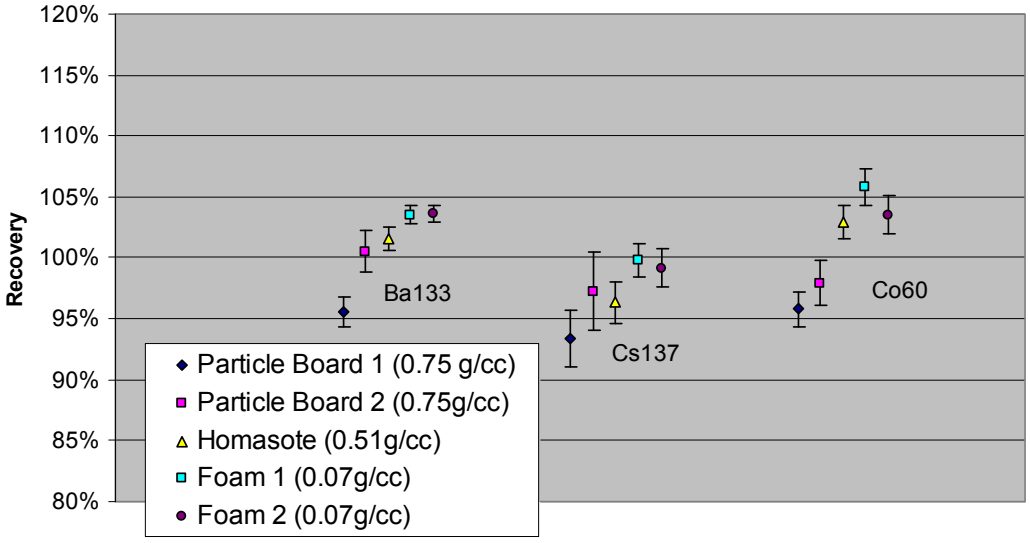


Figure 7 TGS recovery percentage for rod sources measured in US 55 gal verification assay drums

No alternate set of verification drums was available for the 380L overpack drum geometry. To verify this calibration, additional assays were made with individual point sources of Ba-133, Cs-137, and Co-60. Here we show the results of one such assay using the 380L drum with the neoprene matrix (0.4g/cc). The activities of the individual point sources used are listed in Table 4. The recovery percentages are shown in Figure 8.

Nuclide	Activity (μCi)	Unc.
Co60	22.53	3.5%
Cs137	50.36	3.4%
Cs137	40.98	3.4%
Ba133	2.57	3.66%
Ba133	4.83	3.85%
Ba133	5.23	3.85%

Table 4 Point Sources used of 380L neoprene-matrix overpack drum verification

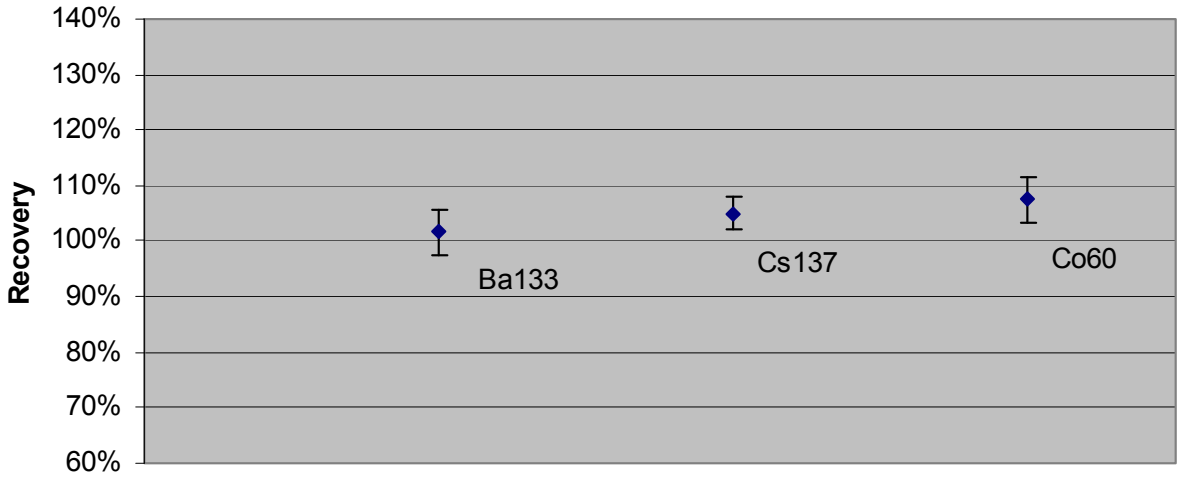


Figure 8 TGS recovery percentages from point-source verification assays in 380L overpack drum with neoprene matrix.

The point source recovery for the 380L overpack drum geometry is seen to be well within the expected accuracy estimates.

CONCLUSIONS

The design and performance characteristics of an automated TGS system for mobile deployment were discussed. The new system incorporates features that permit batch processing and the handling of large and high-density overpack containers. The calibration procedure was described and verification assay results were presented to demonstrate that the system performs within the expectations established for TGS instruments.

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