The Next Generation Tomographic Gamma Scanner

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Abstract

The goal of Non-Destructive Assay (NDA) of radioactive waste is to accurately identify and quantify the radionuclides present in the waste stream. Gamma ray scanning instruments such as the Segmented Gamma Scanner (SGS) have found widespread use in the NDA community. The Tomographic Gamma Scanner (TGS) aims to improve the accuracy of assay results for difficult cases such as a non-uniform distribution of radioactivity in a heterogeneous matrix. The TGS combines high resolution gamma ray spectrometry with 3-dimensional single photon attenuation coefficient images (Transmission image) and single photon Emission images.

Canberra Industries developed its prototype TGS in collaboration with Los Alamos National Laboratory (LANL). The prototype Canberra TGS was used as a Research and Development tool to conduct an in-depth study of the TGS technique. The results of these studies have been reported elsewhere.

Recently, Canberra has built its next generation of TGS systems implementing many advanced features. The new features include an automated variable collimator aperture, an automated detector slide mechanism for adjusting the sample to detector distance, automated attenuator mechanism, and an automatic selection of assay geometry based on the dose rate and density of the assayed sample. The collimator aperture is formed by interleaved layers of tungsten that can be opened and closed to change either the spatial resolution of the TGS measurement or to switch over to an SGS measurement mode. The automated slide mechanism allows the detector to move further back from the high activity drums extending the dynamic range of the system. Alternately, for use with small samples such as cans, the can can be placed on sample pedestal to allow the detector to move closer to the container for improved spatial resolution in either the SGS or TGS modes. The automated attenuator assembly is intended to allow system operation for drums with high surface exposure rates. The assembly is mounted to the front face of the detector shield and collimating aperture.

The paper discusses the features and performance of the next generation TGS.

1. Introduction

The Non Destructive Assay (NDA) of special nuclear materials in waste containers for inventory and safeguards purposes is challenging because of the potentially high degree of variability from item to item. This variability may allow the deliberate addition or removal of special nuclear materials to be made to waste containers to go undetected. These materials could be used in a clandestine nuclear weapons program. The Tomographic Gamma Scanning (TGS) technique combines transmission and emission reconstructive tomography techniques in an effort to improve the accuracy of high resolution gamma-ray spectroscopic measurements. In particular the goal is to reduce the uncertainties associated with the unknown material and density distribution of the waste matrix and also with the unknown distribution of SNM and other radioactive materials present. HRGS is retained in order to unravel the complex spectrum and in order to provide 'good geometry' results - that is peak areas which are relatively insensitive to coherent and small angle scattering

In addition to improving the quality of the assay results the intermediate transmission (linear attenuation map as a function of energy) and emission (by nuclide or line) images, although only of low spatial resolution, can provide powerful additional visual verification and confirmation information about the items.

Reconstructive tomography involves scanning the item in a series of layers or slices from many different orientations or views and using the information to reconstruct a picture of the interior of the object free from the interference effects from underlying and overlying planes. The idea is that if we know the attenuating properties of the interior along with the distribution of activity that a better matrix attenuation correction factor can be derived. The objective is to improve the accuracy of the assay while still retaining a useful detection limit and throughput at reasonable cost. Thus for a 200 liter drum, say, a representation of the item comprising 16 layers each of 88 volume elements (or voxels) is used. This contrasts with the familiar segmented gamma scanner approach which may use 8 to 16 segments, say, with each individual segment being treated as distinct but as homogeneous in matrix and uniform in activity (on a per unit mass of matrix basis). The TGS scan sequence generates a series of data grabs or views which over determine the contents of the voxel grids. Algebraic reconstruction in real space is used to extract a best fit solution consistent with the data and as free from spurious features as possible. The quality of the reconstructed images may be judged by the correspondence between the measured and actual distributions of test cases. The reconstruction model takes into account the changing collimation, attenuation and inverse square law affects at each view. These physical processes acting together provide the modulation and contrast in pattern of view data that allow the images, free from cross talk, to be formed.

The experimental realization of the TGS discussed here has been outlined elsewhere[1-3]. Here we wish to concentrate on the next generation of TGS that has incorporated in it, many new features. These improvements make the instrument suitable for assaying waste streams with a wider range of matrices and activities. We include some preliminary results generated from the new system.

2. The Next Generation TGS

Canberra industries has designed and built the next generation of TGS with the objective of making the instrument applicable to waste streams with a wider range of activities and matrices and as well as with a wider range of nuclides that is not restricted to just plutonium isotopes. Figure 1 shows a picture of the system. The TGS system can be operated in the Segmented Gamma Scanner (SGS) mode, if desired. The selection of TGS or SGS mode of operation is decided based upon dose rate and density measurements of a given waste drum. Canberra has

developed a special software package called the “Supervisor” for automatically deciding the assay mode (TGS or SGS) based on the density and dose rate measurements. Alternatively, the Supervisor software may also be used by the system’s operator to manually set an assay mode for drums in a given waste stream. A highly collimated ^{152}Eu source (15 mCi, 555 MBq) is used to perform the transmission scan.

A Canberra Model BEGE 5030 High Purity Germanium (HPGe) detector is used in the TGS system that has been built. The pulse processing electronics consists of an RC pre-amplifier, a Canberra Model 2060 Digital Signal Processor (DSP), and an Accuspec B Board to facilitate high speed data transfer, and a Canberra Model 1654 NIM Reference Pulser. Rate loss corrections were performed using the reference pulser counts. Data acquisition and analysis was performed using Canberra’s NDA2000 software platform.

Some of the salient features of the next generation TGS are discussed in the following sections.

Figure 1. The Next Generation TGS with fully automated features

The local PLC control pedestal is to the right and the transmission source assembly is to the left. A 300-liter drum is shown on the rotator/translator. The attenuator mechanism is visible in front of the HPGe detector. Between the attenuator(s) and the dewar is located the variable aperture collimator. The dosimeter is mounted on the front of the detector lift and is therefore, not visible in the picture.

When the system is installed at a waste assay facility, the in-feed and out-feed conveyor stubs shown in the picture can be readily integrated with an automated conveyor system that loads and unloads a stream of waste drums.

The sequence of events is as follows. A waste drum is loaded on to a conveyor using a crane or a fork lift. Upon receiving the signal from the PLC, the drum moves along the conveyor and eventually reaches the in-feed portion of the TGS conveyor. The drum is then transferred to a palette centrally located on a translator/rotator platform. The drum is weighed. The platform then moves towards the center-line of the detector-transmission source. The palette is raised up so that the bottom of the drum clears the side rails of the conveyor. The drum is then rotated. The dosimeter located at the front of the detector lift measures the average and maximum dose rates of the drum contents. Based on the bulk density of the drum matrix and the maximum dose rate, the Supervisor software selects either the TGS or the SGS assay mode. Once the assay mode has been selected, the NDA2000 software proceeds to set the geometry which is a combination

of the detector distance, collimator aperture, and the presence or absence of one or more lead attenuators. After the geometry is set, data acquisition is performed followed by data analysis and printing of the reports. In the case of TGS mode, the report includes images of the source distribution.

2.1 Detector Shield and Automated Collimator Assembly

The detector shield minimizes the impact of background gamma radiation and surrounds the sides and extends behind the detector. The shield provided is a minimum of 50 mm thick lead with a low-Z inner liner to minimize the effects of the lead X-rays on the measurement. The collimating aperture consists of lead and tungsten components. The aperture is formed by interleaved layers of tungsten that can be opened and closed to change either the spatial resolution of the TGS measurement or to switch over to an SGS measurement mode. Closing the tungsten leaves forms a diamond shaped aperture from 12.7 mm to approximately 60 mm in diameter. For SGS mode the aperture opens to a height of approximately 95 mm and width of 400 mm. The width of the opening is controlled via the system PLC and operating software.

2.2 Automatic Detector Slide Mechanism

The detector slide mechanism allows the detector to move towards or away from the sample rotator. The slide mechanism provide for a travel of +/- 355 mm from the normal detector position. The slide mechanism is automated to allow the detector to move further back from the high activity drums extending the dynamic range of the system.

For use with small samples such as cans, the can can be placed on sample pedestal to allow the detector to move closer to the container for improved spatial resolution in either the SGS or TGS modes.

2.3 Automated Attenuator Assembly

The automated attenuator assembly is intended to allow system operation for drums with high surface exposure rates. The assembly is mounted to the front face of the detector shield and collimating aperture. The assembly is controlled by the system PLC with the appropriate thickness of attenuator selected based on the measured dose rate for the sample drum.

The attenuator consists of 4 individual attenuators, 3 of lead and 1 of low-Z material. The inner most attenuator is the low-Z attenuator shutter. This shutter is included primarily to shield the detector from the lead X-rays generated in the three lead shutters. The lead attenuating shutters have thicknesses of 9, 8, and 7 mm respectively. Prior to the beginning of an assay, all of the lead attenuators are closed, thus protecting the detector from a potential high activity drum. Depending on the measured dose rate for a given sample drum, the lead attenuating shutters will be opened sequentially. The collimator aperture and the horizontal position of the detector are also automatically adjusted based on the measured dose rate.

These attenuator assembly can be used in either the SGS or TGS modes of operation.

3. Performance Test Results and Discussion

The TGS system was calibrated by placing a set of six mixed gamma rod source standards inside an empty 208-liter drum and performing a TGS assay. The rod sources were inserted at specific radial positions in the drum, with the radii ranging from 50mm to 280mm. The radial positions were arranged in a spiraling fashion. The rod sources consisted of the nuclides ^{133}Ba, ^{137}Cs, and

^{60}Co. The calibration results included in this paper are for the assay geometry where the TGS collimator aperture is set to a value of 50.3 mm, the detector horizontal position is set at the mid-position of the +/- 355.6 mm range, and all of the attenuators are open.

The output of a given TGS analysis is a quantity known as the "TGS Number" and the uncertainty associated with it. The TGS number and its uncertainty are determined at each emission energy, and represents values proportional to the activity or mass of an assayed radionuclide inside the drum. For a calibration count, the activity of the nuclides in the standard sources are known from the certificates. The calibration parameter is then determined as Activity per unit TGS number for a specific nuclide and a specific gamma ray of that nuclide. The raw TGS numbers for empty drum calibration measurement are given in Table 1.

Table 1. TGS Calibration Results (1 μCi = 3.7x10^4 Bq)

Gamma Energy (keV)	TGS Number	Uncertainty	μCi per TGS Number	Uncertainty
276	0.9722	0.0166	191.188	6.646
303	2.1725	0.0233	85.554	2.750
356	6.3186	0.0470	29.416	0.918
383	0.8815	0.0103	210.858	6.844
662	0.9407	0.0125	34.228	1.186
1173	0.7319	0.0143	42.226	1.619
1332	0.6571	0.0147	47.037	1.876

Several measurements were performed to verify the accuracy of the TGS calibration. Two such measurements are discussed below.

3.1 Uniform activity distribution inside a homogeneous matrix

In this assay, the six rod sources were inserted in radial holes drilled through a Homosote matrix (0.43 g.cm^{-3}) drum. The assay was performed for a total time of 1 hour. The assay results are given in Table 2. The transmission and emission images for ^{137}Cs and ^{60}Co gamma rays are given in Figure 2 and 3.

Table 2. TGS Accuracy for a Uniform Activity Distribution

Nuclide	Measured Activity		True Activity		Ratio (Meas/True)	
	Activity (μCi)	Uncert (μCi)	Activity (μCi)	Uncert (μCi)	Ratio	Uncert
Cs-137	33.18	1.23	32.04	1.03	1.036	0.051
Co-60	31.04	0.90	30.05	0.99	1.033	0.045

For all of the results presented in this paper, the uncertainty values are quoted at 1σ standard deviation. In each case, the measured uncertainty includes the statistical component evaluated using the Monte Carlo Randomization (MCR) method[4]. The measured activities are in excellent agreement with the true activities of the nuclides.

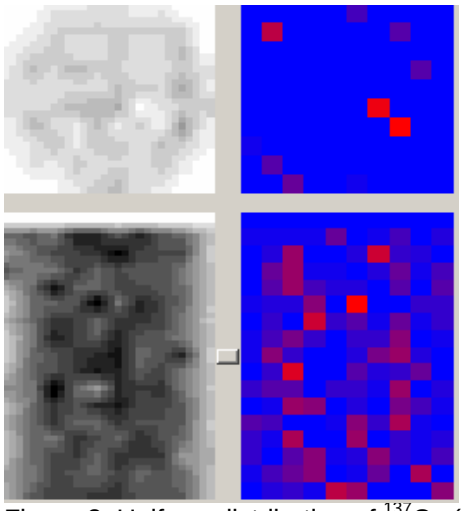

Figure 2. Uniform distribution of ^{137}Cs (662 keV)

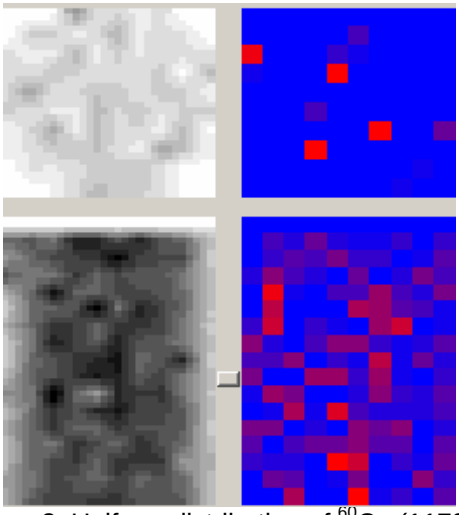

Figure 3. Uniform distribution of ^{60}Co (1173 keV)

The images on the left (in black and white) are the transmission images, and the images on the right (in colour) are the emission images. The transmission images shown are a 2-dimensional projection of the linear attenuation coefficient map (μ) at the given gamma ray energy. The emission images are a 2-dimensional projection of a voxel by voxel distribution of the nuclide activity. In figures 2 and 3, the transmission images show that the matrix is a homogeneous matrix. The emission images indicate the presence of nuclide activity throughout the drum volume, which is consistent with a uniform distribution of activity. In each figure, the top portion is the cross-sectional view of a given layer (layer 8 in Figures 2 and 3).

3.2 Three Point Sources of ^{137}Cs distributed in a homogeneous matrix

A TGS assay was performed by distributing 3 point sources of ^{137}Cs of approximately same activities inside a 208 liter Homosote matrix (0.43 g.cm^{-3}) drum. The results are given in Table 3. The transmission and emission images are shown in Figure 4.

Table 3. TGS Accuracy for 3 point sources inside a Homogeneous Matrix

Nuclide	Measured Activity		True Activity		Ratio (Meas/True)	
	Activity (μCi)	Uncert (μCi)	Activity (μCi)	Uncert (μCi)	Ratio	Uncert
Cs-137	187.5	6.56	178.40	5.35	1.051	0.048

The measured activities are in excellent agreement with the true activities at the 1σ level of uncertainties.

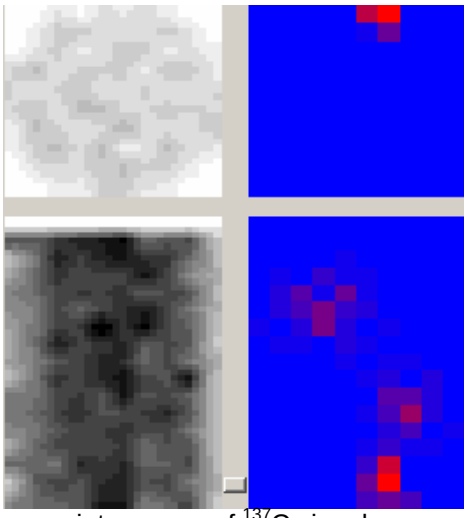

Figure 4. Three point sources of ^{137}Cs in a homogeneous matrix

The transmission image shows the uniform nature of the Homosote matrix. The emission image shows the presence of three regions with elevated levels of source activity. The source at the interface of layers 1 and 2 towards the edge of the drum is clearly seen in the cross-sectional view of the emission image.

3.3 Single Point Source of ^{137}Cs inside a Non-Homogeneous Matrix

A single point source is located inside a non-homogeneous matrix represents a difficult assay situation, with regards to the accuracy of the results. For such situations, the assay results from a non-imaging method might suffer from significant biases (for example a factor of 2). This is especially true if the matrix density is high. For an imaging method such as the TGS technique, the assay results might be more accurate. To explore this, TGS assays were performed by locating a single point source inside non-homogeneous drum matrices with moderate to high densities. The example discussed in this paper is one such typical assay of a ^{137}Cs point source inside a scrap steel drum with a bulk density of 1.0 g.cm^{-3}. The source was located at a radius of 220 mm and at a height of 390mm from the bottom of the drum.

Table 4. Single point source of ^{137}Cs inside a Non-Homogeneous Matrix (1.0 g.cm^{-3})

Nuclide	Measured Activity		True Activity		Ratio (Meas/True)	
	Activity (μCi)	Uncert (μCi)	Activity (μCi)	Uncert (μCi)	Ratio	Uncert
Cs-137	132.1	4.62	108.43	3.25	1.218	0.037

This is a difficult assay scenario from many respects. There is only a single point source, the matrix is non-homogeneous, and the density is fairly high. Considering these mitigating factors, the accuracy of TGS seems fairly reasonable. The images are shown in Figure 5.

In view of the encouraging results that we have obtained for a matrix density of 1.0 g.cm^{-3} we are exploring a variety of analysis methods to further extend the density range of TGS assays. These methods include the “Uniform Layer” and the “Bulk Density” approaches. In the Uniform Layer approach, the linear attenuation coefficient μ is calculated for a few voxels in a given drum layer for which transmission data is available and then averaged. All of the voxels of the given layer are then populated with this average value of μ. The Uniform Layer approach will be useful in assay

situations where the transmission beam is too weak to penetrate the drum matrix, while the drum contents are active enough to register non-negligible count rates in TGS views. In the "Bulk Density" approach, all the voxels in all the drum layers are populated with a value of μ derived based on the bulk density, assuming a matrix composition. This will be useful for drum matrices with very high densities (2 to 3 g. cm^{-3}). The Bulk Density approach will be useful in situations where the operator may only have TGS data available for a high density drum. Also, Bulk Density TGS assays generate confirmatory emission images that will be useful in assaying conditioned waste.

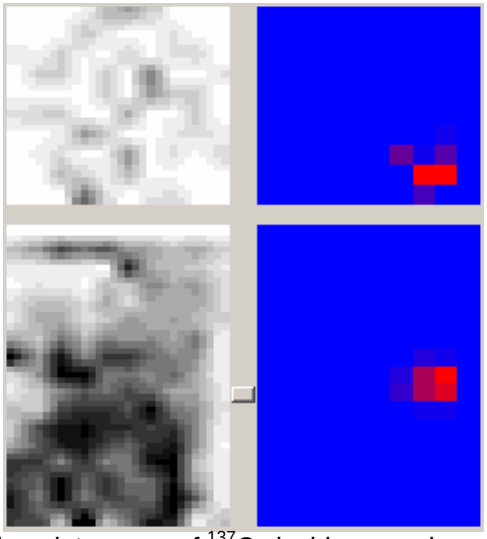

Figure 5. A single point source of ^{137}Cs inside a non-homogeneous matrix

The transmission image depicts the non-homogeneous nature of the scrap steel matrix. The emission image shows the presence of the single point source inside the drum. The image is remarkably constrained within four neighbouring voxels.

4. Conclusions

Canberra Industries has built and tested four fully automated enhanced TGS systems for waste assay. The salient features of this next generation of TGS systems were discussed. The performance of the system was evaluated using results from assays involving homogeneous and non-homogeneous matrices, and uniform and non-uniform source distributions. The design provides qualitative gamma assay capability over the surface dose rate range of up to 100 R/h (1 Sv/hr) and over the density range up to about 3 $g.cm^{-3}$ in a fully automated industrial environment. The TMU estimates for the TGS system are being evaluated and will be reported elsewhere in the near future.

5. References

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