Recent Advancements in Tomographic Gamma Scanning for Non-Destructive Assay – 17321

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ABSTRACT

Canberra Industries has recently designed and built a Tomographic Gamma Scanning (TGS) system for the deployment in a nuclear facility. 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 containers. The TGS system has been optimized to measure 120 liter drums and has the capability to measure containers of various sizes.

Canberra has incorporated numerous enhancements and improvements to the latest system in both its hardware and software components. The signal processing chain and data analysis software have been configured to use either an electronic pulser or digital signal processing (DSP) electronics for dead time corrections. In the case of using the DSP electronics, the need to calibrate and maintain a pulser can be eliminated without sacrificing any performance. For the 120 liter container, the TGS system has been calibrated and validated with three different spatial resolutions, using two collimator aperture sizes, measuring 2.54 and 1.27 cm in width. The system has also been supplied and calibrated with a wide, rectangular collimator (25.4 cm W x 10.2 cm H) for scanning containers solely in the vertical axis. The TGS system also has an automated attenuator assembly, which has the capability to use a combination of attenuators to reduce the count rate for high activity samples. An extensive measurement campaign was performed in addition to the calibration verification to evaluate the accuracy of the system using rod sources, point sources, and a variety of matrices and source distributions. Improvements to the evaluation of the total measurement uncertainty based upon these studies have been incorporated into the analysis software package. Finally, the performance of this new TGS system will be demonstrated in the context of Canberra's previous TGS systems, including several 208 liter-based systems and a smaller, 20 liter container TGS system.

INTRODUCTION

TGS systems have been recently deployed to facilities such as nuclear power plants, waste repositories, and materials handling facilities to assay radioactive waste with low measurement uncertainty [1-3]. In a recent system designed to measure 120 L drums at a reprocessing facility, we have implemented a number of improvements to the hardware and software, including the image reconstruction and analysis routines.

After studies of the impacts on point source location for the 120 L container size [4], an end-effect correction method was developed within the software package. Building upon the uncertainty analysis used in that impact study, we have also applied an assessment of the total measurement uncertainty (TMU) within the TGS analysis software to improve the overall uncertainty representation and facilitate post-measurement sentencing decisions. To support these features the NDA2000 software has been updated and improved.

Based on the default image resolution and settings originally proposed by the LANL developers of the TGS code for 200L drums, we have identified some cases in the use of the methodology for smaller containers where the results are not at the level of performance expected of a TGS analysis. One approach to improve the accuracy was to increase the measurement resolution to optimize the result. We found this approach to be impractical in actual usage, and not meaningful in quantification without a very well defined TMU treatment [5-6]. However, extending the capability of the hardware and software to allow for different scanning resolutions has made available a platform with the capability to perform additional research and development.

A more practical approach was to measure using the default resolution coupled with post-analysis identification & correction. The tools to perform the post-analysis, however, must be implemented and integrated into the analysis. This approach is easier to set up in advance, and can be selected for application only when needed, saving time in the pre-measurement instrument setup as well as in the actual measurement itself. Furthermore the TMU appears to be mathematically more tractable and believable using this approach.

Effective rate-loss corrections are a key aspect of gamma spectroscopy systems to provide quantitatively accurate results in varying or complex radiation fields. This is certainly the case in TGS systems, where both the gamma-emitting material and attenuating items can be localized in a specific region of the container, causing varying input count rates seen by the detector as the system rotates and scans the container. Traditional TGS systems used a periodic, electronic pulser to provide a precise input rate that could be used as a reference to correcting for losses [7]. Developments to the TGS analysis routines were implemented to utilize the rate-loss corrections of the latest digital multi-channel analyzers directly. Extensive testing and comparisons were made and are presented in this paper.

Finally, investigations were made to self-absorption corrections and its importance for TGS system applications. In certain assay situations, the transmission source does not fully probe the attenuating properties of the radioactive material, and this is especially true on scales smaller than the size of the image reconstruction volume element [8]. However, if the particular nuclide emits multiple gamma and X-ray lines during its decay, both the identification through activity consistency checks and corrections can be applied.

First, a brief introduction into the hardware and main components of the 120 L TGS system will be presented, highlighting where the modifications relevant to the new enhancements have been made.

Each later section in the body of this paper highlights one of the several key improvements made within this TGS system, and the final section offers some concluding remarks and comments on future developments.

TGS SYSTEM OVERVIEW

The TGS system constructed recently is designed to measure 120 L containers and is comprised of 3 main assemblies: the transmission source vertical lift, the rotator-translator table, and the detector vertical lift with electrical cabinet. The vertical lifts for the transmission source and detector assembly are synchronized for each TGS assay. A schematic of the full system is shown in the figure below (Fig. 1).

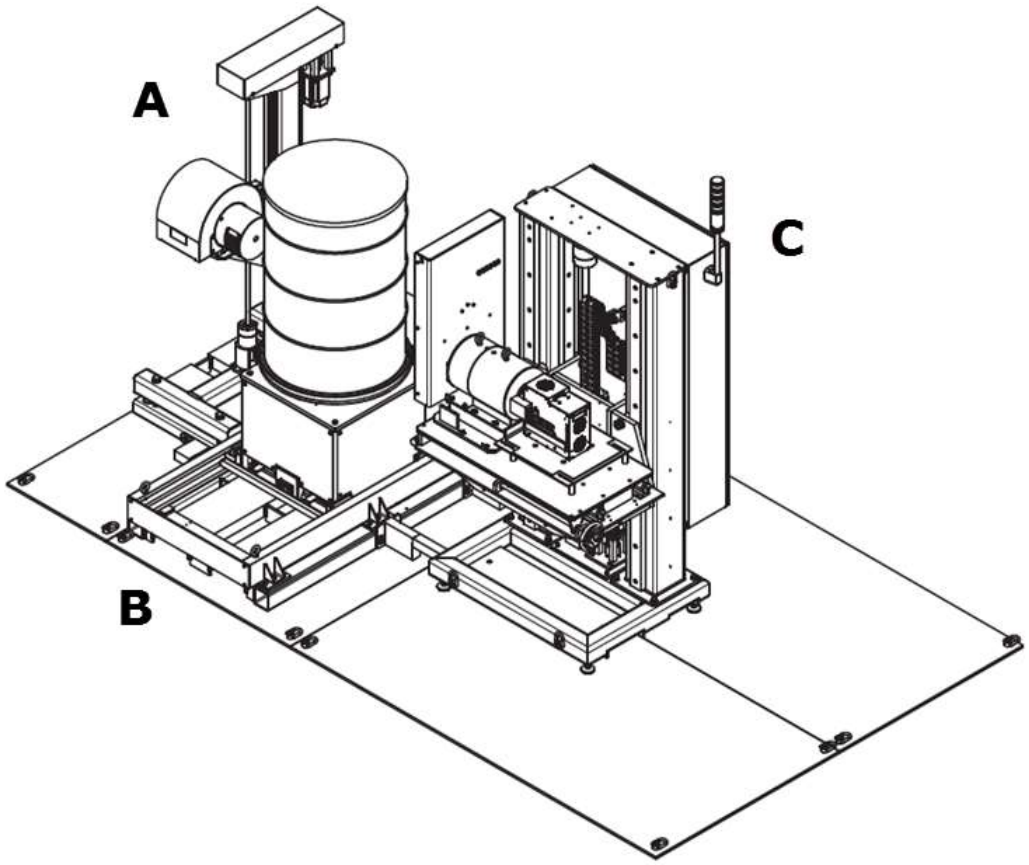

Figure 1. A schematic of the TGS system. The assembly (A) on the left houses the transmission source. The center assembly (B) is the rotator-translator with a drum positioned atop, and the right assembly (C) is the detector lift with collimator and attenuators.

The rotator-scanning platform can accommodate up to 200 L drums, but for this particular system, the drum platter and centering rings were designed for 120 L drums. Some components within the rotator assembly were upgraded to be able to accommodate assay times as high as 24 hours, while maintaining precise container orientation and reckoning needing for proper image reconstruction. The transmission source, housed in the shielding is a Eu-152 source of nominal activity close to 555 MBq to the time of commissioning the system.

The manual collimators provided with the system had collimation width of 2.54 cm for the 10x10 volume element (voxel) per vertical layer and 1.27 cm width for higher resolution configurations. A photograph of the 2.54 cm collimator installed in the system is shown below.

Figure 2. Close-up of the 2.54 cm TGS collimator used in the TGS system during installation.

The detector vertical lift is synchronized with the movement of the transmission source as the container is scanned. A broad-energy HPGe detector with electrical cooling was chosen for its high efficiency and excellent energy resolution, both critical for assaying special nuclear material where isotopics codes might be used in the data analysis. An uninterruptable power supply (UPS) was also provided with the system to ensure the detector is kept cold in the event of a loss of power lasting several hours.

The TGS system was calibrated using rod sources containing a mix of Ba-133, Cs-137, and Co-60, as well as individual nuclide point sources, in a manner similar to the methods in [3]. A number of calibration drums with pre-drilled holes in the matrix materials to place sources at various heights and radii were employed during the calibrations, spanning the density range up to 1.0 g/cc. Table 1 below shows the verification results from both point source and rod source distributions. The TGS system was also supplied with a wide rectangular collimator and calibration, typically reserved for densities greater than 1.0 g/cc.

Table 1. Distribution of 10x10x30 Calibration Assay Results for 120 L drums for the TGS mode in terms of percent deviation from the calibrated response. The density shown in the header of each column is the matrix density.

Gamma Energy (keV)	Rods-only 0.03 g/cc	Rods-only 0.39 g/cc	Point Sources 0.03 g/cc	Point Sources 0.39 g/cc	Point Sources 0.68 g/cc	RMS Average
276.37	-1.01%	6.2%	0.6%	-3.3%	-0.3%	3.18%
302.85	1.30%	0.6%	-1.5%	-1.6%	-0.7%	1.21%
356.01	-0.60%	1.1%	-0.1%	-2.2%	2.9%	1.70%
383.84	1.78%	3.0%	-1.4%	-2.6%	-0.5%	2.06%
661.65	-1.44%	-2.9%	1.2%	1.0%	9.5%	4.53%
1173.24	-0.56%	1.2%	-0.9%	1.9%	-3.0%	1.74%
1332.51	1.98%	1.6%	-4.8%	1.5%	-2.5%	2.76%

HIGH RESOLUTION SCANNING CONFIGURATIONS

The ability to switch between collimators easily allows for the assaying of a particular container with different image reconstruction resolutions. The default resolution with the 2.54 cm collimator has the number of voxels equal to 10x10x30 (width x length x height). When the 1.27 cm collimator is replaced, two finer image resolutions of 14x14x21 and 20x20x21 voxel grids were defined. Table 2 below provides details of each of the TGS resolutions in terms of voxel size and default scanning times.

Table 2. TGS Scanning configuration definitions

TGS Resolution Configuration	# of Voxels	Default Assay Time	# of Spectra	Voxel Width/Length (cm)	Voxel Height (cm)
10x10x30	3000	2 hours	4500	4.9	2.5
14x14x21	4116	2 hours	6174	3.5	3.5
20x20x21	8400	2 hours	12600	2.5	3.5

The primary motivation for supplying calibrations and configuring the TGS analysis software to allow multiple scanning configurations was to provide a platform for studying how image resolution definitions, scanning times, and collimator opening size affected the total measurement uncertainty for a given container size.

It was originally expected that the higher resolution configurations would provide more accurate assessment of the attenuating materials and source localization with finer collimation. Initial verification calibration results shown in Figures 3 and 4 for the higher resolution configurations can be compared to the standard 10x10 voxel

grid size root mean squared (RMS) results in rightmost column of Table 1. FM stands for a foam matrix drum with a bulk density of 0.03 g/cc. SB stands for softboard material, which has a density of 0.39 g/cc. MDF stands for medium-density fiber board, having a density of 0.68 g/cc.

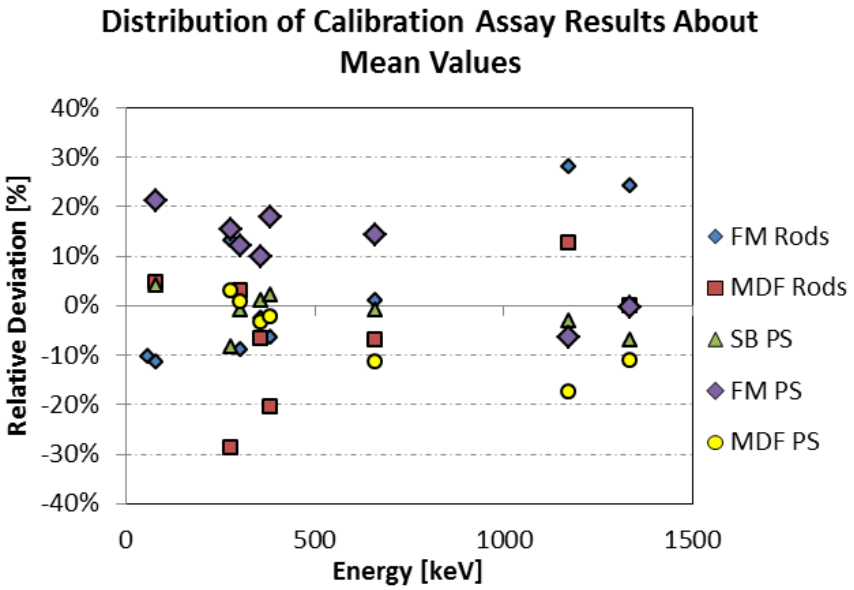

Figure 3. Calibration Assay Deviation with respect to the mean as a function of energy and drum material for the 14x14 image resolution.

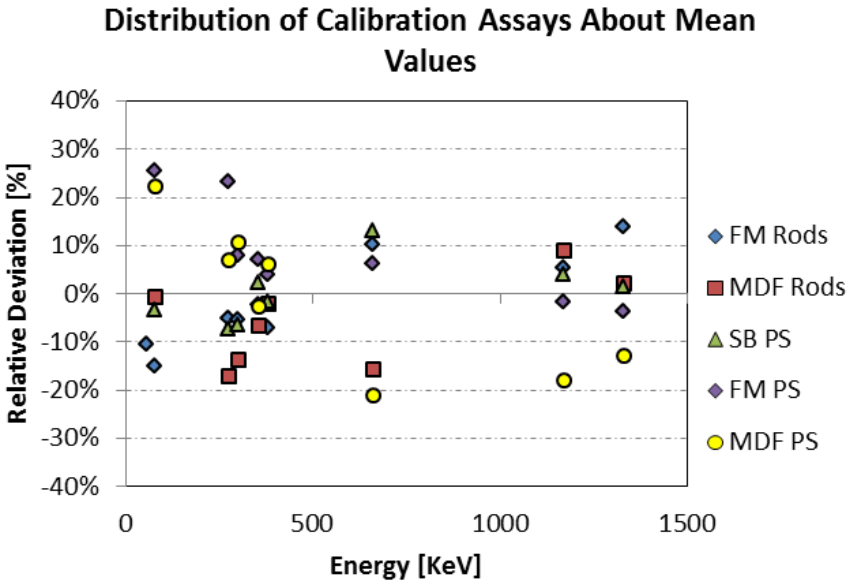

Figure 4. Calibration Assay Deviation with respect to the mean as a function of energy and drum material for the 20x20 image resolution.

After these tests, it does not appear that using the smaller collimator size with the image resolutions as defined in Table 2 improved activity determination using the calibration sources and calibration drums. It has been discussed [5] that the having as much statistics as possible in the count data of both the transmission and

emission scans probably play a central role in the TGS image reconstruction analysis. Simply increasing the number of data grabs or increasing the total assay time with the smaller collimator for the same sized drum at the same distance may not be sufficient alone to improve assay accuracy, and certainly more study is warranted.

END-EFFECT CORRECTIONS TO ADDRESS EXTREME IMPACTS OF SOURCE LOCATION

The impact of point-like sources and their locations within assay containers has been studied with TGS Systems previously for 120 L containers [4], 200 L drums [6], and 15 L can-sized containers [9]. In sensitivity study for 120 L containers, it was observed that for the point sources placed on the very bottom of containers, the activity recovery was reproducibly lower by about 20-30 % than in the bulk of the matrix. These results are consistent with total measurement uncertainty estimates of 5-13% at 1 sigma, depending on density and gamma ray energy, at the 2 or 3 sigma levels. Investigations by analysis or measurements, such as varying TGS reconstruction parameters or raising the drum by several vertical segments (e.g. 10 cm) to simulate the source in the bulk, provided no improvement. The increased bias appeared to also be independent of the default 10x10x30 image resolution and the higher resolutions.

An additional end-effect correction factor was implemented and tested to minimize these measurement scenarios, and the additional uncertainty resulting from the correction was folded into the error budget for all the image resolution configurations. Figure 5 shows a TGS image of an example assay, where a Cs-137 source is placed in the middle of a foam container and a Co-60 source is placed at the very bottom of the drum. Table 3 below compares the activity determination with and without the end-effect correction factor. The Cs-137 source in the middle of the drum is unaffected by the correction and the Co-60 source activity is closer to the expected activity with the correction.

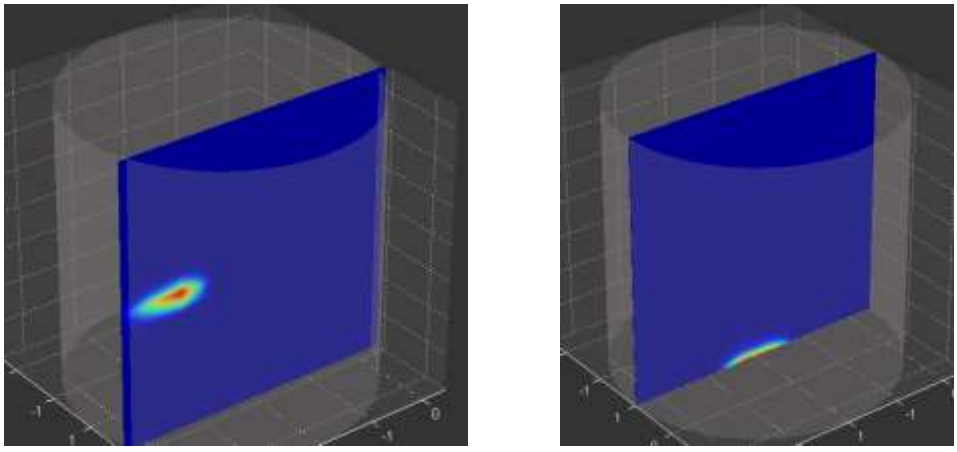

Figure 5. TGS Reconstructed Image of Cs-137 source (left) and Co-60 (right) for testing of the End-Effect Correction. The matrix in this case is the foam matrix of 0.03 g/cc.

Table 3. Extreme End Effect Correction Results

TGS Analysis	Position of Cs-137	True Activity (MBq)	Measured Activity (MBq)	Measured to True Ratio
Without End-Effect Correction	Middle of Drum	1.74	1.75 ± 2%	1.01
With End-Effect Correction	Middle of Drum	1.74	1.76 ± 2%	1.01
TGS Analysis	**Position of Co-60**	**True Activity (MBq)**	**Measured Activity (MBq)**	**Measured to True Ratio**
Without End-Effect Correction	Bottom of Drum	1.55	1.16 ± 2%	0.75
With End-Effect Correction	Bottom of Drum	1.55	1.44 ± 8%	0.93

SELF-ABSORPTION IDENTIFICATION AND CORRECTION

The use of a multi-line transmission source in the TGS system allows for accurate attenuation corrections at a localized region within the assay container at a wide range of energies. This correction is typically limited to the size of the reconstruction voxel, and for some chemical forms of the radionuclides under assay, the solution determined from the transmission alone may not be sufficient. Therefore, any nuclide of interest that emits more than one energy line with well-known branching ratios can provide more information about any self-absorptive properties, leading to higher confidence in the assay result.

First, the activity of any nuclide with multiple lines defined in the TGS analysis is determined on a line-by-line basis. Typically, the final activity result is a weighted-average of the multiple lines, but in addition, a consistency check is performed. The Line Activity Consistency Evaluation (LACE) analysis engine [10] calculate the slope of the logarithm of the ratio of each line to the weighted average or a key line defined by the user as a function of the logarithm of energy and reports a warning in the assay results if the slope is out of a specified range. In well-known matrices or in calibration campaigns, a flagged LACE result can also serve as an excellent quality assurance or diagnostic tool by warning the operator of the system to check the system calibration or the software setup.

In addition to identification of possible lumps of material unaccounted for with full TGS analysis, a self-absorption correction (SAC) can be performed. Details of implementing and testing the SAC engine with this 120 L TGS system can be found in [8], and the figure below shows an example mass determination for each energy line of two different Pu sources (top) and the results of after SAC analysis is

performed (bottom). In the top plot the masses are shown as a ratio to the mass obtained using the 414 keV line. In the bottom plot the masses are shown as a ratio to the expected mass value. Based on these results, the uncorrected values tend to underreport mass for Pu, while one SAC method overcorrects. Two of the methods investigated in [8] appear to zero in on the true mass in the two assays, each having very different source distribution and matrix materials from one another.

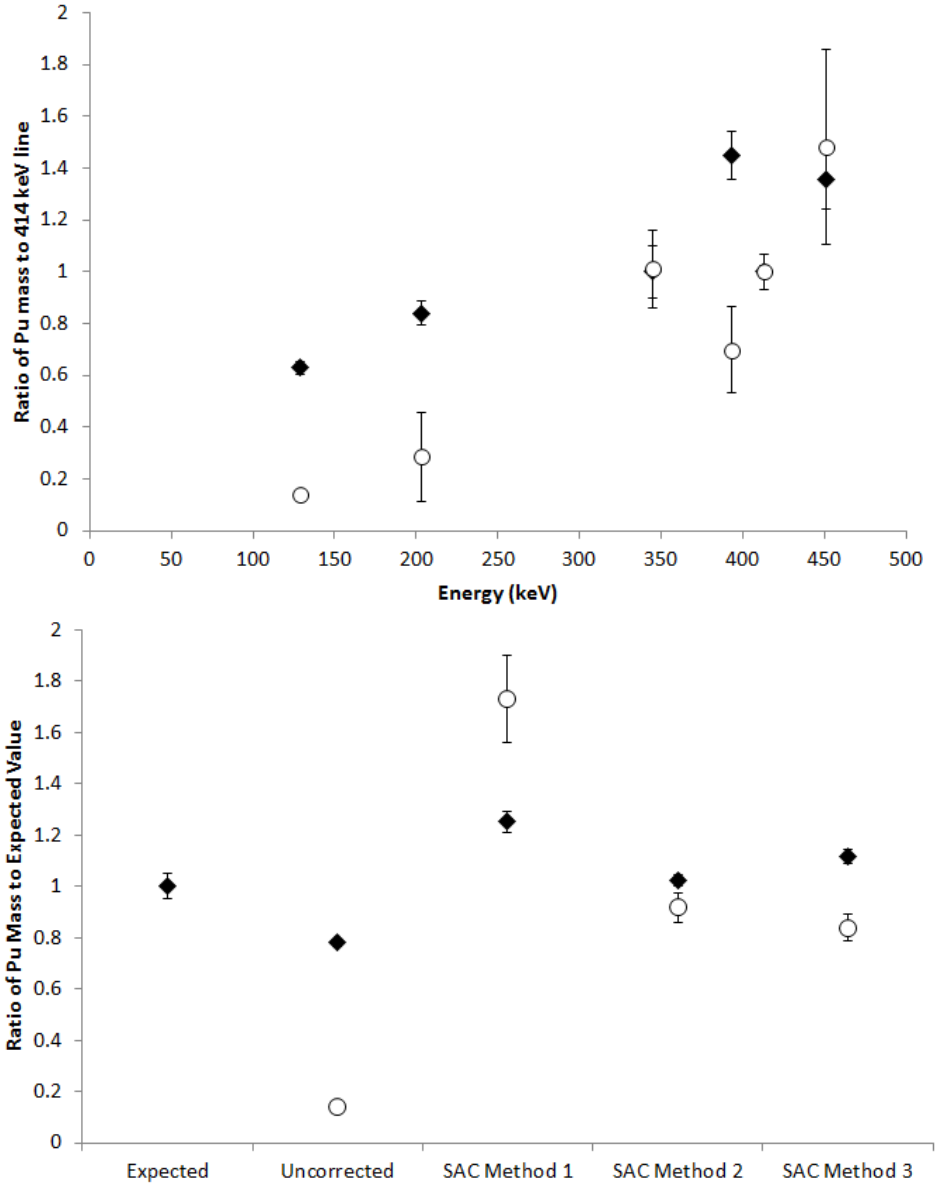

Figure 6. TGS Assay results from two Pu assays showing uncorrected masses as a function of energy (top) and self-absorption correction (bottom) masses using several methods.

RATE LOSS CORRECTIONS

Another significant enhancement implemented on recent TGS systems is to configure the TGS analysis algorithms to use the dead time estimations of the DSP

electronics for rate loss and summing corrections. Traditionally, TGS systems and many gamma NDA systems, use an electronic pulser module [7] for these corrections. In cases where there are irregular objects, or extreme transitions in density such as a highly attenuating piece of metal to an air pocket or a very low density matrix, the spectral grabs from the transmission beam can vary in dead-time by up to 50-60% from one another within the same assay. In most of the configurations of the TGS system, the spectral grabs can be less than a second in length, requiring high repetition rates (e.g. 1000 Hz) for good statistics. This can incur unwanted dead time in very low count rate situations. Another benefit for removing the electronic pulser is to simplify the number of hardware components, eliminating another source of potential noise in the signal chain. The following tests were conducted to verify and validate the modifications to the software routines:

- The proper dead time calculations from the DSP electronics are being written to every spectral grab in an assay
- The use of a pulser is still an option and the correct dead time is also being used in each spectral grab
- Re-analysis of assays acquired prior to the installation of the software modification returns the previous results
- Assay results using the MCA live time determination are consistent with assays using the pulser correction method.

The table below shows an example of the validation testing, where the TGS system's response with and without the electronic pulser for the same container and calibration source configuration. The baseline TGS response values are a result of the using the original software and pulser, while the test assays are with the software modifications. Differences in the lower energy lines of the Ba-133 source could be due to slight misalignment of the sources within, and is consistent with the total measurement uncertainty assessment.

Table 4. Comparison of TGS Response different methods for rate loss corrections

Gamma Energy (keV)	Baseline	Pulser with new software	Ratio of Pulser to Baseline	MCA Live Time with new software	Ratio of MCA to Baseline
276.45	0.043	0.042	0.977	0.041	1.079
302.78	0.106	0.106	1.000	0.103	1.108
355.98	0.304	0.313	1.030	0.303	1.031
383.83	0.044	0.042	0.955	0.043	1.000
661.49	0.584	0.585	1.002	0.568	1.005
1173.16	0.092	0.090	0.978	0.094	1.044
1332.07	0.088	0.093	1.057	0.088	1.011

CONCLUSION

Canberra has incorporated numerous enhancements and improvements in the most recent industrial TGS system commissioned for a nuclear facility. These modifications to both the hardware and software components have allowed for the further characterization of the TGS technique and the interplay between container size, degree of collimation, image reconstruction voxel size, and transmission source activity. Incorporating developments and the quantification of individual uncertainty components of the TGS system have allowed for an improved framework for uncertainty analysis, while increasing understanding of the technique for future system design and optimization. New software features have focused on ease of use, more detailed uncertainty calculations and reporting of each assay result, and increased flexibility for additional correction factors to improve overall accuracy pf the technique. Further studies of the key dependencies for varying container sizes and assay conditions have been planned or are in process.

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