Extending the Dynamic Range of the TGS Through the use of a Dual Intensity Transmission Beam

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Abstract

In order to implement the tomographic scanning technique in automated production environments, the density range of the technique must be extended beyond 2g/cc. At Canberra, we have developed a triple pass scanning protocol using a transmission source much stronger than typically used for general-purpose low-density contact-handleable waste forms. The triple-pass scanning protocol involves an emission scan, an attenuated transmission scan, and a full intensity transmission scan at each segment. The attenuated transmission scan is appropriate for weakly attenuating views, such as the sides of the container, whereas the full intensity transmission beam provides the attenuation information during more severe views. By including both transmission scans, the operator does not have to choose the appropriate beam intensity for each drum, nor repeat the assay with different transmission source settings, thus reducing measurement time. During image reconstruction, the software determines which transmission data to use at each view according to predetermined criteria. This paper presents how the TGS method has been modified and an initial performance assessment.

Introduction

Obtaining a high quality attenuation map is a prerequisite to obtaining an accurate TGS assay [1]. For highly attenuating items, counting precision is a limiting factor for some views. The dynamic range can be extended by using a strong high-energy source in conjunction with a beam modulator allowing high and low transmission modes. For modest attenuation, the weak or low beam intensity is used to obtain transmission factors and when the rates are too low to be viable, the high beam data is used. Ordinarily, the high beam would saturate the detector due to excessive dead-time and pile up; hence, the transmission data from the high beam cannot be used throughout the range. For this reason, a three-pass scanning protocol is used so that emission, low beam transmission, and high beam transmission scans are performed on each layer. The decision of which beam intensity to use in the tomographic reconstruction is made at the time of analysis based on various acceptability criteria.

As to the choice of transmission source, a strong source with only one, or a few, high-energy lines is recommended. For a multi-line source with a spectrum of energies, the soft components are preferentially removed at modest item thicknesses. Meanwhile, a mono-energetic, or nearly mono-energetic, source has the advantage that the rates are concentrated into a few useful peaks and hence the 'straight through' counting rate capability is not wasted on lines that will not penetrate.

This paper describes some of the additional features required to implement a dual-intensity transmission source and three-pass scanning. Specifically, determination of the ratio of high intensity to low intensity transmission beam count rates will be described, as will the impact on the Monte Carlo replicate method, and system considerations. In addition, preliminary results are presented from assays on a dual-intensity transmission TGS system performed using Canberra Industries' NDA2000 software.

Characterizing the High to Low Beam Ratio

The count rate of the transmission beam is not measurable when the beam is unattenuated because of limitations in the capability of the electronic counting circuitry given that the high beam is designed to 'punch' through dense waste items. Therefore, the ratio of the high to low beam is calculated using the following approach.

First, the count rate of the transmission beam in Low-Intensity-Beam mode (i.e. with a sintered Tungsten attenuator in place) is measured directly. Then, an attenuator (such as a sand filled drum) is introduced between the detector the beam and the Low-Intensity count-rate, x, is measured, obtaining:

$$x \pm \sigma_x = f \cdot I_L \tag{1}$$

where f is the attenuation factor through the item introduced and I_L is the unattenuated count rate of the transmission beam in Low-Intensity-Beam mode. Without moving the attenuating item, the count rate, y, is measured in High-Intensity-Beam mode to give:

$$y \pm \sigma_y = f \cdot I_H \tag{2}$$

where I_H is the unattenuated count rate of the transmission beam in High-Intensity mode. These measurements should be collected for a long period to ensure adequate statistics.

From these rates, which are fully corrected for dead-time using the pulser method [2] and, if necessary, peak background, and their associated standard deviation estimates, the ratio between the two beam strengths, r, for each transmission energy is estimated as:

$$r = \frac{y}{x} \pm \sigma_r \qquad \text{where} \qquad \sigma_r = r\sqrt{\left(\frac{\sigma_x}{x}\right)^2 + \left(\frac{\sigma_y}{y}\right)^2} \tag{3}$$

Thus, I_H is determined for each transmission energy by:

$$I_H = r \cdot I_L \pm \sigma_{I_H} \qquad \text{where} \qquad \sigma_{I_H} = I_H\sqrt{\left(\frac{\sigma_r}{r}\right)^2 + \left(\frac{\sigma_{I_L}}{I_L}\right)^2} \tag{4}$$

The estimates of I_L and I_H are thus correlated but, in principle, the uncertainty on r can be arbitrarily small by decreasing the uncertainty on I_L and I_H. In practice, I_L is determined at the beginning of each assay, which also serves as a check on system efficiency, resolution, and other factors.

The approach outlined above is less prone to systematic uncertainty, such as from taking the book value of the mass attenuation coefficient of the material, than calculating I_H directly via Equation (2). The selection of an appropriate item to provide a suitable attenuation factor, f, is open to experimentation for a given system so that suitable counting rates can generate suitable precision in I_H in a viable measurement time. It is also advocated that several different items, different density drums, or other items (e.g. a sand filled drum, a heavy steel drum, a Pb-block) be used for this purpose so that several estimates for I_H can be obtained thereby alleviating potential sources of random reproducibility and any potentially small but unrecognized counting rate dependences that may be present.

In other words, the important parameters for NDA2000 to store about the system are the Low-Intensity Beam count rate, ($I_L \pm \sigma_{I_L}$), the reference date, and the transmission beam ratio, ($r \pm \sigma_r$). The Low-Intensity beam count rate is directly measured at the start of each assay whereas the reference date is a primary system parameter. The transmission beam ratio is determined off-line and entered as a primary system parameter since this value is expected to be practically independent of detector collimator opening and detector to transmission source separation for a given attenuator. The High-Intensity beam count rate, ($I_H \pm \sigma_{I_H}$), should then be calculated and held internally as a derived parameter according to the method described above.

Monte Carlo Replicate Method

In applying the Monte Carlo Replicate (MCR) method [3] to the problem of estimating the statistical assay uncertainty, it is important that the raw count data be perturbed rather than use a scaled rate. In this way, the scatter in the data characteristic of the inherent randomness in the counting statistics will be taken into account in a natural way.

In the TGS assay protocol, the unattenuated count rate in the Low-Intensity mode, I_L, is determined with the drum moved to the side as part of the assay sequence. Thus, I is calculated as:

$$I = \frac{C}{I_0} \text{ [nominally } \pm I \sqrt{\left(\frac{\sigma_C}{C}\right)^2 + \left(\frac{\sigma_{I_0}}{I_0}\right)^2} \text{ at 1-sigma]} \qquad (5)$$

where I_0 is either I_L or I_H and C is the net peak count rate. The selection of the I-value from the low beam or high beam scan is based principally on the dead-time during the grab, as estimated from the reference pulser peak [2], being below a user selectable threshold and the statistical viability of the transmission data. Although not considered further here, there are strategies for dealing with situations where neither beam has useful information.

The MCR method statistically perturbs the number of counts in the background ROI(s) and in the peak ROI using Poisson distribution, thus allowing the number of net counts to fluctuate randomly. In a way, this is analogous to repeating the assay [3]. The perturbed counts can thus be propagated through the entire analysis process to evaluate the impact on the assay result. The difference between MCR for a standard TGS and the dual-intensity TGS is that MCR must include the estimate of the high beam rate, which contains an additional source of uncertainty through the multiplier, r, which is common to all views. Thus, another tier of perturbation is required. In essence, the assay must be performed (on the unperturbed view data) using three values of r corresponding to the best estimate value and the value $\pm \sigma_r$. The 1-sigma systematic assay uncertainty associated with the uncertainty in the r-value is obtained from half the spread in the two assay values obtained using ($r - \sigma_r$) and ($r + \sigma_r$).

There is an analogous effect already present in the standard TGS scan approach in that the estimate of I_0 (=I_L) is subject to a counting uncertainty that affects all views. It is important to realize, therefore, that during an assay r and I_L are independent, (i.e.) the characterization measurement that leads to the estimate of r is separate from the unattenuated count rate I_L measured at the start of an assay. Thus, really what is needed is to perform an analysis with I_L and ($I_L \pm \sigma_{I_L}$) and with r and ($r \pm \sigma_r$) to obtain the uncertainty contributions due to these two sources. Then, replicates need to be run to perturb the net peak rates, keeping within the original dead-time selection or allowing the decision criteria to be flipped. In this way, both the systematic and random counting uncertainties are properly accounted for. In practice, knowledge of the transmission beam properties is typically very good in comparison to other sources of uncertainties that contribute to assay uncertainty.

Implementation

To realize the concept described, a variant of the standard Canberra Industries TGS (CI-TGS) has been constructed. The general-purpose Eu-152 transmission source, which is typically in the range 7-15mCi depending on the HPGe detector selected, was replaced by a Co-60 source in the 250mCi range. The source store was redesigned with additional shielding to maintain the dose rate on contact at all accessible places to less than 2 mSv/h in soft tissue. The source store and mechanism is illustrated in Figure 1.

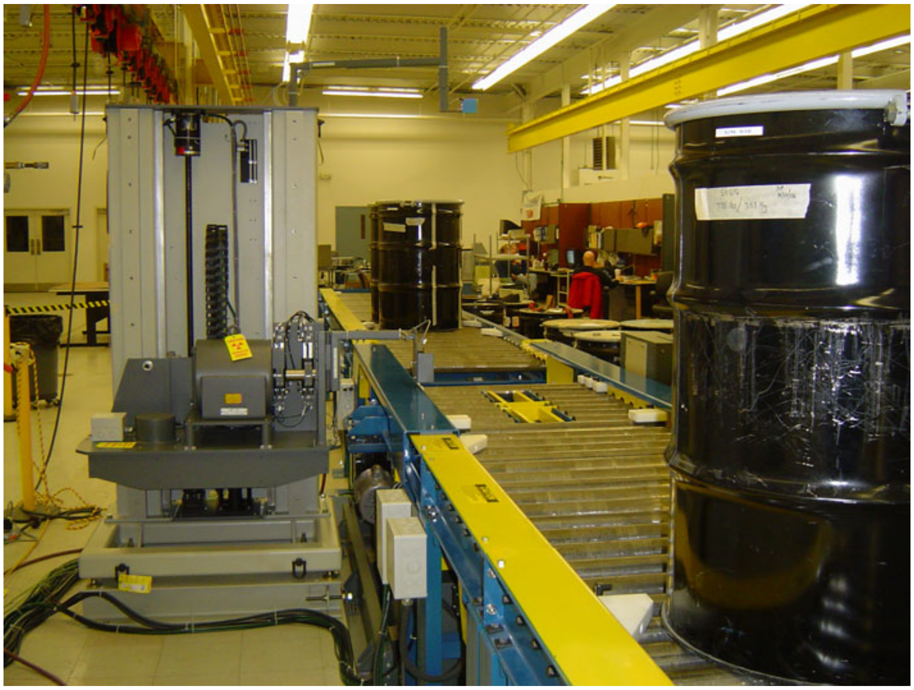


Figure 1 View of the transmission source store mounted on its lift mechanism. The detector lift is out of view on the opposite side of the conveyor, only the collimator is visible.

The beam cone is defined by the aperture in the store and is such that the diamond shaped TGS-collimator, which typically is of the order of the crystal size across the flats of the diamond opening, is always fully illuminated. This maximizes the counting rate in the detector for a given source activity. Just in front of the opening to the transmission store is a mechanism for the movement of cylindrical sintered tungsten. When both the attenuator and the shutter are down (the gravity-selected position in the case of power failure), the beam is switched off and the peak counting rates in the detector are close to close to background rates. With only the shutter raised the beam is in Low-Intensity mode and with both the shutter and the attenuator pieces raised, the beam is in High-Intensity mode. The Tungsten cylinders are oversized radially to quell few scattered radiation from reaching the detector. The combined length of the shutter and attenuator is about 220 mm. The length of the attenuator may be trimmed for a given detector-source combination to take best advantage of the dynamic range.

Co-60 was chose as the transmission source because of its pair of high-energy gammas. Traditionally, Eu-152 is preferred because of its wide energy range of gammas that allow for empirical determination of the attenuation of the energy range. However, for moderate to severely attenuation items only high-energy gammas will penetrate. Thus, most of the intensity of the transmission source does not penetrate the item in the case of Eu-152. Furthermore, if the penetrating lines from Eu-152 at 1112 and 1408 keV are considered somewhat analogous to the lines at 1173 and 1332 keV from Co-60, then the ratio of count-rate available from the high activity Co-60 source is a factor of over 100 times greater than the strongest general purpose Eu-152 source. This increase extends the range of the density of items of interest to 2.5-3.5 g/cc. Consequently, rates are viable for more attenuating items and/or, for some classes of waste, when higher activities are present in the item.

The drawback, however, is that the behavior of the transmission factor as a function of energy can no longer be extracted from the observed transmission data and the materials basis set (MBS) [4, 5] method of interpolating the attenuation map can no longer be applied. This problem is circumvented by allowing the user to select a single representative material, referred to as the Z-effective, Z_{eff}, which is used to provide the energy dependence of the (mass) attenuation coefficient. In practice, within the overall Total Measurement Uncertainty this turns out not to be a major source of bias for gamma ray energies above about 200keV, which is away from the influence of the strong atomic number dependence of the photoelectric cross section.

Preliminary Results

Measurements were performed on three 200ℓ drums, each filled with a different matrix, and eight rods of Co-60, Ba-133, and Cs-137 were used to simulate a radioactive distribution. The combined activities of Co-60, Ba-133, and Cs-137 for all rods were 40 μCi, 246, and 41 μCi, respectively. Assays were performed using Canberra's NDA2000 software on a TGS system using the transmission source setup described above. The first drum was filled entirely with sand, with holes to allow source placement, and had a density of about 1.6 g/cc. The next drum was filled with scrap pieces of steel, referred to as the Sample Steel drum, with an average density of approximately 1.09 g/cc. The last drum, known as the Heterogeneous drum, was filled with quart Plexiglas canisters filled with steel shots, sand, or walnut shells. The average density of the Heterogeneous drum is about 0.64 g/cc. TGS analyses were then performed on these measurements. A Z_{eff} of 14 is chosen for the heterogeneous and sand drums and a Z_{eff} of 26 is used for the sample steel drum. The calibration of the system was performed using the low intensity transmission beam only on an empty drum with the same rods used in these measurements.

For comparison, the drums were analyzed in three modes: low beam transmission only, high beam transmission only, and hybrid transmission. The low beam transmission only analysis is equivalent to the capability of standard TGS. High beam transmission only analysis is the same as for low beam only using the full intensity of the beam for all views. Lastly, the hybrid analysis method uses the both beam intensities of the dual-intensity TGS.

Figures 2 through 4 show the ratio of the reported to expected activities for the 356 and 383 keV lines from Ba-133, the 662 keV line from Cs-137, and the 1173 and 1332 keV lines from Co-60. A ratio of unity would indicate perfect agreement. Note, the presence of the radionuclides in the transmission source data is compensated for because the emission data is used as the peaked background for the transmission.

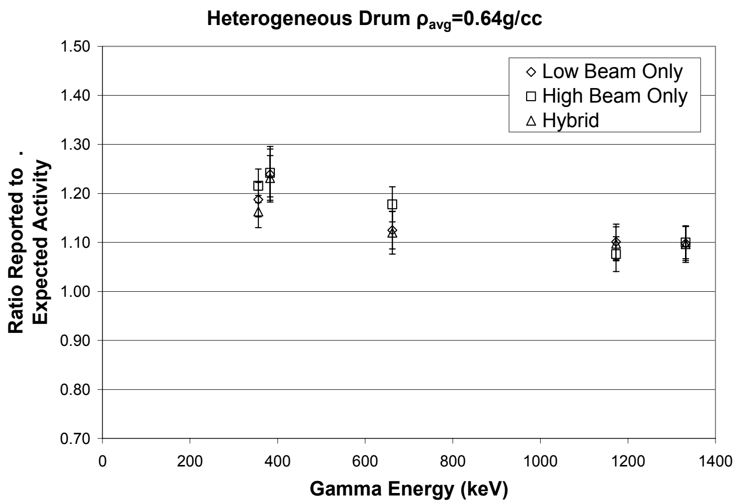


Figure 2 Ratio of Reported to Expected Activity for Various Gammas in Heterogeneous Drum

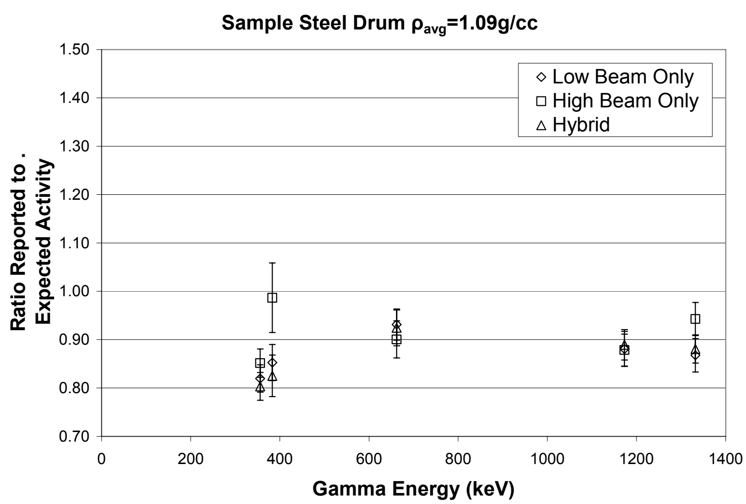


Figure 3 Ratio of Reported to Expected Activity for Various Gammas in Sample Steel Drum

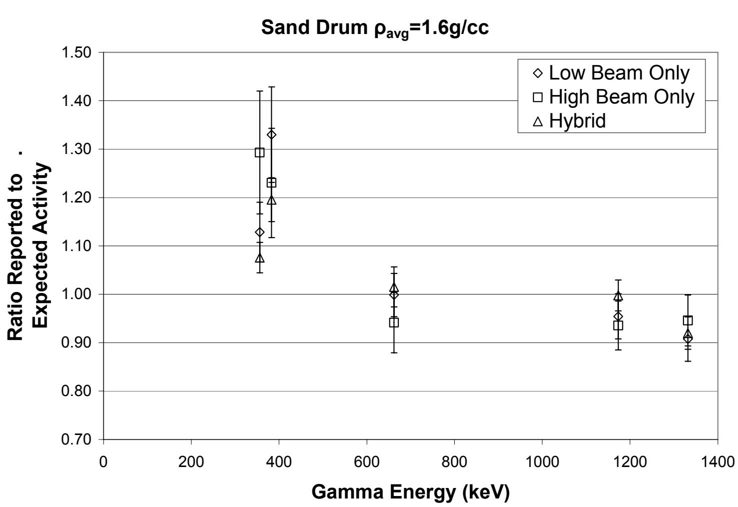
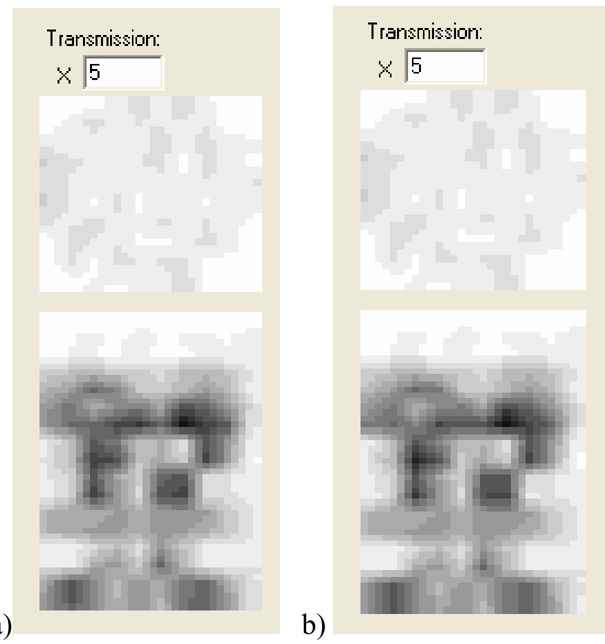


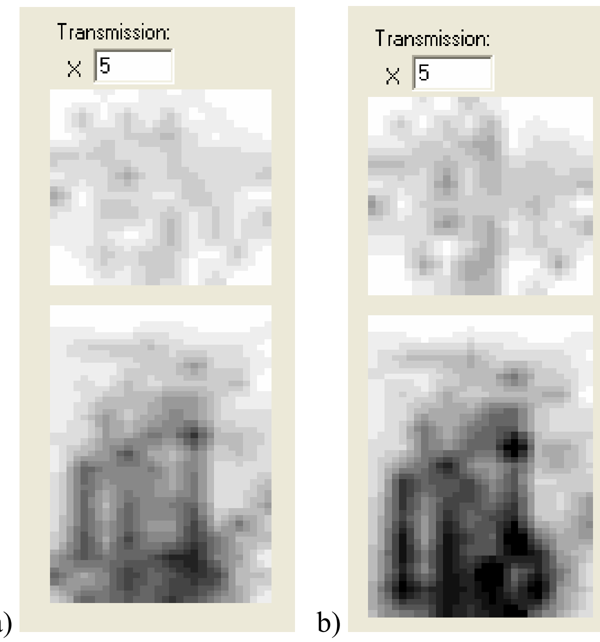
Figure 4 Ratio of Reported to Expected Activity for Various Gammas in Sand Drum

Of further interest is the image of the attenuation map in the drum. Figures 5 through 7 below how a two dimensional attenuation map of each of the drums for Low beam only and for hybrid transmission. The upper part of each figure is a linear attenuation coefficient map across layer 5 of the 16 layer axial scan. The lower part is a projection of the opacity of the drum.



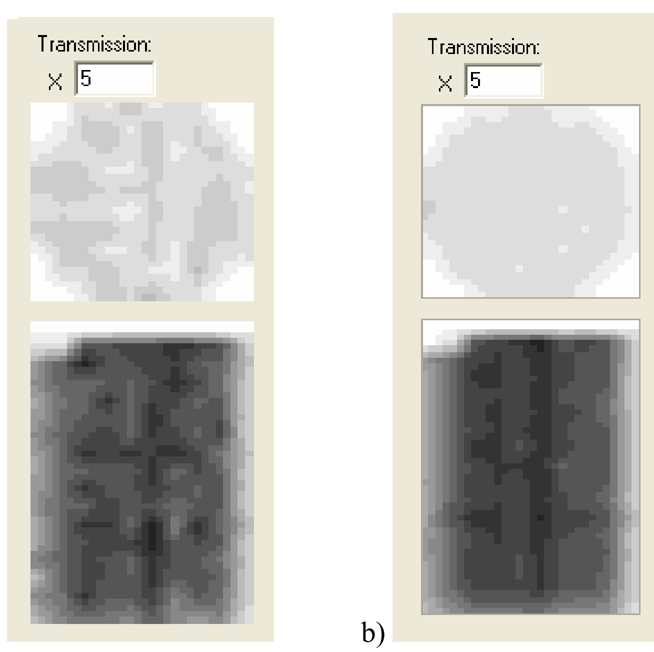
a) b)

Figure 5 Attenuation Maps of Heterogeneous Drum a) using Low-Intensity only and b) Hybrid Transmission



a) b)

Figure 6 Attenuation Maps of Sample Steel drum using a) Low-Intensity only and b) Hybrid Transmission



a) b)

Figure 7 Attenuation Maps of Sand drum using a) Low-Intensity only and b) Hybrid Transmission

Discussion

Using the hybrid transmission, the results are within 20% of the expected except for 383keV in the heterogeneous drum. The results for the heterogeneous drum are biased high, which is probably due to the selection of Z_{eff}. This is realistic of actual operation when the user will not know the composition of the waste matrix. In practice, the TMU will encompass the resulting uncertainty based on a range of Z_{eff}. In the sample steel drum, the statistics are poor for the low-energies of Ba-133; hence, the greater disagreement between those reported activities and the expected. The results for the sand drum are notable for Cs-137 and Co-60, within 10 %.

The attenuation maps are more of a visual record that the hybrid transmission corrects for attenuation better than the single-intensity transmission TGS. A slight improvement can just be seen in the heterogeneous drum. The sample steel drum attenuation map created using the hybrid scan shows more of a contrast between air and the steel than the map from the low-intensity only scan.

The improvement in the attenuation can be seen most profoundly in the comparison of the attenuation maps for the sand drum. The map created with the low-intensity transmission TGS scan has more of a checkered board pattern, indicating the source is not strong enough to penetrate the drum. The hybrid transmission map is much clearer, without the checkered board effect.

In these experiments, the activity within the drum was not increased with density. Therefore, although the linear attenuation map may be improved, the emission map continues to deteriorate with density. The interplay between the two effects will be reported elsewhere.

Conclusions

Canberra has implemented a dual-intensity transmission scan approach and successfully applied it in a fully automatic fashion for tomographic gamma scanning. The experiments described have demonstrated the functionality of the mechanisms and software. Already, an advantage can be seen in using the dual-intensity transmission scan versus a single low-intensity scan for drums of moderate to severe density. Future reports will describe further exploration of high density, more heterogeneous, waste simulations, and optimization of the dual-intensity transmission scan approach.

References

1. R.J. Estep, "TGS_FIT: Image Reconstruction Software for Quantitative, Low-Resolution Tomographic Assays", Los Alamos National Laboratory report LA-12497-MS (January 1993).
2. S. Croft, R. Venkataraman, M.F. Villani, S. Philips and R.J. Estep, "Uncertainty in Rate Loss Corrections Based on Counting a Periodic Pulser", Applied Radiation and Isotopes, 63 (2005) 575–582.
3. R.J. Estep, D. Miko and S. Melton, "Monte Carlo Error Estimation Applied to Nondestructive Assay Methods", 7th NDA and NDE conference, Salt Lake City, May 22-26 2000.
4. R.J. Estep, T.H. Prettyman and G.A. Sheppard, Comparison of Attenuation Correction Methods for TGS and SGS: Do We Really Need Selenium-75?, LANL report LA-UR-96-2575, INMM 37th Annual Meeting, July 28- August 1, 1996, Naples, Florida
5. R.J. Estep, User's manual for TGS_FIT version 2.0, LANL report LA-UR-00-4792