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ACTIVE SOURCE REQUIREMENTS FOR ASSAY OF SLUDGE DRUMS ON THE BIR WIT SYSTEM

G. Patrick Roberson and David C. Camp

INTRODUCTION:

The design of the active source for active and passive computed tomography (A&PCT) is critical with respect to accuracy and throughput. The A&PCT active source requirements are highly dependent upon the attenuation properties of the waste matrix within the drum. One of the most highly attenuating waste matrices is sludge. This waste stream will consist of solidified aqueous waste consisting of IDC 001 first stage sludge and IDC 007 wet sludge. Also, the stream consists of solidified organic waste known as code IDC 003 organic setups. We have evaluated the sludge drum data that was previously acquired on the WIT system and have determined that the active source activity must be increased to provide reasonable throughput. The sludge drum that is evaluated here is drum CEPRF11. CEPRF11 is a test drum that was part of the Nondestructive Assay System Capability Evaluation Project (CEP) and contained an actual Rocky Flats waste that is categorized as code 003 solidified organic waste. The full drum was evaluated and found to be somewhat homogeneous; therefore, a single slice is arbitrarily chosen to represent the entire drum. Slice number 8 is used and is located approximately at the center of the drum. Figure 1 shows the averaged projections for different energies derived from the active sinogram of slice number 8 from the CEPRF11 drum. This is the average of all the projections of slice 8 taken over 180 degrees with an active integration time of 6 seconds. Figure 2 is also a graph showing the average of all the projections for slice 8; however, the active integration time is 30 seconds.

Figure 1: Averaged projections for slice 8 of drum CEPRF11 with 6 sec. active integration time.

Figure 2: Averaged projections for slice 8 of drum CEPRF11 with 30 sec. active integration time.

From the graph shown in Figure 1 it is evident that the counting statistics of the detectors for cords located at the center of the drum are not sufficient for an accurate determination of the linear attenuation coefficient. With an integration time of 6 seconds, the center portion of the drum appears to be totally attenuated for energies at and below 410 keV. For energies above 710 keV there appears to be penetration; however, the counting statistics are no better than 30%. For an integration time of 30 seconds, as shown in Figure 2, there may be some penetration at and below 410 keV; however, the counting statistics are no better than 30%. At 710 keV and above the counting statistics are only 10%.

Three conclusions can be made from the averaged projections of the CEPRF11 drum. First, a long integration time will be required for the active imaging of sludge drums if the active source activity remains the same. The integration time would need to be at least 30 seconds and most likely longer, which would yield unacceptable system throughput for sludge drums. Second, it would be an advantage to use the high energy peaks to extrapolate the linear attenuation coefficient at lower energies. Third, it would be an advantage to increase the active source activity, thereby increasing the active imaging throughput.

Figure 3 shows the active images for slice 8 of the CEPRF11 drum reconstructed from the 30 second data set. Notice that the two high energy reconstructions at 710 keV and 1332 keV indicate that there may be two voids located in the bottom right of the drum. However, the two apparent voids are not as visible in the two lower energy reconstructions that are performed at 280 keV and 410 keV. This may suggest that there is insufficient penetration at these energies for an accurate active image reconstruction.

Figure 3: Active images at different energies from slice 8 of sludge drum CEPRF11 reconstructed from data with 30 second integration time.

Figure 4: Active mode detector coverage of 55 and 83 gallon drums. In active mode the detectors are translated once for each projection acquired. The active-mode cord length pair through a 55 gallon drum containing sludge is shown for each detector.

SIMULATION:

The active source activity required for assaying sludge drums on the WIT system can be better understood using simulation. The sludge drum can be modeled knowing the chemical makeup of the waste matrix material. The simulation was simplified by using only the dominant materials which make up approximately 90% of the sludge matrix. The chemical makeup of the sludge material is shown in Table 1. A bulk density of 1.1 is used for the sludge matrix simulation, which is derived from an average over several thousand actual

drums at INEEL. This density value is somewhat less for code 003 sludge but should be accurate for codes 001, 002 and 007. Using this chemical makeup and the average bulk density, the linear attenuation is calculated at various energies from $^{166\text{m}}\text{Ho}$, ^{60}Co , and ^{152}Eu active sources. Table 2 contains the linear attenuation coefficient for major peaks of the $^{166\text{m}}\text{Ho}$, ^{60}Co , and ^{152}Eu sources. The linear attenuation coefficient is then used to determine the initial activity observed at the detector (I_0) that is required to produce 100 counts per second (cps) after being absorbed by various cord lengths of sludge material. Figure 4 is a diagram of the proposed WIT multiple-detector system showing the location of detectors with respect to the expected active cord lengths for a 55 gallon drum containing sludge. The I_0 value is determined using the following formula:

$$I_{0(100\text{cps})} = \frac{I}{e^{-\mu \times l}}, \quad (1)$$

Where I is the expected counts at the detector after attenuation of I_0 through a cord length l of sludge material and the steel drum wall. I_0 is calculated with a fixed I of 100 cps. The cord length is variable from 0 to 60 cm depending on the location of the detector with respect to the drum. The linear attenuation coefficient, μ , is dependent on energy and the value at each energy of interest is obtained using a LLNL simulation code called TPORT and recorded in Table 2. Using the initial activity that is seen at the detector of the WIT system, the required activity of the active source can be determined using:

$$\text{Activity}_{(mCi)} = \frac{(I_{0(100\text{cps})})}{d\Omega \times Br \times \varepsilon \times Ar \times dps_{(mCi)}}, \quad (2)$$

where Br is the branching ratio of the energy peak of interest, ε is the intrinsic peak efficiency of the detector, Ar is the correction factor used when the 5:1-aspect-ratio septa is inserted in the collimator aperture (the value is 0.8 for the current WIT configuration), and $dps_{(mCi)}$ is 3.7×10^7 disintegrations per second required for one millicurie (mCi) unit of activity. The detector solid angle is denoted by Ω and is calculated using:

$$d\Omega = \frac{A}{4 \times \pi \times d^2}, \quad (3)$$

where A is the detector plane frontal area and d is the detector to source distance. The detector frontal area of the single-detector WIT system is currently 5.398 cm² and will be 5.715 cm² after the multiple-detector upgrade. A detector to source distance of 118 cm is used in the solid angle calculation, which is the current single-detector geometry. However, the multiple-detector geometry is unknown at this time and the detector to source distance could differ slightly, but not substantially.

Table 1: Chemical recipe used to simulate a sludge drum

Item	Constituent	Formula	Amount (% weight)
1	Steel	$\text{Fe}_{985}\text{C}_{15}$	0.72
2	Sodium nitrate	NaNO_3	34.6
3	Potassium nitrate	KNO_3	12.8
4	Ferric sulfate	$\text{Fe}_2(\text{SO}_4)_3 \cdot 9\text{H}_2\text{O}$	7.9
5	Aluminum nitrate	$\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$	19.5
6	Magnesium sulfate	$\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$	15.5
7	Calcium chloride	CaCl_2	9

Table 2: *Energy-dependent information used to determine the active source activity required from ^{166m}Ho and ^{60}Co sources.*

Energy-dependent information for the ^{166m}Ho & ^{60}Co sources			
Energy (keV)	Attenuation coefficient (μ in 1/cm)	Intrinsic peak efficiency (ϵ)	Branching ratio (Br)
280 (^{166m}Ho)	0.1286	0.544	0.305
410 (^{166m}Ho)	0.1103	0.435	0.119
710 (^{166m}Ho)	0.0867	0.3	0.602
1332 (^{60}Co)	0.0637	0.2	1.0

Table 3: *Energy-dependent information used to determine the active source activity required from a ^{152}Eu source.*

Energy-dependent information for the ^{152}Eu source			
Energy (keV)	Attenuation coefficient (μ in 1/cm)	Intrinsic peak efficiency (ϵ)	Branching ratio (Br)
121	0.185	0.65	0.282
344	0.1184	0.484	0.263
778	0.0832	0.28	0.128
964	0.0751	0.24	0.144
1402	0.0621	0.19	0.206

Table 4: *Energy-dependent information used to determine the active source activity required from a ^{133}Ba source.*

Energy-dependent information for the ^{133}Ba source			
Energy (keV)	Attenuation coefficient (μ in 1/cm)	Intrinsic peak efficiency (ϵ)	Branching ratio (Br)
356	0.1168	0.48	0.62

Figure 5-7 are graphs that show the required activity to achieve 100 counts per second at the detector after being attenuated by various cord lengths of sludge material within a 55 gallon steel drum. Each of the graphs have gray shaded areas that represent the cord-length coverage for each detector depending on its position with respect to the sludge drum. Figure 5 shows the required activity for four different energies from the current single-detector configuration consisting of ^{166m}Ho and ^{60}Co sources. Figure 6 shows the activity required for five different energies of an ^{152}Eu source. This activity is determined for the new multiple-detector configuration that will have a slightly larger collimator aperture than the current single-detector configuration. Figure 7 shows the activity that would be required from the 356 keV peak of a ^{133}Ba source and compares the activity to that required by the 344 keV peak of an ^{152}Eu source. Both calculations are made for the multiple-detector configuration.

Rearranging Equation 2 and solving for the unattenuated counts expected at the detector (I_o) yields:

$$I_o = Activity_{(mCi)} \times d\Omega \times Br_{(\Sigma)} \times \varepsilon \times Ar \times dps_{(mCi)}, \quad (4)$$

where the branching ratios are summed for all the source peaks and the intrinsic peak efficiency of the detector is fixed at 0.58, which will provide the greatest I_o counts at the detector (worst case scenario) for the current detector configuration in the WIT system. Expected unattenuated counts verses active source activity are plotted in Figure 8.

Figure 5: Activity of ^{166m}Ho and ^{60}Co required at four different energies to produce 100 counts per second at the detector after being attenuated by various cord lengths of sludge material. The gray shaded area shows the cord length coverage for each detector of the new multiple-detector design.

Eu152 active source activity required for 100 cps at the detector for a 55 gallon drum with 1.1 g/cc bulk density sludge.

Figure 6: Activity of ^{152}Eu required at five different energies to produce 100 counts per second at the detector after being attenuated by various cord lengths of sludge material.

CONCLUSION:

Reasonable system throughput for assaying sludge drums will require greater active source strength than what is currently used on the WIT A&PCT scanner. Unfortunately, increasing the source activity too much will swamp the detector system when measuring the initial beam (I_0) or when any cord is measured that has little attenuation. However, for sludge drums with uniform attenuation properties, it might be an advantage to have an active source with variable activity. The active source might have two activities. This could be accomplished by automatically positioning the source so that either a standard strength source or a source with increased activity is positioned in front of the source collimator aperture. It is possible that the initial (unattenuated) beam of the stronger sources cannot be measured. If this is the case, the I_0 determination can be calculated instead of measured.

The digital gamma-ray spectrometer (DSpec) is capable of count rates of 140,000 counts per second. If the unattenuated count rate was limited to 100,000 counts per second, the active source activity could be approximately 10 mCi of $^{166\text{m}}\text{Ho}$, 20 mCi of ^{152}Eu or 30 mCi of ^{133}Ba . However, the amount of dead time generated by any of these active source activities is unknown and should be evaluated.

There is a choice that must be made with respect to the method of determining the linear attenuation coefficient. First, it could be determined, as it is currently, by using a direct measurement of attenuation at the energy of interest or by interpolating between two different energy peaks. Second, μ could be determined by extrapolating from the higher

energy peaks only. The extrapolation method would not be as accurate as making direct measurements or interpolating; however, less activity would be required if only high energy peaks were used.

Another choice must be made with respect to the type of source or sources to use. A comparison of the ^{133}Ba and ^{152}Eu activity required to generate 100 cps at approximately 350 keV through various sludge cords is shown in Figure 6. This graph illustrates that ^{133}Ba at 356 keV will provide the necessary counts with less activity than ^{152}Eu at 344 keV because ^{133}Ba has a higher branching ratio. The tradeoff is that ^{133}Ba will require another source mixed with it to get the necessary high energy peaks and will cost more than the ^{152}Eu source which can be used by itself.

From graphs shown in Figures 5-7 it appears that a standard ^{152}Eu source activity of approximately 4 mCi would provide sufficient strength at 344 keV and there would be no need to increase the source strength for detector 1 and 6. The required additional source strength for detectors 2 and 5 would be approximately 50 mCi and for detectors 3 and 4 the requirement is 170 mCi to generate 100 cps at the detector. This scenario may be the ideal situation; however, it may not be possible to get source strengths of this magnitude due to a restriction of the physical size of the source container. Additionally, sources with activities greater than 10 mCi exceed the current allowable threshold at BIR; therefore, there is a limit of 10 mCi for the active source activity.

Figure 7: Activity of ^{152}Eu 344 keV peak and ^{133}Ba 356 keV peak required to produce 100 counts per second at the detector after being attenuated by various cord lengths of sludge material.

Figure 8: *Initial counts expected at each of the multiple detectors for a given active source activity. The intrinsic peak efficiency of the new detectors is unknown, however, for this calculation it is fixed at 0.58 which represents the worst case scenario of the current detector used in the WIT A&PCT system.*

If the active source is limited to 10 mCi, it will take approximately 17 seconds to get 100 counts at the center detectors when assaying an average sludge drum. This would reduce the throughput significantly. However, there is another possible solution. A drum that is truly homogeneous will have active projections that are identical over all angles. The homogeneity of a sludge drum can be evaluated by transmission tomography (TCT) or digital radiography (DR) using the linear accelerator and linear detector system within the WIT trailer. If a drum is found to be homogeneous, a single measured projection could be simply duplicated 18 times to produce the required sinogram for active reconstruction. If the drum is homogeneous over all slices, a single projection could be used to reconstruct the entire 3D active image. This is a form of limited angle tomography and should be valid for drums that are truly homogeneous. A single projection of a sludge drum could be acquired in 100s of seconds providing much better counting statistics and yet increase throughput significantly.

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