Preliminary A&PCT Multiple Detector Design

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Preliminary A&PCT Multiple Detector Design

Upgrade of a single HPGe detector A&PCT system to multiple detectors

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EXECUTIVE SUMMARY

Over the past eight years the Lawrence Livermore National Lab (LLNL) has been developing a new technology for the quantitative assay of radioactive isotopes in both low-level and transuranic mixed and non-mixed wastes. This technology is called Active and Passive computed tomography (A&PCT) and is a comprehensive and accurate gamma-ray nondestructive assay (NDA) method that can identify all detectable radioisotopes present in a container and provide a quantitative measure of their activity. The active (ACT) technology can yield quantitative attenuation data (related to density and atomic number) for the waste matrix within a drum. The passive (PCT) technology is used to localize all detectable radioisotopes within a drum and more accurately determine their identity by measuring their emitted characteristic peak(s) within the energy spectrum using high energy resolution spectrometry. The ACT images are used to correct the attenuated PCT data for attenuation by the waste matrix to accurately determine the activity of the internal emitting radioisotopes.

Sufficient real experimental data now exists, in addition to selected simulated data, to conclusively demonstrate that the A&PCT technology works. However, one limiting restriction to our approach has been the long scan times required to assay a drum. Now that we have demonstrated that our approach works, we turn our attention to reduce data acquisition scan times in the ACT and PCT modes without compromising the accuracy of the assay. During our development work, we have studied the fundamental parameters that govern the optimum scanner design with respect to accuracy and speed. The long scan times are due, in part, to the use of only a single high-purity germanium detector for recording data, redundant sampling (over sampling) in the PCT mode, and overhead associated with discrete movement of the drum during data acquisition. Here we describe a new generation A&PCT scanner that incorporates multiple detectors, under sampling, and a continuous motion scanning mode. The graph below shows the expected speed up of the new scanner and is compared to the current single-detector A&PCT scanner. The integration time used for a drum assay is dependent on the waste matrix gamma-ray attenuation and the activity level of the waste's radioisotopes. Depending on the integration time used, the new A&PCT system design should increase throughput by a factor of approximately 10 for long integration times typically used to assay low waste activity, to a factor of 100 for short integration times typically used to assay high waste activity.

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INTRODUCTION

The next generation, multi-detector active and passive computed tomography (A&PCT) scanner will be optimized for speed and accuracy. At the Lawrence Livermore National Lab (LLNL) we have demonstrated the trade-offs between different A&PCT design parameters that affect the speed and quality of the assay results. [KETO95, MAR92, MAR92a, ROB95, ROB94, ROB92] These fundamental parameters govern the optimum system design. Although the multi-detector scanner design has priority put on speed to increase waste drum throughput, higher speed should not compromise assay accuracy. One way to increase the speed of the A&PCT technology is to use multiple detectors. This yields a linear speedup by a factor approximately equal to the number of detectors used without a compromise in system accuracy. There are many different design scenarios that can be developed using multiple detectors. Here we describe four different scenarios and discuss the trade-offs between them. Also, some considerations are given in this design description for the implementation of a multiple detector technology in a field-deployable mobile trailer system.

DESIGN CONSIDERATIONS

System Parameters

In developing a multiple detector design it is important to understand the effects and trade-offs between different system parameters. In this section we focus on what we have learned from our single HPGe detector based A&PCT scanner called IMPACT.[ROB95, ROB94] This multi-detector design study is constrained to 55- and 83- gallon drums that have the following dimensions:

Drum size	ID (in)	OD (in)	Fill height (in)	Drum height (in)
55-gallon drum	22.0	23.3	33.4 or less	36.0
83-gallon drum	25.2	26.5	38.4 or less	42.0

The drum OD includes the lid, clamping ring, and ribs and is not a measure of the drum wall thickness. The drum wall thickness is approximately 0.065 inches. In this design study we are limiting the A&PCT field of view to these two drum sizes. A&PCT can most likely be performed on drums larger than 83 gallons if these drums are overpacks for 83- or 55- gallon drums. Only the activity and waste matrix within the 83- and 55- gallon drums need to be within the system field of view.

In this design study we chose to fix the source-to-object and detector-to-object distances to accommodate both 55- and 83- gallon drums. It would be an optimum case in emission tomography to move the detector as close to a waste drum as possible; however, an 83-gallon drum requires an increase of 1.6 inches of additional detector-to-object distance than a 55-gallon drum. If there were an emission source located at the center of a 55-gallon waste drum with a detector-to-object distance of 20 inches, an additional 1.6-inch distance translates into a $1/r^2$ loss of approximately 14%. Thus, it would not seem to be a severe penalty if we adopt one single fixed distance to assay either a 55-gallon or an 83-gallon waste drum.

Through simulation it was found that there is a trade-off between spatial resolution and signal-to-noise in A&PCT.[KETO95] Further, an optimum system design is dependent on expected emission source sizes and activities. Results of the simulation work reveal that A&PCT system collimators with apertures of 1 to 3 inches perform the best. The detector collimator aperture size defines the A&PCT image voxel size. Also, the aspect ratio (ratio of collimator length to aperture size) of the detector collimator performs best if it is in the range of 5:1 to 10:1. For the ideal case, detectors with high efficiency should be used in the system design so that the largest collimator aperture size (up to but not exceeding 3 inches) can be attained. A large aperture will reduce the assay time in two ways. First, a larger aperture utilizes more detector surface area; and therefore, has a higher photon counting efficiency. Second, a larger aperture yields an advantage of fewer measurement positions (sampling); thus, an assay will require less time with fewer samples of the waste drums. Also, a collimator with a lower aspect ratio will improve counting efficiency. The lower the aspect ratio, the closer the detector will be to the waste drum; hence, the higher the photon counting efficiency due to a larger solid angle.

From this point on we will assume that all of the A&PCT multiple-detector designs we consider have a detector collimator that has an effective aspect ratio of 5:1 to take advantage of a reasonably large solid angle. We have verified through experiments that this aspect ratio provides an accurate assay.[DEC96] Also, we will assume that the design should include a collimator aperture of 2.25 inches to utilize the most detector surface area. This aperture size is determined by evaluating the largest square opening that can be attained using a 100% efficient (relative to a 3" x 3" NaI(Tl) detector at 1.33 MeV) high purity germanium (HPGe) detector. Typically a 100% detector has a crystal diameter of approximately 3.25 inches. Figure 1 shows the relationship of this collimator aperture size to a 100% HPGe crystal. A square aperture size of 2.25 x 2.25 inches should be used so that the corners of the collimator aperture do not extend past the detector crystal.

Knowing the aperture size, the collimator length can be determined. For a 5:1 aspect ratio the length is simply 5 x 2.25 inches or 11.25 inches. If this collimator length exceeds the space available in a field deployable trailer system (e.g. the Waste Inspection Tomography system [BER95, MAR95]), septa can be used to reduce the collimator length yet retain the effective 5:1 aspect ratio. Septa are highly attenuating, dividing-plates that run the length of the collimator. These plates help collimate the gamma-ray beam, providing an effective aspect ratio that is better than that provided by the aperture size alone. Figure 2 shows 1/16-inch septa inserted in a 2.25-inch square collimator opening. For septa that are 1/16-inch thick, the length of the collimator is calculated to be 5.47 inches to achieve an effective 5:1 aspect ratio. This is simply the opening of each quadrant created by the septa (1.094 inches) multiplied by 5.

Figure 1: Maximum collimator aperture size that does not extend beyond a 100% efficient HPGe detector crystal.

Figure 2: For 1/16-inch septa and an aperture of 2.25 inches, a collimator length of 5.47 inches defines a 5:1 aspect ratio.

In each multiple-detector design scenario, described in the multiple-detector design scenario section, it is possible to under sample the passive portion of the A&PCT data set. In A&PCT, sampling is accomplished by integrating (acquiring spectroscopy data) at discrete positions (ray sums) along the x-axis as shown in Figure 3. A set of ray sums at one angular view is collectively called a projection. The set of all projections over a 360- or 180-degree angular range is called a sinogram. The word "sinogram" refers to the fact that a single point within a waste drum traces a sinusoidal curve over the projections when displayed as a 2-D image. An example of a 1-HPGe detector based CT system passive sampling of a drum with an edge-to-edge ray-sum geometry (not under sampled) is shown in Figure 3a. Also shown in the figure is an assumed collimator emission acceptance angle for each detector position. The acceptance angle is a function of the collimator aspect ratio. The acceptance angle shown in the figure is for a collimator with an effective 5:1 aspect ratio, which is achieved using septa.

Figure 3: *Passive CT acceptance angles for edge-to-edge and under-sampled ray-sum geometry for a single HPGe detector A&PCT system with a 5:1 effective collimator aspect ratio. The detector collimators are not shown in either figure. The relative scale between components is correct in the figure.*

The detector configuration shown in Figure 3a is a parallel geometry (defined for active mode) that is currently used in active and passive tomography. In the figure there are dashed lines that represent the crossover points of the detector ray-sum acceptance cones for passive CT. The region between the first and second crossover lines in 3a is where there is at least 100% sampling of the drum, i.e. every portion of the drum in this region is sampled by at least one detector. In this region there is also a portion of the drum that is sampled by two detectors at the same time. Beyond the second crossover point, the drum is sampled by two or three detectors at the same time. In passive mode, this type of geometry yields a large amount of over sampling. Our data reconstruction algorithm compensates for the over sampling; however, measurement time is wasted because of the sampling redundancy. This redundancy has the advantage that assay accuracy and precision may be increased due to an improvement in the additional counting statistics obtained. This improvement is gained because sources are seen in more than one detector at the same time. Simulation should be performed to determine if this is the case and is left for future work. However, even if this is true, it would be better to increase the sampling space between the detectors, effectively removing detectors or ray sums, and increase the integration time, if necessary, to compensate for the loss in the counting statistics. This will reduce the assay time in two ways; first, reducing the number of rays will reduce the assay time because the positioning overhead for a single-detector system is eliminated for each detector that is removed; and second, the reconstruction algorithm will operate faster with fewer ray sums. Therefore, under sampling the emission data in A&PCT is a desirable option for either a single or multiple-detector based scanner.

Under sampling can be performed by different amounts. Here, for the parallel detector configuration, the amount of under sampling is described as the amount of area sampled with respect to the total object area. Only the emission or passive tomography data set can be under sampled. The transmission or active portion must be sampled by at least 100 % (detectors sample the drum with collimator apertures edge-to-edge) because we acquire “parallel” active data and use the filtered back projection (FBP) algorithm for reconstruction. If 100% efficient HPGe detectors are used in a parallel configuration, the physical size of the detectors allow a spacing that is ideal for 50% under sampling. The spacing provides adequate room for collimation and shielding between the detectors to prevent crosstalk. A 50% under sampling geometry is shown in Figure 3b. The first crossover for this geometry is located well in front of the center of the drum. In this geometry, better than half of the drum is sampled by one or more detectors. If the detectors are placed in a geometry that allows 50% under sampling for the passive mode, the active mode will require only one translation to fill in the missing detector collimator space for 100% sampling. A geometry that provides under sampling by greater than 50% will require more than one translation of the detectors in the active mode. The extra translations of the detectors in the active mode will increase scan time. This 50% under-sampling geometry is an important part of a multiple detector A&PCT design.

Figure 4 shows a possible distribution of multiple, 100% HPGe detectors and the resulting 50% under sample coverage on 55- and 83-gallon drum cross sections. It should be realized that this sample coverage is actually in three dimensions; however, for simplicity, only a two dimensional cross section is shown here. For each projection, the area of the drum that is not covered by detectors and areas that are covered by 1, 2, and 3 detectors are displayed in selected colors as described in the figure caption.

Figure 4: One possible multiple detector configuration and resulting emission acceptance angles for a 50% under-sampled ray-sum geometry. The area where there is no detector coverage is shown in yellow. Also, the areas where 1, 2, and 3 detectors overlap are shown in colors outlined gray, blue, and outlined red respectively.

In addition to under sampling, it is also possible to perform continuous motion scanning for both active and passive CT. Continuous motion scanning is desirable because it eliminates the overhead that is required in stopping at discrete scan positions. In our current A&PCT scanning protocol, a waste drum is discretely rotated, translated, and elevated. In this protocol, the axis that best lends itself to a continuous motion is the rotational axis. The rotational stage can provide rapid movement, is robust, and the motion blurring caused by continuous movement should be minimal if the ray-sum data acquisition time ("snapshots") are acquired in sufficiently short periods. The ray-sum snapshots will be acquired by continuously integrating the emission spectra as the waste drum rotates, and the ray sums at different angles are defined by subtracting the last integrated spectra from the most recent integrated spectra. The continuous scanning technique proves to be especially useful when scanning waste drums with high internal amounts of activity.

Figure 5: Total assay time predictions versus integration time per ray sum for current A&PCT single-detector systems. Comparisons are made for edge-to-edge discrete motion sampling, discrete motion with under sampling, and under sampling with continuous motion scanning (as labeled). These predictions are made assuming a 4-second overhead per ray sum for scan geometries that use discrete movement. The assay time predictions include both active and passive data acquisition.

The following discussion of several multiple-detector scenarios present total acquisition time predictions that include both the active and the passive data-acquisition times. These predictions are presented for an edge-to-edge sampling geometry with discrete motion; for under-sampled geometry with discrete motion; and for under sampled with continuous-motion geometry. Currently our A&PCT system uses a single-detector geometry where the overhead in discrete movement scanning is approximately 4 seconds. Typically, for 55 gallon drums, our single detector active and passive CT scans for the edge-to-edge case require 14 drum translations, 21 rotations, and 18 elevations; and for 50% under-sampled protocols, 7 translations, 10 rotations and 18 elevations. Only the emission portion of an A&PCT scan can be under sampled; the active portion must be sampled edge-to-edge in the parallel detector configuration. Figure 5 is a graph showing the total assay time versus integration time per ray sum for the three different sampling protocols discussed. Notice that the continuous scan protocol is only advantageous (i.e. shortens total assay time) for individual ray sum integration times below approximately 10 to 20 seconds.

and 83-gallon drums. For both active and passive modes, this scenario will require 14 drum translations, 21 drum rotations, and 1 drum elevation for edge-to-edge sampling; and 7 translations, 10 rotations and 1 elevation for the under-sampled case in emission mode. This design scenario is a true parallel case in active mode where multiple sources are required, one for each detector. The detectors are assumed to be 100% HPGe detectors, as discussed earlier. Detectors should be spaced so that the size of the collimator shield separating the detectors is the same as the collimator aperture size. If this is true, only one elevation will be necessary to perform a full sampling of the waste drum when 9 detectors are used.

The active source collimator for this type of system must be designed so that there is no crosstalk between detectors. Crosstalk will exist if the aspect ratio of the source collimator is not sufficient and any one of the transmission source activities is measured by more than one detector. This will lead to erroneous measurements of the linear attenuation coefficient that is used to correct for any attenuation of the internal radioactive sources by the waste matrix.

Figure 7: *Total active plus passive mode scan time predictions versus ray sum integration time for vertical in-line multiple detector systems. Comparisons are made for edge-to-edge sampling, and under sampling with discrete or continuous motion scanning.*

Figure 7 is a graph showing the total assay time for the combination of both active and passive modes versus integration time per ray sum for the three different sampling protocols. Again, notice that the continuous scan protocol is advantageous only for individual ray sum integration times below approximately 10 to 20 seconds.

Scenario 2: Horizontal straight in-line multiple-detector array

The horizontal straight in-line scenario is shown in Figure 8 and includes six 100% HPGe detectors configured in a parallel geometry. For both active and passive modes, this scenario will require 1 drum translation, 21 drum rotations, and 18 drum elevations for the edge-to-edge sampling case. For the under-sampled case, 1 translation, 10 rotations and 18 elevations are required for active CT, and no translations, 10 rotations and 18 elevations are required for passive CT. This design scenario is also a true parallel case in active mode where multiple transmission sources are required, one for each detector. Again, the detectors should be spaced so that the size of the collimator shield separating the detectors is the same as the collimator aperture size. If this is true, only one translation will be necessary for edge-to-edge sampling and no translations are necessary in passive mode for the under sampled case if six 100% HPGe detectors are used. As with the vertical in-line scenario, each active source collimator must be designed so that there is no crosstalk between detectors. Figure 9 is a graph showing the total assay time for both active and passive modes for different sampling techniques.

Figure 8: *Horizontal straight in-line scenario for waste-drum assay. Dimensions in the figure are approximate.*

Figure 9: Total assay time predictions for both active and passive modes combined versus integration time per ray sum for horizontal in-line, multiple-detector systems.

Scenario 3: Rotated straight in-line multiple-detector array

A rotated straight in-line design is shown in Figure 10. This system scenario uses multiple HPGe detectors, but are rotated with respect to each other so that they focus toward a single active source position. The detectors are kept in a straight line to simplify the collimator design and reduce its size (footprint). This type of CT system design is typically called a fan-beam geometry where one single active source is collimated to yield a fan beam that illuminates all of the detectors as shown in Figure 10.

Although fan-beam CT systems are common in the active case, they are not as common in the passive case. Some work in passive simulation has been done elsewhere.[BRO92] However, our A&PCT simulation codes cannot currently represent the fan-beam geometry for emission tomography. Therefore, for the emission case, there are many unanswered questions with respect to this geometry that will only be answered when our simulation codes are improved to the point where we can simulate and reconstruct detector geometries that differ from a straight line configuration. This effort is beyond the

scope of this report and is left for future work. Accordingly, there are also no predictions as to the speedup offered by an increased throughput of a system that incorporates this design strategy. However, it is expected that speedups equal to or better than the horizontal in-line scenario could be achieved because the fan-beam option might eliminate discrete translate positioning in both active and passive modes. There are also other advantages and disadvantages of this design scenario. These are discussed in the summary section.

Multiple rotated detectors and single source A&PCT system design

Figure 10: Rotated straight in-line scenario for waste drum assay. Dimensions in the figure are approximate.

Scenario 4: Curved multiple-detector array

A curved scenario is a rotated design where the HPGe detector faces fall along a curved line instead of a straight line. The curved scenario is shown in Figure 11. This type of system design also uses multiple, rotated detectors focused toward a single active source position; however, the HPGe detectors are curved around the waste drum to increase the solid angle of each detector, and therefore improve the systems efficiency. One difference between this design and the rotated design discussed above is that the detector collimator will have a slightly larger footprint. Also, in a transportable trailer system, the detector

assembly may need to translate away from the active source before it is moved to a home position. Like the rotated detector scenario, this system design also uses a fan-beam geometry. Again, no predictions are made for the estimated speedup offered by this type of system design because our emission simulation codes do not yet have fan-beam capability. However, this system design may be the most efficient and could provide the maximum speedup when compared to the other scenarios discussed above. In this scenario there is not only the possibility of a speedup due to the elimination of discrete translation positioning in both active and passive modes, but perhaps a speedup due to better counting efficiency because of the closer-to-drum detector positions. Again, it is important to simulate and experiment with the fan-beam scenarios in emission tomography to determine the potential trade offs in assay accuracy.

Curved configuration of multiple detector and single source design

Figure 11: Rotated and curved in-line scenario for waste drum assay. Dimensions in the figure are approximate.

Comparison of different design scenarios

There are four different multiple detector design scenarios described in this paper, and there are tradeoffs for each. The vertical and horizontal straight in-line (parallel-beam) scenarios require the simplest detector collimator design. These collimators have the

smallest footprint and are ideal for an operating space that is limited, i.e., the limited space that might occur within a portable trailer system. Developing this type of system requires the lowest risk because the parallel-beam geometry is what is currently used in our operating A&PCT scanners, and we know it works. Manufactures of HPGe detector systems prefer the horizontal scenario over the vertical scenario because it is difficult to cool all of the HPGe detectors in the vertical option. One clear disadvantage of both the vertical and horizontal straight in-line scenarios is that they require multiple active sources and somewhat complicated source collimation. These scenarios require larger source collimators that will add extra weight to the scanner and may be a concern in a transportable trailer systems. The active source that is currently used in A&PCT is approximately 3 mCi of $^{166\text{m}}\text{Ho}$. This source is somewhat rare and expensive to produce; however, purchasing multiple sources reduces the cost per individual source (i.e., 6 sources can be purchased for just a little more than twice the cost of one individual source). Also, there are other less expensive options to consider when it comes to the active source used in A&PCT. One option would be to use a mixture of different isotopes. For example, a mixture of ^{133}Ba , ^{152}Eu , and ^{60}Co would produce an adequate number of peaks well distributed in the energy spectrum that can be used to correct the emission images for attenuation. This option reduces the cost of the latter 6 sources by approximately a factor of 2 relative to six $^{166\text{m}}\text{Ho}$ sources.

Total scan time versus integration time

Figure 12: Edge-to-edge sampling technique total assay time predictions versus single ray sum integration time for all design scenarios that are parallel (not including fan beam).

Unfortunately, at this time we are not able to simulate the fan-beam emission geometry (rotated and curved designs). There is more work to be completed in simulating and experimenting with this scan geometry to determine what tradeoffs might occur in the emission assay accuracy and to evaluate the expected speedup that could be gained. Due to this fact, there is no comparison made here in assay time for these design scenarios. However, for both the rotated and curved detector scenarios, there is a possibility of speedup due to the elimination of discrete translation positioning in both the active and passive modes. Also, in the curved scenario, there is a possibility of speedup due to an increased solid angle because the detectors are closer to the drum. The fan-beam design has only one source and a very simple and light collimator compared to the straight in-line cases. A disadvantage of both fan-beam scenarios is that they have detector collimators that are somewhat more complicated in construction and have larger footprints when compared to the straight in-line collimators. It is questionable if these types of detector collimators are practical in portable trailer systems where the operating space is extremely limited.

Total scan time versus integration time

Figure 13: Under sampling technique total assay time predictions versus ray sum integration time for all design scenarios that are parallel (fan-beam scenarios not included).

The vertical and horizontal in-line design scenarios are compared to the current single detector A&PCT system throughput in Figures 12, 13, and 14. Each figure reveals the total assay time for both active and passive CT with respect to integration time for three different

sampling techniques. Figure 12 compares the total assay time of the different design scenarios for edge-to-edge sampling. Notice that the slope in the figure flattens out indicating that the system overhead becomes a dominating factor for integration times below approximately 10 seconds.

Figure 13 shows the comparison of assay time for the 50% under sampled case. If under sampling is used, the horizontal scenario requires less positioning overhead in the passive mode than the vertical scenario because no detector translation is necessary. Again, the total assay time becomes dominated by the system overhead below approximately 10 seconds integration time.

Figure 14: Under sampling with continuous motion total assay time predictions versus ray sum integration time for all design scenarios that are parallel (fan-beam scenarios not included).

A comparison of total assay time when using continuous scan motion and under sampled data is shown in Figure 14. Only the rotational stage has continuous motion in this estimation. There is only a slight affect from the positioning overhead for integration times below 1 second. In this estimation, it is evident that a total scan time of approximately 1 hour could be reached with the horizontal in-line configuration using integration times of 4

to 5 seconds. This type of system scenario is equivalent to what is currently being used, and it is expected that the assay accuracy will be similar. There are no modifications required in the current image reconstruction assay algorithms for either of the straight in-line scenarios.

SUMMARY

Increasing system throughput for the A&PCT technology is a major priority the next generation design. Using multiple detectors in a system design can provide a speedup of system throughput without compromising assay accuracy. The throughput will be increased by at least a factor equal to the number of detectors used, and most likely more because of the positioning overhead that is eliminated when using multiple detectors.

Several parameters have been fixed in this design study. For maximum throughput, 100% HPGe detectors are selected for the system design. These detectors yield a maximum collimator aperture size of 2.25 inches. This aperture size defines the maximum spatial resolution of the A&PCT system. In this paper a collimator aspect ratio of 5:1 has been chosen since it yields sufficient efficiency with precise accurate assay results. The collimator length is defined to be 11.25 inches without septa and 5.47 inches with 1/16 inch thick septa to maintain the 5:1 aspect ratio. Also, in the multiple detector, multiple active source design scenarios, it is important to develop source collimators with sufficiently restrictive aspect ratios to prevent crosstalk between adjacent detectors. Care must be taken to ensure that each source is seen by only one detector at a time. If this is not true, inaccuracies in the assay will occur due to incorrect attenuation corrections from the transmission sources.

There were four different multiple detector design scenarios presented in this paper: a vertical straight in-line multiple detector array (parallel-beam); a horizontal straight in-line multiple detector array (parallel-beam); a rotated straight in-line multiple detector array (fan-beam); and a rotated and curved multiple detector array (fan-beam). It is not clear at this time what advantages and disadvantages would result from using the fan-beam design scenarios. Simulation and experiments should be performed to understand what the tradeoffs are for these fan-beam scan geometries before either is incorporated into a commercial system.

While it is true that qualitative transmission fan beam data sets have been acquired in the NDE field, [HER80, BAR81, and KAK88] relatively little monoenergetic and quantitative transmission fan-beam data have been acquired. Perhaps even more important, to our knowledge, no monoenergetic and quantitative emission fan-beam data have been taken using HPGe detectors with high-energy resolution. Some work in passive simulation and low-energy resolution passive fan-beam tomography has been done elsewhere.[BRO92] At this time, however, we do not have the computer codes to properly simulate what either an ACT or a PCT data set might look like using high-energy resolution HPGe detectors with either of the fan-beam geometry scenarios described in this paper. It is important to note; however, that this should not be difficult or a show stopper but that we do not have experience with nor proven such a system design.

Thus, we do not have monoenergetic, fan-beam, PCT data sets that could be corrected by an appropriate, monoenergetic, ACT, fan-beam data set. Until an appropriate experimental fan-beam-geometry system is built, and both ACT and PCT data sets using monoenergetic gamma rays are obtained and compared to parallel-beam geometry-system results, we believe it is prudent to recommend that neither fan-beam design be constructed. It would simply be too risky to abandon all that has been learned to date using the parallel

beam geometry system in favor of acquiring data with what appears at this time to be a marginally faster fan-beam system.

Multiple HPGe-detectors combined with the same number of multiply collimated transmission sources and configured in a horizontal, parallel-beam geometry system offer the necessary speed and accuracy to acquire both the quantitative, poly-energetic ACT data sets and the poly-energetic under-sampled PCT data sets that will enable detectable radioactive isotopes within waste drums to be measured accurately and quantitatively. At this time, the in-line or parallel-beam systems are the best understood. Our single detector A&PCT scanners operating today use parallel geometry and we have successfully demonstrated that they work. Therefore, there is low risk in developing a parallel multiple detector A&PCT system because they are so much like the single detector systems currently in use. Also, if space is limited, as in a transportable trailer system, the in-line, parallel scenarios may be the best option due to the small footprint of its multiple detector collimator. However, the parallel systems will require a larger and heavier multiple source collimator.

There are three clear disadvantages for the vertical, in line array of multiple HPGe detectors versus the configuration using a horizontal, in-line array. The first is the 50% increase in cost to provide 3 additional radioactive sources and their necessary shielding materials. In addition, there is the same 50% increase in cost to provide three more sets of electronics and shielding materials for 9 versus 6 HPGe detectors required for the vertical 9-HPGe multiple detector array. The second disadvantage occurs due to a manufacturing limitation. The vertical in-line detector scenario is not as desirable as the horizontal design because HPGe detector manufacturers state it is difficult to cool multiple detectors in a vertical configuration.

The third disadvantage of the vertical multiple-detector scenario occurs in those cases when a waste drum is, for example, only one-third full. If one were using a 9-HPGe vertical detector array, then the active and passive scanning times are the same regardless of how full either a 55-gallon or an 83-gallon drum might be. That is, an entire drum will always be scanned with a vertical detector configuration because all slices of the drum are acquired simultaneously for each ray sum with only one drum elevation made to fill in the collimator space between the detectors. On the other hand, if one were using a 6-HPGe horizontal detector array, then the active and passive scanning time could be reduced to approximately 1/3 the time required to scan a “full” waste drum of the same capacity. This is because, in the vertical detector configuration, the detectors can be positioned at any vertical location and the ray sums are acquired simultaneously. Therefore, the scan can start and stop at any slice position, and the empty portion of the waste drum can be ignored, thereby reducing the time required for the assay. The capacity of a waste drum can rapidly be determined using radiography or collimated gamma scanning (CGS) prior to an A&PCT assay. The CGS method can be performed using the A&PCT scanner with no modifications to hardware. This method is a non-quantitative, but rapid technique for identifying the location of activity in each slice of the drum. In this technique the detector is located at the drums center axis of rotation and the drum is continuously rotated to obtain an average of gamma counts per slice. Since less-than-full waste drums occur frequently throughout the nuclear waste complex, the overall A&PCT assay time can be significantly reduced using radiography and the horizontal A&PCT scan configuration.

In conclusion, it is clear that the 6-HPGe horizontal detector array is the preferred multiple detector design scenario at this time. From the design parameters presented and discussed here, it appears that six, properly configured, HPGe-detectors offer the ability to scan both 55-or 83-gallon drums in relatively short times without any significant decrease in accuracy when compared to our current single HPGe detector systems. Actual data

acquisition times depend on the amount of activity within a drum and the waste matrix density. Typical scan times to acquire both the ACT and PCT data sets, and provide isotopic results will range between 1 to 10 hours. The horizontal, detector-array scenario is the best understood and the detector collimator requires the least amount of space. Additionally, the horizontal detector array is preferred over the vertical array because it is the most robust with respect to cooling problems, is less costly, and does not waste scan time on empty portions of the waste drum.

FUTURE WORK

Simulation and experiments should be performed on the 50% under sampled case to determine the tradeoff in assay accuracy when compared to the edge-to-edge sampled case. The effect of under sampling will reduce the overall counting statistics and assay accuracy. Simulation and experiments should be performed to determine the affect of septa thickness on the assay accuracy and detector efficiency. Thicker septa may result in better assay accuracy; however, there is a tradeoff in the efficiency due to a reduction in the detector surface area. Also, simulation and experiments should be performed for the continuous motion scanning mode to determine the tradeoff in accuracy due to the expected motion blurring. The multiple-detector fan-beam scenarios will require simulation and experiments to evaluate their possible speedup and tradeoff in assay accuracy, especially for the passive CT mode.

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