SOURCE IMAGING OF DRUMS IN THE APNEA[a] SYSTEM

David Hensley
Oak Ridge National Laboratory, Oak Ridge, TN 37831

ABSTRACT

The *APNea* System is a neutron assay device utilizing both a passive mode and a differential-dieaway active mode. The total detection efficiency is not spatially uniform, even for an empty chamber, and a drum matrix in the chamber can severely distort this response. In order to achieve a response which is independent of the way the source material is distributed in a drum, an imaging procedure has been developed which treats the drum as a number of virtual (sub)volumes. Since each virtual volume of source material is weighted with the appropriate instrument parameters (detection efficiency and thermal flux), the final assay result is essentially independent of the actual distribution of the source material throughout the drum and its matrix.

INTRODUCTION

The *APNea* System is a neutron assay device which features both a passive mode and an active mode for the nondestructive assay and examination of drums. It is an evolution of technology originally developed[1] at Los Alamos National Laboratory in the 1970s. In its passive mode, it measures the total neutron output from a drum while also measuring the number of correlated neutron events arising from the spontaneous fissioning of isotopes such as ^{240}Pu, ^{244}Cm, or ^{238}U. In its active mode, it uses a pulsed neutron generator to produce neutrons which thermailize within the drum and within the chamber cavity. After the original high energy neutron pulse has dissipated, the system detects neutrons from fission arising from thermal neutron capture by fissile isotopes such as ^{239}Pu or ^{235}U. This active technique is generally referred to as the differential dieaway technique.

Fig. 1a depicts the placement in the *APNea* Unit of the 81 ^{3}He gas-proportional detector tubes used to detect epithermal neutrons. The total detection efficiency is just over 15%,

[a] *APNea* — It takes your breath away!

Mock Matrices

Matrix	$\Sigma Y(0,18)$		Flux	Description
	Liner	Bare		
MT	-	1711	'21365	Empty chamber
MTD	1725	-	27901	Empty lined drum
S	1730	1812	'2364	670 lbs of steel shot
RR	1704	-	<4	Mint condition Raschig rings
SS	-	1698	-	1740 lbs steel shot
S47	931	1057	'2499	47 lbs poly, 685 lbs steel
SOIL	618	-	14368	420 lbs NFS soil
CONC	-	400	'23230	920 lbs ORNL concrete
S140	330	411	'8974	140 lbs poly, 555 lbs steel

Table 1:

but this efficiency obviously cannot be spatially uniform due to a vertical gap between the tubes on the side supporting the neutron generator and due to the double rows of bottom tubes. Fig. 2a shows the sum response of the total *APNea* detector set to a ^{252}Cf point source positioned at various (r, h) locations within a drum, where the measurements were taken over an integral number of full rotations. The h values ranged from the drum bottom to 30 inches in height, the r values ranged from the center of the drum out to 10 inches, just inside the drum. There are four data sets corresponding to four different matrices (see Tab. 1), and these data demonstrate that a drum matrix can severely distort the system response. The data labeled *MT* are for a point source positioned in the empty chamber, and for this quite benign matrix, the response of the *APNea* is nearly flat, with just a slight enhancement at the bottom of the chamber. The *S47* and *S140* matrices are mixtures of steel shot, polyethylene (poly) beads, and vermiculite, where the vermiculite was added as a neutral filler to distribute the matrix uniformly throughout the drum and the steel shot was used to bring the weight of the drum up to approximately 700 lbs. It is interesting that the *S* matrix (with no poly) does very little to distort the response. The *S140* matrix has a major effect, comparable to that of solid concrete. Clearly, any assay measurement dealing with either the *S47* or the *S140* matrix would need to know, in addition to the matrix attenuation parameters, the distribution of source material within the matrix in order to correct for the matrix distortions.

IMAGING EQUATIONS

In order to achieve a response which is independent of how source material is distributed throughout a drum, an imaging procedure has been developed which treats a drum as a set of a large number of virtual (sub)volumes, refered to as **volels**, with the result that the source material is imaged with respect to these voxels. Equations 1–4 are the equations which form the basis for the imaging procedure for four different styles of assay.

$$Y_s(d,\theta) = \epsilon_s(d,V_c) * \rho_s(V_b) \qquad \text{where } V_c = V_b(\theta) \tag{1}$$

$$Y_{sf}(d,\theta) = \epsilon_f(V_c) * \epsilon_f(d,V_c) * \rho_{sf}(V_b) \qquad \text{where } \epsilon_f(V_c) = \sum_d \epsilon_f(d,V_c) \tag{2}$$

$$Y_a(d,\theta,t) = \epsilon_f(d,V_c) * \rho_f(V_b) * Flux(V_c,t) + A(d,\theta) * Fast(d,t) \tag{3}$$

$$Y_{acf}(d,\theta,t) = \epsilon_f(V_c) * \epsilon_f(d,V_c) * \rho_f(V_b) * Flux(V_c,t) \tag{4}$$

$Y(d,\theta)$ is the yield observed in detector d for rotational increment θ, and $\epsilon(d,V_c)$ is the absolute detection efficiency for detector d for neutrons emitted from a virtual volume V_c. The source term $\rho(V_b)$ is defined at virtual volume V_b. The coordinates (r,h,θ) define the virtual volumes: V_c is referenced with respect to the chamber, V_b with respect to the drum. $Flux$ is the thermal neutron flux available at V_c at time t, with respect to the neutron generator pulse. $Fast$ is the detection response function for detector d with A as the normalization factor for the current measurement. The subscripts s, sf, f, a, and acf refer to singles neutrons (e.g., from (α,n) reactions), spontaneous fission events, fission events, active measurements, and correlated active measurements, respectively. The factor

$\epsilon_f(V_c)$ is the choice for a correlation technique wherein the detection of the first neutron of a cluster is by any of the detectors and Y_{sf} is the number of neutrons correlated in time with the first neutron. There is an implied sum over V_b in all of Eqs. 1–4.

Equation 5 is the operational definition for the derivation of $\epsilon(d, V_c)$. A ^{252}Cf source positioned at (r, h) points in a characterization drum serves the purpose of a $\delta(V_b)$ function, for which case ϵ is equal to Y. $Flux$ is determined by placing a thermal flux detector at each (r, h) position of a characterization drum and measuring the flux. In all of the equations, both ϵ and $Flux$ should be annotated to indicate that they are chosen to best represent the current matrix of interest. The method for choosing the appropriate mocked-up matrix from which to obtain each characterization function is not covered in this paper, but it is assumed that ultimately such a choice can be made (see Ref. 2). Fortunately, as long as the choice of characterization matrix is close, the imaging results are quite good, as the relative image is insensitive to small changes in the matrix. The absolute intensity of the image is another matter and will be discuss in Refs. 2,3. The shape of $Fast$ in Eqs. 3 is assumed to be independent of the matrix, and the magnitude of $A(d, \theta)$ reflects the character of the matrix of interest.

$$Y_s(d, \theta) = \epsilon_s(d, V_c) * \delta(V_b) \tag{5}$$

The most common imaging configuration for the *APNea* uses (r, h, θ) points with $r = 0, 8$ inches; $h = 1, 6, 12, 18, 24, 30$ inches; and θ defining eight equal azimuthal segments of a full rotation. This configuration corresponds to 54 virtual volumes, as schematically depicted in Fig. 1b. Currently the 81 tubes of the *APNea* Unit are arranged into 12 distinct detector packs, two per surface of the chamber. This arrangement is depicted in Fig. 1a for the door and back wall. The division of tubes is clear in the floor and the south wall, but the division for the north wall and the top is to assign the middle tubes to one pack and the outer tubes to another pack. The number of data points is larger than the number of virtual volumes to be solved for: $\begin{array}{l}\#data = 12 * 8 = 96 \\ \#V_b = 6(8+1) = 54\end{array}$ Consequently, given that the functions $\epsilon(d, V_c)$ and

$Flux(V_c, t)$ are known, the appropriate equation above can be solved for the desired source term $\rho(V_b)$.

The active imaging utilizes Eq. 3. While this equation has a form that appears to be different from that of Eq. 1, the characteristics of the two equations are essentially the same. The problem, just as in the passive imaging, requires back projecting the source term via the response matrix which is now the product of efficiency times flux. The introduction of time (relative to the neutron generator pulse) enhances the quality of the active imaging in subtle ways which will be discussed below. The $A(d, \theta) * Fast(V_c, t)$ term is established during the imaging procedure and can be viewed simply as a term to correct the measured yield for the direct affect of the neutron generator pulse.

The method used for solving the imaging equations is based on a least squares approach. An uncertainty value for each data point is assigned based on counting statistics and including corrections for background or accidentals. Using these values to form a weighting matrix, χ^2 is formed as in Eq. 6 and minimized. It is necessary to impose a boundary condition on the minimizing procedure or unphysical results are obtained. The primary condition is that $\rho(V_b) \geq 0$, for all V_b, otherwise significant quantities of negative source will be found. Under not very extreme conditions, an overall negative answer can be derived. As a consequence of this boundary condition, it was necessary to find the appropriate minimum in χ^2 by an iterative approach. Derivatives of $\chi^2$with respect to $\rho(V_b)$ are used in an iterative method modeled on Newton's Method for finding zeros of a function. Because this straightforward approach ignores correlations between the volume elements, it is necessary to damp the iterations (especially the early ones) so that the process doesn't oscillate out of control.

$$\chi^2 = 1/df * \overline{(\vec{Y} - \epsilon * \vec{\rho})} * \omega * (\vec{Y} - \epsilon * \vec{\rho}) \qquad \text{where } \omega \equiv 1/\Delta^2 Y \tag{6}$$

An important consideration has to do with the uniqueness of the iteration convergence procedure. If the initial guess differs from the desired solution in certain ways, the iteration process may never approach the solution but can wander off into a predictable kind of error.

One way of visualizing this feature of the imaging process is to divide the response into two conceptual pieces: $Y = \epsilon * (\rho_{symmetric} + \rho_{asymmetric})$. Inconsistencies in the system tend to make any source appear to be somewhat asymmetric. Thus there is a natural tendency in the iteration process for source material to move from the core (symmetric) out into the annulus (asymmetric) but not vice versa. It is a feature of the *APNea* imaging procedure that it is especially sensitive to asymmetric sources (i.e., θ-varying responses) such as off-axis point sources. A further and related problem is a *symmetric ambiguity* in that the imaging can become confused between core sources versus symmetric annulus sources. This problem is most pronounced near the vertical center of the drum, a region for which the top and bottom detectors are less capable of supplying radius information. Simply put, the imaging algorithm favors moving source material from the core out into the annulus, but as the iterative procedure progresses, it may have no way to move material back into the core, though that may be the correct solution. This feature will be demonstrated in a later section.

To deal with this *symmetric loss*, a compensation mechanism is introduced into the imaging procedure which tugs at material in the annulus, moving some of it into the core. The attempt is to balance this compensation against the perturbing effects which tend to move material incorrectly out into the annulus. Experience has found that as the iteration procedure converges to the solution the compensation can be reduced in strength and eventually set to zero. But, even in the vicinity of the solution, small inconsistencies can still introduce significant errors if many more iterations are used. Thus, the imaging procedure needs to be terminated as soon as little improvement in the quality of fit is found.

APNea IMAGING CHARACTERISTICS

The vertical detectors in the north and south walls of the *APNea* Unit have the greatest sensitivity to θ of the detector packs. Fig. 3a,b shows the response for pack N2 (see Fig. 1a) to a ^{252}Cf source at a height of 18 inches moved from the nearer side of a drum to the opposite side — this is done in a variety of matrices described in Tab. 1. The *MT* response maps out the pure geometric effects. For the purposes of the imaging algorithms, it should be noted that the efficiency response is a smooth function of radius, although it is not a linear relationship. Unlike many photon based imaging systems, the efficiency response is not easily described by a simple attenuation exponential, particularly because of the scattering enhancement. The scattering enhancement can be seen in the figure as several of the matrices have a response at $r > 7$ inches which is greater than the empty chamber response. This is clearly a feature of neutron scattering, and it is remarkable that concrete appears to have the strongest scattering enhancement. Because the response is further complicated by the size of the detector packs, it is approximated in $\epsilon(d, V_c)$ in the imaging algorithm by choosing several points from these response curves, and a functional form for the attenuation is not used.

An interesting effect of the matrix on the line-of-sight imaging can be seen in Fig. 3c,d. In the lower graph are plotted the E1 detector pack results for a point source positioned at $r = 8$ viewed in four different matrices. The E1 detector pack is the top pack on the rear wall as shown in Fig. 1a and is a horizontal pack, nearly two feet high and three feet wide, whose bottom is about 20 inches up from the bottom of the drum. The yield in this detector peaks on the fifth θ segment, at which θ point the source is nearest to the detector pack, and it increases with h as the source is moved through the values 6, 18, to 30 inches. Clearly even this quite large detector pack is doing a credible job of defining where a point source is. It is quite sensitive to the vertical position of the source, and a similar sensitivity is evidenced when the source is moved radially, from the center out to the edge of the drum. The presence of a matrix attenuates the signal from a point source at the back of the drum, and this attenuation enhances the front to back relative sensitivity of the pack. Fig. 3c shows the results for just the $h = 1$ and 6 measurements. Of interest is the result that the responses do not peak at $\theta = 5$ for the *MT* matrix — in fact there is a minimum in the response at this position. The reason for this is fairly simple. At $(r, h) = (8, 6)$, the source is sufficiently far from the drum center and 20 inches below the detector pack such that the detector pack E2 below pack E1 shields the E1 pack from the source when the source is nearest the pack. But, the result is quite different when there is significant matrix material present, even when there is little attenuation as is the case with pure steel. Though the detector is partially shielded from a direct line of sight of the point source as described for the *MT* matrix, there is sufficient scattering in the non-empty matrix that the maximum response is again at $\theta = 5$. This is further evidence that scatter is an important aspect of neutron imaging, and this feature would lead one to suspect that the neutron image would be terribly blurred. However, these results are also evidence that imaging is still possible, since the response accurately corresponds with the actual position of the source. Not surprisingly, imaging in the *APNea* is most sensitive to responses from detectors nearest source material, but even the remote responses have the requisite information to enable a reasonable imaging result.

The plots in Fig. 4 show the difference in sensitivity to drum rotation between vertical detectors in the wall and horizontal detectors in the top and bottom of the *APNea* Unit. A height of $h = 18$ was chosen to show the response in top and bottom detectors for a source positioned in the nominal vertical center of the drum. By comparing the $r = 4$ with the $r = 8$ responses in *SOIL* or *CONC*, it is seen that the top and bottom detectors have a harder time contributing to the radial imaging sensitivity at this height, since the response magnitudes don't change much. Again, there is a surprisingly large azimuthal response for the *CONC* matrix. The N1 and N2 detectors differ in that N2 comprises the middle 3 tubes on the north wall (Fig. 1a,b) while N1 includes the two groups of 4 tubes on either side. It is interesting that there is so little relative difference in Fig. 4c,d in the response of these two packs, though, as expected, there is somewhat more contrast in the N2 response.

The active response has a number of special features in addition to (or possibly as a product with) the passive features already discussed. First of all, the thermal neutron flux function is generally not uniform across the chamber. Fig. 5a shows the flux, integrated from $300\mu s$ out to 3ms, as a function of radius in the drum, where the neutron generator is effectively on the right side of the figure at a distance of approximately 21 inches from the drum center. The flux for *MT* and *MTD* is nearly constant across the chamber, but the introduction of a matrix, particularly one containing hydrogen, immediately modifies the flux pattern so that it now drops off with distance from the generator. Fig. 5b shows the corresponding results for the dieaway time character of the flux. While the dieaway time of the flux for the two empty matrices is nearly constant, there is a definite minimum near the drum center when a reasonable matrix material is present. The dieaway time increases as one approaches the edge of the drum as some of that flux is coming in from the cavity which has a slower dieaway time than has the drum matrix. This effect is more pronounced on the far side of the drum where the *native* flux is less and is comparable to the leak-in flux. This is especially noticeable for the *S47* matrix which has so little native flux — for this matrix the increase in the magnitude and the dieaway time of the flux at $r = -10$ inches is rather incredible.

There is a two fold advantage to including time as one of the imaging algorithm variables. The first is that by incorporating time and the *Fast* function in the imaging procedure, the analysis can be pushed into times closer to the generator pulse where there the quantity of usable flux is increasing. The gain in usable flux in moving in from $700\mu s$ to $300\mu s$ is typically more than a factor of two. Fig. 5c plots three different measures of the flux seen in the *MTD* and *SOIL* matrices: the flux available at $t = 0$, estimated from the shape of the flux dieaway, the flux available after $300\mu s$, and that available after $700\mu s$. The change in usable flux for an empty drum is about a factor of 2, but the increase in available flux for *SOIL* is very dramatic. The core flux increased by a factor of 6 and the front edge flux by a factor of 4. Fig. 5d shows the incremental increase in flux between 300 and $700\mu s$ for *SOIL*, and this highlights the desirability of moving the assay forward in time into $300\mu s$, if possible. This incremental increase can obviously increase the sensitivity of the active assay, but a subtle point is that the increase in the sensitivity to the drum core is even more dramatic.

The imaging sensitivity to the core is helped by another feature of the flux profile. Since the response matrix for the active imaging is $\epsilon(d, V_c) * Flux(V_c, t)$ there are some noticeable differences between the passive imaging and the active imaging. If one takes the detector efficiency response for *SOIL* from Fig. 3 and multiplies it by the corresponding flux profile from Fig. 5a then one creates a very steep product response. The sections of the *APNea* Unit closer to the neutron generator are especially sensitive to material near the surface of the drum, even more sensitive than during a passive measurement. However, for detectors on the side opposite the neutron generator, the falloff of the flux reduces the sensitivity of these detectors to the annulus relative to that for the core. Although their response is still more sensitive to the annulus than to the core, the relative sensitivity to the core has improved by at least a factor of 4 over that of both the active (forward) measurement or a passive spontaneous-fission measurement.

RESULTS

When the imaging methodology of Equation 1 is applied to the *S47* matrix data set, the results of Fig. 2b are obtained. The improvement in the imaged points over the raw measurements is quite striking but is obviously not perfect. The points that are far above the *correct* answer are points at $r = 10$ inches, which are outside the range of the algorithm calibration set — or, equivalently, these points are at the outer edge of the outer virtual volumes. For these points the algorithm is having to extrapolate in order to fit the data. More telling are the deviations at $h = 12, 18, 24$ for the $r = 4, 6$ points.

Tab. 2 shows a tabular version of a drum image. The column on the left represents the core of the drum, the 8 columns on the right represent the annulus spread out over the 8 azimuthal segments. Tabs. 3–5 give details of the imaging results for the entire $S47$ data set. All of these tabular images were generated with the lowest level of sophistication for the imaging algorithm. The characterization functions were specified at $r = 0, 8$ with $h = 1, 6, 12, 18, 24, 30$, leading to a total of 54 volumes, as depicted schematically in Fig. 1b.

RELATIVE DRUM IMAGE

$r=0$				$r=8$				
$h=30$	-	-	-	-	-	-	-	-
$h=24$	-							-
$h=18$	-			θ				-
$h=12$	1	2	3	4	5	6	7	8
$h=6$	-							-
$h=1$	-	-	-	-	-	-	-	-
CORE				**ANNULUS**				

Table 2:

Each set of tabular images is at a fixed value of radius while the source is moved from $h = 1$ up to $h = 30$ inches. Zeros have been suppressed in order to accentuate the point source. As expected, at $r = 0$ in Tab. 3, the values for the core approach 1000. Deviations here most clearly reflect the irregularities in the data and calibration sets but, more importantly, highlight the fragility of the imaging process when dealing with the symmetric ambiguity and symmetric loss problem. The $(r, h) = (0, 16)$ result shows the problem of source material leaking out into the annulus while the imaging procedure was working at dividing the source at $h = 16$ between the two defining vertical segments at $h = 12$ and $h = 18$. At this lowest level of sophistication, the imaging procedure has no clear dynamic to improve the image by moving the material back into the core. Note that the problem is scarcely evident at $h = 27$, also between defining h-segments. The major difference is that the source was near enough to the top that the top detectors could resolve the symmetric ambiguity previously mentioned. If one follows the $h = 16$ image for values of $r > 0$ (see Tabs. 4–5), the image quickly sharpens as the source approaches the drum surface, and the amount of symmetric contribution rapidly diminishes.

These results expose one of the principle errors encountered in the imaging process. Note in Fig. 2b that the $r = 4$ and 6 points appear to deviate from the desired answer more strongly as the center of the drum is approached. The image becomes less accurate with respect to r when the source is far from the bottom or top, that is, when the source is

$S47$ Matrix Image

Point Source at R=0 Inches

.	.	.	.	.	.	.	.	.	$\Leftarrow$	.	.	.	.	.	.	1	.	.
.	.	.	.	.	.	.	.	.	$h = 1$	.	.	.	.	.	3	3	.	.
.	.	.	.	.	.	.	.	.		967	.	.	.	.	4	5	1	.
.	.	.	.	.	.	.	.	.		.	.	.	.	.	3	3	.	.
.	.	.	.	.	.	.	.	.	$h = 18$	.	.	.	.	.	.	.	.	.
965	.	.	4	11	16	.	.	.	$\Rightarrow$	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	$\Leftarrow$	111	.	1	.	.	.	2	2	.
.	.	.	.	.	.	.	.	.	$h = 6$	722	5	4	.	.	2	10	12	7
.	.	.	.	.	.	.	.	.		103	.	.	.	.	.	1	6	2
177	.	.	.	.	.	.	.	.		.	.	.	.	.	.	.	.	.
410	26	35	8	1	25	22	1	.	$h = 24$	.	.	.	.	.	.	.	.	.
259	7	9	.	.	7	4	.	.	$\Rightarrow$	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	$\Leftarrow$	606	.	4	.	.	13	16	.	.
.	.	.	.	.	.	.	.	.	$h = 12$	343	.	3	.	.	1	10	.	.
.	.	2	2	.	.	.	.	.		.	.	.	.	.	.	.	.	.
971	.	4	4	.	1	.	.	.		.	.	.	.	.	.	.	.	.
.	.	2	2	.	.	.	.	.	$h = 27$	.	.	.	.	.	.	.	.	.
.	.	1	.	.	.	.	.	.	$\Rightarrow$	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	$\Leftarrow$	967	.	.	.	3	8	5	3	.
.	.	.	.	.	.	.	.	.	$h = 16$	.	.	.	.	.	5	3	.	.
598	12	16	5	6	22	19	14	6		.	.	.	.	.	.	1	.	.
139	22	27	21	17	23	18	17	10		.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	$h = 30$	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	$\Rightarrow$	.	.	.	.	.	.	.	.	.

Table 3:

buried within the absorbing drum matrix. Deviations in the $r = 0$ measurements are a result of minor errors in the data set and the characterization set. Such errors arise from counting statistics or from small non-uniformities in the matrix. Since $r = 8$ is one of the defining points for the imaging algorithm, the amount seen in the table images in the core is essentially zero, and the results seen in Fig. 2b are nearly perfect. The other defining point, at $r = 0$, also has very good results but is fighting ambiguities and significant attenuation problems. When the source is positioned at $r = 10$, it is outside the algorithms response set. Then, although the core strength is zero as it is supposed to be, and the table image in Tab. 5 is correct (but only **relatively** so), the **absolute** answer deviates strongly from the desired answer. This is a result of the code using a two-point model for the required efficiency correction and having to extrapolate out to the 10 inch point. Of more practical interest is the deviation of the $r = 4, 6$, particularly as h approaches 18 inches, close to the vertical center of the drum.

Fig. 6a shows some minor improvement to the results of Fig. 2b achieved by introducing a symmetric loss compensation mechanism. Additional data sets at $h = 16$ and 27 inches have been included in the figure. Obviously, this compensation mechanism has done nothing to improve the results at $r = 10$ because these points have no way of being improved within this choice of response functions. However, Fig. 6b shows the difference when the defining voxel set is changed from $r = 0, 8$ to $r = 0, 10$. Now there is a straightforward way to accommodate the $r = 10$ points and the outer radius points are brought into line, but with an understandable loss in precision for the inner radius points as compared to Fig. 6a. The imaging code is largely a linear code and the use of just two radius points to define a radial position leads to interpolation errors. An obvious way to improve this would be to introduce a second annulus. Using the same values of h but with $r = 0, 4, 9$ to define two annuli, one achieves the results shown in Fig. 6c. The $r = 9$ annulus has brought the outer points into much better agreement but with some loss for the $r = 8$ points. Fig. 6d shows the further improvement by choosing $r = 0, 5, 10$ to define to annuli. This clearly gives the best overall results for this case, though the $r = 8$ points are less well defined. The electronic implementation of the current *APNea* does not allow this imaging with two annuli to be done for other than a point source, and it does not, consequently, have the imaging resolution to implement the full 102 voxel image to its fullest advantage. But the overall improvement from this approach can be seen. Now the points at $r = 10$ are accommodated while the interpolation to the inner radius points is generally good and more consistent.

One comment on the imaging has to do with homogeneity. Neutrons are admirable probes since they are much less affected by dense matrices than are x rays or γ rays. Thus, minor inhomogeneities in the matrix are of little concern. As a matter of imaging practicality, the *APNea* implementation of imaging assumes that the matrix has azimuthal symmetry but does not require that there be vertical homogeneity. In particular, if the drum is only

$S47$ Matrix Image

Point Source at R=4 Inches

.	.	.	.	.	.	.	.	.	$\Leftarrow$	.	.	.	.	.	.	1	.	.
.	.	.	.	.	.	.	.	.	$h = 1$	.	.	.	12	88	31	6	.	.
.	.	.	.	.	.	.	.	.		414	.	8	68	174	52	7	.	.
.	.	.	.	.	.	.	.	.		.	.	2	32	90	5	2	.	.
.	.	.	.	.	.	.	.	.	$h = 18$	.	.	.	.	.	.	.	.	.
456	.	.	103	362	77	.	.	.	$\Rightarrow$	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	$\Leftarrow$	.	.	7	15	88	47	1	.	.
.	.	.	.	.	.	.	.	.	$h = 6$	448	.	.	49	158	39	.	.	.
.	.	.	.	.	1	.	.	.		.	.	.	20	111	4	.	.	.
.	.	.	38	80	.	.	.	.		.	.	.	3	3	.	.	.	.
395	.	4	66	113	18	.	.	.	$h = 24$	.	.	.	.	.	.	.	.	.
.	.	3	55	129	82	9	.	.	$\Rightarrow$	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	1	.	.	$\Leftarrow$	379	.	6	34	134	108	.	.	.
.	.	.	.	.	.	.	.	.	$h = 12$	144	.	1	15	108	33	.	.	.
.	.	.	2	64	.	4	.	.		.	.	4	9	17	.	.	.	.
363	.	4	95	225	85	19	.	.		.	.	.	.	.	.	.	.	.
.	.	6	26	83	12	1	.	.	$h = 27$	.	.	.	.	.	.	.	.	.
.	.	1	.	.	.	.	.	.	$\Rightarrow$	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	$\Leftarrow$	673	.	.	6	202	108	.	.	.
.	.	.	.	.	.	1	17	1	$h = 16$	.	.	.	.	6	.	.	.	.
382	.	.	.	.	7	108	131	31		.	.	.	.	.	.	.	.	.
.	8	.	.	.	28	116	121	36		.	.	.	.	.	.	.	.	.
.	1	.	.	.	3	.	.	.	$h = 30$	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	$\Rightarrow$	.	.	.	.	.	.	.	.	.

Point Source at R=6 Inches

.	.	.	.	.	.	.	.	.	$\Leftarrow$	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	$h = 1$	.	.	.	.	.	9	3	179	4
.	.	.	.	.	.	.	.	.		104	.	.	.	.	19	81	380	55
.	.	.	.	.	.	.	.	.		.	.	.	.	.	.	.	161	.
.	.	.	.	.	.	.	.	.	$h = 18$	.	.	.	.	.	.	.	.	.
161	.	.	.	.	.	185	585	67	$\Rightarrow$	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	$\Leftarrow$	.	1	.	.	.	.	3	162	18
.	.	.	.	.	.	.	.	.	$h = 6$	154	.	.	.	.	.	82	319	33
.	.	.	.	.	.	.	.	.		.	.	.	.	.	.	18	203	.
.	.	.	.	.	.	.	201	.		.	.	.	.	.	.	.	.	.
157	.	.	.	.	1	44	271	13	$h = 24$	.	.	.	.	.	.	.	.	.
.	.	.	.	.	2	62	239	5	$\Rightarrow$	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	$\Leftarrow$	164	.	.	.	.	.	90	307	102
.	.	.	.	.	.	.	.	.	$h = 12$	26	.	.	.	.	.	12	248	.
.	.	.	.	.	.	.	142	.		.	.	.	.	.	.	1	44	.
123	.	.	.	3	8	120	438	65		.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	97	.	$h = 27$	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	$\Rightarrow$	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	$\Leftarrow$	326	.	.	.	.	.	34	570	69
.	.	.	.	.	.	.	57	.	$h = 16$	.	.	.	.	.	.	.	.	.
127	.	.	.	.	14	62	342	57		.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	35	276	26		.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	$h = 30$	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	$\Rightarrow$	.	.	.	.	.	.	.	.	.

Table 4:

$S47$ Matrix Image

Point Source at R=4 Inches

.	.	.	.	.	.	.	.	.	$\Leftarrow$	.	.	.	.	.	.	1	.	.
.	.	.	.	.	.	.	.	.	$h = 1$	.	.	.	12	88	31	6	.	.
.	.	.	.	.	.	.	.	.		414	.	8	68	174	52	7	.	.
.	.	.	.	.	.	.	.	.		.	.	2	32	90	5	2	.	.
.	.	.	.	.	.	.	.	.	$h = 18$	.	.	.	.	.	.	.	.	.
456	.	.	103	362	77	.	.	.	$\Rightarrow$	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	$\Leftarrow$	.	.	7	15	88	47	1	.	.
.	.	.	.	.	.	.	.	.	$h = 6$	448	.	.	49	158	39	.	.	.
.	.	.	.	.	1	.	.	.		.	.	.	20	111	4	.	.	.
.	.	.	38	80	.	.	.	.		.	.	.	3	3	.	.	.	.
395	.	4	66	113	18	.	.	.	$h = 24$	.	.	.	.	.	.	.	.	.
.	.	3	55	129	82	9	.	.	$\Rightarrow$	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	1	.	.	$\Leftarrow$	379	.	6	34	134	108	.	.	.
.	.	.	.	.	.	.	.	.	$h = 12$	144	.	1	15	108	33	.	.	.
.	.	.	2	64	.	4	.	.		.	.	4	9	17	.	.	.	.
363	.	4	95	225	85	19	.	.		.	.	.	.	.	.	.	.	.
.	.	6	26	83	12	1	.	.	$h = 27$	.	.	.	.	.	.	.	.	.
.	.	1	.	.	.	.	.	.	$\Rightarrow$	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	$\Leftarrow$	673	.	.	6	202	108	.	.	.
.	.	.	.	.	.	1	17	1	$h = 16$	.	.	.	.	6	.	.	.	.
382	.	.	.	.	7	108	131	31		.	.	.	.	.	.	.	.	.
.	8	.	.	.	28	116	121	36		.	.	.	.	.	.	.	.	.
.	1	.	.	.	3	.	.	.	$h = 30$	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	$\Rightarrow$	.	.	.	.	.	.	.	.	.

Point Source at R=6 Inches

.	.	.	.	.	.	.	.	.	$\Leftarrow$	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	$h = 1$	.	.	.	.	.	9	3	179	4
.	.	.	.	.	.	.	.	.		104	.	.	.	.	19	81	380	55
.	.	.	.	.	.	.	.	.		.	.	.	.	.	.	.	161	.
.	.	.	.	.	.	.	.	.	$h = 18$	.	.	.	.	.	.	.	.	.
161	.	.	.	.	.	185	585	67	$\Rightarrow$	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	$\Leftarrow$	.	1	.	.	.	.	3	162	18
.	.	.	.	.	.	.	.	.	$h = 6$	154	.	.	.	.	.	82	319	33
.	.	.	.	.	.	.	.	.		.	.	.	.	.	.	18	203	.
.	.	.	.	.	.	.	201	.		.	.	.	.	.	.	.	.	.
157	.	.	.	.	1	44	271	13	$h = 24$	.	.	.	.	.	.	.	.	.
.	.	.	.	.	2	62	239	5	$\Rightarrow$	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	$\Leftarrow$	164	.	.	.	.	.	90	307	102
.	.	.	.	.	.	.	.	.	$h = 12$	26	.	.	.	.	.	12	248	.
.	.	.	.	.	.	.	142	.		.	.	.	.	.	.	1	44	.
123	.	.	.	3	8	120	438	65		.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	97	.	$h = 27$	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	$\Rightarrow$	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	$\Leftarrow$	326	.	.	.	.	.	34	570	69
.	.	.	.	.	.	.	57	.	$h = 16$	.	.	.	.	.	.	.	.	.
127	.	.	.	.	14	62	342	57		.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	35	276	26		.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	$h = 30$	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	$\Rightarrow$	.	.	.	.	.	.	.	.	.

Table 4:

partially full or if the matrix material changes dramatically in the vertical direction, then this can be easily accommodated in the efficiency and flux response functions. It seems reasonable that fluids might settle or condense preferentially in the bottom of the drum. Such vertical differences can be accommodated by shaping the response functions appropriately, and all of the imaging will then proceed correctly. If, however, the matrix is not azimuthally symmetric, the methodology simply ignores this. The principle example the *APNea* System has encountered was supercompacted waste with the waste in the form of compacted cubes stacked in a drum. Thus the matrix was square and not cylindrically symmetric. The aggravation of trying to recognize and treat a square matrix was too much and the reward was too small to try to introduce a square imaging algorithm. Similarly, the consequence of leaning a cylinder of water or poly containing waste against the side of a drum would be to cause genuine concern that the imaging was appropriate. The development of vertically nonhomogeneous response functions will be discussed in Ref. 2.

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While there are four different assay techniques, there is essentially only one imaging procedure. For the passive assay, this methodology is applied to the correlated neutrons associated with spontaneous fission or to the singles neutrons (generally arising from (α,n) reactions). The methodology is extended to the active assay by introducing a thermal flux response for each of the voxels and by introducing a term to deal with the fast response of the detectors to the generator pulse. The time dependence is treated explicitly in the active analysis algorithms, permitting the active data to be analyzed closer in time to the neutron generator pulse. It is important to emphasize that the imaging technique has not simply corrected for material in the center of the drum. It has separated out a response to the core which is, in most realistic cases, a small fraction of the response to the outer layers of the drum. It is one thing to apply the appropriate correction to material which is in the center of a dense matrix, but it is a more difficult problem to generate the appropriate image of the core relative to that of the annulus so that the core is accurately assayed.

$S47$ Matrix Image

Point Source at R=8 Inches

.	.	.	.	.	.	.	.	.	⟸	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	$h = 1$	.	.	162	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.		.	41	561	41	.	.	.	.	.
.	.	.	.	.	.	.	.	.		.	.	192	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	$h = 18$	.	.	.	.	.	.	.	.	.
.	.	998	.	.	.	.	.	.	⟹	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	⟸	.	.	190	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	$h = 6$	.	37	505	43	.	.	.	.	.
.	.	.	.	.	.	.	.	.		.	.	221	.	.	.	.	.	.
.	.	285	3	.	.	.	.	.		.	.	.	.	.	.	.	.	.
7	21	379	34	2	.	.	.	.	$h = 24$	.	.	.	.	.	.	.	.	.
.	11	248	3	.	1	.	.	.	⟹	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	⟸	.	.	446	14	.	.	.	.	.
.	.	.	.	.	.	.	.	.	$h = 12$	.	17	521	.	.	.	.	.	.
.	.	35	.	.	.	.	.	.		.	.	.	.	.	.	.	.	.
.	13	910	13	.	.	.	.	.		.	.	.	.	.	.	.	.	.
.	.	26	.	.	.	.	.	.	$h = 27$	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	⟹	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	⟸	.	44	885	46	.	.	.	.	.
.	.	47	.	.	.	.	.	.	$h = 16$	.	.	22	.	.	.	.	.	.
.	18	509	58	.	.	.	.	.		.	.	.	.	.	.	.	.	.
.	.	365	.	.	.	.	.	.		.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	$h = 30$	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	⟹	.	.	.	.	.	.	.	.	.

Point Source at R=10 Inches

.	.	.	.	.	.	.	.	.	⟸	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	$h = 1$	.	.	.	.	.	96	.	.	.
.	.	.	.	.	.	.	.	.		.	.	.	.	.	795	.	.	.
.	.	.	.	.	90	.	.	.		.	.	.	.	.	108	.	.	.
.	.	.	.	.	255	.	.	.	$h = 18$	.	.	.	.	.	.	.	.	.
.	.	.	.	.	653	.	.	.	⟹	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	⟸	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	$h = 6$	.	.	.	.	.	899	.	.	.
.	.	.	.	.	.	.	.	.		.	.	.	.	.	100	.	.	.
.	.	.	.	.	485	.	.	.		.	.	.	.	.	.	.	.	.
.	.	.	.	.	336	.	.	.	$h = 24$	.	.	.	.	.	.	.	.	.
.	.	.	.	.	177	.	.	.	⟹	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	⟸	.	.	.	.	.	302	.	.	.
.	.	.	.	.	.	.	.	.	$h = 12$	.	.	.	.	.	697	.	.	.
.	.	.	.	.	63	.	.	.		.	.	.	.	.	.	.	.	.
.	.	.	.	.	936	.	.	.		.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	$h = 27$	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	⟹	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	⟸	.	.	.	.	.	775	11	.	.
.	.	.	.	.	.	.	.	.	$h = 16$	.	.	.	.	.	212	.	.	.
.	.	.	.	.	728	.	.	.		.	.	.	.	.	.	.	.	.
.	.	.	.	.	271	.	.	.		.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	$h = 30$	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	⟹	.	.	.	.	.	.	.	.	.

Table 5:

partially full or if the matrix material changes dramatically in the vertical direction, then this can be easily accommodated in the efficiency and flux response functions. It seems reasonable that fluids might settle or condense preferentially in the bottom of the drum. Such vertical differences can be accommodated by shaping the response functions appropriately, and all of the imaging will then proceed correctly. If, however, the matrix is not azimuthally symmetric, the methodology simply ignores this. The principle example the *APNea* System has encountered was supercompacted waste with the waste in the form of compacted cubes stacked in a drum. Thus the matrix was square and not cylindrically symmetric. The aggravation of trying to recognize and treat a square matrix was too much and the reward was too small to try to introduce a square imaging algorithm. Similarly, the consequence of leaning a cylinder of water or poly containing waste against the side of a drum would be to cause genuine concern that the imaging was appropriate. The development of vertically nonhomogeneous response functions will be discussed in Ref. 2.

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The imaging procedure should be called *imaging* largely by analogy, since the assay fitting equations for the *APNea* System have focused mainly on providing a position dependent correction for source material scattered through a drum matrix. But rather good images are, in fact, obtained which could have application for possible drum remediation or for verification of expected source distribution characteristics. The principle result is that, since each virtual volume of source material is imaged and weighted with the appropriate instrument responses (detection efficiency and thermal flux), the final assay value is essentially independent of the actual distribution of the source material throughout the drum and its matrix.

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