The Add-A-Source Matrix Calibration of a Large Neutron Box Counter - 8382

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ABSTRACT

A general purpose passive neutron box counter has been designed, constructed and factory calibrated. The instrument is intended to sort and assay Transuranic Uranium (TRU) waste according to the Waste Isolation Pilot Plant (WIPP) criteria in containers ranging from drums to large boxes and crates. A multi-position Cf Add-A-Source (AAS) capability has been built into the system to determine gross matrix correction factors. The Cf source capsule runs in a U-shaped guide tube beneath the powered roller conveyor used to move the containers into the assay cavity from the loading station. The factory calibration involved measuring a wide range of matrix materials and densities in 208-liter (55 US-gal.) barrels, Standard Waste Box (SWB), Standard Large Box (SLB-2), and Ten Drum Overpack (TDOP) containers. For each container a Volume Weighted Average (VWA) rate and an AAS perturbation factor was determined and the relationship between them was established for the full range of conditions expected to be encountered operationally.

In this paper we describe the calibration procedure which used Cf-252 as a surrogate for Pu-240 to map out the spatial responses for the various container-matrix combinations. A particular challenge was the scale of the measurement campaign which was directly related to the large volume of some of the containers. The reduction of the data was also challenging because for the larger items with high concentrations of hydrogen steep spatial gradients were observed in the response. For this reason simple volume-element averaging of the data to derive VWA quantities was inadequate and numerical-integration approaches of the 3-dimensional maps were explored. The response maps were also used to create point-source contributions to the Total Measurement Uncertainty (TMU), but this work is not the subject of this paper. The wide range in container size also required varying numbers of AAS interrogation position. For the drums a single AAS position was used while for the SWB and TDOP six positions were used to achieve better coverage of the cross-section. The SLB-2 has a larger cross section still and ten positions of the AAS were used for this container.

The AAS calibration parameterizations for the various containers will be described along with the difficulties associated with a calibration of large containers.

INTRODUCTION

A general purpose passive neutron box counter has been designed and built [1]. The counter utilizes 320 He-3 proportional tubes divided into 80 counting channels and arranged in a 4π geometry about the assay cavity. The assay cavity is 206 cm (81”) wide by 305 cm (120”) long by 201 cm (79”) tall with the height being measured from the top of the conveyor, and is designed to accommodate a range of sizes of containers including the possible use of a container pallet during assay. Factory calibrations have been performed for the following container types:

208-liter drum, Standard Waste Box (SWB), Standard Large Box-2 (SLB-2), and Ten Drum Overpack (TDOP). An Add-A-Source Matrix Correction assembly has been incorporated into the counter using a built-in interrogation source.

The AAS calibration procedure is intended to provide a correction for the moderating effects of waste containers. The objective is to produce a matrix correction calibration curve for the Reals (i.e. coincidence) rate based on a given container [2]. The basic form of the calibration curve is given in the following equation:

$$y = a_o + a_1 x + a_2 x^2 + a_3 x^3 \qquad \text{(Eq. 1)}$$

where y is defined as the volume perturbation and x is defined as the AAS perturbation. The volume perturbation is determined by measuring a neutron source at various positions in the container and then computing a volume average of the results. The basic gross matrix correction assumes the matrix is homogeneous and that the activity is uniformly distributed in the matrix. The volume weighted average corresponds to a uniform specific activity distribution in the matrix. Heterogeneity and non-uniformity are then accounted for in the TMU. The AAS perturbation is measured for the same matrix and container without the volume source but instead using a strong Cf-252 interrogation source that is introduced into the counter next to the container. During normal counter operation the AAS is contained in a shielded well outside the assay chamber. During an AAS measurement the source is inserted into the assay chamber and a measurement is made at each of the predefined spatial locations of the AAS. The perturbations are defined for the net Reals rates taken over all AAS positions by:

$$y = \frac{R_o^V}{R^V} - 1 \qquad \text{(Eq. 2)}$$

and

$$x = \frac{R_o}{R} - 1 \qquad \text{(Eq. 3)}$$

Where R_o^V, R^V are the volume-averaged Reals rates for the empty container and container with matrix respectively. R_o and R are the corresponding AAS Reals rates. The AAS correction factor CF is defined as:

$$CF = 1 + y \qquad \text{(Eq. 4)}$$

The volume averaged Reals rate R^V is determined by:

$$R^V = \frac{\sum_{i=1}^{N} w_i R_i^V}{\sum_{i=1}^{N} w_i} \qquad \text{(Eq. 5)}$$

where R_i^V are the constituent volume element rates for the N volume elements and w_i are the weights associated with the position of the source within the container. The weights can be determined by a relative volume calculation or by Monte Carlo simulation. The rates R_i^V should be dead-time and background corrected.

For each geometry and matrix an AAS rate is obtained from an average over the rates of all the AAS positions used for that geometry. At each AAS position the assay software reports an AAS rate which has been averaged over the measurement cycles used for the assay at that position as well as an uncertainty. If there are n AAS positions the rate is defined as:

$$R = \sum_{i=1}^{n} \frac{R_i}{n} \qquad \text{(Eq. 6)}$$

where R_i is the (background corrected) AAS rates for the i-th position.

AAS CALIBRATION MEASUREMENTS

An AAS calibration curve is required for each container type that will be assayed in the counter. For each container two kinds of measurements are required; volume perturbation measurements and AAS perturbation measurements. The number of required perturbation measurements varies with each type of container.

The volume perturbation measurements are typically obtained by measuring a point source at several spatial locations within the container. In order to map out the variation in moderating effects over the entire volume of the container, the number of spatial locations required will increase with increasing size of the container.

The AAS perturbation measurements are made with a Cf-252 interrogation source (~75uCi) built in to the counter. This source runs along a U-shaped tube under the conveyer at the bottom of the assay cavity with each leg of the “U” equidistant from the symmetry axis of the counter. The U-shaped stainless steel tube sits in a reflector to improve neutron coupling to the assay item. The reflector is a block of Stainless Steel 5 cm (2”) high by 10 cm (4") wide which provides sufficient neutron scattering. There are ten AAS positions along this “U” shape, with five positions on each leg and a gap in the position spacing for the bend in the "U"; (the position spacing is therefore not fully uniform). Depending on the container type the number of required AAS positions could comprise all ten positions or some subset of these positions in order to determine the AAS perturbation for the container.

For a given container both types of perturbation measurements must be performed for each matrix type (including the void or empty container case) used in the generation of the AAS calibration. The empty container is treated as the non perturbing reference case and by definition the AAS correction factor is unity.

The system has been designed to handle a wide range of container types. Here we discuss the AAS calibration for 208-liter drums, SWB, SLB-2, and TDOP.

208-liter (55-gallon) Drums

In order to obtain a volume average response for a 208-liter drum, measurements were made with a Cf-252 point source at four radial positions and five heights for a total of 20 measurements per drum as shown in Fig. 1.

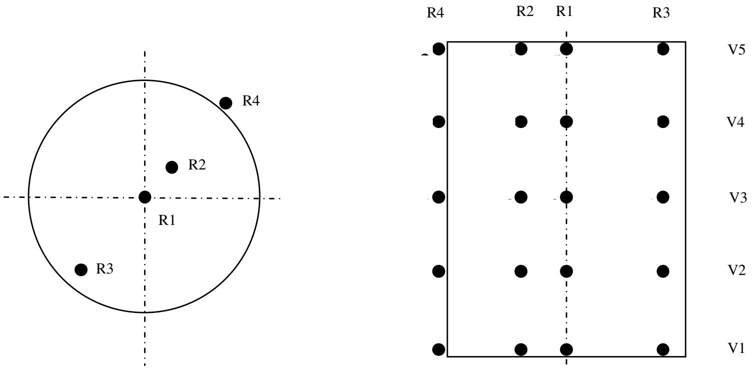

Fig. 1. Source positions used for 208-liter drum and TDOP AAS calibrations.

The first three radial positions were determined by source tube locations typical of PDP-style drums; R1 (center of the drum), R2 (14 cm), and R3 (23 cm). A fourth radial position R4, was chosen by attaching the source to the outside surface of the drum in order to map out the full extent of the variation in response for each matrix. Source heights were determined by choosing the vertical center, top of the matrix, bottom of the matrix, and the two intermediate positions between the top (bottom) and the center of the drum. For a standard 208-liter drum the vertical positions correspond to 0, 22.5, 43, 65.5, and 86 cm from the bottom of the drum matrix. When the drum matrix did not completely fill the drum, the heights were chosen relative to the matrix fill.

A total of 9 drums, including the Reference (Empty) drum, were used for the AAS calibration (see Table I). For each matrix type the volume-averaged Cf-252 source rate was calculated and the volume perturbation was obtained as described previously (Eq. 2). The Reals rates at each radial position were weighted by a factor proportional to the cylindrical volume corresponding to that radius and summed to obtain the VWA response for that matrix.

The AAS rate and corresponding perturbation was obtained using the Cf-252 add-a-source measured at a single position located directly under the drum. Since the AAS was constrained to travel along the U-shaped track, the drum location was not centered in the assay cavity. Given the relatively small size of the drum volume to the assay volume, as well as the uniformity in response of the counter this was not an issue of concern. For reproducibility in measurement the drum location was marked on the palette used to load the drum.

Table I. 208-Liter Drums Used for AAS Calibration

Material	Nominal Densities (g/cc)
Reference (Empty)	0
Homasote	0.40
Particle Board	0.72
29kg Polyethylene	0.13
Poly Vermiculate	0.31
100% Poly	0.59
Cellulose	0.35
Cellulose 2	0.66
Polyethylene 2	0.73

The measured data were fitted using a second order polynomial as this was found to provide the best fit to the data. The constant term a_3 in Eq. 1 was therefore fixed to value of 0, and the constant term a_0 was held to a fixed value of 0 to ensure that the curve passed through (0, 0), i.e. CF = 1 for the Empty container. The fitting was performed using the Deming Least Squares Fitting Program [3]. All data points together with the Reals calibration curve are shown in Fig. 2.

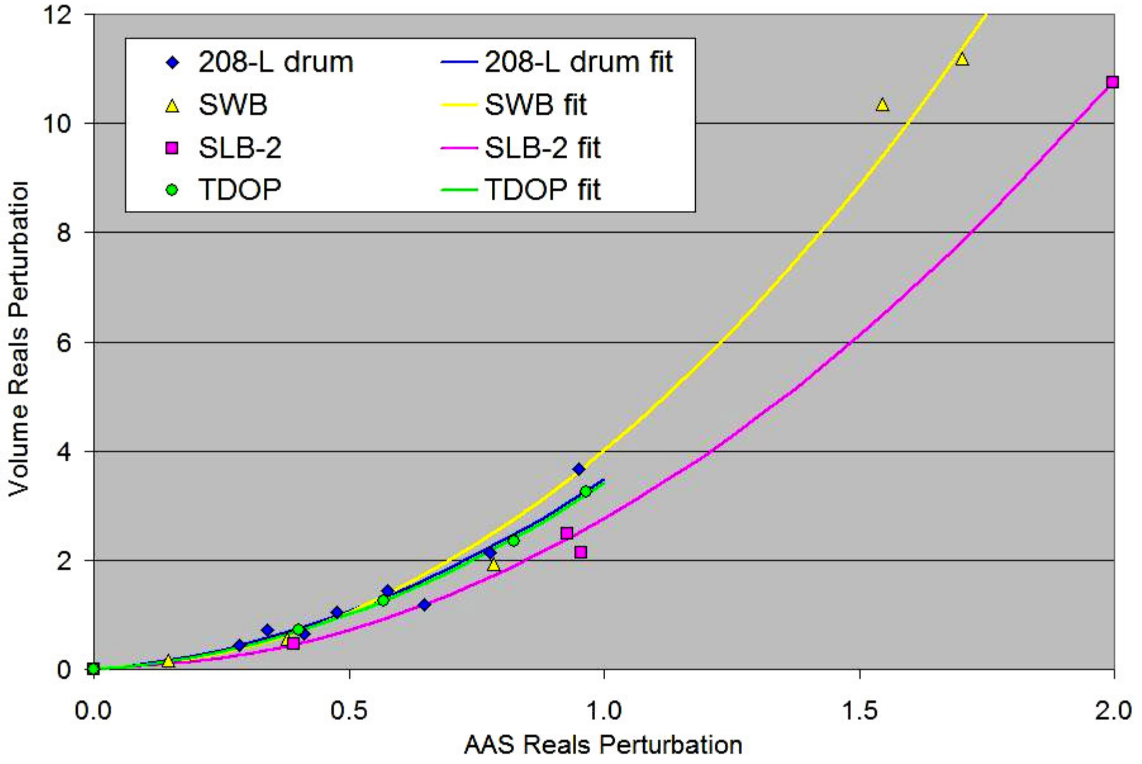

Fig. 2. Reals Add-A-Source calibration curves for different containers shown with data points.

Standard Waste Box (SWB)

The SWB container is made of steel with a wall thickness of 0.3 cm (0.125“). The inner length breadth and height of the box are, 175 cm (68.75”), 131 cm (51.75”) and 100 cm (39.56”) respectively. The length mentioned above is the along the axis of the box. Since the box itself is rounded at the ends, the length along the long side of the box is only 114 cm (45”). To establish the AAS calibration for the boxes, special large modules containing a mixture of plywood, cardboard, and high-density polyethylene (HDPE) have been procured. The matrix material was contained in four separate modules that fill the SWB. A total of five matrices were used, ranging in density and moderator content from 0.035g/cc of 100% polyethylene foam to ~0.90 g/cc of a mixture of plywood and polyethylene. In addition the void (empty) container was also measured as the reference part of the AAS calibrations. The list of matrices used for the SWB AAS calibrations is provided in Table II.

Table II. SWB Matrices Used for the AAS Calibration

Material	Nominal Densities (g/cc)
Reference (Empty)	0
100% poly (100% polyethylene foam)	~0.035
Cardboard (100% corrugated cardboard)	~0.13
CardPly (60% by volume corrugated cardboard + 40% by volume plywood)	~0.30
PolyPlyCard (20% by volume corrugated cardboard + 30% by volume polyethylene + 50% by volume plywood)	~0.60
PolyPly (20% by volume plywood + 80% by volume high density polyethylene)	~0.90

The volume average measurements were performed at 20.3 cm (8”) intervals in all three spatial dimensions. In order to reduce the total count time required for calibration quadrant symmetry was assumed so that measurements were performed only in the front-right quadrant of the container. The rates were measured for 16 horizontal positions covering the whole quadrant at five different heights, giving a total of 80 source positions per SWB per matrix for the volume average measurements. The horizontal positions in which the source was placed were determined by the pre-fabricated holes in the matrix (or by the jig for the empty container). The holes amount and corresponding locations for SWB as well as for all other containers were specifically chosen, so that they would uniformly cover the whole matrix volume, and allowed completion of the AAS calibration within a reasonable time frame. Source heights were determined by choosing the vertical center, a position 2.5 cm below the top of the matrix, a position 2.5 cm from the bottom of the matrix, and the two intermediate positions between the top (bottom) and the center of the container. For a standard SWB container and the matrices used, the vertical positions corresponded to 2.5, 20.9, 41.9, 62.9, and 81.3 cm (1, 8.25, 16.5, 24.75, and 32 inches) from the bottom of the SWB matrix. In addition to the measurements performed in the given quadrant, two random positions in each of the other three quadrants were also chosen for measurements. The rates obtained at these locations were then compared to the ones measured at the corresponding symmetric locations in the initial quadrant in order to check the matrix uniformity.

The Reals rates at each source position were weighted using the equivalent volume weighting method. In this method the weighting factor is proportional to the matrix volume surrounding each particular source location. The AAS average rate and perturbation was obtained for the add-a-source measured at six positions under the box. The measured Volume and AAS Reals perturbations were then used to build a calibration curve shown on Fig. 2.

Standard Large Box – 2 (SLB-2)

The SLB-2 container is made of steel with a wall thickness of about 0.5 cm (0.1875”). The inner length, breadth and height of the box are, 259 cm (102”), 160 cm (63”) and 168 cm (66”) respectively. To establish the AAS calibration for the boxes, special large modules containing a mixture of plywood, cardboard, and polyethylene were used. The matrix material is contained in three separate modules that fill the SLB-2 container. Each module weights from about hundred (foam) to more than one thousand (plywood) kilograms. These modules had to be loaded/unloaded using a fork-lift every time a different matrix was needed for the calibration. Four matrices ranging in density and moderator content from 0.027 g/cc of 100% polyethylene foam to ~0.50 g/cc of 100% plywood were used. Each module consisted of a large number of sheets either bolted or strapped together with pre-fabricated holes going from top to the bottom. The void (empty) container was measured as the reference case. The list of matrices used for the SLB-2 AAS calibrations is provided in Table III below.

Table III. SLB-2 Matrices Used for AAS Calibration

Material	Nominal Densities (g/cc)
Reference (Empty)	0
100% polyethylene foam	~0.027
100% polyethylene foam	~0.064
100% corrugated cardboard	~0.17
100% plywood	~0.50

The volume average measurements were performed at 40.6 cm (16”) intervals in all three spatial dimensions. Similar to the SWB calibration all measurements were performed only in the front-right quadrant of the container (see Fig. 3). The rates were measured for 12 horizontal positions covering the whole quadrant at five different heights, giving a total of 60 source positions per SLB-2 per matrix for the volume average measurements. The horizontal positions in which the source was placed were determined by the pre-fabricated holes in the matrix (or by the jig for the empty container). Source heights were determined by choosing the vertical center, a position 2.5 cm below the top of the matrix, a position 2.5 cm from the bottom of the matrix, and the two intermediate positions between the top (bottom) and the center of the container. For a standard SLB-2 container and the matrices used, the vertical positions corresponded to 2.5, 39.4, 78.7, 118.1, and 154.9 cm (1, 15.5, 31, 46.5, and 61 inches) from the bottom of the matrix. Six random measurements throughout the rest of the SLB-2 volume were also performed in order to check the matrix uniformity. The somewhat coarse spatial sampling (compared to the SWB which is smaller container) was a compromise driven by practical consideration – namely how to complete the experiments in a timely fashion.

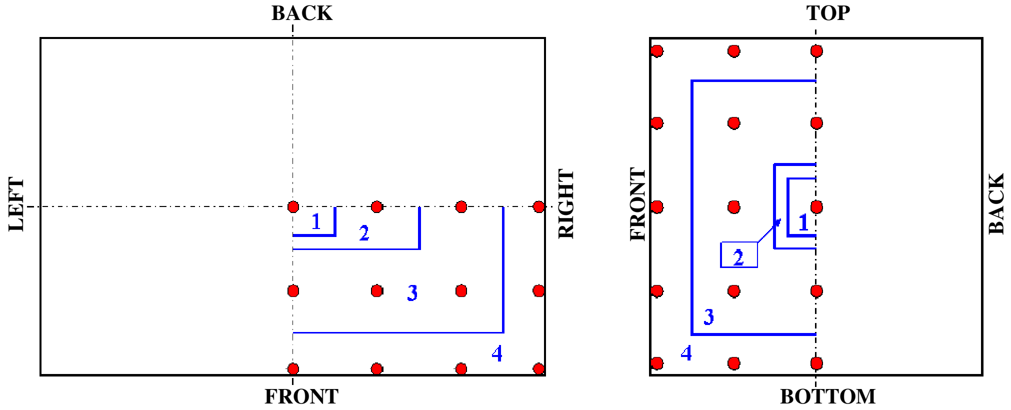

Fig. 3. Top and Cross-section views of SLB-2 showing shell boundaries (blue solid lines) and source measurement positions (red circles).

The equivalent volume weighting method was initially used to weight the Reals rates at each source position. The results showed that for the highest (hydrogen) density matrix (Plywood) the Reals volume perturbation value was smaller than might be expected when compared with the volume perturbation value for a similarly dense matrix in the SWB container. This most likely indicated that the equivalent volume weighting method may not be appropriate for larger containers of higher densities (AAS perturbation >1, AAS CF >2.5). The discrete volume weighting scheme used in the AAS calibrations is based on an equivalent volume extent for each source position which assumes an approximately linear response profile between measurement points within the matrix, so the linear interpolation suffices. If the response profile is considerably non-linear (high curvature) then an alternate weighting method must be implemented to better account for the large difference in response between the center of the matrix and the edge of the matrix.

Because of that, a few different methods were used to weight the Reals rates in case of SLB-2 container. One method was based on different volume proportions by dividing the volume of the matrix into concentric shells (volume shell method). Another method was based on using the actual response profiles of the measured rates. In this case the 3D-surfaces representing Reals rates at five different heights were used to determine the volume-averaged Reals rate for the SLB-2. A third approach was based on using Monte Carlo simulations to mimic the measured responses – with Monte Carlo results being benchmarked to the reference case. One challenge in the Monte Carlo method is knowing the exact composition of the matrix material.

These various approaches are simply alternative levels of numerical integrations and may also simply reflect different orders in which the spatial integration is performed (expanding surfaces, stacked sheets etc.). For example, several different AAS correction factors were obtained for a plywood matrix in this study with boundary values ranging from about 6.2 (equivalent volume weighting scheme) up to about 18 (MCNP calculations). The plywood matrix rich in hydrogen content and having weight of about 3500 kg (7700 lbs) was the most severe case, which was close to the maximum allowable container weight (4536 kg or 10000 lbs). The alternate weighting method chosen here was based on using volume shells where the weight is inversely proportional to the volume of the shell, and all points within a given shell share the same weight, see Fig.3. This method produced the AAS correction factor of about 12.8 for plywood matrix. Such a wide range of possible correction factors for high density matrices should be reflected in the TMU.

The AAS average rate and perturbation was obtained for the add-a-source measured at ten positions under the SLB-2. The measured Volume and AAS Reals perturbations were then used to build a calibration curve shown on Fig. 2.

Ten Drum Overpack (TDOP)

The TDOP is a large cylindrical container designed to hold ten 208-liter drums; the drums can be arranged in two stacked layers. The inner diameter of the TDOP is 167 cm (65.75”) and its inner height is 185 cm (73”). The walls are made of 0.5 cm (0.0625”) steel.

To establish the AAS calibration for the TDOP a collection of 208-liter drums was gathered to best span the expected contents of a typical TDOP. Four different configurations of the 208-liter drums were used for the TDOP AAS calibration, see Table IV. The volume distribution of the TDOP was sampled by source positions chosen within the 208-liter drums inside the TDOP. Ten 208-liter drums were placed in the TDOP and for each drum a combination of sources was used to approximate a volume average distribution within that drum. Here the five Cf-252 sources of approximate equal strength were distributed randomly within one of the 208-liter drums. This approximates a uniformly active drum and serves as one of the volume average measurements for the TDOP. Fig. 1 shows the sample of twenty locations in a 208-liter drum from which the five source positions were randomly chosen. The measurement was then repeated for each of the 208-liter drums (sources distributed randomly in each case) to give ten volume average measurements for the entire TDOP. The layout of the drums in the two layers within the TDOP is shown in Fig. 4 below, where the numbering scheme is used to uniquely identify each drum for record-keeping purposes.

The radial locations on each 208-liter drum (Fig. 1 and 4) were oriented along the radial line of the TDOP. This ensures, on average, an equitable sampling of the radial distribution of the TDOP. To further avoid radial biases, within each layer alternate drums were oriented so that the R4 position is varied between the center and outer edge of the TDOP. The drums are also staggered by 36° between the two layers as seen in Fig. 4. This further distributed the source locations within the TDOP volume and additionally allowed easy access to the source locations in the bottom layer without having to move the drums in the top layer.

Table IV. TDOP Matrices Used for AAS Calibration

Material	Nominal Densities (g/cc)
Reference (Empty)	0
Configuration #1	~0.43
Configuration #2	~0.50
Configuration #3	~0.30
Configuration #4	~0.24

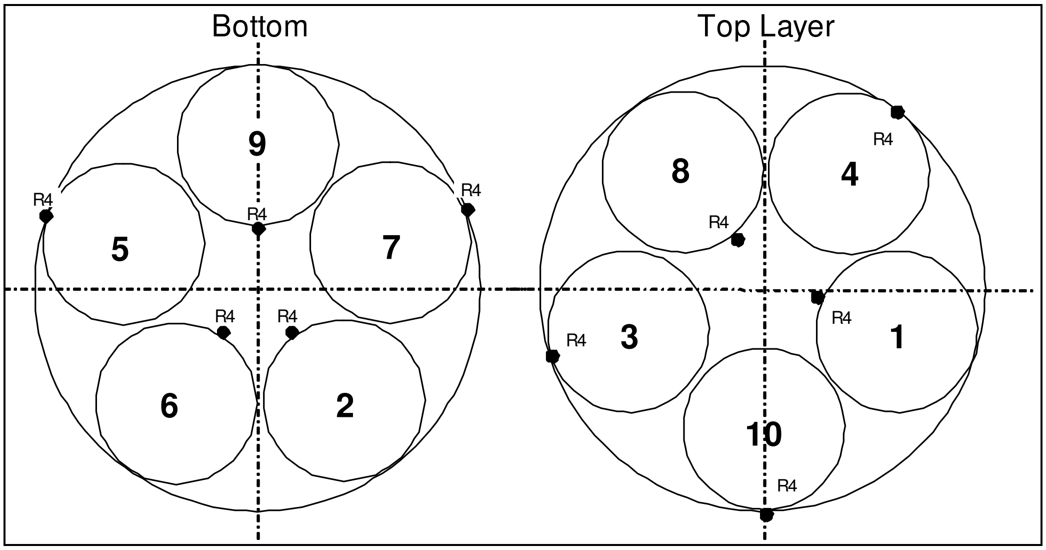

Fig. 4. Top view of 208-liter drum locations within the TDOP for the bottom and top layers. Note the relative orientations of the R4 position in a given layer. Also note the offset in drum position between the two layers.

For the AAS perturbation measurement six AAS positions were used for the TDOP. Unlike the other container types, however, the non-uniformity of the TDOP matrix can possibly make the AAS perturbation measurement sensitive to the spatial arrangement of the 208-liter drums within the TDOP. In order to account for this sensitivity the AAS perturbation measurement for all TDOP configurations, except the Empty one, was repeated with the TDOP rotated 72° at a time (i.e. four additional AAS perturbation measurements). The AAS perturbation value used for the given matrix was then an average over all five measurements. In the case of the Empty TDOP, the volume perturbation measurements were accomplished by locating the Cf sources within an empty 208-liter drum configured with copper/aluminum jig. For each measurement the empty drum was placed in one of the locations shown in Fig. 4, and the source distribution was chosen randomly for each drum placement as described previously.

A total of five matrix configurations, including the Reference (Empty) TDOP were used for the AAS calibration. For each TDOP matrix configuration the volume-averaged Reals rate was calculated and the volume perturbation was obtained. The Reals rates for each measurement were weighted equally since the combination of sources inside a 208-liter drum was assumed to represent a uniform source distribution within that drum. For each matrix configuration the AAS rates were calculated from the average AAS perturbation values obtained for the five TDOP orientations of the matrix, where each value was in turn an average of the rates from the six AAS positions used in any one AAS measurement. The measured Volume and AAS Reals perturbations were then used to build a calibration curve shown on Fig. 2.

FUTURE WORK

While the quality of the AAS calibration can be relatively easy evaluated for small containers like 208-liter drums, it presents a big challenge for larger boxes such as SWB and SLB-2. This is mainly due to the fact that it is virtually almost impossible to mimic a uniform source distribution within a matrix using point sources, unless thousands of measurements have been performed. A certain weighting scheme has to be used to average the Reals rates from point source measurements and that introduces an additional uncertainty in the results. The AAS correction performance evaluation is not a subject of this paper and will be presented elsewhere. Our future work will also include refining of the weighting scheme used to derive the volume weighted average rates for SLB-2 container. Here we have described only the AAS calibration. We shall discuss elsewhere the contribution to the measurement uncertainty associated with applying the AAS correction: including AAS calibration uncertainties, AAS precision, and deviation from the calibration conditions.

CONCLUSIONS

In this paper we described the AAS calibration procedure for the various container-matrix combinations. Overall the AAS correction works well in effectively correcting for matrix effects in cases where the matrix and radioactive contents are uniform. For large containers such as the SLB-2 containing highly moderating matrix the AAS correction may introduce significant uncertainty to the final result. The most significant part of the uncertainty comes from the fact that a point source was used during the calibration to mimic a uniformly distributed source based on weighting factors applied at each point. While the equivalent volume weighting method was shown to work well with small containers it was necessary to come up with a different method for SLB-2 where a high gradient in the Reals rates was observed throughout the high density matrix.

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