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DESIGN AND OPERATION OF A GAMMA RAY DETECTOR SYSTEM FOR CONFIRMATORY MEASUREMENTS OF LARGE BOXES AND OBJECTS

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ABSTRACT

This paper describes the design and operation of a gamma-ray detector system used for confirmatory measurements of large boxes, such as the B-25 and SWB. The instrument employs either 2 or 4 shielded and collimated high purity germanium (HPGe) detectors to quantify the radionuclide content of the waste contained in the samples being measured. The sample is weighed on a load cell prior to the measurement. The box mass determines the average density correction. The sample is then moved sequentially into the pre-determined measurement positions. Measurements of the activity of the box or object are made at one or more positions on each side of the box. Preliminary results are presented for measurements with sources in different positions within a representative test matrix. Comparison is made between distributed source and point source analysis of the data.

INTRODUCTION

The ANTECH Model 3702-B25 is a modular, high efficiency, high-resolution gamma ray spectroscopy assay system designed to detect and accurately assay radio-nuclides in waste crates, boxes and other large objects. Although physically large, a rectangular box such as the B-25 offers relatively simple assay geometry. The assay system employs High Purity Germanium (HPGe) detectors to make multiple measurements of the container. The measurement positions are pre-selected to ensure complete measurement coverage of the container volume. A series of measurements are performed and thereby multiple estimates for the activity inside the container are obtained.

The underlying assumptions for the box counter measurements are two-fold:

1. The matrix material is uniform in attenuation characteristics throughout the box volume.
2. The radioactive material embedded in the matrix is uniformly distributed throughout the matrix material.

It is vitally important to recognize the relevance and importance of these two assumptions in measuring waste with the box counter. If the counter is used indiscriminately to measure any waste box where these assumptions are significantly violated, then very large and undetected errors are likely to arise.

Figure 1 presents an engineering drawing of the two-detector variant of the box counter. The box horizontal translation mechanism can be seen with the load cell on which the box or object is placed. Also visible are the two HPGe detector units mounted on two motorized lifting pillars.

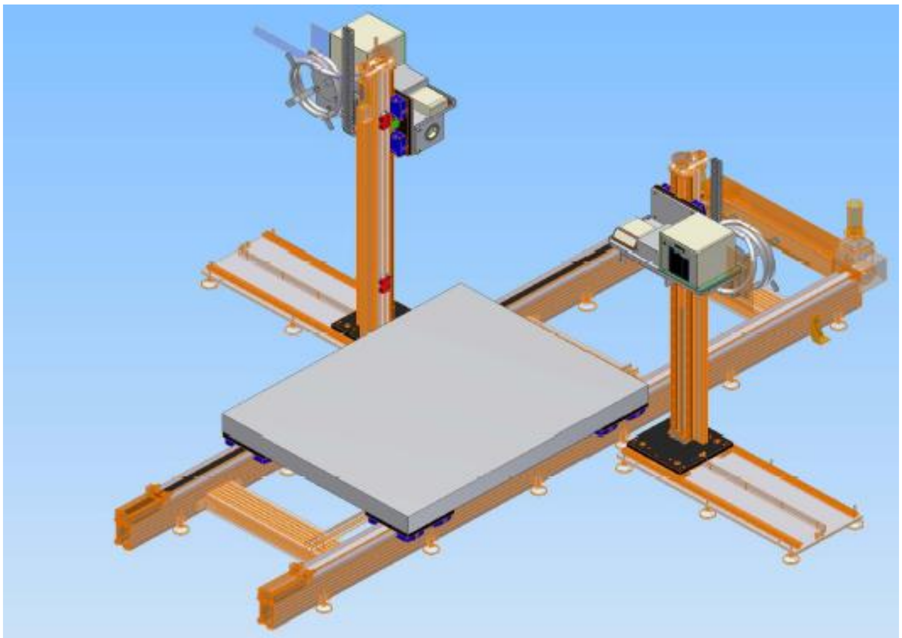

Figure 1. Mechanical layout of the Model 3702-B25 Gamma ray Box Counter

MECHANICAL AND ELECTRICAL DESIGN

The largest component of the box counter is the horizontal translation mechanism on top of which the load cell is mounted. The unit, which employs a belt drive, is designed to weigh and translate boxes and objects with a net weight of greater than 6 metric tons. It is designed to move the box horizontally to one or more positions so that gamma ray spectroscopy measurements can be performed.

In the photograph in figure 2 the two detector platforms or shelves can be seen mounted on two lifting pillars. The detector electronics are mounted on top of the shelf and the detector (inside its lead shield and collimator) is mounted below the shelf. The vertical position of each detector can be changed by means of a motor, which is under computer control. By moving both the box and the detectors any measurement position on each side of the box can be accessed. Typically a B-25 box is measured using 6 detector positions on each side, 3 positions above and 3 below the mid plane of the box.

Each detector is cooled by the ORTEC X-Cooler II electro-mechanical cooling unit, which sits on top of the detector shelf. The instrument uses two ORTEC DSPEC Pro digital spectrometers to acquire the gamma spectral data for each detector. The data is analyzed and archived on the central measurement control computer. Motion control for moving both the box and the detector shelves is achieved using an Allen Bradley programmable logic controller (PLC).

OPERATION

The measurement is performed after the box is placed on a moving table that incorporates a load cell. The measured mass of the box contents is used to determine an average density and this information is used to generate a matrix attenuation correction. The acquisition results for the HPGe detectors are corrected for geometric factors and gamma ray attenuation factors and each individual measurement is weight averaged over the volume of the container to produce a best estimate of the container total activity. The degree of consistency in the reported activity amongst the individual measurements suggests the true homogeneity of the container matrix and radioactive source material. Individual position measurements that deviate from the weighted mean of all position measurements indicate "outliers". These “outliers” are pointers to inconsistencies within either the matrix or the source distribution. “Outliers” indicate measurable non-homogeneity of the sample.

After the box is loaded and the mass is measured, the box is moved into the first measurement position. In this position 2 or 4 detectors determine the activity arising from a portion of the box based on a calibration. The box is then re-positioned depending on the total number of measurement positions that have been pre-selected and associated with a specific collimator configuration. Typically, each side of the box is divided into several different regions, each of which is measured, ranging from 1 to 6. In the case of the 2-detector system, the detector on each side of the box is repositioned (either manually or under motor control) halfway through the measurement as measurements may be performed at two different box heights. For the 2 detector system, the measurement time is double that of the 4 detector system.

DATA ACQUISITION AND ANALYSIS

Data acquisition and analysis is based on the use of BOXCOUNTER software, which controls box and detector movement through the PLC and the operation of the data analysis codes GammaVision and IsoCorr. Data are acquired and gamma ray spectra are analyzed by GammaVision for each box measurement position.

Figure 2. An ANTECH Model 3702 –B25 Gamma Box Counter in operation. The B-25 box is in the load position.

ANTECH IsoCorr software performs attenuation correction for each volume element in the volume of the box seen by the detector for each separate box measurement position. For each box measurement IsoCorr uses the density derived from the load cell and the detector response from the GammaVision analysis and calculates the total activity uniformly distributed over the volume assuming uniform attenuation over the volume.

Comparison of box measurements at different positions reveals "hot spots" and is useful to validate the uniformity assumptions. Separate box measurement results are averaged to get total activity.

MEASUREMENT RESULTS AND CONCLUSIONS

The Box Counter calibration confirmation process is used to demonstrate that the assay detectors used to collect emitted gamma rays and the associated algorithms used to reduce the collected data provide consistent results that correspond to expected values from a known source. This calibration measurement is performed to confirm that the mechanical and analytical aspects of the measurement process are fundamentally correct. Calibration confirmation is generally performed after a system calibration has been completed, but may be initiated at any time to verify that measurement results return a correct value.

The underlying assumptions concerning box counter assay were presented in the introduction. In the case where a point source is used for confirmation measurements, assumption 2 is egregiously violated; therefore, we expect the IsoCorr calculated results to vary with the position of the source in the matrix. However, despite the non-compliant dispersion configuration for the point source, there is a direct correlation between the measured activity and the known activity of the source. Since a point source clearly does not comply with our assumption 2 above we calculate the expected values based on a point source computation, and compare these values with those actually obtained from the measurements. We expect that the differences between the values thus obtained can be explained by analyzing the physics of the violated assumptions. Also, the consistency of values for subsequent confirmation measurements provides a strong indicator of proper instrument performance.

Test Conditions

For our initial confirmation measurements, two ^{152}Eu sources with a combined activity (as of July 1, 2009) of 0.741 MBq (20.04 mCi) were used together in several positions within a surrogate sample box of plywood into which five vertical holes had been drilled to facilitate placing the source.

The point source was placed successively in the vertical center of the test holes labelled 1 through 5. The measured gamma-ray emission data from each of these five different measurement positions were analyzed, both by point-source calculations and by IsoCorr. In each instance, the point-source values for each of the gamma energy peaks from europium are given by GammaVision, which provides the individual gamma peak count rate information input to IsoCorr.

For each measurement position, the detectors are placed 40 cm from the respective box faces.

In source position 1, the source location is 22 cm from the front box face and 98 cm from the back box face, so that the matrix attenuation distance was 22 cm for the front detector and 98 cm for the back detector, making the total distance from the front detector 62 cm, and from the back detector 138 cm.

In source position 2, the source location is 41 cm from the front box face and 79 cm from the back box face, so that the matrix attenuation distance was 41 cm for the front detector and 79 cm for the back detector, making the total distance from the front detector 81 cm, and from the back detector 119 cm.

In position 3, the source was placed in the center hole in the box, so that the matrix attenuation distance from each detector was 60 cm, and the distance from each detector was 100 cm.

Positions 4 and 5 simply reverse the distances from the two detectors.

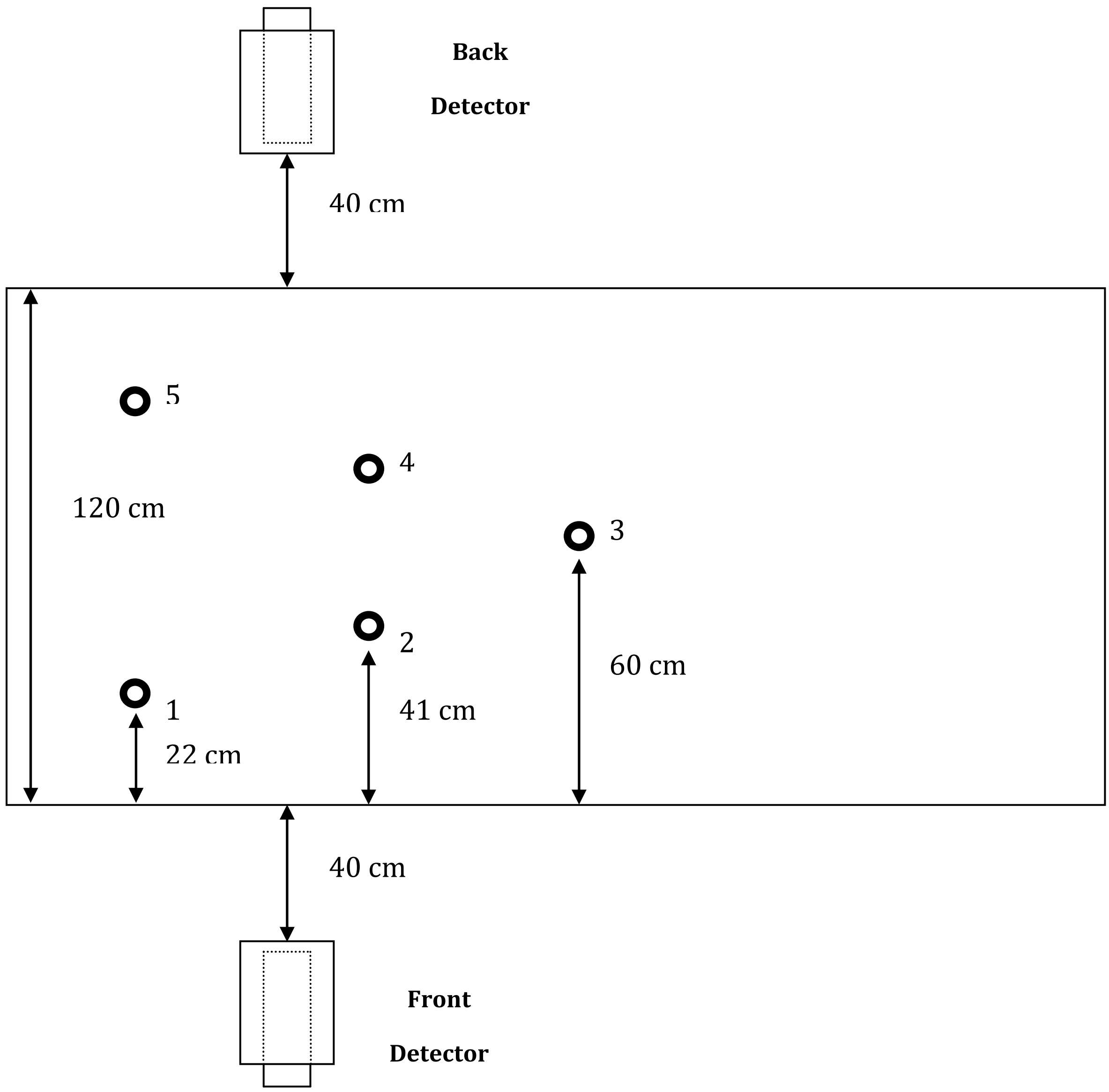

Figure 3. Plan view of the measurement positions in the test box.

Test Configuration

Container Characteristics:

Box Dimensions:	180 cm x 120 cm x 120 cm
Box Weight (kg):	Gross 1418
	Tare 475
	Net 943
Container Material:	Steel, Density (ρ) 7.8, Atomic Number (Z) 26
Container Wall Thickness:	0.3175 cm

Matrix Characteristics:

Material Type:	Combustible (Plywood), Density (ρ) 0.3638, Atomic Number (Z) 6

Source Characteristics:

Isotope:	2 x 10 μCi ^{152}Eu, Activity (A) = 7.41 x 10^5 dis/sec

Test Discussion and Results

The general formula for the expected response from a point source is given by:

$$R = \varepsilon \times A \times BR \times GF \times T_c \times T_m \qquad \text{Equation 1}$$

where:

ε = detector efficiency at the gamma peak of interest

A = total source activity

BR = branching ratio of gamma peak of interest

GF = solid angle geometry factor

T_c = source transmission through container wall

T_m = source transmission through matrix

And:

$$T_c = e^{-\mu_c \times \rho_c \times x_c} \qquad \text{Equation 2}$$

where:

μ_c = container mass attenuation coefficient

ρ_c = container density

x_c = container wall thickness

A similar formula holds for the transmission through the matrix material, so that the following values are obtained for the given gamma-ray energies:

Table 1. Point Source Transmission Values

Gamma Energy (keV)	122.78	344.3	778.9	1408.08
Container Transmission	0.48	0.77	0.85	0.88
Matrix Transmission (22 cm)	0.32	0.44	0.56	0.65
Matrix Transmission (41 cm)	0.12	0.22	0.34	0.45
Matrix Transmission (60 cm)	0.043	0.11	0.21	0.31

The solid angle geometry factor is simply the fraction of the solid angle subtended by the face of the detector; hence:

$$GF = \pi \times \frac{r_d^2}{4\pi \times r^2} \qquad \text{Equation 3}$$

where: r_d = detector face radius (2.6 cm)

r = distance from source to detector

So that we have for the three source positions (total distance to detector = 62, 81 and 100 cm):

$GF_{62} = 4.3 \times 10^{-4}$; $GF_{81} = 2.6 \times 10^{-4}$; $GF_{100} = 1.69 \times 10^{-4}$

We then obtain the following calculated and measured detector counts:

Table 2. Comparison of Calculated to Measured Count Rates

Gamma Energy (keV)	121.78	344.3	778.9	1408.08
Branching Ratio	0.2924	0.27	0.13	0.2121
Detector Efficiency	0.743	0.37	0.189	0.108
Calculated Counts (22 cm)	10.7	11.1	3.8	4.3
Measured Counts (22 cm)	9.3	9.9	3.8	4.0
Calculated Counts (41 cm)	2.3	3.2	1.36	1.73
Measured Counts (41 cm)	1.0	1.7	0.95	1.59
Calculated Counts (60 cm)	0.58	1.13	0.62	0.92
Measured Counts (60 cm)	0.27	0.61	0.42	0.67

The measured counts are those returned by GammaVision for the gamma energy peaks specified. It is to be noted that since the GammaVision values are simply the background-subtracted values in the peak regions of interest, they are unaffected by attenuation or geometry, and their correspondence to the calculated values is a reflection on the statistical precision with which GammaVision can fit the selected peaks and make the correct background subtractions.

The discrepancies between the calculated and measured values with the source at the center position (30% - 50%) are doubtless due to the very low source count rates. From the center position (60 cm) the relative geometry significantly reduces the gamma rays that reach the detector. The recorded signals are fewer than are observed with a source closer to the detector and the curve-fitting algorithm is taxed by the small differential observed between measured signal and ambient background. The difference in measured counts from the source at the center position is dominated by signal-to-noise considerations and not by attenuation differences between this position and the position with the source at the edge of the box. The calculated counts and the measured counts at the edge position, where the source is relatively close to the detector, are statistically identical.

IsoCorr Analysis

The following table shows the various IsoCorr values at the four major ^{152}Eu gamma-ray energy values, along with the average IsoCorr transmission values, the calculated actual transmission values for the point source at the stated position, and the ratio of the two transmission values.

As a rough approximation of estimating the difference between the IsoCorr "average" transmission values and the actual point-source transmission values, we calculate the ratio between the two and apply it as a correction to the IsoCorr values. This will be a rather crude approximation because the transmission through the matrix material is not linear, but it does show that the correction proceeds in the right direction.

Table 3. Transmission Ratios

Gamma Energy (keV)	121.78	344.3	778.9	1408.08
IsoCorr Values (22 cm) in MBq activity	2.26	2.13	2.02	1.99
IsoCorr Values (41 cm) in MBq activity	0.214	0.347	0.538	0.645
IsoCorr Values (60 cm) in MBq activity	0.065	0.135	0.254	0.325
Transmission Ratio (22 cm)	0.82	0.80	0.84	0.88
Transmission Ratio (41 cm)	2.2	1.6	1.4	1.3
Transmission Ratio (60 cm)	6.0	3.2	2.24	1.8
"Corrected" IsoCorr (MBq) (22 cm)	1.8	1.7	1.7	1.75
"Corrected" IsoCorr (MBq) (41 cm)	0.47	0.55	0.75	0.83
"Corrected" IsoCorr (MBq) (60 cm)	0.4	0.43	0.57	0.58

With the consideration of the poor counting statistics from a very weak calibration source, the confirmation data in the table above is entirely consistent with the physics of a point source compared with the assumption of distributed source materials in a homogeneous matrix.

The suggestion is that this calibration matrix be used for future comparisons of the europium source placed in the two extreme positions (the center and the edge positions) to ensure that the system calibration has not changed.