A Single Tower Configuration of the Modular Gamma Box Counter System – 13392

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ABSTRACT

Canberra's Standard Gamma Box Counter System is designed to perform accurate quantitative assays of gamma emitting nuclides for a wide range of large containers including B-25 crates and ISO shipping containers. Using a modular building-block approach, the system offers tremendous flexibility for a variety of measurement situations with wide ranges of sample activities and throughput requirements, as well as the opportunity to modify the configuration for other applications at a later date. The typical configuration consists of two opposing towers each equipped with two high purity germanium detectors, and an automated container trolley. This paper presents a modified configuration, consisting of a single tower placed inside a measurement trailer with *three* detector assemblies, allowing for additional vertical segmentation as well as a viewing a container outside the trailer through the trailer wall. An automatic liquid nitrogen fill system is supplied for each of the detectors. The use of a forklift to move the container for horizontal segmentation is accommodated by creating an additional operational and calibration set-up in the NDA 2000 software to allow for the operator to rotate the container and assay the opposite side, achieving the same sensitivity as a comparable two-tower system.

This Segmented Gamma Box Counter System retains the core technologies and design features of the standard configuration. The detector assemblies are shielded to minimize interference from environmental and plant background, and are collimated to provide segmentation of the container. The assembly positions can also be modified in height and distance from the container. The ISOCS calibration software provides for a flexible approach to providing the calibrations for a variety of measurement geometries. The NDA 2000 software provides seamless operation with the current configuration, handling the data acquisition and analysis. In this paper, an overview of this system is discussed, along with the measured performance results, calibration methodology and verification, and minimum detectable activity levels.

INTRODUCTION

The Segmented Box Counter System is an example of one of Canberra's Non Destructive Assay systems, designed for flexibility and large containers [1]. This gamma-ray waste assay system characterizes and quantifies waste ranging in size from 108 liter drums up to intermodal shipping containers for material accountancy, shipment to repositories, or free release in accordance to regulatory standards or guidelines [2,3,4]. While many different configurations of the system have been deployed, they have several key components in common. Each system includes a minimum of one detector assembly and one tower. A detector assembly consists of a high purity germanium detector, cryostat, collimation, and shielding. The detector assemblies are placed on vertical towers, which allow for height adjustment depending on the object to be assayed. The collimation is cylindrical and comparatively broad at 40 degrees, and so the detectors have a large field of view. The collimators serve more to reduce background and focus the field of view to the container rather than to restrict the field of view to a given segment, as is common practice with other segmented gamma scanners.

One or more detectors may be situated on a given tower, which can be fixed or on rail system. A common configuration has two detector assemblies, each on two towers, and the assay object is passed between the two towers on a conveyor. For full coverage of large objects, the container stops at several points automatically while passing through the tower assemblies. If a conveyor is not installed, the container must be manually moved. Each of these stops are termed "platform positions," and at each platform four segments are measured – two on each side, at an upper and at a lower height. This configuration is shown in Figure 1.

Figure 1. A common configuration of the Modular Box Counter is shown, consisting of two towers with two detector assemblies each and a conveyer system.

SYSTEM DESCRIPTION

The system discussed here utilizes three detector assemblies and a single tower (Figure 2). This allows for three segments per platform position on a given side. To assay both sides of the container, the container can first be assayed at each platform position on one side, rotated 180 degrees after the first pass, and then assayed on the second side with the original tower position as the container is moved past the tower again. Primary components of this system include three Broad Energy Germanium Detectors each mounted in a collimating shield, a detector tower with vertical adjustable screw drive system, three Inspector 2000 multi-channel analyzers, a laptop computer, and software designed to acquire and analyze gamma-ray spectra from the system. Additionally, this system features an automated liquid nitrogen fill system, which provides unattended automatic filling of the cryostats according to a user programmable weekly schedule.

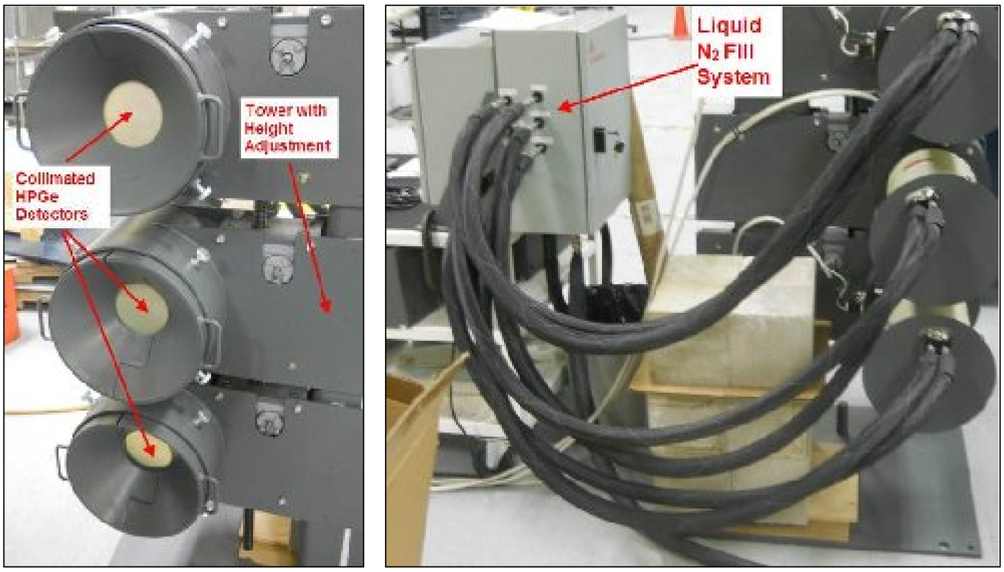

Figure 2. Detectors, Shielding, Tower, and Liquid Nitrogen Fill System are shown. In the view to the left, the tower is partially hidden by the detector assemblies.

The single tower configuration of the modular segmented box counter system allows for the entire system to be placed in a single trailer. This allows for even greater flexibility, as the trailer can be moved to the required measurement site. Furthermore, because of positioning of the system within the trailer, it can be designed to assay items viewed through the trailer wall. This application allows the system to assay large and unwieldy items, without any need to bring them inside a constrained environment. At the same time, this allows for the most protection to the NDA system and prevents it from being exposed to weather. In this case, the trailer wall becomes part of the measurement geometry, and the absorption characteristics of the trailer wall are corrected for in the efficiency calibration.

The Liquid Nitrogen (LN2) Multi-Detector Fill System is designed to automatically fill several high purity germanium detectors having multi-attitude cryostats. The system is controlled by a Programmable Logic Controller (PLC) which operates cryogenic solenoid valves for sequential filling of the cryostats. A 7 day programmable timer will initiate a fill cycle according to a schedule programmed by the user. The timer provides accurate timekeeping and maintains all programmed set points during a power failure using a lithium battery which provides years of reserve power if the control enclosure were to remain powered off for an extended period of time. A fill cycle can also be started manually without the need to be initiated by the programmable timer.

The fill system consists of two individual enclosures, the control enclosure which contains the control electronics including the timer and PLC, and the manifold enclosure which contains the cryogenic valves and a Liquid Nitrogen sensor. The manifold enclosure is connected to each cryostat and a pressurized liquid nitrogen source using insulated stainless steel flexible hoses. The liquid nitrogen sensor works on the principal of thermal conductivity and is internally heated to help differentiate between the gas and the liquid phase of the nitrogen. The liquid nitrogen sensor is used in the process of purging the manifold and filling the individual cryostats.

When power is first applied to the enclosure, the PLC performs a series of internal diagnostics. If the diagnostics pass, the PLC loads the fill program from memory and begins to monitor the inputs waiting for the activation of a fill cycle either manually or from the programmable timer. The switches and status lights on the control enclosure provide the user with direct mechanism control and status. LED indicators provide information about control power, fill status, and fault status. Furthermore, the fault indicator exhibits different behaviors for an emergency stop, a liquid nitrogen sensor error, a purge cycle error, and fill errors specific to a particular cryostat, aiding in faster diagnosis of the problem during a system malfunction.

The electrical enclosure monitors an emergency stop push button. When the emergency stop push button is pressed, power is removed from the cryogenic valves causing them to close. Additionally, the manifold enclosure is equipped with a pressure relief valve on the liquid nitrogen intake designed to vent when the internal pressure exceeds 172 kPa.

The overall footprint of the tower with detectors and shields installed and the liquid nitrogen fill system is approximately 88 by 92 by 277 cm (LxWxH). When the system is used in a trailer, the electrical and manifold enclosures are mounted to a common bracket and bolted to a trailer wall shelf. This is not included in the aforementioned footprint dimension. The total weight of the system including the lead shielding is near 1090 kg.

METHODOLOGY

The system calibration was performed utilizing Canberra's In-Situ Object Counting System (ISOCS) mathematical calibration software, integrated with NDA 2000's acquisition and analysis software [5]. This mathematical calibration approach uses ray tracing techniques to determine gamma ray efficiency for the specified geometry using the specified combination of germanium detectors [6]. The method has been validated successfully in many applications [6,7,8,9]. When utilized with an NDA system, a model of the assay item is created with an ISOCS geometry template. It is evaluated at a range of densities and energies for each detector and at each platform or segment position.

Because germanium detectors are all different internally, an ISOCS characterized detector is used in the system, and its particular efficiency response is built into the mathematical model and resulting efficiency calculations. Model efficiency responses at a range of item densities for the individual platform positions or segments as well as a combined efficiency response for a full assay are folded into the acquisition and analysis software to provide a multi-curve efficiency calibration. At run time, the exact efficiency used is determined by interpolation of the multi-curve efficiency calibration at the density of the assay container and energy of the nuclide lines identified.

The calibration of the 3-detector single tower box counter is designed for a B-25 box assayed at a distance of 1 meter from the endcap faces of the detectors. The box can be assayed directly or through a trailer wall. The B-25 box measures 183 by 117 by 119 cm (L x W x H). The container walls are 0.267 cm thick and made of steel. The tare weight of the container is 317.5 lbs without the lid or 338 kg with the container lid. Two count types are defined for the system:

a “One Side Scan”, in which case three platform positions were measured on one side of the container, and a “Two Side Scan” where three platform positions were measured on one side of the container, the container was rotated 180 degrees, and then three platform positions were measured on the far side of the container.

The ISOCS geometry model uses the Simple Box Template. This model approximates the B-25 container and does not include the various reinforcing elements of the box or supporting structures. For each detector, the collimation is modeled with the Circular Collimator template, which is configured to simulate the Box Counter collimator. The aluminum detector cover is modeled with the generic absorber. The radioactivity is modeled uniformly throughout the matrix material of the containers, and the efficiency calculations are performed using cellulose as the uniform matrix material. The density is varied from 0.001 to 1.75 grams per cubic centimeter, using nine discrete density models.

The model is pictured in Figure 3 below for a single detector at one of the platform positions. Also included in Table I is a description of the ISOCS input parameters used to create the geometry model for the efficiency calibration. The ISOCS calculation was performed at 23 calibration gamma ray energies, spanning from 30 keV to 3.0 MeV.

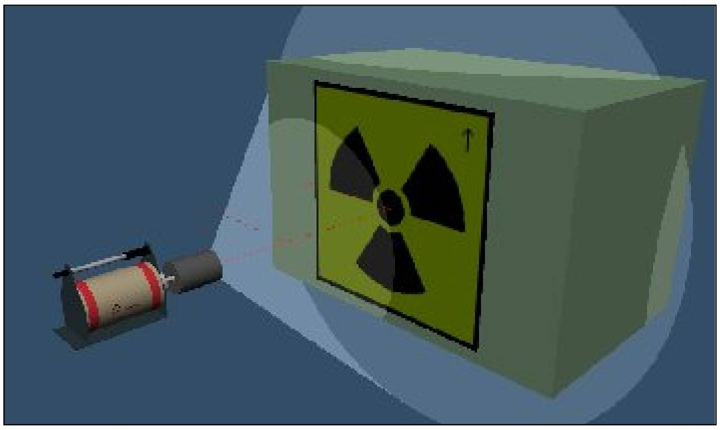

Figure 3. Example ISOCS model of B-25 box is displayed. Only the middle detector is pictured here.

The multi-curve emission efficiency calibration was loaded into the NDA 2000 software using its calibration utility. The efficiencies were interpolated by a polynomial fit between energies and densities, thereby generating the efficiency multi-curve from which the efficiency can by calculated at any energy and density. The efficiency model for this system was fit in energy using an interpolated model, and in density model using an empirical approximation of a rectilinear object [5].

Table I. The model key parameters, values and their descriptions are listed for the B-25 box model, based on the Simple Box template.

Parameter	Value	Description
1Absorber	7.87	Thickness of generic absorber (mm)
1AMaterial	Aluminum	Thickness of generic absorber
d1.1	2.67	Container wall thickness (mm)
d1.2	1828.8	Container inner length (mm)
d1.3	1193.8	Container inner height (mm)
d1.4	1168.4	Container inner depth (mm)
1mater	csteel (carbon steel)	Container material
1density	7.86	Container material density (g/cc)
d3.1	1193.8	Source – bottom layer height (mm)
3mater	cellulose	Source matrix material
3density	various based on matrix	Source matrix density

For the B-25 Box geometries viewed through a trailer wall, the model is modified to include an additional generic absorber. The attenuation as a function of energy through the trailer wall is determined and is used to define a composite material, which is then used as the generic absorber in the modeled geometry.

Mathematical efficiency tools were also utilized to design a verification container that would use line sources to approximate a uniform distribution activity in the sample container. First, an ISOCS model of a uniform activity distribution throughout the B-25 container was created, and the summed efficiency from each detector position was evaluated at a range of energy values. This efficiency served as a reference to the final calibration, which considers a uniform matrix and activity distribution. Then, another model was created, but this time in the ISOCS Uncertainty Estimator. This model consisted of six detectors (with positions corresponding to the three detector locations at three platform positions) and six cylindrical "hotspots" distributed throughout a B-25 non-radioactive matrix. The hotspots had dimensions corresponding to the rod sources used for verification measurements, and the locations of these hotspots were randomly placed throughout the matrix by the ISOCS Uncertainty Estimator for each model. Several hundred models were evaluated, and then the results were filtered to reflect only models with efficiency results in the same order of magnitude of the uniform model efficiency results. The distribution of the hotspots in these models were used to help guide a first guess of a controlled hotspot model, where the hotspots were placed strategically for reproducibility, symmetry when viewed from either side of the box, and relative efficiency contribution per hotspot. The model was refined through several iterations until good agreement of the hotspot model (summed over 6 detector positions) and the uniform model was achieved. Figure 4 shows the final locations of the rod sources within the calibration matrix, and Figure 5 displays the agreement of the hotspot model to the uniform model. Figure 6 shows the relative contribution of each of the rod sources with hotspot numbering consistent with Figure 4.

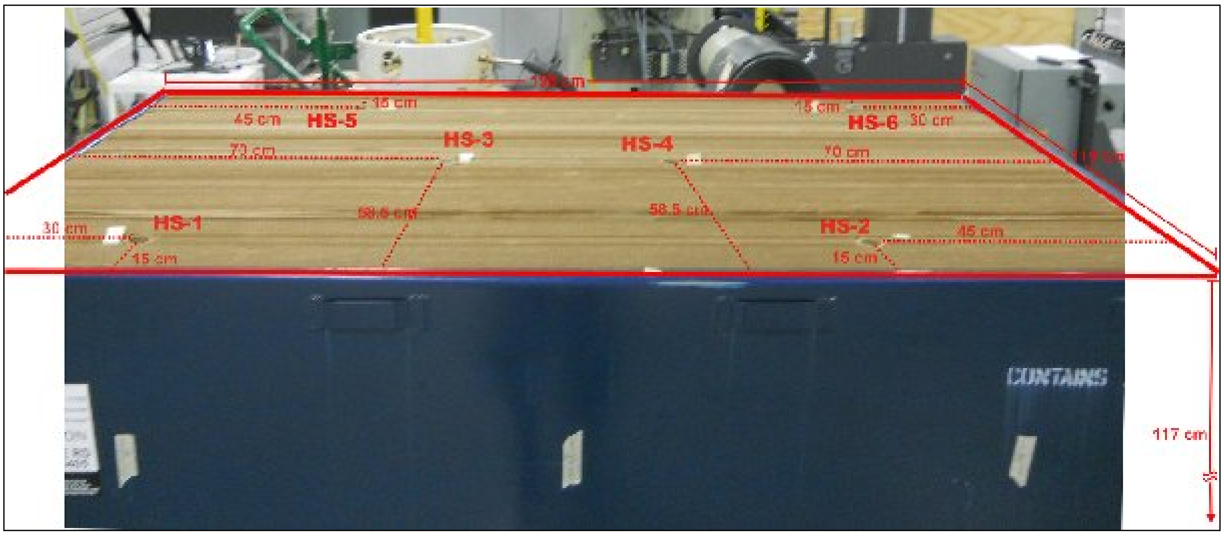

Figure 4. The verification container approximating a uniform activity distribution with 6 rod sources placed in specific locations is pictured. The location of each of the rod sources in the matrix is labeled “HS”. Rod sources were centered vertically in the matrix and are 809 mm in length.

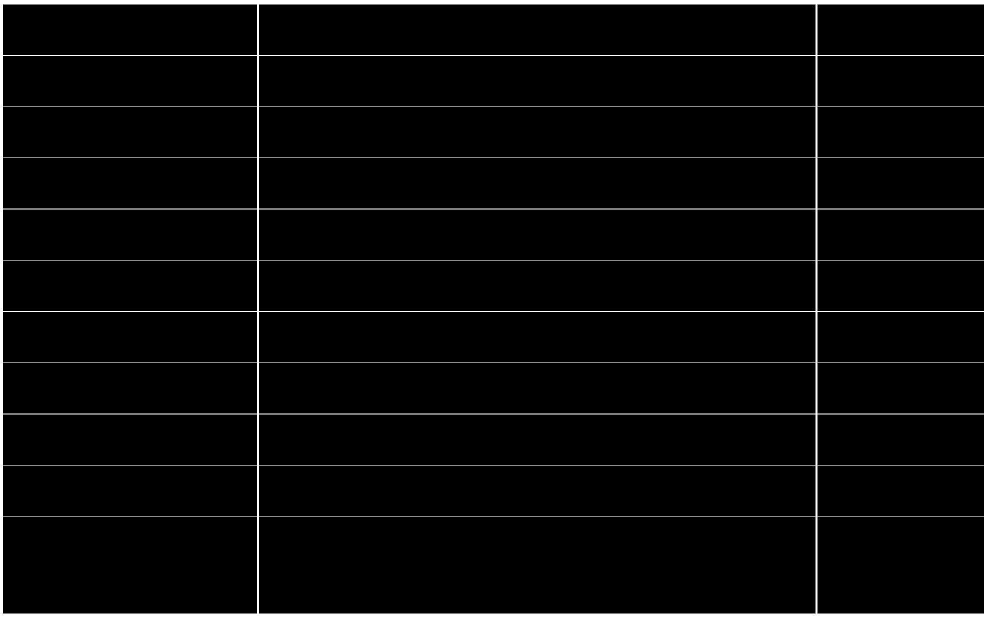

Figure 5. The modeled efficiency for the matrix container with 6 hotspots is compared to a uniform distribution of activity in a container of the same size. The matrix material considered is cardboard at 0.16 g/cc.

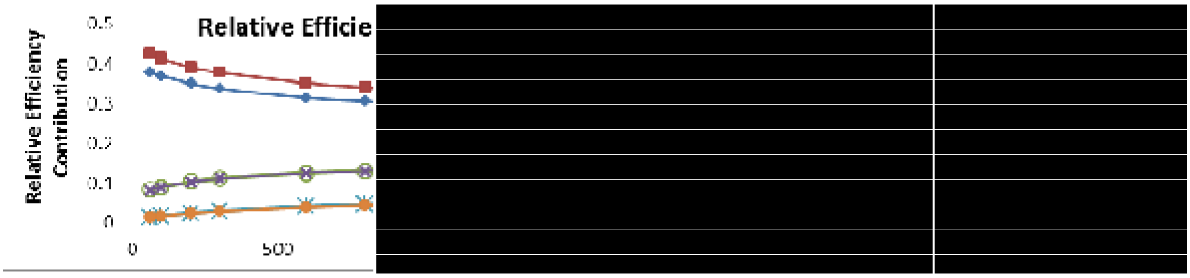

Figure 6. The relative contribution of 6 modeled hotspots in the B-25 container is calculated and normalized to 1. This shows that while the front two hotspots dominate the efficiency contribution, at 600 keV about 25% of the efficiency contribution is from the center two hotspots, which is significant**.**

PERFORMANCE & MDA

Verification measurements were performed with a B-25 container consistent with the dimensions described for the system calibration. The container was packed with two-ply standard cardboard material of density 0.16 g/cc for a total weight of 722 kg, and was arranged in vertical sheets to create a uniform matrix and to minimize shine paths.

The matrix material was removed in six locations and replaced with a cardboard cylindrical tube. These locations were placed at the coordinates indicated in Figure 4 and are designed to allow the insertion of radioactive sources in specific and reproducible locations within the cardboard matrix. The locations of the source tubes are designed to approximate a uniform source matrix in the B-25 container, as discussed in Methodology. The distribution of source tubes is symmetrical when viewed from either side of the container, and are offset to minimize obstruction of the sources further from the detector tower from those closer to the tower.

During calibration verification, six line sources were placed in the six cylindrical source tubes distributed throughout the B-25 cardboard matrix. The six line sources contain about equal quantities of radioactive isotopes Am-241, Ba-133, Cs-137, and Co-60, evenly deposited in an epoxy matrix inside an aluminum casing. The active length of each the rod source is 809 mm, and the sources were suspended in the source tubes such that they were vertically centered in the B-25 box.

At the end of the verification assay, the measured activities are compared against the decay corrected true certificate activity of the sources standards. An attenuation factor due to the aluminum casing of the line sources is analytically calculated and applied to the true activity values. Verification measurements were performed both using a one side scan and a two side scan. In both counts, the B-25 container was placed 87 cm from the detector faces. The B-25 box rested on movable wheels, raising the container by 10 cm. The centerlines of the detectors were positioned at 114 cm, 81 cm, and 48 cm from the floor for the top, middle, and bottom detector assemblies, respectfully.

The results are represented in Figure 7 and tabulated in Table II. Good agreement for the nuclides of interest for the system's application (i.e., Cs-137 and Co-60), validates the efficiency curve calibrations. Presented also are the Ba-133 results at 356 keV, which show an energy dependent bias but are within an acceptable uncertainty for this application, as this is likely to be less than uncertainties resulting from non-homogeneity of the sources distribution. Am-241 at 60 keV results (not shown) also show a similar bias. Reported is the activity as determined by the gamma ray line at the indicated energy for each nuclide. The agreement of the true to measured assay results is well within acceptable limits.

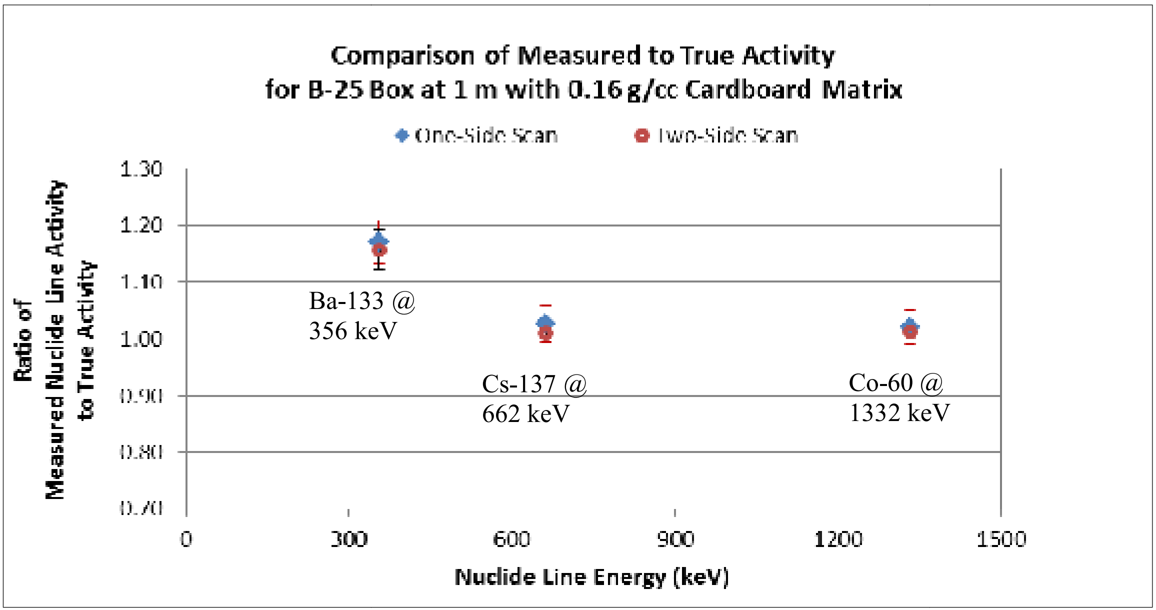

Figure 7. Verification results for a B-25 container assayed with the single tower configuration of the modular box counter system are graphed as a function of energy. For each nuclide, the measured line activity is reported and compared against the true activity.

Table II. Verification results of for a B-25 container with 6 hotspots configured to approximate a uniform activity distribution are listed. The system multi-curve calibration is for a uniform B-25 matrix distribution.

Nuclide & Line Energy	Ba-133 (kBq) @ 356 keV	Cs-137 (kBq) @ 662 keV	Co-60 (kBq) @ 1332 keV
True Activity	5924.39 ± 177.73	1026.11 ± 30.78	948.63 ± 28.46
Measured Line Activity			
One-Side Scan	6941.87 ± 94.69	1053.60 ± 2.89	968.40 ± 1.47
Two-Side Scan	6857.10 ± 48.00	1037.72 ± 10.38	961.01 ± 1.45
Measured Line Activity / True Activity			
One-Side Scan	1.17 ± 0.04	1.03 ± 0.03	1.02 ± 0.03
Two-Side Scan	1.16 ± 0.04	1.01 ± 0.03	1.01 ± 0.03

The detection limits of the box counter for Cs-137 and Co-60 were measured with the calibration matrix without any sources present. The background rates were measured during a one side scan and used for other the configurations. Also shown in Table III are the detection limits of the B-25 container with the box counter configuration being two detectors on opposing towers. The efficiencies of a typical two-tower box counter were estimated from the existing system. The following assumptions are made for all of the detection limit calculations:

- B-25 Container
- Uniform Activity and Matrix Distribution
- Summed Spectrum Analysis (all positions summed together)
- Nominal Background Rate : 0.1 uSv/hr (0.01 mR/hr)
- 5% False Alarm / 95% Detection Probability
- Spectral Background region-of-interest : 1.274 full-width-at-half-maximum

The total assay time of the one-sided scan of the single tower system and the two tower system is 1800 seconds. The two-sided scan, single tower system is presented for 3600 seconds, keeping each horizontal scanning position the same length of time. Unlike to the calibration verification data, the efficiencies used in calculating the single tower detection limits include the trailer wall.

Table III. Detection limits of box counter and similar counters of other configurations are listed. All units are in pCi/g.

Nuclide	**Matrix**	**Matrix Density**	**Single Tower 3 DET / Tower One Sided Scan BE5025**	**Single Tower 3 DET / Tower Two Sided Scan BE5025**	**Two Tower 2 DET / Tower Single Pass BE5025**
Cs-137	Cellulose	0.25	0.058	0.040	0.035
Cs-137	Cellulose	1.75	0.045	0.031	0.028
Co-60	Cellulose	0.25	0.043	0.030	0.027
Co-60	Cellulose	1.75	0.031	0.021	0.019

CONCLUSION

In this paper, the design, construction, and verification of a single tower box counting system has been presented. The 3-detector single tower configuration shows similar performance as other configurations, but has advantages in increased flexibility of assay container sizes and shapes. This system continues to highlight the application of mathematical modeling in NDA system calibrations, as demonstrated by the successful verification measurements of a B-25 container. It is useful to consider mathematical modeling for other NDA measurement tools as well, such as design of verification containers. This reduces time and cost in developing a highly effective calibration and/or verification container. The system discussed here also demonstrates an application of an automated liquid nitrogen fill system. The Modular Segmented Gamma Box counting system continues to be a proven non-destructive assay system readily configurable for many applications.

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