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DESIGN, DEVELOPMENT AND TESTING OF AN AUTOMATED SEGMENTED GAMMA SCANNER FOR MEASURING NUCLEAR POWER STATION RADIOACTIVE WASTE

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ABSTRACT

This paper describes the design, development and testing of an updated and automated segmented gamma scanner (SGS) for measuring radioactive waste generated at a nuclear power station. The instrument retains the capabilities of the original SGS developed by Parker and Martin at the Los Alamos National Laboratory and now widely used for radioactive waste assay. It also incorporates additional features to improve measurement efficiency and reduce cost. These features include continuous helical scanning of the waste drum, the use of a single lifting pillar to move both the detector and transmission source and a re-designed SGS collimator and both transmission source shield and transmission source shutter mechanisms. Updated motion control electronics, based on the use of a programed logic controller (PLC) have been incorporated to address potential future obsolescence. The SGS employs a 40% high purity Germanium detector with electro-mechanical cooling and state of the art digital spectroscopy counting electronics for gamma ray spectrum data acquisition. Testing of the unit has been performed with both point sources and rod sources, which are traceable to international standards. Typical test drums, each with six distributed re-entrant tubes and with different density matrices, have been employed with the rod sources to validate both the calibration and the measurement performance of the SGS for drums of different density. Benchmarked Monte Carlo MCNP calculations have been performed and the calculation results agree and confirm the replicated measurement results for a variety of drum density configurations.

INTRODUCTION

The Segmented Gamma Scanner (SGS) has been established as a particularly versatile and effective means of measuring drums and other objects for both safeguards purposes and radioactive waste assay. The original SGS development work of Parker and Martin [1] at the Los Alamos National Laboratory (LANL) and the resulting increased use of SGS measurement technology incorporating drum segmentation and transmission corrections for attenuation has made a significant contribution to improving the quality of radiometric measurements over the last 35 years. The insights of Parker and Martin into the limitations of conventional Far Field or "one shot" measurements have been confirmed again by recent work [2].

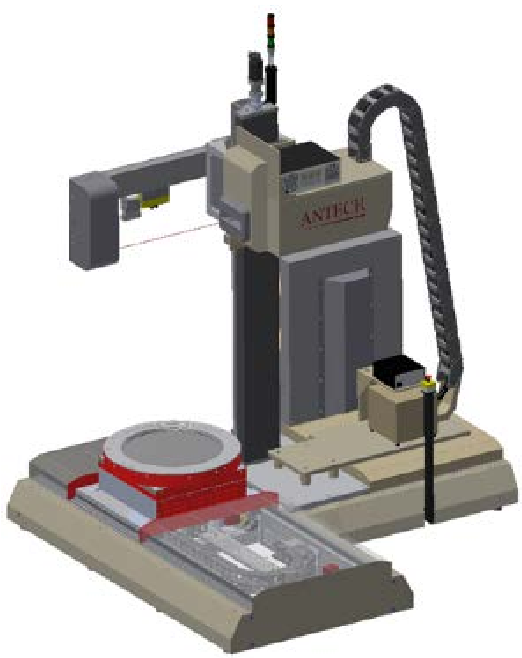

Figure 1. Design concept for the Mk3 SGS.

The present instrument, designated the ANTECH Mk3 SGS, is based on the original LANL SGS and the design of earlier ANTECH SGS instruments. It was developed as a standard specification SGS for the measurement of radioactive waste contained in 200 litre drums at nuclear power stations. It has several additional features, which extend the measurement capability of earlier ANTECH SGS instruments, and these features are described in a later section. Note that the system does not include advanced features that have been included in the ANTECH Wide Range SGS [3, 4, 5] such as the variable aperture collimator and the transmission source safe. The design concept for the instrument is shown in Figure 1.

An SGS measures drums and objects by subdividing the drum into separate vertical segments. A critical feature is the inclusion of a transmission source so that the gamma ray attenuation of each segment can be determined. For each vertical segment two gamma ray spectra are recorded, one for the transmission and one for the emission measurement. In a single pass measurement only one spectrum is recorded for each vertical segment from which both the transmission and emission data is obtained.

The fundamental assumption of the SGS is that each cylindrical vertical segment of the drum is homogeneous and has a uniform distribution of activity and uniform gamma ray attenuation. Each vertical segment may have a different activity and attenuation. Errors arise if this condition is not met. These errors are generally small for low-density matrices and small deviations but they can be very large [2] and can be greater than a factor of 10 for highly heterogeneous drums. For heterogeneous drums the errors may result in either over or under reporting of the drum activity.

The total correction factor for relating SGS instrument response to actual counts in the gamma ray emission spectrum from the radioactive material being measured consists of three independent correction factors: rate-related losses in the full-energy gamma-ray peak, attenuation due to the sample container itself (container wall), and self-attenuation in the matrix material. (Note that sufficient dispersal of radioactive material in the sample is assumed such that self-attenuation can be ignored – in other words there is no “self absorption”.)

The rate-related correction factor is determined by comparing a full-energy rate-correction source peak (an independent radioactive peak associated with the detector only and not subject to variation with sample parameters), both with no sample and with the sample present. In this way, the correction for rate effects is easily determined. The sample container attenuation is similarly easily determined by simply measuring the attenuation with an empty container compared to no container in place.

However, the determination of the matrix attenuation is geometry dependent. It is quite easy, for example, to calculate the attenuation for a plane slab of material, if we define the transmission (reciprocal of the attenuation) as the ratio of gamma-ray intensity on the egress side of the slab to the intensity on the input side. This exact formula is given by:

$$CF_{(att)} = \frac{-\ln(TR)}{1 - TR}$$

Where:

CF is the matrix correction factor

TR is the transmission as just defined.

For cylindrical samples, an approximate formula involves a complex combination of modified Bessel functions and modified Struve functions for the far-field case (where dimensions of the sample are small compared to the measurement distance). A first-order approximation to this complex formula is given by:

$$CF_{(att)} \cong \frac{\frac{-\pi}{4}\ln(TR)}{1 - TR^{\frac{\pi}{4}}}$$

This has the same form as the slab formula, except the transmission is raised to the π/4 power. A general form of the equation for the attenuation factor can be written as:

$$CF_{(att)} \cong \frac{-A * ln(TR)}{1 - TR^{A}}$$

In their original work, Parker and Martin [1] found by experiment with various samples that over a wide variety of attenuations, sample sizes, and sample-detector distances that a value of A= 0.82 yields accuracies within one or two per cent. This includes a correction for the fact that positioning the detector close to the drum or sample may violate the far field geometry assumption. Based on these studies, it has become industry practice to use the following formula for the matrix attenuation factor:

$$CF_{(att)} \cong \frac{-0.82 * \ln(TR)}{1 - TR^{0.82}}$$

The total correction factor is simply the product of the three correction factors.

DESIGN AND OPERATION

The ANTECH Mk3 Segmented Gamma Scanner, or SGS, is a robust, comprehensive and automated radioactive waste assay system for measuring waste in drums. It retains all of the capabilities of the original LANL SGS and the features of earlier ANTECH SGS designs. The Mk3 SGS design uses a single lifting pillar to move both the high purity Germanium (HPGe) detector and the transmission source and holder in the vertical plane. The instrument employs an ORTEC 40% HPGe Profile detector (GEM-F7040P4) with electro-mechanical cooling (X-Cooler3) and the DSPEC-50 digital spectroscopy counting electronics for gamma ray spectrum data acquisition. Figure 2 is a photograph of the unit during factory testing.

Additional features include drum weight measurement, drum rotation platform horizontal positioning using slide rails, dose-rate pre-scanning using a Geiger-Muller detector, helical drum

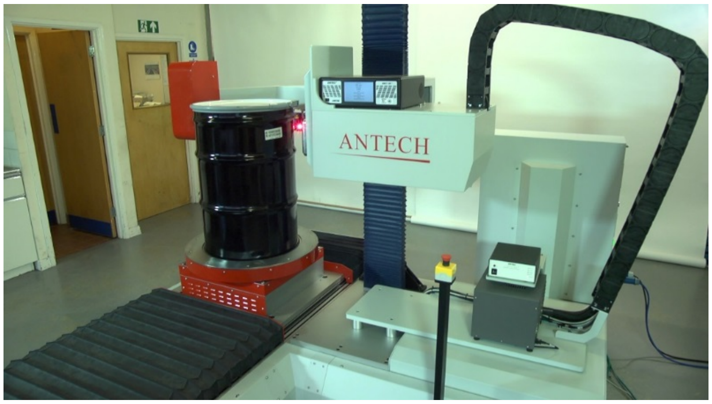

Figure 2. Photograph of the Mk3 SGS.

scanning and variable segment height, an optimised collimator with automated filter for detector dose-rate reduction and a drum bar code reader. An Allen Bradley program logic controller (PLC) provides motion control for the vertical, horizontal and rotational axes of motion as well as control of the transmission source shutter mechanism as well as the tungsten filter built into the collimator.

An optimised collimator has been designed with a slightly restricted radial field of view. An MCNP Monte Carlo analysis [6] has demonstrated that by forgoing gamma rays from the outer edges of the drum in the detector field of view, there is a net benefit in terms of reduced gamma ray background. An automated tungsten filter is incorporated into the detector collimator. The filter may be deployed in order to reduce the detector dead time during the measurement of high dose-rate drums. The collimator ensures that the detector field of view includes almost all of the drum width. The collimator aperture height determines the minimum segment height during helical scanning of a drum.

A new transmission source holder and shutter mechanism has been included in the Mk3 SGS design. The mechanism will ensure failsafe operation as the shutter is returned to the closed position under gravity in the event of a power failure. The new shutter of greater thickness and greater diameter is designed to reduce the background radiation arising from the Eu-152 transmission source. The transmission source holder and shutter mechanism can be seen in Figure 3. Figure 4 provides a view of the collimator with the transmission source in the open or exposed position. The HPGe detector end cap is visible through the collimator aperture.

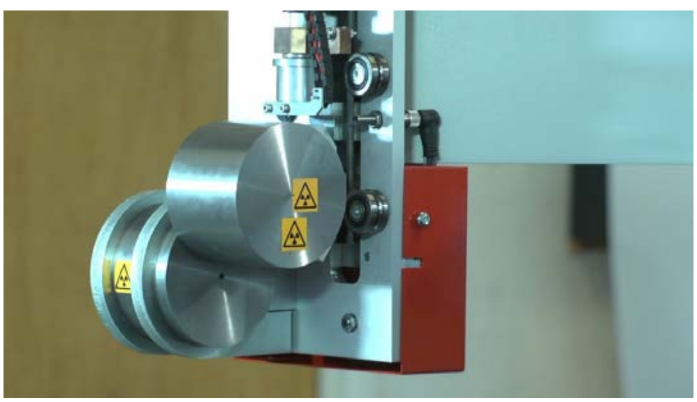

Figure 3. Transmission source holder (shield) and shutter mechanism.

Comprehensive motion control electronics based on an Allen Bradley Programmed Logic Controller or PLC are housed in a screened electronic control cabinet. The PLC is used to control the drum rotation, drum scanning, deployment of the tungsten filter and the movement of the rotation platform. The electronic communication between the system components has been simplified in that a single cable carrying both power and signal is used to connect the motor drives in the electronics cabinet with the motion control motors. All communication within the instrument is by means of Ethernet.

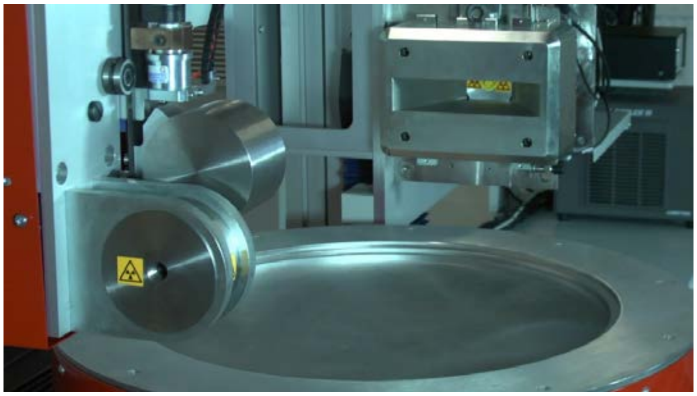

Figure 4. View of the collimator with the transmission source in the exposed position.

During operation, the drum is loaded onto the rotation platform and moved on slide rails into the measurement position. Initially, the drum is aligned and the detector shelf is raised for bar code reading. Once the bar code, which is used to identify the drum, has been read, the drum is re-positioned for surface dose-rate pre-scanning. The number of segments used for dose-rate pre-scanning is selectable by the user. The results of the dose-rate pre-scanning and the drum weight measurement are used to determine the drum segment height, drum rotation speed and the filter deployment as required. See Figure 5.

The drum assay is normally performed in two scans. The transmission measurements are made to determine the drum density or drum attenuation for each measured drum segment. During the transmission scan the transmission source shutter is opened in order to expose the transmission source, see Figures 3 and 4. In the transmission measurement, gamma rays from the Eu-152 transmission source pass through the drum where they are attenuated by the matrix materials before being counted in the Germanium detector. A gamma ray spectrum is recorded for each segment of the drum and the data is used to provide an attenuation correction for each segment. The shutter is closed at the end of the transmission measurement. In an analogous manner the emission measurement is made and a gamma ray emission spectrum is recorded for each segment.

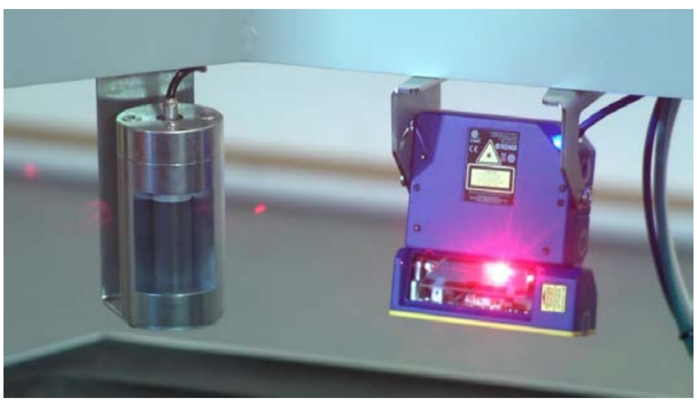

Figure 5. G-M detector and Bar Code reader

Once the measurement is completed, the transmission data from the Eu-152 transmission measurement is used to provide the density correction for the emission data for each segment. This is the key advantage of the SGS measurement method for measuring radioactive waste and results in improved measurement accuracy and precision when compared to far field measurements of waste.

MEASUREMENT RESULTS

The SGS HPGe detector was calibrated using traceable point sources to provide both the energy scale and the detection efficiency calibration. The calibration was verified by performing repeated measurements using the same point sources. Eu-152 rod sources in four different 200-litre matrix drums were used for calibration validation. The measurement results are presented in Tables 1 to 6.

Table 1. Point source at the centre of an empty matrix.

Matrix Material	Measurement Time (min)	Reference Activity (Bq)	Measured Activity (Bq)	Deviation %
Empty	30	817000	8.13E+05	1.06%
Empty	30	817000	8.20E+05	1.93%
Empty	30	817000	8.05E+05	0.06%
Empty	30	817000	8.07E+05	0.31%
Empty	30	817000	8.08E+05	0.44%
Empty	30	817000	7.98E+05	-0.81%
Empty	30	3980000	3.94E+06	0.53%
Empty	30	3980000	4.02E+06	2.58%
Empty	30	3980000	3.97E+06	1.30%
Empty	30	3980000	3.98E+06	1.56%

Table 2. Eu-152 Rod Sources in an empty matrix.

Matrix Material	Measurement Time (min)	Reference Activity (Bq)	Measured Activity (Bq)	Deviation %
Empty	30	1754212	1.65E+06	-4.49%
Empty	30	1754212	1.64E+06	-5.07%
Empty	30	1754212	1.66E+06	-3.91%
Empty	60	1754212	1.61E+06	-6.81%
Empty	60	1754212	1.61E+06	-6.81%

Table 3. Eu-152 Rod Sources in a sawdust matrix.

Matrix Material	Measurement Time (min)	Reference Activity (Bq)	Measured Activity (Bq)	Deviation %
Sawdust	30	1754212	1.67E+06	-3.33%
Sawdust	30	1754212	1.69E+06	-2.18%
Sawdust	30	1754212	1.67E+06	-3.33%
Sawdust	60	1754212	1.67E+06	-3.33%
Sawdust	60	1754212	1.65E+06	-4.49%

Table 4. Eu-152 Rod Sources in a water matrix.

Matrix Material	Measurement Time (min)	Reference Activity (Bq)	Measured Activity (Bq)	Deviation %
Water	30	1754212	1.75E+06	1.30%
Water	30	1754212	1.80E+06	4.19%
Water	30	1754212	1.76E+06	1.88%
Water	60	1754212	1.78E+06	3.03%
Water	60	1754212	1.76E+06	1.88%

Table 5. Eu-152 Rod Sources in a sand matrix.

Matrix Material	Measurement Time (min)	Reference Activity (Bq)	Measured Activity (Bq)	Deviation %
Sand	30	1754212	1.57E+06	-9.12%
Sand	30	1754212	1.61E+06	-6.18%
Sand	30	1754212	1.67E+06	-3.33%
Sand	60	1754212	1.57E+06	-9.12%
Sand	60	1754212	1.60E+06	-7.39%

Table 6. Eu-152 Point Sources at different radial positions.

Source Position	Matrix Material	Measurement Time (min)	Reference Activity (Bq)	Measured Activity (Bq)	Deviation %
mid height tube 0	Sand	30	3910000	864000	-77.90%
mid height tube 1	Sand	30	3910000	2370000	-73.15%
mid height tube 3	Sand	30	3910000	7050000	-39.39%
mid height tube 6	Sand	30	3910000	1050000	80.31%
mid height tube 0	Water	30	3910000	1290000	-67.01%
Tubes 1-6	Water	30	1727592	1800000	4.19%

Once the SGS measurement is complete and all of the gamma ray spectra for the different segments (for both transmission and emission) have been recorded, the data analysis process takes place. Based on a traceable energy and efficiency calibration of the collimated HPGe detector, and using a pre-selected library of gamma ray data, the SGS analysis software determines the quantity of each selected radionuclide present in each segment of the waste drum. The analysis software determines the radioactivity content for the drum as a whole using the transmission corrected emission data obtained for each segment. On completion of the measurement, the drum rotation platform is moved using the slide rails to the load/unload position and the SGS is ready to receive the next waste drum.

Correct calibration of the SGS is an important aspect of ensuring that the SGS measurement process, whether for safeguards measurements or radioactive waste assay, produces accurate results. Typically the calibration process involves three stages. These include the HPGe detector calibration, calibration verification and finally calibration validation of the SGS instrument. The calibration is performed with the HPGe detector in its collimator and employs traceable point sources, which are calibrated and traceable to national standards and which cover the relevant energy range of SGS operation. Typically two point-sources, Am-241 with a lower energy gamma ray at 59.5 keV and Eu-152 with several gamma ray lines and a higher energy gamma ray at 1408 keV, are employed.

The calibration establishes the relationship for the HPGe detector of the energy scale and the detection efficiency for gamma rays of various energies. The calibration relates only to point sources and does not address SGS geometric factors and attenuation. Calibration verification involves repeating the measurement several times to confirm the reproducibility of the calibration. It must be performed with the same sources used in the calibration.

The third stage, the calibration validation, takes into consideration the geometric factors specific to the SGS measurement geometry and the transmission correction for matrix attenuation. It involves measurements with traceable calibrated sources, which are different from the sources employed in the previous two steps of the calibration process. Calibration validation measurements are best performed with sources that simulate a uniform distribution of activity and uniform matrix within a test drum so that the uniform source and matrix condition is met for each measured segment. This requirement can best be achieved using rod or line sources distributed appropriately in a rotating drum. Typically 6-rod sources of equal activity are placed in equal radial volumes of a rotating drum and spaced in an appropriate helical configuration. This configuration of rod sources provides a close approximation to a real radioactive drum with a uniformly distributed source. The total activity of the drum is the sum of the activities of the 6-rod sources.

It is sometimes necessary to use point sources in a drum for calibration validation. For higher density matrices the SGS assumptions are violated and the measured activity will be different from the correct activity in the drum. If the point source is near the centre of the drum the activity will be under reported. If it is located near the periphery of the drum the activity will be over reported. For a given matrix there will be a radial position where the measured point source activity will have the same value as an equivalent distributed source. MCNP modelling can be employed to establish correction factors relating point source activity to the equivalent distributed source activity.

The Mk3 SGS was calibrated in the manner described above. The traceable point calibration sources had an error in their calibration of about 3%. The calibration validation was performed using 6 calibrated Eu-152 rod sources, each of 80 cm in length placed in a helical array in 200 litre drums successively in four different matrices. The four uniformly distributed matrices with their densities (in units of $g{\cdot}cm^{-3}$) are: empty (air) 1.205E-03, sawdust 0.144, water 1.000 and sand 1.579.

The Calibration validation data for the Mk3 SGS is presented in Tables 2 to 5 for the four matrices of empty (air), sawdust, water and sand. The errors are generally as expected except for the empty matrix case. The larger error is due to source attenuation in the plastic material in which the rod sources are encapsulated and the plastic tube surrounding the rod sources. This additional attenuating material surrounding the rod sources violates the assumption of homogeneity across the segment and is therefore not adequately captured in the transmission correction for attenuation. This additional attenuation has only a very small influence on the measurements of higher density matrices where the resulting error is very small. The results of the other calibration validation measurements are as expected.

Measurements have also been made of point sources at the centre of an empty matrix and the results are tabulated in Table 1. Although the point sources violate the assumption of uniform source distribution, there is effectively no attenuation correction so the errors are small. This is not the case with the data in Table 6, however. Here the point sources have been placed in re-entrant tubes in a highly attenuating sand matrix. The tube positions range from tube 0 on the central axis of the drum to tube 6, which is near the periphery of the drum. As described earlier, the activity for the sources in the centre is significantly under reported and the effect decreases, as the source is re-positioned in tubes 1 and 3. When the source is positioned in tube 6 (near the periphery of the drum) the source activity is significantly over reported. In all of these cases the SGS assumption of uniform source distribution in each vertical segment is violated.

CONCLUSIONS

This paper describes the design features and presents data reporting the measurement performance of the ANTECH Mk3 SGS. The design features include an optimized detector collimator, which incorporates an automated integral tungsten filter of 20 mm thickness to reduce detector dead time for the measurement of higher activity drums. A significant source of background radiation during SGS emission measurements arises from the leakage of gamma rays through the transmission source shutter mechanism. The redesign of the transmission source shutter mechanism addresses this problem and significantly reduces the effect of background in the HPGe detector due to the transmission source. Dose-rate pre-scanning of the drum provides benefits to the measurement process. The information obtained from pre-scanning and the drum weight measurement is used to automatically control the deployment of the tungsten filter and the selection of drum segment size for the measurement. The operator may also select these parameters manually.

The calibration and operation of the Mk3 SGS has been confirmed by the validation measurements and very good agreement has been achieved between the reference and measured values of activity. The dangers of ignoring the basic assumptions of SGS measurements have also been demonstrated for the case of point sources in a highly attenuating matrix.

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