Development of a Wide Range Segmented Gamma Scanner for Measuring Radioactive Wastes Arising in the Chinese Nuclear Industry - 16261

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ABSTRACT

There is a requirement to measure a variety of challenging radioactive waste forms generated by the Chinese nuclear industry. These range from low activity waste to high activity waste with a high content of Cs-137 and waste in high density 200 litre drums. This paper describes the design, development and testing of an updated and automated Wide Range Segmented Gamma Scanner (WR-SGS) specifically configured for Chinese nuclear industry radioactive waste measuring requirements. 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, and separate lifting pillars to lift the detector and the transmission source. In place of a transmission source shutter mechanism, the source is placed in a shielded safe when not in use. The design also incorporates a variable aperture collimator, and tungsten filters that can be deployed for the measurement of high activity, high dose-rate drums. Updated motion control electronics, based on the use of a programed logic controller have been incorporated to address potential future obsolescence. The WR-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 WR-SGS for drums of different density. The measurement results have been compared with the reference decay corrected activity values and very good agreement is achieved, confirming the measurement performance of the instrument.

INTRODUCTION

A variant of the Wide Range Segmented Gamma Scanner (WR-SGS) optimised to meet the demanding requirements of radioactive waste measurement for the Nuclear Industry in China has been designed, built and tested with radioactive sources. As a comprehensive automated assay system for measuring radioactive waste in drums, the instrument incorporates many of the features of earlier ANTECH Wide Range SGS instruments, [1, 2, 3]. These WR-SGS instruments are in turn based on the original and widely used SGS instrument developed by Parker and Martin [4] at the Los Alamos National Laboratory.

The present instrument also includes improvements incorporated into the ANTECH Mark 3 SGS. These improvements, including a review of the basic principles and analysis algorithms of SGS operation have been reported recently [5]. The design concept for this variant of the WR-SGS is shown in Figure 1.

Fig. 1. Design concept view of the model G3251-200 WR-SGS configured for radioactive waste encountered in China.

The Wide Range SGS has been designed with a small footprint and with flexible low level roller conveyor access so that it can be easily deployed into existing radioactive waste measurement facilities in China and coupled to existing conveyor and waste handling systems. It includes a special design of compact electrically powered drum rotation mechanism built into a conveyor section in the measurement position, avoiding the need for special conveyor coupling mechanisms.

The instrument incorporates conventional features of the WR-SGS including a 40% efficient High Purity Germanium (HPGe) detector, which is electro-mechanically cooled, and a strong Eu-152 gamma ray transmission source with an intensity of 1.1 GBq (30 mCi) for determining the attenuation of high-density drums. Additional features include a variable aperture collimator, drum weight scale, Geiger-Muller detectors for drum dose-rate scanning and a separate lifting pillar for transmission source scanning and a transmission source safe to reduce the background dose-rate from the transmission source when it is not in use.

Radioactive waste drums in China can vary over a wide range of both drum density and activity with many drums having high surface dose-rates. Three of the features of the WR-SGS are important and relevant for radioactive waste measurements in China. First, the strong transmission source will allow heavy drums of higher density to be measured. Second, the variable aperture collimator (VAC), with a large aperture, will allow the instrument to make sensitive measurements of low activity drums. Third, the VAC, with a restricted aperture, can measure medium dose-rate drums and, by deploying one or more tungsten filters, measure high dose-rate drums.

DESIGN AND OPERATION

Figure 2 is a photograph of the fully assembled instrument prior to Factory Acceptance Testing. Although the design of the instrument has incorporated many features of other ANTECH WR-

SGS instruments, some design features are specific to the present system and make the instrument more suitable and relevant to measuring radioactive waste drums encountered in the Chinese nuclear industry.

One of these is the compact drum rotation platform incorporating powered conveyor rollers, load cells for measuring drum weight and an electrically powered drum rotation mechanism based on a cruciform. The cruciform is connected to an electric motor and guide mechanism, which lifts the drum clear of the rollers prior to rotating the drum.

Once drum rotation is complete, the cruciform is realigned with the rollers and lowered into a position that is recessed below the level of the rollers and the weight of the drum is taken on the rollers. The powered rollers of the instrument can then transfer the drum to either of the plant conveyor sections connected to the drum rotation platform. Figure 3 is a photograph of the drum rotation platform with conveyor rollers.

Important features of the WR-SGS are the compact size of the instrument as a whole and the narrow width and the relatively low height of the drum rotation platform incorporating conveyor rollers. These features facilitate the integration of the WR-SGS into existing radioactive waste facilities in China such as nuclear power plants and radioactive waste processing plants.

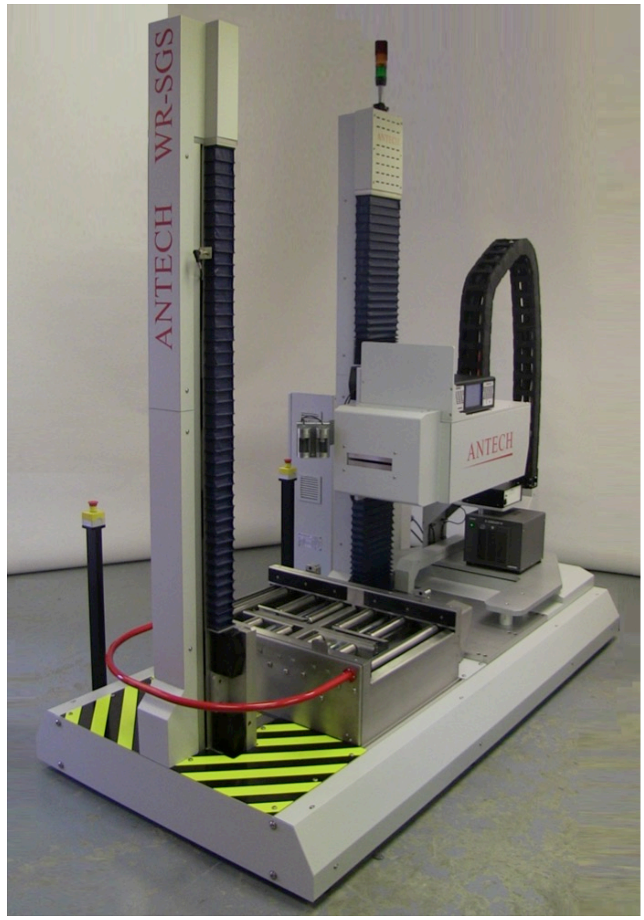

Fig. 2. Photograph of the ANTECH model G3251-200 WR-SGS prior to Factory Acceptance Testing.

The WR-SGS has been designed as a compact unit in order to fit into existing nuclear facilities in China. Due the constraint of limited facility space for the instrument and its small footprint, it is not possible to increase the drum detector separation as a means of reducing the detector dead time for high dose-rate drums. For this reason the variable aperture collimator has been re-designed to improve the shielding of the detector from off-axis sources and to incorporate the automated tungsten filters, which may be engaged to reduce detector dead time when measuring very high dose-rate drums. Significant tungsten filters with thicknesses of 10, 20, and 30 mm can be selected depending on the measured surface dose-rate of the drum.

A drum measurement sequence begins when a radioactive waste drum is transferred from one of the external conveyors on either side of the instrument to the rollers of the drum rotation platform. The rollers automatically position the drum to allow the rotation mechanism to raise the drum and begin rotation. Figure 3 is a photograph of the cruciform rotator. On the left of the photo, the top of the transmission source in the source safe storage position is visible.

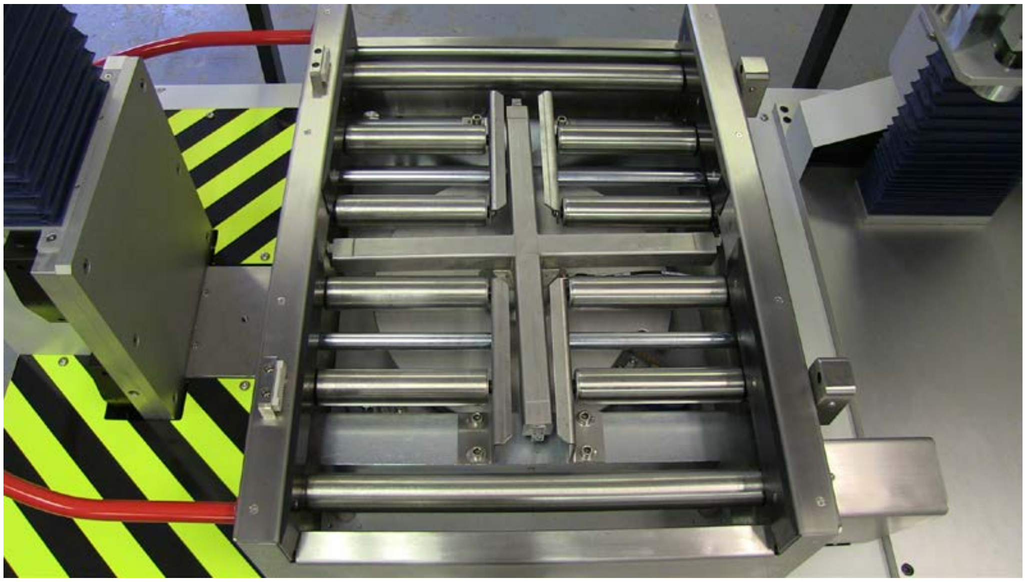

Fig. 3. The cruciform rotator and conveyor rollers are shown in the photograph.

Once the drum is loaded onto the rotator, the detector-lifting pillar moves the detector platform to perform a pre-scan of the drum using the shielded and collimated Geiger-Muller dose-rate detectors, which cover a wide range of possible drum surface dose-rates. The Geiger-Muller detectors are used to assess drum surface dose-rate during the pre-scan and the variable aperture collimator (VAC) are shown in Figure 4.

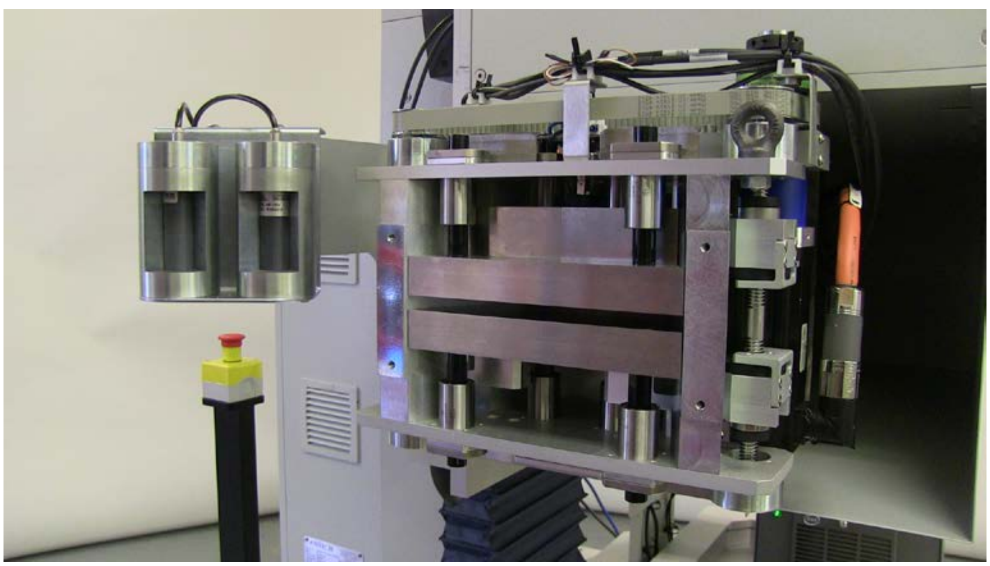

Fig. 4. The Geiger-Muller detectors and the variable aperture collimator (with guards removed) in the partially open position are shown in the photograph.

The instrument uses the measurement of drum weight and surface dose-rate to set automatically the measurement parameters. These include the collimator aperture, the deployment of filters if required and the segment size for drum transmission and emission measurement scanning.

Two helical scans are made of each drum in what is called two-pass mode. First a transmission measurement scan is performed in which the ORTEC™ 40% efficient HPGe detector and the Eu-152 transmission source are aligned in order to determine the drum density for each drum vertical segment. After the transmission scan is completed the transmission source is returned to the shielded transmission source safe.

The emission measurement scan is then performed using only the HPGe detector. Separate gamma ray spectra are obtained for each vertical segment of the drum for both transmission and emission scan measurements. The VAC may be used to select different segment heights for different drums depending on drum density and surface dose-rate. The total measurement time is typically 30 minutes, including the pre-scan. The drum measurement can take place in a completely automatic manner, or all of the measurement parameters can be set or adjusted by an operator.

The detector can be cooled by liquid nitrogen or, as in the present case, electro-mechanical detector cooling using an ORTEC™ X-Cooler-3 electro-mechanical cooler is employed.

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 filters, the movement of the platform rollers and the loading and unloading of drums from and to the external roller conveyers. 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.

The Wide Range SGS is controlled from a workstation, which is connected by an Ethernet link and a hard-wired Emergency Stop circuit. The Workstation can be local to the instrument or at a remote location if high dose-rate drums are being measured. Indicator lights on the Workstation and in a beacon on the transmission source-lifting pillar show the status of the instrument. The operation of the instrument is directed and monitored by a series of software screens displayed on the Workstation. Comprehensive analysis software is available to both display and analyse the measured gamma ray spectra in order to determine the radioactivity content of a waste drum.

The Wide Range SGS is designed to make accurate measurements of the radionuclide content of a wide variety of radioactive waste drums of varying drum density and surface dose-rate, including high activity drums used in the Chinese nuclear industry. At the lower end of the activity range the drums have surface dose-rates of significantly less than 2 mSv/h (200 mrem/h). At the higher range of activity, drums will have surface dose-rates of up to 50 mSv/h (5 rem/h) due to the high content of Cs-137.

The model G3251-200 WR-SGS, which is a variant of the ANTECH Wide Range SGS, provides an enhanced measurement capability, which is particularly applicable and suitable for measuring the wide range of radioactive waste found in China.

MEASUREMENT AND CALIBRATION PROCESS

A Eu-152 point source with multiple gamma ray energy peaks was employed to establish the detector energy and efficiency calibration for the ORTEC™ GEM-F7040P4 HPGe detector incorporated into the WR-SGS. The calibration source was mounted in a low attenuation plastic capsule and is traceable to international standards. The calibration was verified using repeated measurements with this same source to ensure that the results of the calibration measurement were reproducible.

The third stage to the calibration process involves validation measurements. These validation measurements confirm the correct functioning of all of the measurement components including the detector and collimator, the drum geometry and the attenuation correction incorporated into the analysis algorithms. In order to validate the measurement process simulated uniform density drums with different attenuating matrices were measured.

The measurement performance of the instrument has been determined by measuring a range of uniform density matrix drums containing a set of Eu-152 line or rod sources located in re-entrant tubes positioned on an equal volume basis within the drum. When rotated, the test drums with volume distributed line sources simulate waste drums of different density each with a uniformly distributed radioactive source. The results of the calibration validation measurements are reported in the next section.

MEASUREMENT RESULTS

Measurement data from the preliminary testing of the WR-SGS is included in TABLES I, II, III, IV and V. The result of the measurement of a Cs-137 point source in an empty drum is displayed in TABLE I. As there is no attenuation in the matrix, very good agreement is achieved between the measured and reference source activity.

TABLE I. Measurement of a Cs-137 point source located at the centre of an empty drum. The decay corrected activity of the source is 6.77E+05 Bq.

Run	Matrix Material	Drum weight (kg)	Measurement time (min)	Measured Cs-137 activity (Bq)	Variation from known activity (%)
FATPoint 1	Air	1.2	30	6.72E+05	-0.3%

Preliminary validation measurements using relatively low activity sources, a fixed collimator aperture of 50 mm and no filters were performed using four test drums with uniformly distributed matrices of air (empty), sawdust, water and dry sand. The same set of six-rod sources with a total activity of 1.70 x10^6 Bq (45.95 microCi) has been used for each measurement in the different matrix drums.

The six-rod sources were positioned in six re-entrant tubes distributed in each of the test drums. The spacing and location of the re-entrant tubes is such that each of the six-rod sources is located in an equal volume of the drum. As the drum is rotated, the detector sees the set of rod sources as a uniformly distributed source of equivalent activity to the sum of the activities of the six sources. The results of the validation measurements are tabulated in TABLES II to V.

TABLE II. Empty matrix measurements of 6 Eu-152 rod sources distributed in a rotating drum simulate a uniform source distribution. The equivalent matrix density is 1.205E-03 $g{\cdot}cm^{-3}$.

Run	Matrix Material	Drum weight (kg)	Measurement time (min)	Measured Eu-152 activity (Bq)	Variation from known activity (%)

AT3	Air	1.1	30	1.63E+06	-4.1%
AT4	Air	1.2	30	1.58E+06	-7.1%

TABLE III. Low-density measurements of 6 Eu-152 rod sources distributed in a rotating drum filled with a sawdust matrix simulate a uniform source and matrix distribution. The sawdust matrix density is 0.144 $g{\cdot}cm^{-3}$.

Run	Matrix Material	Drum weight (kg)	Measurement time (min)	Measured Eu-152 activity (Bq)	Variation from known activity (%)
AD10	Sawdust	28.9	30	1.57E+06	-7.6%
AD11	Sawdust	28.9	30	1.59E+06	-6.5%
AD12	Sawdust	28.9	30	1.60E+06	-5.9%

TABLE IV. Medium density measurements of 6 Eu-152 rod sources distributed in a rotating drum filled with a water matrix simulate a uniform source and matrix distribution with medium matrix attenuation. The water matrix density is 1.000 $g{\cdot}cm^{-3}$.

Run	Matrix Material	Drum weight (kg)	Measurement time (min)	Measured Eu-152 activity (Bq)	Variation from known activity (%)
ACNT2	Water	210.3	60	1.64E+06	-3.5%
ACNT3	Water	210.3	60	1.65E+06	-2.9%
AD4	Water	210.3	30	1.69E+06	-0.6%
AD5	Water	210.3	30	1.70E+06	0.0%
AD6	Water	210.3	30	1.68E+06	-1.2%
ADSh4	Water	210.3	15	1.63E+06	-4.1%
ADLo3	Water	210.3	75	1.65E+06	-2.9%
AD4Col10	Water	210.3	30	1.68E+06	-1.2%
FATWater	Water	213.2	30	1.73E+06	1.8%
FATWater2	Water	214.2	30	1.62E+06	-4.7%

TABLE V. Higher density measurements of 6 Eu-152 rod sources distributed in a rotating drum filled with sand simulate a uniform source and matrix distribution with higher matrix attenuation. The sand matrix density is 1.579 $g{\cdot}cm^{-3}$.

Run	Matrix Material	Drum weight (kg)	Measurement time (min)	Measured Eu-152 activity (Bq)	Variation from known activity (%)

AD8c2	Sand	318.4	90	1.67E+06	-1.8%
FATSand	Sand	321.5	30	1.73E+06	1.8%
FATSand3	Sand	321.4	30	1.75E+06	2.9%

Errors in the results for the rod source measurement data for the empty drum matrix in TABLE II and the data for the sawdust matrix in TABLE III are larger than one would expect. These larger errors are due to an uncorrected self-attenuation of about 6% in the rod sources for the 1408 keV gamma ray line from Eu-152. The rod sources are housed in a plastic material, which is 18 mm in diameter and which has approximately the same density and attenuation as the water matrix. This effect is not measured and corrected when the transmission correction measurement is made as it is localised to the rods.

In TABLES IV and V the drum weight varies by about 3 kg. This was a result of a revision in the tare weight of the measured drums for measurements made at a later time.

In the measurements reported in TABLES IV and V with matrices of water and sand the self-attenuation in the plastic of the rod sources is similar to the attenuation of the matrix materials, and is therefor corrected by the SGS analysis.

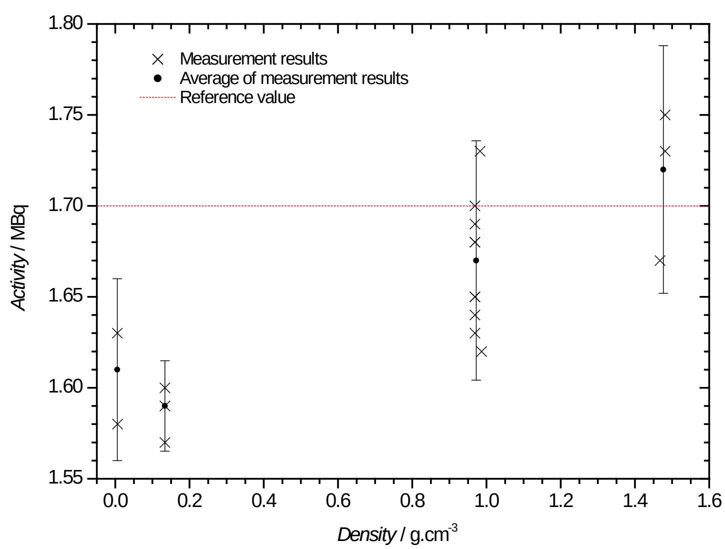

Fig. 5. Collective data from the measurements of the six-rod sources in the four different matrices.

The measured activities for the rod source measurements in the four different matrices are plotted as a function of matrix density in Figure 5. For comparison, a line indicates the reference total activity of the six sources of 1.70 $x10^6$ Bq (45.95 microCi). With the exceptions that have been discussed there is very good agreement between the measured and reference values.

CONCLUSIONS

A variant of the Wide Range Segmented Gamma Scanner (WR-SGS) optimised to meet the demanding requirements of radioactive waste measurement for the Nuclear Industry in China has been developed and preliminary tests have been carried out with calibrated radioactive sources, which are traceable to international standards. The instrument is applicable to both nuclear power stations and radioactive waste handling and processing facilities. The design incorporates features for measuring a wide range of both density and activity in drums from very low to relatively high activity with high surface dose rates.

In addition to standard features of the WR-SGS, such as the variable aperture collimator, helical drum scanning, shielded transmission source safe and pre-scanning of drums using a Geiger-Muller detector, the instrument incorporates a small footprint, low-height conveyor rollers and drum rotation platform and automatically deployable tungsten filters. These additional features allow the instrument to be integrated into and used in existing nuclear facilities where space is at a premium as well as in new nuclear facilities in China.

The intense Eu-152 gamma ray transmission source with an activity of 1.1 GBq (30 mCi) permits the attenuation and activity of high-density drums to be determined. A filter is deployed to reduce the source intensity when a transmission measurement is made of low-density drums. When the transmission source is in the safe during emission measurements, the source makes a negligible contribution to the radiation background allowing the instrument to make accurate measurements of very low activity drums. The combination of the variable aperture collimator and the integrated tungsten filters also allows the instrument to be used to measure high dose-rate drums containing both activation and fission products, which are commonly found in radioactive waste in China.

The instrument has been tested at the lower end of the activity range corresponding to equivalent drum surface dose-rates of a few micro-Sv/h. Very good agreement has been obtained between the known and measured activities of the sources in the test drums for a variety of different homogeneous matrices of different densities. The measurements confirm both the correct operation of the instrument as well as its applicability to a wide range of radioactive waste measurement applications.

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