Design and Performance Testing of a Novel Far Field Gamma System to Assay Radioactive Waste in 400 and 200 litre Drums -15339

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ABSTRACT

A Far Field Gamma ray Measurement system has been developed for measuring and assaying both 400 and 200 litre waste drums with a wide range of activity at nuclear power stations. These include radioactive waste drums with surface dose-rates of less than 2 mSv/h (200 mrem/h) and, at the higher range of activity, 400 litre drums with surface dose-rates of up to 50 mSv/h (5 rem/h). The assay system incorporates an electromechanically cooled high purity Germanium profile detector and advanced digital spectroscopic analysis electronics. A novel optimised conical-trapezoidal collimator has been incorporated to reduce the effect of the radioactive background in addition to the conventional detector lead shield with tin and copper graded lining to reduce the effect of lead X-rays. Two features have been incorporated to reduce detector dead time and maintain detector resolution when measuring high activity drums. The first is the inclusion of two automated tungsten filters of different thickness as an integral part of the detector collimator. The filters are used in conjunction with an automated rail system on which the detector platform is mounted. The detector can be positioned at different distances from the drum surface in order to reduce detector dead time. The deployment of the filters and the adjustment of the drum – detector position are automatically controlled based on a user defined dose-rate limit table. The data is provided by two Geiger-Muller dose-rate detectors, which are used to measure the drum surface dose-rate. This data is subsequently used to adjust the detector position and in cases of higher dose-rate deploy one or other of the tungsten filters. The drum rotation platform incorporates a load cell to determine drum weight and hence the drum density. This information is used to calculate an attenuation correction based on the assumption of uniform drum density and uniform distribution of activity within the drum. Where the waste drums have a more complicated and known regular internal structure, such as a small radioactive region surrounded by an annulus of shielding material, the analysis algorithms incorporated into the far field geometry and attenuation correction spectroscopic data analysis code are able to make a more accurate determination of drum activity than would be possible assuming a completely uniform drum. The detector energy and efficiency calibration is achieved using a point source with multiple gamma ray energy peaks. The response of the high purity Germanium detector is also modelled using the Monte Carlo Neutron Photon code and the model is benchmarked using the measured point source calibration data. The performance of the instrument has been determined for 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. When rotated, the test drums with volume distributed line sources simulate waste drums of different density each with a uniformly distributed radioactive source. The measurements have been validated using Monte Carlo simulations.

INTRODUCTION

The ANTECH Model G3620-400 Far Field Gamma Monitor (FFGM) is a far field waste assay instrument for gamma ray spectroscopic measurements of the radionuclide content of both 200 and 400 litre drums containing radioactive waste. The Far Field measurement process is sometimes referred to as a “one shot measurement”. The measurement instrument employs the Far Field measurement protocol where the entire drum is in the field of view of the detector. The drum is weighed by a load cell built into the rotation platform at the start of the measurement to determine the average drum density. During the measurement the drum is rotated while a single gamma ray spectrum is obtained by a high purity Germanium (HPGe) spectroscopic detector.

The two important assumptions of the Far Field measurement process are that the matrix material in the drum is uniform - of a constant density and composition and that the radioactivity being measured is uniformly distributed throughout the drum. As long as these assumptions of homogeneity are observed in general and the deviations are not great, measurement errors will not be large. Rotating the drum helps to reduce the error that would arise if a drum has radial in-homogeneity in either the matrix or the distribution of radioactivity.

A Far Field Gamma ray Measurement system has been developed for nuclear power stations for measuring and assaying radioactive waste drums with a wide range of activity including both very low activity and relatively high activity. These include 400 and 200 litre drums with surface dose-rates of significantly less than 2 mSv/h (200 mrem/h) and, at the higher range of activity, 400 litre drums with surface dose-rates of up to 50 mSv/h (5 rem/h). An artist concept drawing of the model G3620-400 Far Field Gamma Monitor is shown in Fig. 1.

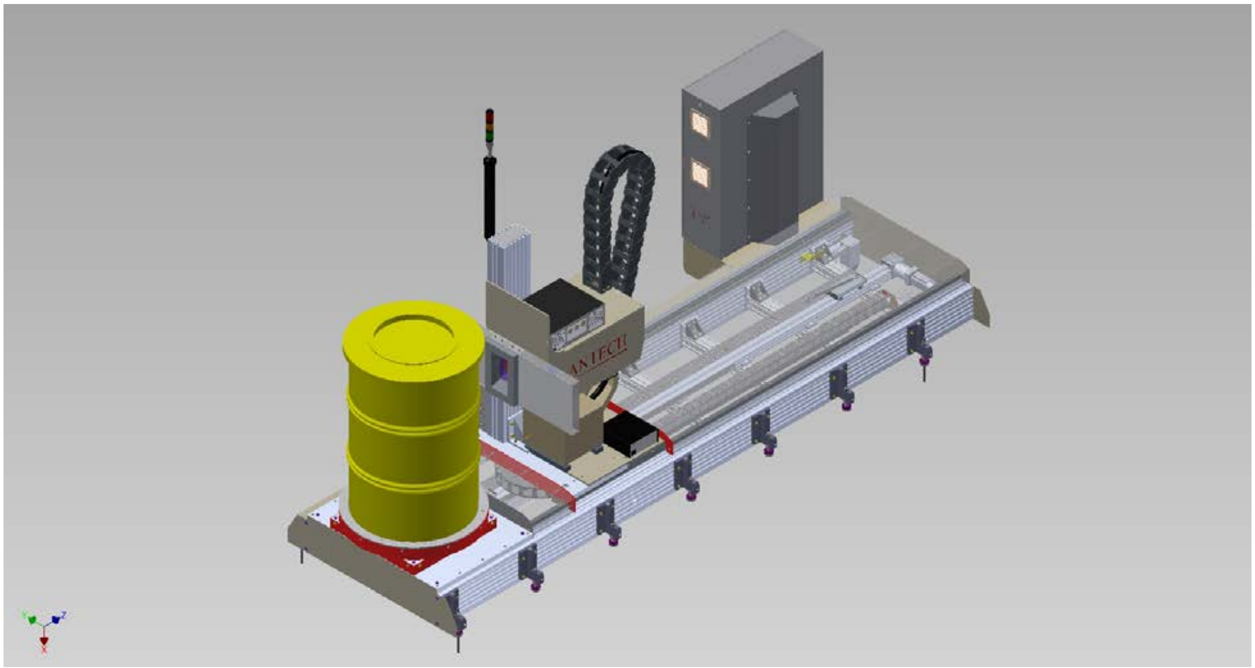

Fig. 1. Artist concept view of the model G3620-400 Far Field Gamma Monitor.

The far field gamma ray measurement method is widely used in radioactive waste assay for a variety of waste containers including both drums as well as rectangular objects such as waste boxes. Examples of the application of the technique to other waste measurements are provided in references [1,2], which describe far field measurements of both radioactive waste drums and

B-25 waste boxes.

Figure 2 is a photograph of the model G3620-400 Far Field Gamma Monitor. In the photograph a number of components of the instrument can be seen including the HPGe detector electromechanical cooler, detector collimator, tungsten filters incorporated into the collimator assembly, detector pillar, detector horizontal axis of motion (to the rear of the pillar), Geiger-Muller (G-M) detectors for surface dose-rate determination and a test drum on the rotation platform. The instrumentation cabinet containing the motion control electronics and programmed logic controller (PLC) is to the left rear of the photograph.

Fig. 2. Photograph of the model G3620-400 Far Field Gamma Monitor.

DESIGN

The assay system incorporates an electromechanically cooled ORTEC™ high purity Germanium (HPGe) profile detector with 40% detection efficiency and advanced digital spectroscopic analysis electronics based on the DSPEC-50. The HPGe detector is housed in a stainless steel encased lead shield with a shielding thickness of 50 mm and with a tin and copper graded lining to reduce the effect of lead X-rays. A novel optimised conical-trapezoidal collimator has been incorporated to reduce the effect of the radioactive background during drum measurements. The drum rotation platform includes a load cell to determine drum weight and hence the drum density.

Two features have been incorporated to reduce detector dead time and maintain detector resolution when measuring high activity drums. The first is the inclusion of two automated tungsten filters of different thickness as an integral part of the detector conical-trapezoidal collimator. The second is an automated rail system on which the detector platform is mounted. The detector can be positioned at different distances from the drum surface in order to reduce detector dead time. In operation the first option is to move the detector and increase the detector – waste drum distance, as this method of dose-rate reduction does not degrade the low energy portion of the gamma ray spectrum.

The deployment of the filters and the adjustment of the drum – detector position are controlled by two Geiger-Muller (G-M) dose-rate detectors. Two G-M detectors are employed to cover a wide dose-rate range and they are used to measure the drum surface dose-rate. For a high dose-rate drum and in response to the signal from the G-M detectors, the software will check the user-defined table of dose-rates and corresponding detector positions and filter deployments. Based on the data in the table and the measured dose-rates the system will adjust the detector position and increase the drum – detector distance if required. In cases of even higher dose-rate and if the distance adjustment is insufficient to reduce adequately the detector dead time, the system will deploy one or other of the tungsten filters.

MEASUREMENT AND DATA ANALYSIS PROCESS

In Far Field measurements of radioactive waste drums the input data is the drum weight and a single gamma ray spectrum measured by a detector whose field of view is the entire drum envelope. The Far Field geometry analysis algorithms have to assume that every volume element (often referred to as a voxel) in a drum has the same activity and matrix density. A constant density results in each voxel having the same gamma ray attenuation. In the analysis process, the activity contribution or amount of radioactivity in each voxel is summed (taking into consideration matrix attenuation) to calculate the total activity in the drum.

The FFGM employs the ANTECH ISOCorr™ far field geometry spectroscopic analysis code, which operates in conjunction with the ORTEC spectroscopy analysis code GammaVision™. ISOCorr is functionally equivalent to other Far Field analysis codes such as ISOCS™, ISOTOPIC™ and SNAP™. Although detailed implementations differ, the operation of all of these codes is based on the assumptions stated in the previous paragraph.

The activity summation in the Far Field method using ISOCorr takes into consideration the attenuation or reduction in the gamma ray signal from each voxel resulting from gamma ray absorption. Gamma ray absorption takes place as gamma rays arising in a voxel pass through other voxels as they travel to and are detected in the HPGe detector. Therefore, for a given gamma ray count rate in the detector, the Far Field measurement process will estimate a higher activity per voxel to take into consideration the gamma ray attenuation of the drum matrix materials. Assuming a given count rate in the HPGe detector, the measurement process will estimate an increasing activity per voxel as the drum density increases. Accurate measurements will be produced if the waste drums meet the assumptions mentioned earlier. Errors will arise if the assumptions are not met. Two simple examples illustrate this point:

- If the fill height is not correct and the drum is not full, the analysis process will under-estimate the activity in the drum, as it will have assumed that there are more voxels containing activity than the actual number of voxels with activity. It will also underestimate the density and as a result the gamma ray absorption.

- The opposite error can arise and the activity in a drum may be over-estimated if, instead of a distributed source, the drum contains a point source. Again in this case the error increases as the drum density increases. This effect is due to the incorrect compensation for absorption of gamma rays throughout the drum volume. Measurement errors as large as a factor of 10 (1,000%) may arise due to the non-uniform distribution of activity in a radioactive waste drum.

The model G3620-400 Far Field Gamma Monitor provides accurate measurement results when used correctly and when the measurement assumptions are valid. It provides high sensitivity with low minimum detectable activity (MDA) and short measurement times. The instrument has a relevance to the measurement of radioactive waste in a wide variety of applications. It is particularly applicable to high activity waste and it is also an accurate and sensitive measurement instrument for measuring low density, low activity radioactive waste.

Where the waste drums have a more complicated and known regular internal structure, such as a small radioactive region surrounded by an annulus of shielding material, the analysis algorithms incorporated into the ISOCorr geometry and attenuation correction code are able to make a more accurate determination of drum activity than would be possible assuming a completely uniform drum. To use this feature the internal geometry of the drum must be known and the geometry data and material information must be entered in the container set-up configuration screen of the Far Field Gamma Monitor Software.

MEASUREMENT RESULTS

An Eu-152 calibration point source (traceable to international standards) 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 FFGM. The response of the HPGe detector was also modelled using the MCNP Monte Carlo code and the model was benchmarked using the measured point source calibration data.

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 measurements have been validated using benchmarked MCNP simulations.

Measurement data from extensive testing of the Far Field Gamma Monitor is included in TABLES I, II, III and IV. Tests were performed using the 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 1.93 $x10^6$ Bq (52.16 microCi) has been used for each measurement. The six-rod sources are 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.

Measurements of each matrix containing the rod sources have been made at three different positions of drum – detector separation of 40.4, 140.4 and 240.4 cm. In the data tables (detector position column) these positions are referred to as “Front”, “Middle” and “Back”.

The Far Field Gamma Monitor is fitted with three configurations of tungsten filter to reduce the dose-rate seen by the HPGe detector. These are:

- No filter.
- 15 mm tungsten filter.
- 30 mm tungsten filter for the highest activity drums

Measurements for all possible configurations (3 detector positions, 4 matrix drum types, 3 filter configurations) numbering 36 in total have been included in the testing. The data is displayed grouped by matrix type, drum detector distance and filter configuration. The column entitled “Variation” reports the difference of the measured activity value from the total activity of the six-rod sources of 1.93 x10^6 Bq.

Note that the differences between the measured and declared values are small and most errors are well below 10%. Measurements of higher density matrices with filters have poorer counting statistics, which results in larger variations. This effect can be seen in some of the measurement results for the water and sand matrices. In reality, the filters will only be used where the count rates are high so poor counting statics will not occur in normal operation with the filters.

The slightly higher errors associated with the sawdust matrix are due, we believe, to variations in density of the matrix and moisture content within the matrix.

Overall, excellent agreement has been achieved between the calibrated rod source total activity and the measured total activity in the four test matrices measured in different positions. These measurements demonstrate that the Far Field Gamma Monitor is operating correctly and producing accurate results over a wide range of matrix density and source strength.

TABLE I. Empty Drum Measurement Data

Run	Measurement			Container		Measurement Results			
	Detector Position	**Filter**	**Drum Matrix**	**IsoCorr Matrix Density g/cc**	**Stand off Distance cm**	**Net count in peak**	**Net count in peak Uncertainty %**	**Reported Corrected Activity Bq**	**Variation (Difference from Total Rod Activity of 1.93x10^6 Bq)**
NC2	Front	None	Empty	0.001	40.4	12575	0.94	1863000	-3.47%
NC20	Front	15mm	Empty	0.002	40.4	8492	1.14	1944000	0.73%
NC21	Front	30mm	Empty	0.002	40.4	3862	1.67	2069000	7.20%
NC1	Middle	None	Empty	0.001	140.4	5104	1.45	1926000	-0.21%
NC34	Middle	15mm	Empty	0.002	140.4	1827	2.37	1936000	0.31%
NC35	Middle	30mm	Empty	0.002	140.4	442	4.9	1984000	2.80%
NC14	Back	None	Empty	0.002	240.4	3081	1.86	1880000	-2.59%
NC36	Back	15mm	Empty	0.002	240.4	747	3.75	1899000	-1.61%
NC37	Back	30mm	Empty	0.002	240.4	185	8	1959000	1.50%

TABLE II. Sawdust Drum Measurement Data

Run	Measurement			Container		Measurement Results			
	Detector Position	Filter	Drum Matrix	IsoCorr Matrix Density g/cc	Stand off Distance cm	Net count in peak	Net count in peak Uncertainty %	Reported Corrected Activity Bq	Variation (Difference from Total Rod Activity of 1.93x10^6 Bq)
NC16	Front	None	Sawdust	0.122	40.4	10373	1.03	1953000	1.19%
NC19	Front	15mm	Sawdust	0.125	40.4	7120	1.25	2096000	8.60%
NC40	Front	30mm	Sawdust	0.125	40.4	3229	1.83	2237000	15.91%
NC17	Middle	None	Sawdust	0.125	140.4	4277	1.59	2073000	7.41%
NC73	Middle	None	Sawdust	0.126	140.4	6543	1.28	2118000	9.74%
NC43	Middle	15mm	Sawdust	0.125	140.4	3133	1.87	2135000	10.62%
NC45	Middle	30mm	Sawdust	0.125	140.4	796	3.54	2298000	19.07%
NC18	Back	None	Sawdust	0.125	240.4	2658	1.99	2090000	8.29%
NC47	Back	15mm	Sawdust	0.125	240.4	636	4.09	2084000	7.98%
NC44	Back	30mm	Sawdust	0.125	240.4	292	5.85	1999000	3.58%

TABLE III. Water Drum Measurement Data

Run	Measurement			Container		Measurement Results			
	Detector Position	Filter	Drum Matrix	IsoCorr Matrix Density g/cc	Stand off Distance cm	Net count in peak	Net count in peak Uncertainty %	Reported Corrected Activity Bq	Variation (Difference from Total Rod Activity of 1.93x10^6 Bq)
NC9	Front	None	Water	1.003	40.4	13388	0.9	1803000	-6.58%
NC54	Front	15mm	Water	1.003	40.4	2973	1.87	1928000	-0.10%
NC55	Front	30mm	Water	1.003	40.4	598	4.24	1861000	-3.58%
NC10	Middle	None	Water	1.003	140.4	2675	1.95	1923000	-0.36%
NC56	Middle	15mm	Water	1.003	140.4	639	3.96	1946000	0.83%
NC65	Middle	30mm	Water	1.003	140.4	150	8.16	1939000	0.47%
NC11	Back	None	Water	1.003	240.4	1073	3.05	1911000	-0.98%
NC58	Back	15mm	Water	1.003	240.4	226	6.65	1681000	-12.90%
NC59	Back	30mm	Water	1.003	240.4	72	11.79	2237000	15.91%

TABLE IV. Sand Drum Measurement Data

Run	Measurement			Container		Measurement Results			
	Detector Position	**Filter**	**Drum Matrix**	**IsoCorr Matrix Density g/cc**	**Stand off Distance cm**	**Net count in peak**	**Net count in peak Uncertainty %**	**Reported Corrected Activity Bq**	**Variation (Difference from Total Rod Activity of 1.93x10^6 Bq)**
RepSand 7	Front	None	Sand	1.584	40.4	5218	1.45	1778000	-7.88%
NC8	Front	15mm	Sand	1.584	40.4	2292	2.15	1888000	-2.18%
NC53	Front	30mm	Sand	1.584	40.4	484	4.7	1915000	-0.78%
NC3	Middle	None	Sand	1.585	140.4	2129	2.21	1986000	2.90%
NC29	Middle	15mm	Sand	1.584	140.4	497	4.66	1962000	1.66%
NC30	Middle	30mm	Sand	1.584	140.4	113	9.41	1893000	-1.92%
NC7	Back	None	Sand	1.584	240.4	817	3.5	1902000	-1.45%
NC52	Back	15mm	Sand	1.584	240.4	188	7.29	1826000	-5.39%
NC31	Back	30mm	Sand	1.585	240.4	61	12.8	2476000	28.29%

CONCLUSIONS

This paper describes the design of a new Far Field Gamma Monitor with several novel features. The instrument has been designed, built and tested with calibrated radioactive sources, which are traceable to international standards. The instrument incorporates a novel conical-trapezoidal collimator to reduce background and both detector movement and tungsten filters to extend the range of measurements to include high dose-rate drums. Adjustment of the detector – drum separation and the deployment of filters is automatically controlled in response to dose-rate measurements made by Geiger-Muller detectors.

Calibrated and uniformly distributed rod sources employing Eu-152 have been constructed and positioned in test drums in an appropriate geometric configuration so that when the drums are rotated, the rod sources simulate uniformly distributed sources within the drums. Four different drum matrix materials, covering a range of densities have been employed in the performance testing of the FFGM using the rod sources.

The limitations of the Far Field measurement method, based on the necessary assumptions of homogeneity of density and source distribution, have been emphasized. Measurement results have been presented for measurements of a range of drum matrices, detector - drum positions and filter deployments. Excellent agreement has been obtained between the known and measured activities of the sources in the test drums.

The measurements confirm both the correct operation of the instrument as well as its applicability to a wide range of radioactive waste measurement applications. The measurements have been validated through comparison with benchmarked MCNP calculations.

REFERENCES

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