Measurement and Analysis of Fuel Element Debris (FED) from the Hinkley Point A Magnox Reactor - 25559

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ABSTRACT

In the UK, the first generation of nuclear power reactors employed natural uranium metal fuel, clad in Magnox, an alloy of magnesium with small amounts of aluminium and other metals. The Magnox cladding of the unenriched uranium metal fuel provided a non-oxidizing covering to contain fission products deposited in the reactor fuel during operation. These so-called Magnox reactors were graphite moderated and CO2 cooled. All Magnox reactors have ceased operation and are now in decommissioning. An early aspect of the decommissioning process involved stripping the Magnox cladding from the natural uranium fuel rods. The uranium fuel rods were transported to Sellafield for reprocessing and the Magnox cladding and other fuel element hardware, known collectively as Fuel Element Debris (FED), was deposited in concrete vaults for later recovery. That recovery process is now underway and involves the requirement to measure the FED, which at Hinkley Point A is stored in 210 litre drums. This paper describes the High Resolution Gamma Spectrometry (HRGS) Drum Assay System installed at the NRS (Nuclear Remediation Services) Hinkley Point A Site for the measurement of 210 litre drums of intermediate level waste (ILW) FED prior to compaction of each drum. FED is a mixture containing Magnox metal, very small pieces of uranium fuel and nimonic springs. The nimonic springs contain high levels of Co-60 as a result of neutron capture by Co-59 in the springs during reactor operation and resulting in high dose rates in the FED. The Drum Assay System is installed in a shielded cell in the Concrete Box Loading Facility (CBLF) and integrated into the CBLF conveyor and plant control system. The mechanical and electrical design, barcode reader, position sensors, safety circuit and control system of the Drum Assay System ensure safe remote operation inside the shielded cell. To cope with the range of FED activities required, the system was fitted with a variable aperture collimator (VAC) with integrated tungsten filters, and a laser position sensor to check the width of the open aperture. This position sensing feature has enabled outstanding measurement performance for both high and low activity drums and delivered a low minimal detectable activity for Cs-137 in the presence of high Co-60 backgrounds. The Drum Assay System measures and processes the data and exports the results to the plant waste tracking and package records database. The paper incorporates design information for the various system components as well as factory acceptance test (FAT) data for the performance of the system.

INTRODUCTION

The first generation of Nuclear Power Stations (NPS) in the UK, employed Magnox reactors. These reactors served the country well and are now all in decommissioning after many years of electric power generation. Employing natural uranium metal fuel and clad in Magnox, an alloy of magnesium and aluminium, the 'Magnox' reactors were graphite moderated and CO2 cooled. Fission products produced during reactor operation were deposited in the uranium metal fuel and the Magnox cladding.

The initial phase of the decommissioning process involved stripping the Magnox cladding from the natural uranium metal fuel rods. The uranium fuel rods were then transported to Sellafield for reprocessing and the Magnox cladding and other fuel element hardware, known collectively as Fuel Element Debris (FED), was deposited in concrete vaults for later recovery. The FED in addition to Magnox fuel cladding, includes some pieces of broken uranium fuel as well as nimonic springs containing significant quantities of Co-60. The dominant gamma ray signal is from the fission product Cs-137 in the fuel and cladding.

At Hinkley Point A (HPA) Magnox Nuclear Power Station, the decommissioning process includes the recovery and measurement of Magnox FED originally stored in the concrete vaults on site since defueling and the shipment of uranium fuel rods to Sellafield. This involves the requirement to measure the FED, which at HPA, is currently stored in 210 litre drums.

The HPA specification for the project required that the instrument for the assay of FED must be capable of performing measurements of FED contained in 210 litre drums subject to strict conditions. These include having sufficient accuracy and resolution that both the Cs-137 and Co-60 inventory can be determined for each drum in the presence of a very high dose-rate from the nimonic springs containing significant quantities of Co-60. A detection limit of less than 2 GBq of uniformly distributed Cs-137 must be achieved for a drum in the presence of 50 GBq of Co-60.

ANTECH have considerable experience both working with NRS (formerly Magnox Limited) and designing and supplying FED measurement solutions. These include two FED assay systems at Trawsfynydd NPS, (NFEDER and SFEDER), [1] and a FED assay system at Berkeley NPS. With this experience, ANTECH was selected by Magnox to supply the FED measurement system for HPA.

Working together with NRS physics and design staff and based on the technical scope and measurement requirements, three potential options of measurement technologies to achieve the stated measurement requirements have been considered. These included the Open Detector method (OD), the Segmented Gamma Scanning (SGS) method and finally the Wide Range-SGS (WR-SGS) method.

In the Open Detector method (open detector geometry), all parts of the waste package or drum contribute to the response of the detector. In other words, the field of view of the detector crystal, or part of the detector crystal if a shadow shield is used, includes the whole of the drum. This is the most common method employed for radioactive waste drum assay. In the SGS method [2] the drum is measured in fixed height horizontal segments, and this may require the detector to be partially shadow shielded. (Note that by definition, an SGS [3] employs a transmission source for density correction although, due to the homogeneity of the FED and gravel matrices, a transmission source is not included in the current design for HPA). The WR-SGS [4] is a variant of the SGS and employs a Variable Aperture Collimator (VAC). This is a useful feature allowing different sized segments to be measured. This may be required to compensate for widely different count rates (gamma ray fluxes) across a drum and brings flexibility to the design.

FED MEASUREMENT OPTIONS

All three potential methods (options) provide acceptable results based on the preliminary modelling analysis that had been performed using a somewhat arbitrary choice of parameters. The OD Method provides acceptable results but with the least measurement flexibility. The preliminary analysis suggested that for drums of Co-60 greater than 51 GBq, a tungsten filter will be required to reduce the dose. If a filter were introduced to overcome the case of a drum with more than 50 GBq of Co-60, then the Minimum Detectable Activity (MDA) would increase by about a factor of 10. With the OD (Far Field) method it is not possible to differentiate between a fuel fragment and a uniform distribution of contamination in the drum.

In addition to measurements of FED, there is an additional requirement to measure drums of contaminated gravel, whose characteristics were provided by NRS. The measurement of these 196 litre radioactive retrieved gravel drums could be improved through the implementation of a different collimator and the repositioning of the detector in relation to the drum instead of an OD measurement.

Of the segmented methods, the SGS (fixed 5mm rectangular aperture at 1m from the drum and without transmission source) provides adequate results but does not provide a significant improvement over the OD method (fixed 2.7cm circular aperture at 3m from the drum). The restriction of the efficiency to cope with the worst-case drum, limits the low activity detection performance. The segment-by-segment analysis allows for the identification of a fuel fragment if present in a FED drum. It also provides an additional activity factor in that it will cope with drums of up to 70 GBq without the use of a tungsten filter. A practical benefit is that the footprint of the instrument is much reduced as the distance between the detector and the drum is decreased.

The WR-SGS variant (variable aperture and without transmission source) has the same advantages as the SGS but has superior performance compared to the Open Detector method for both lower activity FED drums and radioactive gravel drums as a result of the variable aperture capability. Key performance differences are listed in Table 1, below.

Table I: Summary of Differences in Performance between Open Detector (Far Field) and WR-SGS Measurement Methods.

No.	**Measurement Description**	**Open Detector**	**WR-SGS**
1	Maximum Co-60 activity for dead-time less than 60% for FED drums (0.35 g·cm^{-3})	51 GBq	70 GBq (with 5 mm opening)
2	Minimum total assay time to achieve a counting accuracy of better than 5% for FED drums with less active nimonic springs (Co-60 activity of 0.0125 GBq)	4 minutes	0.21 minutes (with 40 mm opening)
3	Minimum Detectable Activity of Cs-137 in presence of 50 GBq of Co-60 in a FED drum	9.66 MBq	18.3 MBq (with 5 mm opening)
4	Normalised Detection Efficiency for Cs-137 in a drum with gravel matrix (2.5 g·cm^{-3})	1	19.4 (with 40 mm opening)

Assessment of the comparison data presented in Table 1:

1. Both assay systems (Open Detector and WR-SGS) have been designed to meet the specification of a dead-time of less than 60% in the presence of 50 GBq of Co-60, in the high activity FED drums. The maximum count rate is kept below 100,000 s^{-1}.

2. The use of a rapid pre-scan in the WR-SGS method slightly increases the total measurement time but allows for the choice of alternate aperture or segment size. This is important for the older lower activity FED drums (0.0125 GBq Co-60 content) and the higher density radioactive gravel drums. It will also be relevant for some of the high activity FED drums (nominal 50 GBq Co-60) where, following a pre-scan, some of these drums can be measured with a larger aperture (segment size) with lower MDA or consequently shorter measurement time where the count rate is high enough.

3. The required detection limit is 2 GBq of Cs-137, which is about 100 times larger than calculated values. Both assay systems are so sensitive to Cs-137 and relatively immune to Co-60 that the total assay time can be reduced to 10-15 minutes, while maintaining very low MDA values for Cs-137. See also the note above.

4. In the absence of expected values of the Cs-137 activity inside the gravel drums, the normalised detection efficiency is used for comparing the two assay methods. It is clear that significantly shorter measurement times can be achieved using the WR-SGS measurement method for radioactive gravel drum measurements.

As a result of the preliminary analysis, it was concluded that an instrument based on either Open Detector technology or WR-SGS technology would meet the requirement of the specification. However, the choice of the WR-SGS technology (excluding the transmission source) brings several advantages. These include flexibility to adapt the performance should circumstances change, shorter measurement times for lower activity FED drums and radioactive gravel drums based on greater sensitivity, higher dose-rate tolerance without the use of filters and optimisation of measurements following a pre-scan. In consultation with physics staff from NRS, the WR-SGS (without transmission source) was chosen to achieve greater measurement flexibility. A further advantage is that this choice facilitates further measurement optimisation including reduction in measurement times for the high Co-60 (nominal 50 GBq) FED drums.

MODELLING THE WR-SGS OPTION

Modelling for the detailed design and analysis of the WR-SGS option is based on the same MCNP (5) modelling process that was employed to consider the original three measurement methods. The model assumes a 40% HPGe detector contained in a lead shield with the collimator in front of the detector. The model has the drum surface 1 m away from the front face of the HPGe detector and the detector collimator has a 5 mm aperture and a length of 119 mm so that the detector views the drum in 16 segments. The detector collimator position will be assumed to be accurate to within 0.25 mm (5% at the narrowest opening of 5 mm).

With the detector aligned on the first drum segment (bottom of the drum), an initial problem considered in the model was the significant dose rate seen by the detector through the collimator shield arising from FED at the top of the drum. The reciprocal problem exists with the detector positioned to see the top of the drum. An enhanced tungsten shield of 50mm thickness was added to the model to reduce the dose rate seen by the detector when viewing the drum from a position aligned at or near the bottom of the drum and at or near the top of the drum. Figure 1 compares the spectrum integral detection efficiency (counts of any energy measured by the detector) arising from each segment with the detector placed at the bottom segment (No. 1). The figure shows the results for calculations both for standard shielding and the enhanced shielding.

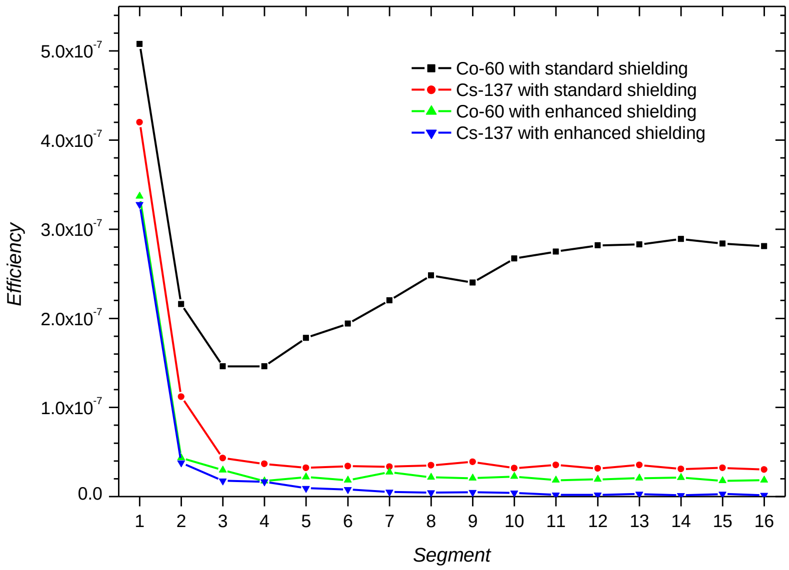

Fig. 1. Spectrum Integral detection efficiency for Co-60 and Cs-137 volume segments (1/16th height of the drum) with the detector placed at the bottom segment (Segment 1). The Co-60 activity in one volume segment is equal to 3.125 GBq. The Co-60 activity for the whole drum is 50 GBq. The density of the FED matrix is equal to 0.35 $g \cdot cm^{-3}$.

It can be seen in Figure 1 that the enhanced shielding is necessary and in a practical design it may need to be increased. In the preliminary design the tungsten filter has also been included to address the possibility of a statistically unlikely concentration of several nimonic springs near the surface of the drum and effectively contributing counts to a single segment. The detection efficiencies for Co-60 and Cs-137 have been calculated for the preliminary model both with and without the tungsten filter deployed.

In the end the use of the enhanced tungsten shield was avoided by recessing the detector into the lead shield to provide an appropriate reduction of the dose rate seen by the detector when positioned at or near the ends of the drum. This avoided a redesign of the variable aperture collimator saving both cost and project time.

The MCNP model has been used to calculate a large number of characteristics of the system as a function of the input count rate, the effective segment height (VAC aperture), FED density and other parameters, including enhanced shielding. Tables of these characteristics have been calculated which confirm the operating characteristics of the HPA FED assay system over a wide range of operating conditions. The sample list of the parameters calculated with the MCNP model and some of the results are as follows:

1. Minimum Detectable Activities for relevant radionuclides, including Am-241 and Eu-154. The MDAs vary for different collimator openings.
2. Recommendations on the VAC aperture size (number of segments selected) for given operating conditions, for example the provisional recommendation from calculations are 3, 8, 20 & 50 mm. The 3mm opening will require 24 segments. The 8mm opening will require 9 segments. The 20mm opening will require 4 segments. The 50mm opening will require 2 segments. There is a trade-off between the measurement time and the resolution of any horizontal variation of the activity. The assay system is configurable, and this will be done at the commissioning stage.
3. The MCNP calculations determined that the graded lead shield needed to be 50mm thick.
4. Minimum assay times have been calculated as a function of segment size and input count rate.
5. Overall assay system systematic uncertainty from physics considerations with the components added in quadrature was determined to be 13.3%

FED MEASUREMENT SYSTEM

The assay system supplied to the Hinkley Point A facility is based on a variation of the ANTECH Wide-Range Segmented Gamma Scanner, customised in response to the measurement challenge associated with measuring FED. The HPA variant of the WR-SGS incorporates a variable aperture collimator (VAC) typical of ANTECH G3250 series of instruments. This allows the field of view of the collimator to change automatically from 2mm to 50mm, in order to measure high count rate samples. In addition, due to the large activity range of the samples, the detector column is positioned at a greater distance from the drum than is typical, with the VAC collimation adapted to match the extended measurement distance. Given the homogeneity of the waste contained in the drums, the HPA assay system does not include a transmission source. The omission of a transmission source is based on the NRS physics teams knowledge of both the FED waste and the radioactive gravel, which allows the assumption of a uniform density distribution and reproducible drum fill height.

During the measurement process, a drum is automatically loaded onto the assay system via a mating conveyor section that connects to the plant conveyor. As an automated measurement process, the HPA assay system is integrated with the overall system automated drum handling equipment. It is installed in a shielded cell within the Concrete Box Loading Facility (CBLF) and integrated into the CBLF conveyor and plant control system. A bar code reader is included to identify individual drums, and the assay system is coupled to the plant data network to convey instrument status, handshake signals for conveyor control and to transfer assay results.

Once loaded onto the turntable, a FED drum is moved into the measurement position for a pre-scan, where the weight is measured. The drum activity is assessed by a vertical scan with the detector recording the input count rate over the height of the drum. From the drum weight and the pre-scan results, parameters are automatically selected for the main emission scan, including number of segments, rotations per segment and collimator aperture size to ensure adequate counting statistics.

The assay system then carries out an emission scan from the top to the bottom of the drum, summing the activities of the segments, and producing a pass/fail decision with respect to the drum loading requirements of the CBLF. The assay system is entirely automated, only requiring operator intervention (manual mode) in the case of a drum which has failed the loading test and requires alternative management, or if a system error occurs. The HPA FED assay system is displayed in the photograph in Figure 2. The photograph was taken prior to installation of the system in the CBLF.

Fig. 2. The HPA FED Assay System shown in a photograph taken prior to installation in the shielded cell of the CBLF. The drum rotation platform is in the load position.

For quality assurance (QA), the assay system included a QA check, featuring a Cobalt/Caesium mixed disc source positioned in a shielded housing on an extended arm at the top of the detector vertical axis of motion. When initiated by an operator, the vertical axis drives to a set position which exposes the source to the detector in order to confirm the full width at half maximum, the centroid position and the net peak counts in the gamma ray spectrum. This facility provides a quality assurance check of the detector calibration and detector state of health. The QA check system has a time limited validity period that can be set, based on the customer requirements, to ensure the quality of the measurement. In addition, the unit subtracts the background measurement from each scan to ensure only contributions from the drum are factored into the analysis. A background measurement is required for each collimator aperture, with any failed or expired backgrounds disabling the appropriate measurement configuration.

FED Assay System Hardware

The Assay System hardware consists of a detection plinth assembly and a rotary axis and drum traveller. The detection plinth assembly is a fixed frame assembly onto which the detection pillar is mounted, providing the vertical motion of the detector (the Y1 axis) by way of a linear ball screw. The detection pillar holds a 40% HPGe detector with ultra-high-count rate (TRP) preamplifier housed within a lead shield assembly. Detector cooling employs an ORTEC Integrated Cryocooling System (ICS) mounted behind the lead shield. The assay system multi-channel analyser is an ORTEC DSPEC 50, and it is positioned above and behind a shielding plate. On the front of the lead shield, the VAC provides an adaptable field of view of the drum for the detector, varying the collimator aperture opening based on activity. The VAC is made of steel and tungsten plates, providing a limitation on the gamma ray background seen by the detector. The VAC is fitted with a laser distance sensor which acts as a secondary positional indicator. The VAC is shown if Figure 3 with the covers removed.

At the rear of the detector pillar plinth assembly, a network of I/O blocks for signal, sensor and control electronics is housed under a protective metal housing. On the right of the plinth is the electronics enclosure housing the programmable logic controller (PLC), safety circuity and servo drive electronics used to control the assay system motors.

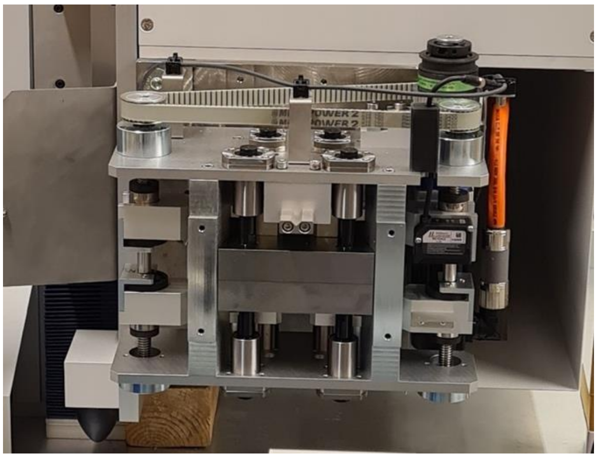

Fig. 3. The Variable Aperture Collimator (VAC) shown with the covers removed. The VAC operates by changing the separation between the central two tungsten plates, (shown in the closed position).

The rotary axis and drum traveller sub-assemblies of the assay system facilitate drum handling for the loading/unloading of the drums and the measurement process. The drum traveller (X-axis) provides horizontal motion for the rotary axis and drum turntable, moving drums from the 0-position for the assay to the load/unload position. It couples with the CBLF in feed conveyor. This horizontal drum traveller facilitates integration with the CBLF conveyor network and is driven by a ball screw unit protected by bellows. The rotary axis provides a mounting point for the drum turntable which provides the rotation for FED drums during the measurement. The drum turntable incorporates an integrated weigh scale and rollers on the top surface to couple with the CBLF conveyor.

FED Assay System Supporting Components

The assay system supporting components includes the conveyor section which connects the system to the CBLF plant conveyor, the operator workstation, and a CCTV System for viewing the assay system remotely. The Conveyor section is a short roller-style conveyor designed to connect the assay system to the CBLF conveyor and is configured with compatible rollers. It includes position sensors, and an end designed to connect with the drum turntable of the rotary axis, making for seamless drum transfers.

The operator workstation consists of a 21.5” panel PC mounted in a steel enclosure which also houses status indicators and safety and control circuits which are integrated with the HPA assay system. The panel PC has a Windows 10 operating system and incorporates ANTECH *GammaScan+* software, which has been specifically modified to meet the Magnox requirements for the HPA assay system. The workstation enclosure is fitted with the following controls and indicators:

a) A motion inhibit key switch which is connected to the system I/O network and is used to provide system security by restricting motion of any axes when in the ‘Off’ position,
b) A key-resettable emergency stop button (with key release) which enables the operator to render the system safe in an emergency situation,
c) Green and red status indicators which provide the operator with information about the status of the system, reflecting the on-system LED beacons. Green indicates ‘Measurement in Progress’; Red is for ‘System Fault’,
d) A system ‘Reset’ pushbutton, which is used to clear an emergency stop when the hazardous situation has been resolved.

The HPA assay system also includes a stand-alone CCTV system mounted next to the operator workstation. Cameras are positioned in the HPA assay system shielded cell, within the CBLF. They are positioned to provide the operator with the capability to remotely view all key parts of the system.

TESTING AND SYSTEM PERFORMANCE VALIDATION

At the time of writing, although the HPA FED Assay System has been installed in the shielded cell of the CBLF, the only test results available are those obtained during Factory Acceptance Testing (FAT). Preparations for calibration of the assay system on site have been made with the acquisition of an empty Magnox FED drum which will be used with a calibrated source during on-site commissioning and subsequently to check and renew the calibration, as required.

Concern was expressed early in the project about the reproducibility of the variable aperture collimator (VAC) apertures, and as such the decision was made to implement a laser distance measurement to provide independent verification of the collimator aperture opening for each movement of the jaws. As it is critical that the resetting of the aperture is highly reproducible, a set of measurements were undertaken to establish the variation to the pre-set aperture sizes and validate the accuracy of the hardware. The variation data is displayed in Figure 4.

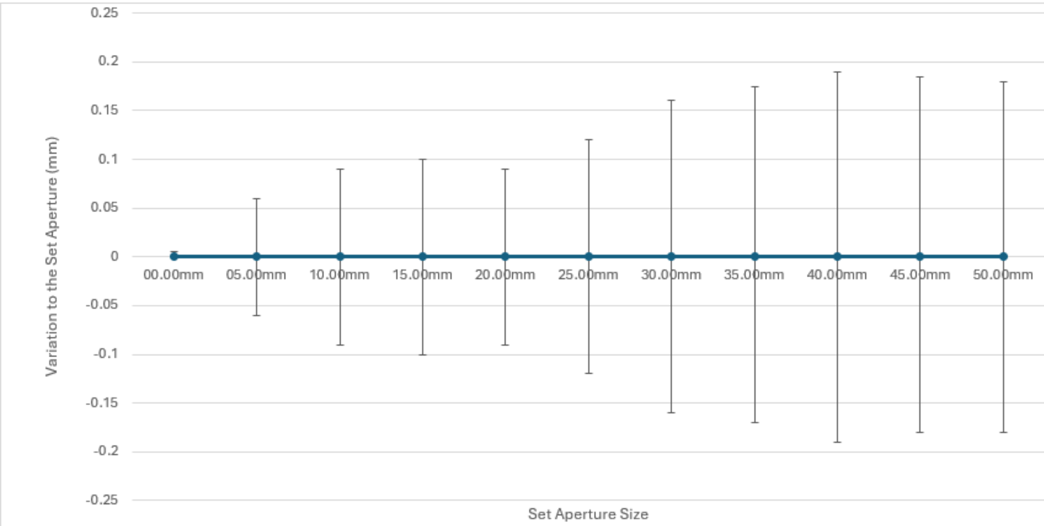

Fig. 4. Variation in the set aperture for the variable aperture collimator (VAC).

In Figure 4 the error bars above the zero line are an average variation observed when opening the collimator plates to the relevant aperture size. The error bars below the zero line are the average variation observed when closing the collimator plates to the relevant aperture size. The variations are almost symmetric when opening or closing the collimator plates to reach an aperture size. All of the variations are about 1% or less and the percentage variation becomes smaller as the aperture size increases.

For the FAT measurement, an ANTECH standard calibration drum was employed with 7 re-entrant tubes to allow the insertion of sources at different heights and radial positions. Six of the re-entrant tubes are arranged in a helical pattern such that each tube is located in an annular region of the drum, and each annular region of the drum is of equal volume. Rod sources can be placed in each of the outer 6 tubes. When the drum is rotated, to an external detector the drum appears to have uniformly distributed activity. The rest of the drum can be filled with a uniform matrix of the required density. The rod source (80m long) is made up of 8 active elements retained in an outer tube. This is the approach used with a set of Eu-152 rod sources, which are routinely used for verification and validation of measuring instruments.

An alternative method of simulating a homogenously distributed source in a drum is achieved by positioning a point source at the drum mid-height and near the mid-radius. The exact radial position of the point source depends on the drum matrix attenuation (mass attenuation coefficient), the energy of the gamma ray photo peak being counted, the collimator aperture and distance of the drum from the detector. This approach was employed in the FAT measurement reported below.

Of a number of FAT measurements performed, one is reported below, which demonstrates the correct functioning of the assay system:

a) A drum containing a wood sawdust matrix was loaded onto the system.
b) A 6.4MBq Cs-137 source was placed in the drum at the mid-radius and height position to approximately replicate the signal from a uniform drum. The source was placed in a holder to replace an Eu-152 active element.
c) A 3.0MBq Co-60 source was placed in the drum at the mid-radius and height position to approximately replicate the signal from a uniform drum. The source was placed in a holder to replace an Eu-152 active element.
d) All the rest of the 6 re-entrant tubes were populated with 47 of the Eu-152 rod sources (5 rods with 8 element and one with 7 and the Cs and Co sources) giving a total Eu-152 activity of 1.15MBq.

Measurement setup:

- Container: Standard drum
- Drum Net Weight: 38.0kg
- Collimator opening: 50mm
- Collimator opening measured: 49.989mm
- Number of segments: 32
- Time per segment: 101s
- Rotations: 10
- Segment height: 25.8 mm

Measurement results:

a) Cs-137 activity: 7.7MBq +/- 14.4kBq
b) Co-60 activity: 3.1MBq +/- 17kBq
c) Eu-152 activity 1.34MBq +/- 19kBq

Type 1 (counting statistics) uncertainties only are quoted in the results, above. From the results, it is concluded that the calibrations are acceptable. Additional points to note:

a) The material is sawdust (wood with a low moisture content), not Magnox, and therefore has a different set of mass attenuation coefficients.
b) The Eu-152 was measured using the 1408keV line. Other lines could be used which will give slightly different results.
c) The radial positioning of the Cs-137 source was not optimum and was constrained by the re-entrant tube location.

CONCLUSIONS

This paper describes the design, development and testing of a unique assay system for measuring Magnox reactor fuel element debris (FED) contained in 210 litre drums at the Hinkley Point A decommissioned Magnox reactor. The assay system is based on modular WR-SGS technology developed by ANTECH, but in this specific case, not employing a transmission source. This feature has been omitted from the design as the FED waste is homogeneous with a matrix of uniform composition.

As a result of a feasibility study involving three measurement technology options that met the specification and the subsequent detailed modelling and optimisation of the selected option, an enhanced measurement solution has been developed. The method minimises measurement error and produces accurate assay results in a 30-minute measurement time, or less, depending on the activity of the drum. Above all, it minimises the problem of overclassification of waste activity which was one of the objectives in the design of the WR-SGS precursor instrument.

The measurement technology arising from this development project can be applied to other decommissioned Magnox nuclear power stations where FED is processed and stored in a similar way.

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