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DESIGN AND OPERATION OF THE COMBINED TECHNOLOGY AUTOMATED WASTE CHARACTERIZATION SYSTEM

J. A. Mason - A.N. Technology Ltd., Unit 5/6,Thames Park, Lester Way, Wallingford, Oxfordshire,OX10 9TA, United Kingdom

M. R. Looman - A.N. Technology Ltd., Unit 5/6,Thames Park, Lester Way, Wallingford, Oxfordshire,OX10 9TA, United Kingdom

R. A. Price - A.N. Technology Ltd., Unit 5/6,Thames Park, Lester Way, Wallingford, Oxfordshire,OX10 9TA, United Kingdom

ABSTRACT

This paper describes the design and operation of the Combined Technology Automated Waste Characterisation System (CTA-WCS) at JRC Ispra. The WCS was designed for the measurement of fission products and uranium and plutonium containing waste arising from nuclear fuel and nuclear materials processing and reactor operations. The WCS covers a range of activity including Low and Intermediate Level Waste (LLW and ILW). The system is designed to measure the waste in 200 and 400 (440) litre drums with a maximum drum weight of 1500 kg. Gamma-ray measurements of radio-nuclide content are performed by a gamma ray measurement station which functions as either a Segmented Gamma Scanner (SGS) or Tomographic Segmented Gamma-ray Scanner (TSGS). Either of these two techniques may be employed to perform the functions of drum screening, non-destructive examination (NDE) and, where appropriate, final drum assay. Coupled to the gamma ray station is a surface dose-rate measurement station, which employs 6-shielded Geiger-Muller detectors. Active and passive neutron measurements are performed by an advanced, graphite lined Differential Die-away (DDA) system, which comprises the neutron measurement station. The DDA performs conventional passive neutron totals, coincidence, and multiplicity counting and active DDA total neutron counting. Data analysis is based on the use of a range of matrix calibrations, some determined by Monte Carlo analysis. Linking the gamma ray and neutron measurement stations is an automated roller conveyor with a 20 drum buffer capability and a weight measurement station. Drums are identified by bar code reading technology. Once loaded, the system performs automatic assay of up to 20 drums and then returns the drums to the buffer position on the conveyor. The first WCS of this type was supplied to the European Commission at the Joint Research Centre (JRC) Ispra in northern Italy and it was commissioned at the end of 2007. It is now in a phase of pilot operation. Results will be presented from the first drum measurement campaign.

INTRODUCTION

In this paper the measurement characteristics of the Combined Technology Automated Waste Characterisation System (CTA-WCS) will be reviewed and measurement results presented from the first measurement campaign. The WCS [1,2] was designed to measure both 220 and 440 litre drums, the latter with a maximum weight of 1500 kg. The assay technologies include surface dose rate measurement, Segmented Gamma Scanning (SGS), Tomographic Gamma Scanning (TGS) and active and passive neutron assay by means of the differential die-away (DDA) method.

The WCS is designed to perform radiometric measurements of fission products, activation products and other radio-nuclides as well as determine the quantity of Uranium and Plutonium in contact handled waste drums. A variety of waste matrices can be measured including homogeneous, heterogeneous, hard, soft, decommissioning waste and legacy waste from nuclear fuel processing. In addition to assay, the TGS provides the system with a non-destructive examination (NDE) capability by generating images of the distribution of both absorbers and radio-nuclides within drums. The WCS also determines both the weight and surface dose of the drums.

The assay stations are linked by a heavy-duty roller conveyor, which includes a load cell (to measure drum weight) and bar code readers. The conveyor incorporates a 20 drum buffer store to permit automatic, batch operation. The conveyor is controlled by a PLC and in conjunction with the computer controlled assay stations allows the assay of up to 20 drums in a 24-hour period.

A waste characterisation system based on the design described in this paper has been built and commissioned by ANTECH at the Joint Research Centre, Ispra, a laboratory operated by the European Commission and located in northern Italy. The WCS is currently in a phase of pilot operation. Full capacity operation has been demonstrated with a series of 20-drum overnight fully automated assays completed successfully in the initial phase of operation. A total of over 250 drums have been measured in the initial period.

An artist's concept drawing of the WCS is displayed in Figure 1. It shows clearly the layout of the various components of the system. Figure 2 is a photograph of the completed WCS. Both Gamma Measurement Station (foreground) and Neutron Measurement Station (background) can be seen in the picture.

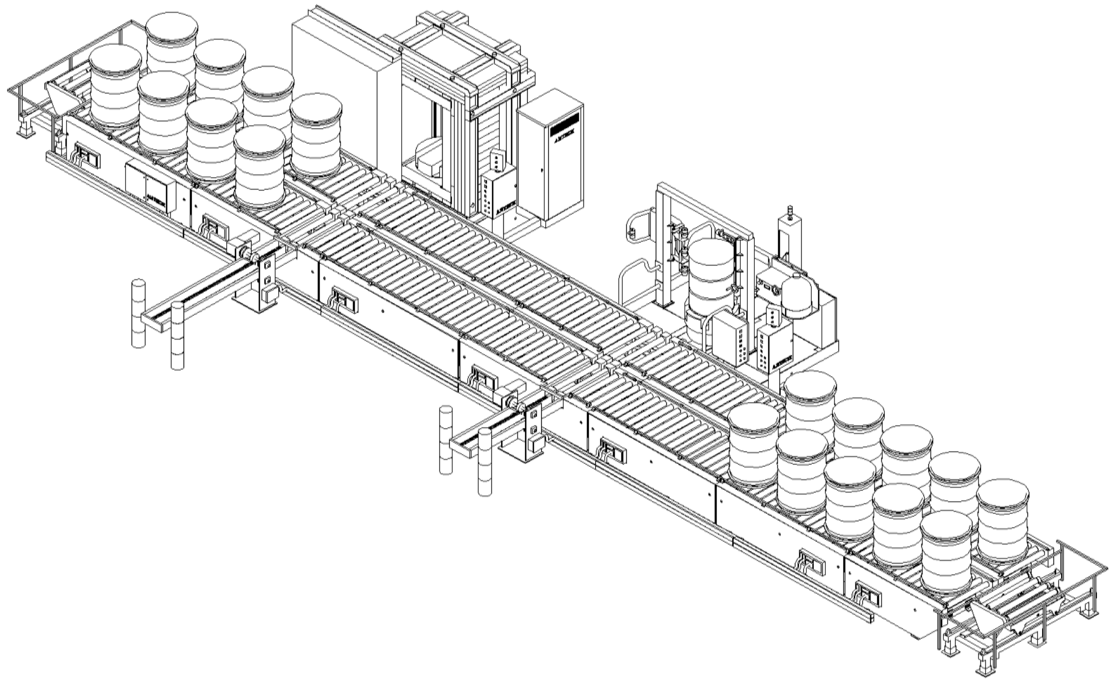

Figure 1 – Combined Technology Automated Waste Characterisation System.

PLANT AUTOMATION AND THE CONVEYOR

The WCS plant automation is implemented as a distributed control system. It combines dedicated instrumentation industrial control equipment with computers controlling the functions of different instruments. Internal communications are provided by Fieldbus and Ethernet technology, which have greatly reduced the extent of plant wiring compared to conventional measurement systems.

A Facility Control Computer (FCC) controls the automation functions of the WCS and a Measurement Control Computer (MCC) controls the measurement process including each of the individual measurement instrument computers. The FCC is linked to a programmable logic controller (PLC), which directly controls the roller conveyor and provides all system interlocks including the emergency stop system.

Drums are loaded onto the conveyor in either a manual or automatic mode from the drum transfer system (DTS). Once loaded, drums circulate around the conveyor system in a counter clockwise manner using the drum transfer mechanisms at either end of the conveyor system. Drums are loaded into each of the measurement stations using parallel beam loading systems that are also controlled by the PLC. Drum weight measurement using the installed load cell as well as drum bar code reading is performed automatically. The entire measurement process of the WCS can be operated in either manual or fully automated mode measuring from 1 to 20 drums at a time.

Once drums are loaded for WCS assay the operator sets-up and configures the measurement of the 'batch' of drums. The batch can be any number of drums from 1 to 20, but the drums must be all of the same type (either 220 litre or 440 litre). In the batch the measurement sequence is specified. Either SGS or TGS analysis may be chosen and if appropriate, drums may be selected to bypass the Neutron Measurement Station. This would be the case if plant knowledge were used to confirm that no fissile material were present in certain drums.

Figure 2. Photograph of the JRC Ispra Waste Characterization System (WCS) showing the tandem conveyor with the gamma measurement station in the foreground and the active/passive differential die-away based neutron measurement station towards the far end of the conveyor.

GAMMA MEASUREMENT STATION

The gamma measurement station encompasses three different measurement functions. A dedicated instrument employing 6 Geiger Muller detectors performs the first function, which is drum surface dose rate measurement. The second and third measurement functions are performed by a Tomographic Segmented Gamma Ray Scanner (TSGS) that operates in either SGS or TGS measurement mode. Both the SGS and the TGS have been described in detail elsewhere [3] so only an abbreviated description is included in this paper. The SGS and TGS share common components. These include a lead shielded high purity germanium (HPGe) detector, a digital spectrometer, a lead and tungsten collimator, a shielded Eu-152 Gamma Ray transmission source and a drum rotation platform.

The SGS measurement takes place as the waste drum is rotated about its vertical axis. The detector measures the drum in vertical segments either segment-by-segment or as a continuous scan. Typically a drum is measured using 16 segments. A transmission measurement is made by scanning the waste drum with the transmission source shutter in the open position. If appropriate, a separate emission measurement is performed with the transmission source shutter closed. Drum rotation reduces the effects of non-uniformity in the waste density and nuclide distribution.

Once the scanning process is completed and all drum segments have been scanned the analysis software determines the radio-nuclide content and hence the activity of the drum for selected radio-nuclides. At the end of the measurement the results data is transferred to the MCC and tabulated with other measurement results.

TGS measurements involve measuring drums in segments as for SGS measurements, however, in the case of the TGS, while the drum is rotated, it is also moved in the horizontal direction (translated). Instead of acquiring a single large gamma ray spectrum for each segment, 150 separate spectra are obtained as the drum rotates and is translated. These 150 spectra are acquired for both the transmission and emission measurements.

The 150 spectra taken for transmission constitute a set of data that can be solved to yield the distribution, or map, of attenuation coefficients throughout the segment of the sample or drum. The measurement equations are over specified and the solution uses a maximum likelihood analysis. This results in the determination of a map (after a geometric transformation) of attenuation coefficients in a rectangular grid suitably superimposed on each segment. The attenuation map enables the operator to 'visualise' the variation of the density (governed by the collimator size and voxel resolution) in regions of the drum. This serves a non-destructive examination (NDE) function similar to 'real time radiography' but with three-dimensional information at reduced resolution.

Emission data is obtained in a similar manner but with the transmission source shutter closed. For the analysis of the emission data, the additional information obtained from the transmission measurement allows the emission data to be corrected for attenuation. In other words, in the case of the TGS, the map of attenuation is used to correct the measured source distribution across the matrix (voxel by voxel and then segment by segment). The TGS extends the range of gamma-ray measurement technology, as it is able to more correctly determine the attenuation corrected radionuclide inventory in heterogeneous matrices compared to SGS, which assumes that matrices are homogeneous.

The WCS is configured so that either SGS or TGS is used in a measurement (of one or up to 20 drums), but not both techniques at the same time. The dose rate instrument measures all drums entering the Gamma Measurement Station.

NEUTRON MEASUREMENT STATION

Active and passive neutron measurements are performed by a graphite-lined Differential Die-away (DDA or DDT) system. The DDA is an active and passive neutron measurement device for determining the fissile content of waste drums. In passive mode it is employed to determine the mass (or activity) of plutonium in a waste drum using neutron coincidence or neutron multiplicity counting. Neutron coincidence and neutron multiplicity counting is based on the Point Model developed by W. Hage [4].

In active interrogation mode a pulsed neutron generator is employed to determine the ^{235}U and ^{239}Pu content of waste drums by induced fission using totals neutron counting. With appropriate matrix calibration and flux normalisation it is possible to infer the total fissile mass at low levels contained in the waste drum from the total neutron count rate as measured in fast neutron detectors.

Cadmium shielded, polyethylene moderated fast neutron ^{3}He detector packages are used to measure fast neutrons arising from both spontaneous fission (passive mode) and induced fission (active mode). In active mode the prompt induced fission neutrons are detected after a time period (~800 μs) when neutrons from the initial generator burst have been cleared from the fast detector packages. Additional ^{3}He flux monitors are placed in the measurement chamber and provide a measure of the interrogating neutron intensity and its die-away characteristics.

In passive neutron mode the DDA operates as a conventional passive neutron coincidence counter for measuring spontaneous fission from even numbered isotopes of plutonium (principally ^{240}Pu) using correlated neutron pairs and neutron total count rates. The theory and operation of the DDA in active mode has been discussed in great detail elsewhere [3]. Despite the presence of the graphite liner, the DDA achieves a passive detection efficiency of 13%.

MEASUREMENT RESULTS - DOSE RATE

Dose rate data is recorded for each drum that is measured by the Dose Rate Measurement Station of the WCS. Six Geiger Muller detectors are positioned so that three measure the bottom, middle and top of the circumference of the drum and two additional sensors measure the dose rate on the top surface and bottom surface of the ends of the drum. A final shielded detector measures the dose rate at 1 m from the drum surface. All of the measurements take place while the drum is rotated. The six calibrated Geiger Muller detectors provide a comprehensive measurement of the surface dose rate and dose rate at 1 m for all drums, which pass through the WCS.

Figure 3 provides a plot of the measurement results of all six sensors for a typical waste drum. In this particular case, it can be seen that the middle sensor measuring the drum circumference has identified a so-called hotspot with a significantly higher dose rate.

MEASUREMENT RESULTS FOR SGS AND TGS

As has been described earlier, gamma ray measurements of waste drums are performed either by segmented gamma scanning (SGS) or tomographic gamma scanning (TGS). Results are presented which provide a comparison for a specific drum of the results of SGS and TGS measurement. In Figures 4 and 5 the results of emission measurements for TGS and SGS are presented for drum number 0059. The TGS images (Figure 4) show both the magnitude and distribution at Co-60 activity across a plane through the bottom of the waste drum. The second view shows the vertical distribution activity as seen through one face of the drum.

In contrast in Figure 5 the SGS result is displayed. This is a plot of the activity of the two principal gamma ray lines of Co-60 as a function of the measured vertical segments within the drum. Note that both analyses reveal significantly higher activity at the base of the drum. in figures 4 and 5.

The results of both TGS and SGS transmission measurements for drum 0059 are displayed in Figures 6 and 7. In Figure 6, as for Figure 4, the view on the left shows a diagrammatic representation of the magnitude of the attenuation (or density) and its distribution across a plane through the bottom of the drum. The view on the right shows the vertical distribution of attenuation as seen through one face of the drum.

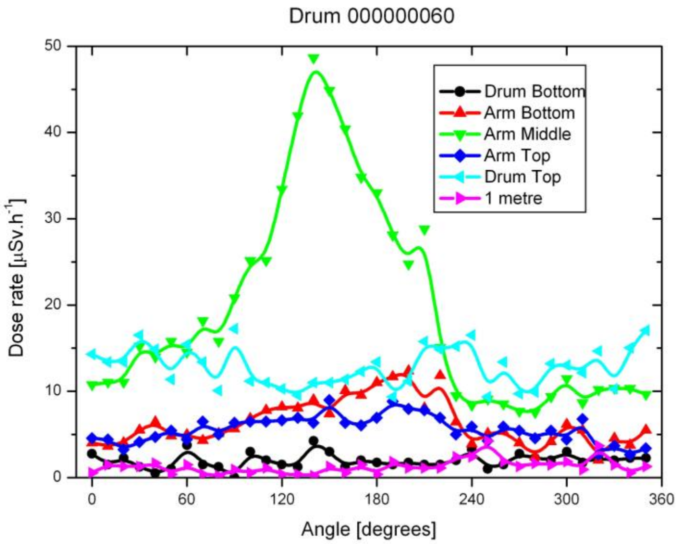

Figure 3. In this figure the dose rate from each of the six-shielded Geiger-Muller detectors is plotted as a function of the angle of rotation of the drum. It can be seen from the plot that there is a hot spot at a point near the surface in the middle or central region of the drum. This dose rate data is recorded for each measured drum.

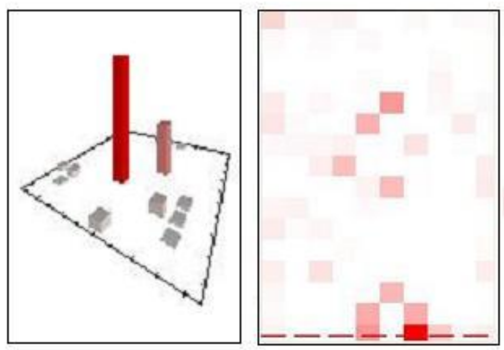

Figure 4. In this figure the results of the tomographic emission-scan of a typical waste drum No. 0059 measured by TGS are displayed. The view on the left shows the magnitude of the activity for Co-60 and its distribution across a plane through the bottom of the drum. The view on the right shows the vertical distribution of activity as seen through one face of the drum. The dashed line is the plane through the bottom of the drum appropriate to the left hand view.

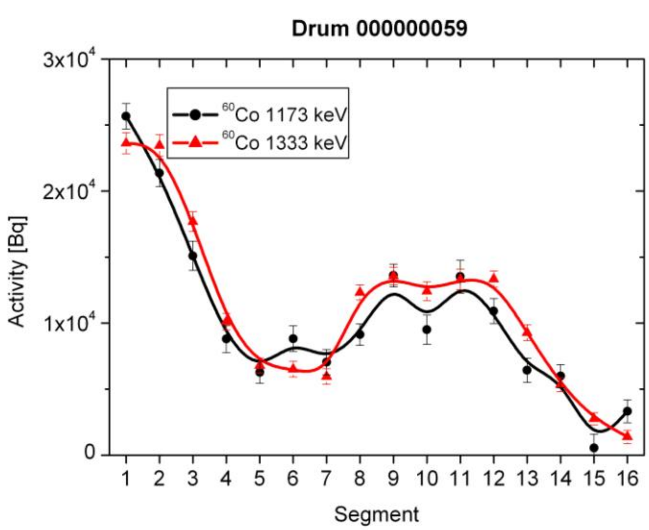

Figure 5. The SGS emission-scan results for the same drum (previously measured by TGS and displayed in Fig. 4 are displayed in this figure. The activities of both Co-60 peaks are plotted as a function of the 16 vertical scan segments.

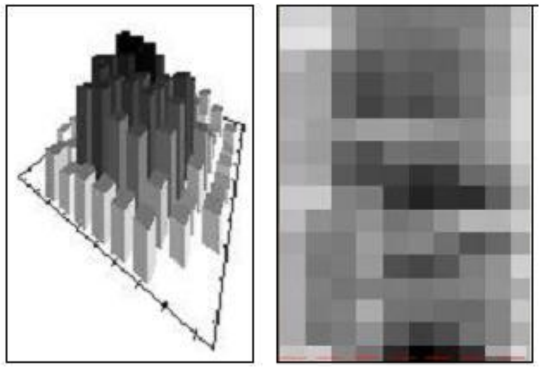

Figure 6. This figure shows the results of the tomographic transmission-scan of a typical waste drum No. 0059 measured by TGS. The view on the left shows the magnitude of the attenuation (or density) and its distribution across a plane through the bottom of the drum. The view on the right shows the vertical distribution of activity as seen through one face of the drum. The dashed line at the bottom of the right hand view is the plane through the bottom of the drum appropriate to the left hand view.

Figure 7 provides the equivalent SGS transmission measurement for the same drum. The percentage transmission for five different gamma ray lines of differing energy is plotted as a function of the vertical segments within the drum. Note that both Figures 6 and 7 reveal significant attenuation in the drum at the bottom (segment 1) and in the middle of the drum (segments 8 and 9).

Both TGS and SGS measurement methods determined the total activity within a drum. The SGS method has higher sensitivity and is appropriate for a wide range of drum matrix types. For highly heterogeneous drum, the TGS method is often more appropriate. Both measurement and analysis methods are available as part of the capability of the waste characterisation system.

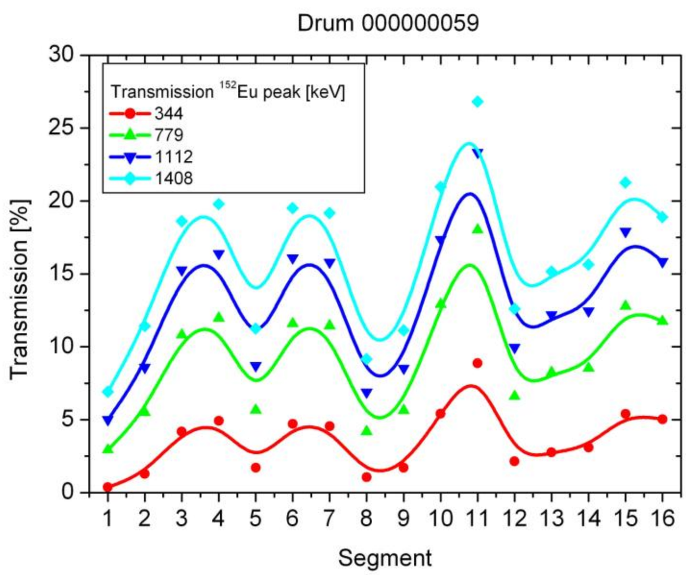

Figure 7. The SGS transmission-scan results for drum No. 0059. Note the lower transmission at the base of the drum (segment 1) and in the middle of the drum (segments 8-9), which corresponds to higher density regions as revealed by the TGS transmission images shown in Figure 6.

NEUTRON MEASUREMENT RESULTS

The neutron measurement station performs both passive and active neutron measurements of waste drums. Figure 8 displays calibration curves for passive neutron coincidence measurements for three different matrix types. The 'Reals' coincident rate is plotted as a function of the Pu-240 effective mass for each matrix drum type. Good results are obtained for technical combustible (TCO220) and metallic (MET220) matrices. The results are not satisfactory for the simulated bitumen matrix (BIT220). The measurements were made using small plutonium samples placed in re-entrant tubes in the simulated waste drum matrices. In the case of the bitumen test drum the results are not useful. The bitumen matrix test drum had higher bitumen content than real bitumen conditioned waste drums and represents an overly pessimistic case. It is clear from these results that the passive measurements are applicable to the measurement of larger quantities of plutonium in waste.

Active neutron measurements employing the differential die-away (DDA or DDT) method are much more sensitive and are applicable to the measurement of both plutonium and uranium in small quantities. In Figure 9 measurement data is presented for the measurement of three fissile samples and one active background. The measurements were made with Pu-239 samples ranging in mass from 151 mg to 8.5 g in an empty matrix. Each plot represents the cumulative detected fast neutrons as a function of time for 30,000 repeated measurements. The data from plutonium sample measurements can be compared with the data obtained by a background measurement with no fissile material present in the measurement chamber.

Further measurements of small samples in an empty matrix are displayed in Table 1 and in Figure 10. Small plutonium oxide powdered disk samples ranging in mass from 7 to 372 mg were measured in the DDA. Both the measured data and the result of an MCNP simulation to correct for self-shielding are presented in Table 1 and in Figure 10. It can be seen that for samples with the mass of greater than about 75 mg self-shielding becomes important. Most of the waste matrices, which are to be measured by the DDA are expected to have distributed samples where the self-shielding effect will not be significant.

An assessment and determination of the sensitivity and minimum detectable mass for the DDA is presented in Table 2. The first result for Pu-239 in pellet form with no matrix (table column 2) is based on an experimental measurement. It may be compared with an MCNP simulation for an equivalent sample and void matrix, which is displayed in the third column of the table.

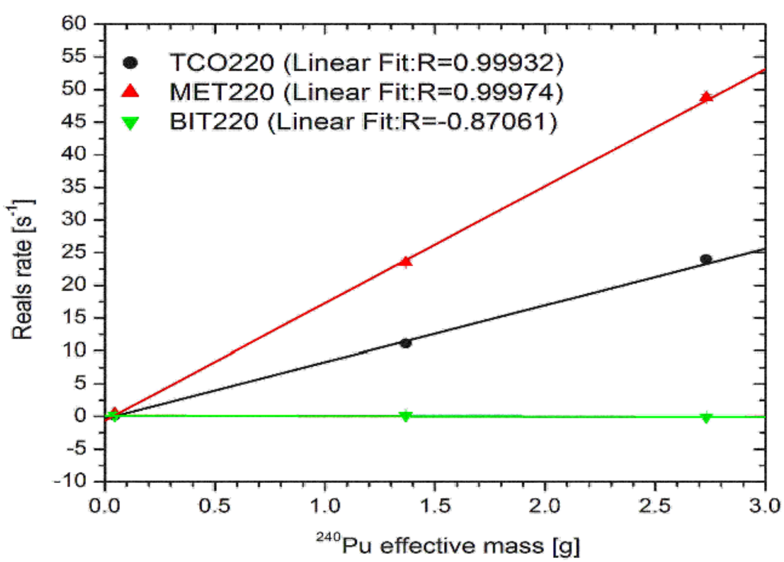

Figure 8. This figure shows calibration curves relating the Reals coincidence rate to the Pu-240 effective mass for three different matrix types.

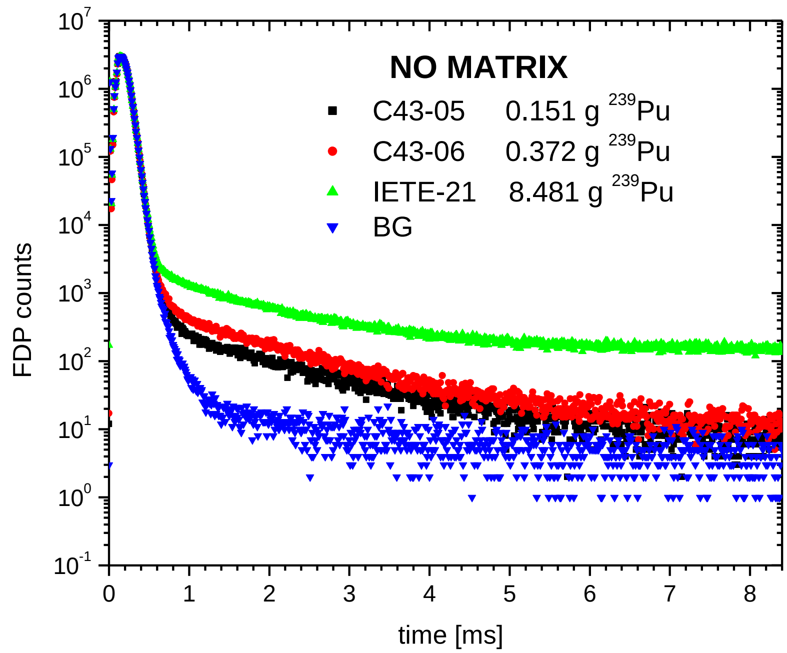

Figure 9. This graph shows the measurement data for 3 measurements of fissile samples and one background measurement. Each curve is the cumulative histogram of 30,000 individual measurements. The cumulative counts in the fast detector packages (FDP) are plotted as a function of the time at which a fast neutron is detected from the time of the neutron generator pulse (time 0). The peak on the left side of the plot is the 14 MeV neutron pulse from the neutron generator.

Table 1. This table contains the results of active neutron DDA measurements of a range of plutonium powder disk samples. The mass of the samples ranges from 7 mg to 372 mg. These results (including self-shielding correction) are plotted in Figure 10.

Sample		Net Signal S = E-L [counts]				
ID	Pu239 mass [mg]	Measured (not corrected for Self-Shielding)				Corrected
		Value	Std Error	N	STDEVP	Value
C43-01	7.37	1208	70	10	111	1208
C43-02	15.04	2345	38	5	43	2464
C43-03	37.44	5453	204	7	270	6134
C43-04	72.29	10050	251	5	281	11845
C43-05	150.61	18575	410	5	459	24677
C43-06	372.34	33496	397	5	444	61008

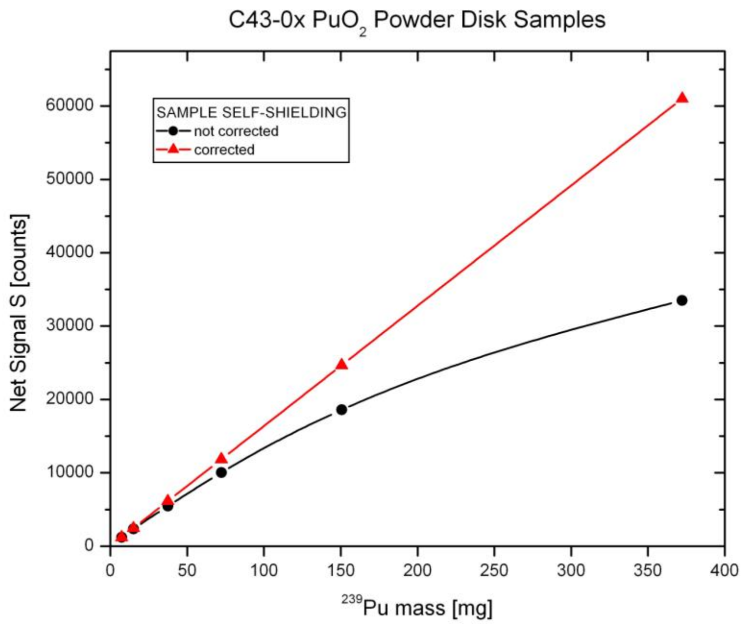

Figure 10. Active neutron differential die-away results for the measurement of a variety of PuO2 powder disk samples. The results of an MCNP simulation to correct for self-shielding are also plotted. The relevant data is tabulated in Table 1.

MCNP simulations for both plutonium measurement and uranium measurement for volume-distributed sources in drums with different matrices are tabulated in the remaining columns of Table 2. For equivalent geometries a comparison can be made of the detection level for Pu-239 and U-235 using columns 4 and 5 of Table 2. Finally in columns 6, 7 and 8 detection level simulation results are presented for the three different matrix drum types of metal waste (MET220), technical combustible waste (TCO220) and finally bitumen conditioned waste (BIT220).

The minimum detectable mass for either plutonium or uranium is displayed in row nine of the table. These results are consistent with a determination of the minimum detectable mass in an empty matrix for Pu-239 based on measurements of the active background in the DDA. Based only on background and using the Currie Limit conventions for minimum detectable mass, a result of 1.9 mg was obtained for Pu-239. This is entirely consistent with the results displayed in column 4 of Table 2.

Table 2. Measured and simulated data for the detection levels for the active differential die-away are displayed in this table. The detection level results are determined on the basis of Currie Limit conventions.

Container/Sample	Pellet		Drum (Volume Source)				
Nuclide	Pu239	Pu239	Pu239	U235	Pu239	Pu239	Pu239
Matrix	Void	Void	Void	Void	MET220	TCO220	BIT220
Experiment/Simulation	EXP	SIM	SIM	SIM	SIM	SIM	SIM
Active Signal S [counts]	182448	214325	3282539	1238358	1034644	3361995	297554
Active Background ABG [counts]	3357	3357	3357	3357	3446	4028	3682
S_{net}=S-ABG [counts]	179091	210968	3279182	1235001	1031198	3357967	293872
Calibration Factor [counts/g]	10567	12447	193476	123500	60842	198125	17339
Minimum Detectable Mass [mg]	39.1	33.2	2.1	3.3	4.5	1.5	16.3
Minimum Detectable Activity [Bq]	9.0E+07	7.6E+07	4.9E+06	2.7E+02	1.03E+07	3.41E+06	3.73E+07
Drum matrix mass [kg]					178.5	39.7	212.2
Minimum Detectable Activity per gram [Bq/g]					58	86	176

CONCLUSIONS

This paper describes the Combined Technology Automated Waste Characterisation System (CTA-WCS), which is a fully automated state-of-the-art nuclear waste assay system. It is capable of measuring a wide variety of waste types in a range of matrices arising from nuclear fuel and nuclear materials processing, reactor operations and military wastes. It is applicable to LLW, ILW and TRU wastes and may be employed for contact handled and some remoter handled wastes. Measurement data is presented from the implementation of the system at the Joint Research Centre at Ispra, a research facility operated by the European Commission in Italy.

At the core of the WCS is a combination of non-destructive assay techniques including surface dose rate measurement, SGS, TGS and finally active and passive neutron assay based on the use of the DDA. These measurement techniques are deployed to achieve the measurement of a wide range of nuclear waste materials to a high degree of sensitivity. The WCS implemented at JRC Ispra meets the Italian National waste characterization requirements for sentencing nuclear waste, Guida Tecnica Nr. 26.

The Tomographic Segmented Gamma Scanner (TSGS) is the most comprehensive gamma-ray measurement solution for the assay of a broad range of waste types and combines conventional high-resolution gamma spectrometry, segmented gamma scanning and three-dimensional tomographic imaging and NDE capabilities in one complete system. The Differential Die-away (DDA) operated in active mode is the most sensitive assay technique for the measurement of low levels of fissile material in waste. Linking the two measurement stations is an automated mechanical handling system with a 20-drum capacity storage conveyor, drum weight measurement station and surface dose measurement station. Once loaded, the system is designed to perform automatic unattended assay and return up to 20 drums to the buffer conveyor in a 24-hour period.

Measurement data covering all aspects of the operation of the system and using both calibrated sources and real waste drums are presented. A comparison is made between the results and capabilities of both the SGS and the TGS gamma ray assay techniques. Measurement data for both active and passive neutron assay of fissile material is presented, as are minimal detectable masses for both Pu-239 and U-235.

The Waste Characterisation System described in this paper is the most comprehensive high throughput waste assay solution of its type for the automated and unattended measurement of nuclear waste. The system meets and exceeds its design specification. It also achieves high sensitivity for the measurement of fissile material in waste.

The WCS is the first of its type oriented to the high throughput measurement and remedial examination of waste materials for future long-term storage.

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