WASTE ASSAY AT THE FREE RELEASE THRESHOLD USING A BOX MONITOR - 10007

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ABSTRACT

In the nuclear power industry it is common practice to clear radioactive wastes for free release and reduce disposal costs by using box monitors (BM) employing plastic scintillation photon detectors. This is possible because of the excellent detection levels achievable with the high energy and high yield photons emitted from contaminants such as Cs-137 and Co-60. However, this practice appears to be less applicable, but theoretically feasible, in the nuclear weapons industry where contaminants such: as plutonium (Pu), depleted uranium (DU) and enriched uranium (EU) compositions emit photons with lower yields and energies. Hence the Atomic Weapons Establishment (AWE), at Aldermaston in the UK, has recently procured and commissioned a large (350 l counting chamber) BM in order to evaluate its performance and identify areas of applicability.

The BM suppliers detection level measurements and calculations have been verified using traceable sources. Detector counting efficiency has been mapped throughout the assay chamber when empty and when full of a variety of waste materials and objects. Isotopic counting efficiencies have been measured as a function of source activity and photon energy. Finally the background variation for commonly encountered materials (e.g. soil, paper, PVC, steel, coveralls etc.) has been measured in order to determine the effect on detection levels due counting statistics and different concentrations of Naturally Occurring Radioactive Materials (NORM).

It has been concluded that the BM has the potential to assay Pu, DU and HEU waste streams at the current free release thresholds (e.g. 0.4 Bq/g above NORM for Pu wastes). However, a number of requirements must be met in order to achieve this. The BM must be sited in an area with low and non-fluctuating photon background. The waste streams must be pre segregated into materials with low photon attenuation properties, low NORM concentrations and similar isotopic fingerprints.

INTRODUCTION

In the UK ‘free release’, for radioactive wastes, generally equates to less than 0.4 Bq/g above NORM, with a much higher threshold of 11.1 Bq/g being applied to DU. However, it is likely that future harmonisation of European legislation will reduce these activities to 0.1 Bq/g for some isotopes, such as Pu-239. Hence the target for AWE waste streams is a detection level of better than 0.1 Bq/g for Pu and HEU contamination, which appears feasible using commercially available BM technologies employing plastic scintillation photon detectors.

This paper begins with a description of the BM that AWE has recently procured and a verification of isotopic detection levels, provided by the BM supplier, using traceable sources. Then detector efficiency is examined as a function of source activity, photon energy and source location within an empty and filled counting chamber containing simulated waste materials. Finally background variation over time is assessed in order to quantify the effect of this on detection levels.

BOX MONITOR SPECIFICATION

The AWE BM detects photons from 50 keV up to 2 MeV and has a 350 l counting chamber (63.5 cm high, 63.5 cm wide, 87 cm deep). All six sides of the chamber are surrounded with plastic scintillation photon detectors (50 mm thick) and lead shielding (25 mm thick). The aluminium base plate of the chamber is linked to a load cell in order to provide a measure of the waste mass. Waste items are introduced and removed using doors at the front and rear of the monitor (figure 1). The make and model of the unit is CANBERRA Cronos-11.

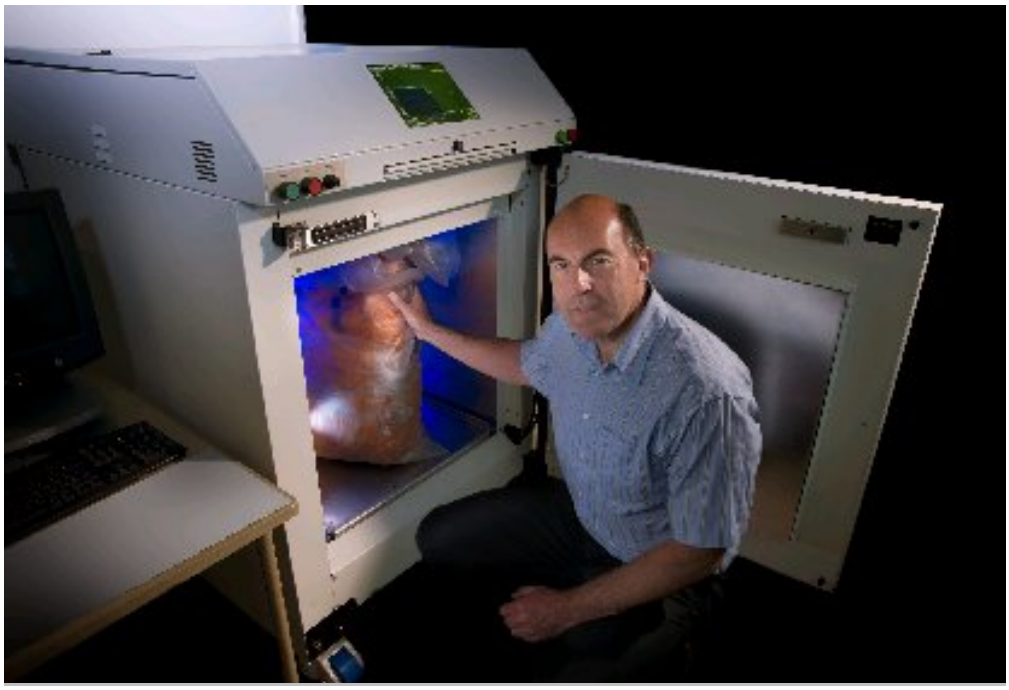

Figure 1 Box Monitor being loaded with a bag of coveralls

DETECTION LEVEL VERIFICATION

Table 1 compares the isotopic detection levels measured or calculated by the supplier, for a 60 s count time and a gamma background of 0.1 μSv/h, with those measured at AWE using traceable AWE sources positioned on the centre of the weighing plate. The Currie formula was applied to the counting data from the AWE measurements in order to derive the detection levels:

$$MDA = [(4.653 \sqrt{B}) + 2.706] \div (T \times F) \qquad \text{(Eq. 1)}$$

where:
MDA = Minimum Detectable Amount or Detection Limit (Bq)
B = Background counts = 4450 counts per second (cps) x 60s = 267000 counts
T = Count time (s) = 60 s
F = Detector response factor (cps/Bq) net counts per second above background

The above formula is only valid if the square root of the background is equal to the standard deviation of the background and where there is no variability in detector response factor (counting efficiency). It has been applied to derive a comparison with the manufacturer's data presented in table 1. Subsequently this paper examines variability in detector efficiency and background in order to evaluate the impact on detection levels.

AWE Sources

The Am-241, Cs-137 and Co-60 sources were encapsulated in thin plastic disks giving little photon self absorption within the source material. However, the HEU and EU sources had more significant photon self absorption effects and a greater spread of photon energy emissions. The HEU source consists of a 1 g foil of 93 % U-235 (73 kBq), 1.22 % U-234 (2.8 MBq) and other uranium isotopes. The overall activity of the source is 3 MBq. The foil is around 200 microns thick and is encapsulated by 1 mm of steel. The DU source is a 7.5 g disk (25 mm diameter, around 800 microns thick), containing 99.6 % U-238 (92 kBq), 0.4 % U-235 (2.4 kBq) and other uranium isotopes encapsulated in plastic. The overall activity of the source is 132 kBq.

Comparative Detection Levels

Table 1 Comparative Detection Levels For 60s Count of a Point Source in the Centre of the Weighing Plate

Isotope	kBq	keV	F (cps/Bq)	MDA AWE (Bq)	MDA SUPPLIER (Bq)
Am-241	40.3	60	0.060	668	480
Cs-137	3.47	662	0.503	80	100
Co-60	1.96	1173 & 1332	0.995	40	55
U-235*	-	186*	-	-	120*
Th-234*	-	93*	-	-	1200*
Pa-234m*	-	1001*	-	-	18000*
HEU	3,000	Multiple	0.00635	6314	-
DU	132	Multiple	0.042	955	-

Note – these MDAs were computed using only the gamma emission noted; true MDAs when using all gamma and x-ray emissions should be lower.

Good agreement, between AWE measurements and supplier measurements and calculations, was noted for Am-241, Cs-137 and Co-60 sources with negligible photon self absorption within the source. Comparisons for the HEU and DU sources were more difficult because of complications associated with uranium self absorption effects and variations in detector efficiency for the greater spread of photon energies emitted.

However, it is possible to reconcile the supplier MDA values in table 1 with those measured using the AWE uranium sources. The HEU source self absorption is around 35 % at 186 keV (U-235) (1) and 50 % at 98 keV (U-Ka1). Hence the total self absorption of all photon emissions (53 – 238 keV) is estimated to be in the region of 50 %. The 186 keV emission is estimated to provide around 50 % of the photon flux (from tables of branching ratios) and U-235 around 2.5 % of the total HEU activity. Hence:

$$MDA \times S \times Y \times A = 6314 \times 2 \times 0.5 \times 0.025 = 158 \text{ Bq (supplier = 120 Bq)} \qquad \text{(Eq. 2)}$$

where:
S = photon self absorption correction factor for HEU source = 2
Y = fraction of photon yield at 186 keV = 0.5 (i.e. around half of the HEU photons at 186 keV)
A = fraction of HEU activity from U-235 = 0.025.

A similar calculation may be performed for DU. The high energy Pa-234m photons are of low yield, but only lightly attenuated by the DU. In contrast the higher yield photons from 63-98 keV are self absorbed by 60-80 % (1). Hence an overall photon absorption correction factor of 3 is estimated for the DU source. The 93 keV photon is estimated to provide around half of the photon flux and the U-238 around 70 % of the DU activity:

MDA x S x Y x A = 955 x 3 x 0.5 x 0.7 = 1003 Bq (supplier = 1200 Bq) (Eq. 3)

where:
S = photon self absorption correction factor for DU source = 3
Y = fraction of photon yield at 93 keV = 0.5 (i.e. around half of the DU photons at 93 keV)
A = fraction of DU activity from U-238 = 0.7

DETECTOR EFFICIENCY VARIATION

Linearity of Counting Efficiency

Table 2 shows that the counting efficiency for Am-241 was independent of source strength from 465 up to 259,000 Bq. Measurements were made with the source placed in the centre of the weighing plate. This equates to 0.13 up to 74 Bq/g Pu for a 35 kg bag of soft waste. However suppliers have indicated linearity in excess of 5 MBq Cs-137. This equates to around 50 MBq Am-241 or 500 MBq Pu (14.3 kBq/g for 35 kg of soft waste).

Table 2 Counting Efficiency versus Source Strength

Bq	F (cps/Bq)
465	0.056
3100	0.063
40300	0.060
259000	0.061

Counting Efficiency Variation With Photon Energy

Table 3 summarises the counting efficiencies (cps/Bq and cps/gamma) for Am-241, Cs-137 and Co-60. Once again, measurements were made with the source positioned in the centre of the weighing plate The high energy photon counting efficiencies (cps/gamma per second (gps)) were roughly a factor of 3 higher than at low energy.

Table 3 Counting Efficiency Versus Photon Energy

Isotope	keV	F (cps/Bq)	F (cps/gps)
Am-241	60	0.060	0.167
Cs-137	662	0.503	0.592
Co-60	1173 & 1332	0.995	0.498

Counting Efficiency Variation With Source Location (Empty Chamber)

The Am-241 source was mounted at the intersections of a grid marked on a sheet of cardboard (63.5 x 63.5 cm) and the counting efficiency (cps/Bq) measured at different locations throughout the measurement chamber in order to generate an average detector response factor together with maximum and minimum values.

The source positions were at the centre of a square grid at 6.3, 18.9, 31.5, 44.1 and 56.7 cm from the side and top/bottom walls. This was repeated at depths of 8.7, 26.1, 43.5, 60.9 and 78.3 cm from the front wall. Table 4 summarises the results for the 3 dimensions that define the point source location.

Table 4 Counting Efficiency E (%) Versus Source Distance (cm) From Chamber Walls

Distance from top (cm)	Distance from left (cm)	E at 8.7 cm from front (%)	E at 26.1 cm from front (%)	E at 43.5 cm from front (%)	E at 60.9 cm from front (%)	E at 78.3 cm from front (%)
6.3	6.3	5.58	7.79	8.53	7.26	5.69
18.9	6.3	6.50	7.46	7.89	7.18	6.40
31.5	6.3	6.27	7.33	7.27	6.85	7.04
44.1	6.3	5.58	6.61	6.64	6.54	6.77
56.7	6.3	4.72	5.57	5.73	5.94	5.40
6.3	18.9	6.54	7.63	8.10	8.00	7.03
18.9	18.9	6.59	6.90	7.40	6.96	7.42
31.5	18.9	6.69	6.75	6.63	6.84	7.30
44.1	18.9	6.38	6.09	6.58	6.70	7.46
56.7	18.9	5.78	5.78	5.71	6.35	6.44
6.3	31.5	6.58	7.43	8.10	7.70	6.82
18.9	31.5	6.74	6.79	6.97	7.15	7.43
31.5	31.5	7.06	6.60	6.72	6.89	7.59
44.1	31.5	6.77	6.27	6.37	6.35	7.04
56.7	31.5	5.59	6.00	6.20	5.99	6.32
6.3	44.1	6.39	7.48	7.91	7.59	7.05
18.9	44.1	6.72	6.74	7.37	7.44	7.34
31.5	44.1	6.86	6.78	6.86	7.15	7.43
44.1	44.1	6.82	6.69	6.48	6.89	7.04
56.7	44.1	5.92	5.87	6.36	6.42	6.42
6.3	56.7	4.97	7.15	7.92	7.50	6.34
18.9	56.7	5.97	7.37	8.02	8.05	7.18
31.5	56.7	6.66	7.06	7.83	7.96	6.79
44.1	56.7	6.37	7.03	7.12	7.28	6.82
56.7	56.7	5.39	6.12	6.33	6.37	5.59

The average efficiency was 6.78 % with a maximum value of 8.53 % (+25.8 %) and a minimum value of 4.72 % (-30.4 %). The lowest efficiencies were measured in the corners and towards the bottom of the chamber, with the highest towards the top and in the centre of the chamber.

Counting Efficiency Variation With Source Location (Full Chamber)

The chamber volume (350 l) was filled with 35 kg of coveralls, contained within a number of PVC bags, in order to represent a soft (low Z) waste matrix with a bulk density of 0.1 g/cc. Taking advantage of the symmetry of the chamber, source positions were measured only in the right front quarter, using a new grid marked on the source mounting card at 7.9, 23.7, 39.5 and 55.3 cm from the top wall and 26.5, 15.9 and 5.3 cm from the right side wall. This was repeated at depths of 7.3, 21.8 and 36.3 cm. Table 5 summarises the results for the 3 dimensions that define the point source location. As before the source was mounted at the grid intersections on the card, but this time surrounded by a number PVC bags containing coveralls.

The average efficiency for the filled chamber was 6.06 %. The maximum response was 7.59 % (+ 25.2 %) and the minimum 4.76 % (-21.5 %). Again the lowest efficiencies were towards the bottom of the chamber and in the corner, whilst the highest were towards the top and centre of the chamber. This small reduction in detector efficiency, compared to an empty chamber, appears inconsistent with the known mass attenuation coefficients for 60 keV photons. These indicate 40-50% reduction in efficiency for 35 kg of 0.1 g/cc coveralls. Hence further measurements were made with the source buried within bags of coveralls, rather than sandwiched between them. Table 6 summarises the results.

Table 5 Counting Efficiency E (%) Versus Source Location (Full Chamber)

Distance from top (cm)	Distance from right (cm)	E at 7.3 cm from front (%)	E at 21.8 cm from front (%)	E at 36.3 cm from front (%)
7.9	26.5	5.59	7.10	6.97
23.7	26.5	6.54	6.06	6.32
39.5	26.5	6.12	4.90	5.35
55.3	26.5	5.26	4.76	4.80
7.9	15.9	5.99	7.16	7.05
23.7	15.9	6.43	6.16	6.42
39.5	15.9	6.21	5.48	5.31
55.3	15.9	5.56	4.97	5.07
7.3	5.3	4.38	7.57	7.59
23.7	5.3	5.73	6.76	7.28
39.5	5.3	6.62	6.93	6.71
55.3	5.3	5.17	6.22	5.85

Three bags around 12 kg each (around 35 kg total), measuring roughly 60 cm high by 45 cm wide by 30 cm deep (0.15 g/cc), were positioned to fill the chamber evenly. The Am-241 source was buried at a number of locations and the counting efficiency measured (table 6).

Table 6 Counting Efficiency E (%) Versus Buried Source Location

Source height	Source width	Source depth	E (%)
Towards top	Central	Central	7.35
Middle	Central	Central	4.95
Towards bottom	Central	Central	4.23
Towards top	Central	Towards front	6.88
Middle	Central	Towards front	5.38
Towards bottom	Central	Towards front	3.92

The average efficiency in table 6 (5.45 %) is a little lower that in table 5 (6.06 %). This is probably due to the greater density of the 3 bags (0.15 g/cc) compared to that employed to achieve the results in table 5. Burying the source in the centre middle of the coverall bags gave an efficiency of 4.95 %

Counting Efficiency With Objects Present in the Chamber

The measurements in table 5 are applicable in situations where the chamber is filled with low bulk density, low Z material, such as: paper, PVC, clothing, wood. For high density/high z waste streams, such as: lead bricks, steel etc. the waste must not have significant internal shielding. For example, surface contaminated lead bricks could be measured one at a time to avoid one brick shielding a source on another brick. Thick steel pipes, which were contaminated on the pipe interior, would not be suitable for low level Am-241 measurements, but might be suitable for other nuclides. Table 6 summarises the efficiencies obtained when positioning an Am-241 source on/in various objects within the chamber.

Table 7 Counting Efficiency (%) Versus Source/Object Location

Source position	Object position	E (%)
Centre of HEPA filter	20 kg HEPA filter in centre	2.51
Centre of HEPA filter	12 kg HEPA filter in centre	1.79
Side of lead block	2x 11 kg lead blocks in centre	2.73
Side of steel block	4 kg steel block in centre	2.84
Base of lead block	2x 11 kg lead blocks in centre	1.01
Base of steel block	4 kg steel block in centre	1.53

The greater reductions in efficiency noted, when compared to soft waste, highlight the difficulty associated with calibrating for hard waste streams.

BACKGROUND VARIATION

Empty chamber backgrounds

Initial measurements were carried out in facility A with the standard 1 inch of lead shielding fitted. The Cronos was then moved to facility B and the trials repeated with and without a second (optional) inch of lead shielding fitted. Table 8 summarises the background cps achieved for an empty chamber.

Table 8 Background cps achieved in different facilities

Detector	Facility A (cps)	Facility B (cps)	Facility B with extra lead fitted (cps)
Front	534	339	255
Base	635	425	313
Left	671	369	268
Top	848	497	354
Right	738	447	313
Rear	763	382	273
All	4189	2459	1776
SD	10	5	5

The reason for the background reduction is thought to be siting the Cronos well away from the brick walls in facility B compared to facility A. Gamma spectra from the brickwork indicated significant NORM present in the building materials. Background variation studies in facility A indicated a 10 cps background standard deviation (SD) for repeat 600 s counts during a normal working day. This was much higher than the 3.3 cps SD reported on a background of 1344 cps by other workers (2). However relocating the Cronos to facility B reduced the background by 40 % and reduced the SD from repeated measurements by 50% to 5 cps. Adding additional lead shielding improved the gross background, but did not improve the SD from repeated measurements (Table 8). The measured SD from repeated measurements is still about 3 times larger than would be expected from counting statistics alone. Possible causes are normal facility operations with radioactive material and radon emanation. Further tests will be done in order to better define the cause.

Full chamber backgrounds

Studies in facility A indicated that dense metal objects (e.g. lead bricks) reduced the background slightly (around -2 cps/kg). This is thought to be due to photon shielding. Synthetic materials had little effect on the background when present as low bulk density material. However, natural materials (e.g. cotton, paper, wood) consistently elevated the background slightly (around + 3 cps/kg). Materials with high NORM concentrations (e.g. soil) gave much higher background elevation (around +40 cps/kg).

Repeating these measurements in facility B, with 35 kg of new orange coveralls in the chamber, gave a background of around 2590 cps with a SD of around 5 cps. This data is plotted in the form of a Shewart chart in figure 2. The mean background cps is marked with a green line and the 2x SD and 3x SD limits are marked in red. Adding the optional extra inch of lead shielding and repeating the measurements gave a further reduction in background cps to 1900, but the SD was still around 5 cps for repeat measurements over a normal working day. The background was, in both cases, elevated over the empty chamber values in Table 8 by around 130 cps (i.e. + 3.7 cps/kg).

The orange coveralls are composed of cotton and the measurements indicated a small net count rate which may be attributable to NORM. Materials, such as soils, contain relatively much higher concentrations of NORM. Hence a sample of uncontaminated waste must be measured in order to establish the detector response. Materials must then be segregated into groups of equal NORM concentration

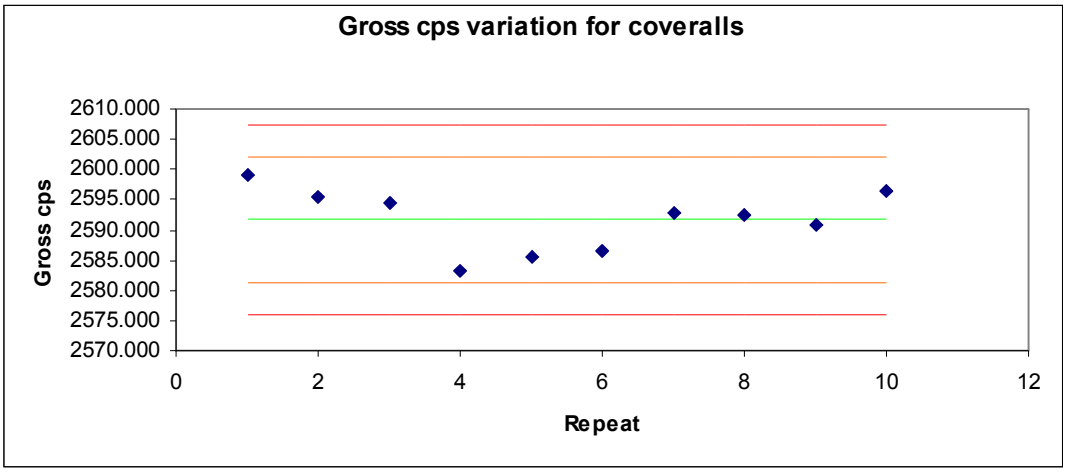

Figure 2 Background variation in facility B with mean, 2x SD and 3x SD limits indicated

Background variation with NORM

In order to investigate the effect of NORM a number of typical waste materials were monitored (600 s count) in facility B, with the extra lead shielding fitted:

- 35 kg orange coveralls with a bulk density of around 0.15 g/cc
- 45 kg wooden boards (60x86x17 cm), 0.5 g/cc
- 22 kg compressed PVC bags (45x30x15 cm), 1.1 g/cc
- 20 kg paper with a bulk density of around 0.17 g/cc
- 37 kg steel in the form of 2 brackets (30x15x15cm)
- 15 kg bucket of soil with a bulk density of around 1.4 g/cc

Table 9 summarises the net counts measured for these sample materials. Natural materials (e.g. paper, cotton, wood) gave a significant positive net count. Steel gave a small negative net count and this was probably due to photon shielding. The PVC net count was slightly positive. These trials highlight the importance of carefully characterising uncontaminated samples of the waste to be measured. These samples should be a close match in terms of physical characteristics (e.g. size, density, mass).

Table 9 Net cps/kg for commonly encountered waste materials

Waste Material	Net cps/kg
Steel	-0.4
PVC	+0.8
Wood	+2.8
Coveralls	+3.7
Paper	+3.8
Soil	+40.7

Repeat measurements on the reference 35 kg of coveralls established that the standard deviation was about 5 cps total, or 0.15 cps/kg with a mean of 3.7 cps/kg. This test needs to be repeated

with samples from other batches of coveralls and with clean samples of other waste materials that we plan to assay. This uncertainty must be propagated into the activity and MDA calculations.

DISCUSSION

For the Pu isotopic compositions, typically encountered at AWE, Am-241 (Pu-241 daughter) provides around 99.9 % of the photon yield over the Cronos-11 operating range (50 keV up to 2 MeV). Hence application of the isotopic fingerprint for the waste stream, to the Am-241 results, yields the total Pu alpha and beta activity. In most cases a multiplication factor of around 10 is needed. Hence the MDAs noted previously (table 1) may be adequate for measurements at the current exempt thresholds (e.g. 0.4 Bq/g for Pu wastes).

Using the background SD, during a normal working day, of 5 cps (achieved with coveralls), an efficiency of 6.06 % (achieved for Am-241 using 35 kg of clean coveralls) (table 5) a simplistic MDA may be calculated:

Detection Level = 4.65 x 5 / (0.0606 x 35,000) = 0.011 Bq/g (0.11 Bq/g Pu) (Eq. 4)

Another consideration is the increase in background counts from otherwise uncontaminated waste materials of interest. For example, table 9 indicates that 35 kg of the new orange coveralls has a net count rate of 129.5 cps above the background count rate for an empty chamber. This is equivalent to 129.5/0.0606 = 2.14 kBq Am-241 or 21,400/35,000 = 0.61 Bq/g Pu and would need to be subtracted from the measured activity from a bag of potentially contaminated coveralls. Furthermore, the uncertainty from this NORM background correction must be propagated into the final contaminated/clean decision. For example, using the 5 cps SD from repeat measurements of the reference 35 kg of coveralls, and assuming that there is no additional batch-batch variation, will raise the equation 4 values to around 0.16 Bq/g Pu.

Other materials, such as PVC, did not give as large a positive net count rate above background, but soil counts were relatively high (table 9) as may be expected given the presence of NORM in soil and the efficiency for these materials and densities will also be different than for the coveralls. Hence it is important to segregate wastes before monitoring into those with similar background counts, similar isotopic fingerprints and similar photon attenuating properties.

Provided that the chamber is filled with around 35 kg of low bulk density, low Z material, such as: PVC, paper, wood, rubber, plastic, coveralls etc. the detector efficiency (cps/Bq) for Am-241 is relatively uniform at around 6% +/- 1.5% throughout the chamber. This variation in detector efficiency with location, material, mass and density needs to be propagated into detection level calculations and more rigorously investigated for the full range of waste counting scenarios likely to be encountered.

High density, high Z objects such as lead bricks, steel plates, HEPA filters with metal casings on 4 sides etc. would be more difficult to assay accurately because of the greater variation in counter efficiency (Table 6). Furthermore high Z objects can lead to negative net counts due to absorption of background radiation (Table 9). Objects with a high degree of shielding, such as thick steel pipes with internal contamination, would be unsuitable for measurement of Am-241. However, nuclides with more penetrating photons would be easier to measure.

Another consideration is the potential presence of other photon emitters such as fission products (e.g. Cs-137, Co-60) or uranium compositions (e.g. HEU or DU) in addition to Pu. Hence it is also important to segregate wastes according to contaminant.

As noted previously it would be feasible to assay both HEU and DU waste streams at the exempt threshold. However, the self-attenuating properties of the sources used to calibrate the Cronos-11 would need to be well established because of the differential source self absorption and detector

efficiencies for the wide range of photon energies emitted. Alternatively, the response factors in table 1 could be used on the understanding that activity would be overestimated. By contrast Am-241 essentially has only the 60 keV emission and negligible self absorption within the source and therefore facilitates much easier calibration.

CONCLUSIONS

The Cronos-11 has the potential to assay Pu, HEU and DU waste streams at the current exempt thresholds (e.g. 0.4 Bq/g for Pu wastes) and is close to the 0.1 Bq/g Pu target, but improvements in stability of background and precision of calibration and correction factors still need to be made before this target of 0.1 Bq/g Pu can be achieved.

HEU and DU calibrations with the foil or disk sources available will overestimate activities and detection levels by a factor of around 2 or 3 if the source self-attenuation is not corrected.

Waste streams assayed must be pre segregated into materials with similar photon attenuation properties, similar NORM concentrations and similar isotopic fingerprints.

Measurement uncertainties (geometry/matrix) for lightly attenuating waste streams are +/- 25 % and this should be folded into detection limit calculations.

Other sources of uncertainty include uncertainty in the isotopic fingerprint and in the NORM corrections.

Calibration of the Cronos-11 for Am-241 (Pu) measurements is relatively straightforward compared to our available HEU and DU sources because of the multiple photon energies associated with uranium compositions and source internal absorption, as compared to the single 60 keV emission from Am-241 associated with Pu compositions.

Assay of other materials (e.g. high density and high Z items) will involve careful calibration and verification of the impact on background variation from shielding and NORM contamination.

RECOMMENDATIONS

Investigate background variation (shielding, NORM contamination) from all waste streams likely to be encountered.

Rigorously investigate variations in detector efficiency for the full range of waste counting scenarios likely to be encountered

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