TRU/LLW Segregation using Passive Neutron Coincidence Counting - 10072

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ABSTRACT

VT Group have significantly reduced the detection limit of their high efficiency passive neutron multiplicity counter using an innovative technique based on rejection of the cosmic ray induced neutron background component.

In a well shielded neutron counting chamber, such as VT Group's TRU-D$^®$ Drum multiplicity counter, the main sources of coincident neutron background counts will be interactions of cosmic rays with both the materials used to construct the measurement chamber and within the waste item being measured. By installing plastic scintillator detectors around the measurement chamber and connecting them into the time stamped data acquisition employed on this system, a pulse train is generated that includes both cosmic ray events (detected by the scintillators) and neutron events (detected by the neutron detectors). The software analysis of the pulse train has been configured to identify neutron signals that are correlated in time with the cosmic ray event. Subsequent analysis results in a substantial reduction in the coincident neutron background signal without affecting any true signal emanating from fissile material within the waste item.

Applying this methodology, significant reductions in the detection limit have been demonstrated using our development system. For a production system using this technology, the 99% confidence detection limit is 0.5 mg Pu-240 equivalent mass for all tested waste matrices for the typical 60 minute measurement time. This detection limit is low enough to facilitate segregation of LLW from TRU waste at the 100 nCi/g level ($\equiv$ 3.7 kBq/g).

INTRODUCTION

VT Group's TRU-D$^®$ Drum Monitor (Fig.1) is a high efficiency passive neutron multiplicity counting system with several advanced features to yield the best possible measurement performance. The system is designed with a close-fitting hexagonal measurement chamber and has two concentric rings of neutron detectors, giving a neutron detection efficiency of 35%. This system is also designed to have a low background through the use of background shielding and low atomic number construction materials inside the measurement chamber.

Fig. 1. TRU-D® Drum Multiplicity Counting System.

The Drum Monitor incorporates VT Group's patented [1][2] neutron counting technology based upon the timestamping of pulses from the neutron detectors (often referred to as list mode data acquisition). Individual head amplifiers are located directly on each detector and connected to local "hubs", which output digital neutron events onto a fibre optic ring. The digital pulse stream is passed to a PC based timestamping card for software analysis, which is either performed in real time and/or written to file for later re-analysis.

The neutron counting electronics extends the simple timestamping concept by additionally identifying each neutron event with the detector of origin. The recording of the detector information greatly expands the possibilities for analysis of the neutron pulse data, and several applications that have been developed are reported elsewhere [3]. The cosmic ray background correction methodology described in this paper is made possible by the ability to record the detector identification and pulse arrival time, which allows different types of detectors, in this case plastic scintillators, to be incorporated into a neutron counting system and contribute signals to the recorded pulse train.

The TRU-D® Drum Monitor system was developed for measurement of 200 litre drums containing TRU waste. However, a significant proportion of TRU waste at the Sellafield plant in the UK is known to contain negligible amounts of plutonium, and could therefore be recategorised as LLW, resulting in substantial cost savings with respect to subsequent waste processing and disposal. In the UK, the limit for disposal of alpha contaminated material as LLW is 4 GBq/t. However, as the total annual disposal limit of the national Low Level Waste Repository (LLWR) is 300 GBq, for a typical drum mass of 60 kg, only 1250 drums at the 4 GBq/t limit could be disposed of each year. Therefore in order to maximise the amount of material that can be disposed of as LLW it is necessary to be able to determine the alpha contents of such drums at a much lower level. Currently any waste with a plutonium alpha content greater than 0.1 GBq/t requires special clearance for disposal. A system that can reliably sentence drums at 0.4 GBq/t would be of major benefit allowing several thousand drums per year to be disposed of as LLW. These alpha activity limits mean that the plutonium detection limits for recategorisation of TRU waste as LLW are very low, typically being of the order of a few milligrams in a standard 200 litre waste drum. To give some example values, at the 0.4 GBq/t limit for a typical waste drum with a gross weight of 50 kg, the isotopic composition of the plutonium must be taken into consideration. If an isotopic composition of 20% Pu240 effective is assumed, the 0.4 GBq/t limit equates to 0.9 mg of Pu240 effective mass. However, if an isotopic composition of 10% Pu240 effective is assumed, the 0.4 GBq/t limit equates to only 0.7 mg of Pu240 effective mass. Similarly, if an isotopic composition of 30% Pu240 effective is assumed, the 0.4 GBq/t limit equates to 1.3 mg of Pu240 effective mass. It should also be noted, however, that in order to successfully segregate LLW drums at this level, the limit of detection of the radiometric instrument needs to be considerably lower than the sentencing threshold.

Previously only active neutron counting systems were capable of achieving the required plutonium detection limits; however, a significant proportion of the waste drums at Sellafield are also contaminated with uranium (for which the disposal limits are considerably higher), and the additional presence of U-235 prevents the use of active neutron systems for LLW segregation of Pu waste streams. However, the development described in this paper allows the current generation of high efficiency passive neutron systems to be capable of segregating the LLW at a 0.4 GBq/t level. This has been made possible by improving upon the current background correction techniques.

The Minimum Detectable Activity (MDA) of a passive neutron counting system is limited by the uncertainty in the measured background coincidence count rate [4]. Conventionally a waste item measurement is background corrected by subtracting the observed count rate from an empty chamber measurement performed prior to the waste item measurement – this was the approach applied previously by the TRU-D® Drum Monitor system, and has hence been used for comparison in this paper. In order to achieve a low MDA it is therefore necessary to "know" the background as precisely as possible and also to be certain that the "known" background value is applicable for the particular waste item being measured at the time of measurement. However there are certain factors which can significantly affect the ability to determine a suitable background count rate:

Random background variations – The coincident background rate is small and best described by Poisson counting statistics. Due to the infrequent nature of these background events, long measurement durations can be required to obtain a good estimate of the true coincidence signal. Such measurements are usually segmented, i.e. divided in to a number of equal time intervals, in order to allow statistical filtering of outliers and derivation of standard error on the measurement result. Care must be taken in the choice of segment length and statistical filter in order to ensure that any genuine neutron coincidence signal is not accidentally rejected.

Air pressure –	It is known that the background neutron count rate for both total and coincident neutron events has a dependence on atmospheric air pressure. During periods where the air pressure is changing rapidly, there is potential for the actual background count rate during a waste item measurement to be statistically incompatible with the previously acquired background value, which can lead to bias in the measurement result.
High atomic number materials –	Similarly it is known that certain high atomic number materials can produce a coincident neutron background due to interactions with cosmic rays [5][6]. This enhanced neutron signal can be partially removed by suitable segment filters and truncation techniques, however the residual neutron signal leads to enhanced coincidence background which is not accounted for by the reference background. Therefore for such high atomic number materials the measurement result can be significantly overestimated.

In order to minimise the MDA, it is necessary for the designers of passive neutron systems to account for the above effects. This can be done, to a certain extent, by designing a high efficiency chamber with suitable background shielding and minimising the amount of high atomic number materials used in its construction. The variation in the background signal can be minimised by employing suitable statistical segment filters, and removal or truncation of segments containing high multiplicity events. Other more advanced corrections are possible, when the waste type is known, a background determined for an inactive stimulant maybe used and when the waste type is less well defined additional information determined from separate neutron interrogation or RTR measurements can be used to select an appropriate background correction. These techniques can be used to good effect in certain cases but rely on assumption that the background count rate is consistent and can be accurately estimated,. VT Group have taken this one step further by the development of an innovative in measurement cosmic ray background correction methodology [7], which has been implemented on our TRU-D® Drum Monitor system.

COSMIC RAY BACKGROUND CORRECTION

The cosmic ray flux at sea level is mainly composed of high energy muons, but also comprises electrons liberated by ionisations, decay products from other interactions and less commonly higher mass particles such as protons and other atomic nuclei may reach sea level. The cosmic ray flux varies inversely with air pressure. The cosmic ray flux detectable with commercially available scintillator detectors also varies with air pressure with the majority of this signal attributed to the muon component of the flux.

It is known that the background neutron count rate also varies with air pressure [4] and that cosmic ray interactions with high atomic number materials within a waste item cause a coincident neutron signal [5][6]. It has been shown that cosmic rays can be correlated with neutron bursts seen in a lead pile [8].

A large component of the total neutron background signal is due to larger bursts of neutrons caused by interactions of the charged atomic nuclei. These relatively infrequent events can yield a large number of neutrons which consequently give a high multiplicity signal and can be easily identified and removed by segment truncation and filtering techniques. The remaining component of neutron background consists of a larger number of smaller bursts; the detected low multiplicity of such events make these indistinguishable from fission events and therefore difficult to remove by statistical techniques.

However long background measurements show that this remaining signal exhibits a strong correlation with air pressure indicating that this component is also likely to be directly related to cosmic ray interactions. For example the dominant component of the cosmic ray flux, muons, interact with materials producing neutrons by either spallation or capture reactions, and such reactions will typically produce a small number of neutrons.

It is therefore considered that a direct measurement of the cosmic ray flux would provide useful information about the background during the neutron measurement. It may also be possible to directly correlate individual neutron events with cosmic ray events. This would then lead to the ability to reduce the measured background and improve the MDA for passive neutron systems.

Commercially available plastic scintillator detectors [9] were selected for measurement of the cosmic ray flux. Plastic scintillators should be sensitive to all of the charged particle components of cosmic rays, and due to the very high energy of these particles, most will pass straight through the 2.5cm thick plastic whilst still depositing a considerable amount of energy. This results in a light pulse which is amplified by a photomultiplier tube to give an output which can be fed directly into the VT Group's neutron counting electronics. This permits the events from scintillators to be included within the neutron pulse stream output from the neutron detectors. Previous work with these scintillators has determined that muons comprise the vast majority of the detected signal. However, it is noted that they are also sensitive to gamma ray interactions, and a suitable discriminator setting is required to remove this component of the signal. As the cosmic rays are typically of very high energy and the particles travelling at relativistic speeds, it can be considered that any interaction with the materials in the waste item or measurement chamber will occur at almost the same instant as the cosmic ray is detected in the scintillator detector. The resultant neutrons from both spallation and capture reactions will be emitted promptly and will be detected by the neutron detectors following the normal Rossi-Alpha distribution.

Initial experimental trials were performed in which a pile of lead bricks (200kg) was surrounded with plastic scintillator detectors and placed inside the TRU-D® Drum Monitor measurement chamber. Fig.2 shows a 100 s segment of neutron count data from the recorded pulse train. The time between successive neutron pulses is plotted against the time in the pulse train. The signals from the plastic scintillator detectors were fed into the pulse train, and although Fig.2 only shows the neutron events, the cosmic ray events have been used to highlight neutron events that occur within a defined "veto" time interval of 125μs of each cosmic ray event.

It can be seen that the neutron events lie in two distinct horizontal bands: the upper band corresponds to random, single neutron events as would be expected from the Poisson distribution for a total background count rate of 4 cs^{-1}; the lower band shows neutron events detected within a short time interval of another event, and these events typically contribute to the coincident or "Reals" neutron background in a passive neutron coincidence counting (PNCC) measurement. The majority of these Reals background events occur as single events in the lower band (meaning that only two neutrons were detected close together), but as can be seen there are occasional vertical streaks (for example, at approximately 15s) corresponding to high multiplicity bursts of neutrons. These infrequent large bursts of neutrons, result in high multiplicity events which dominate the reals signal but will normally be removed by applying a statistical filter to the time-segmented data. It is the more frequent single events that give rise to the reported neutron coincidence background rate.
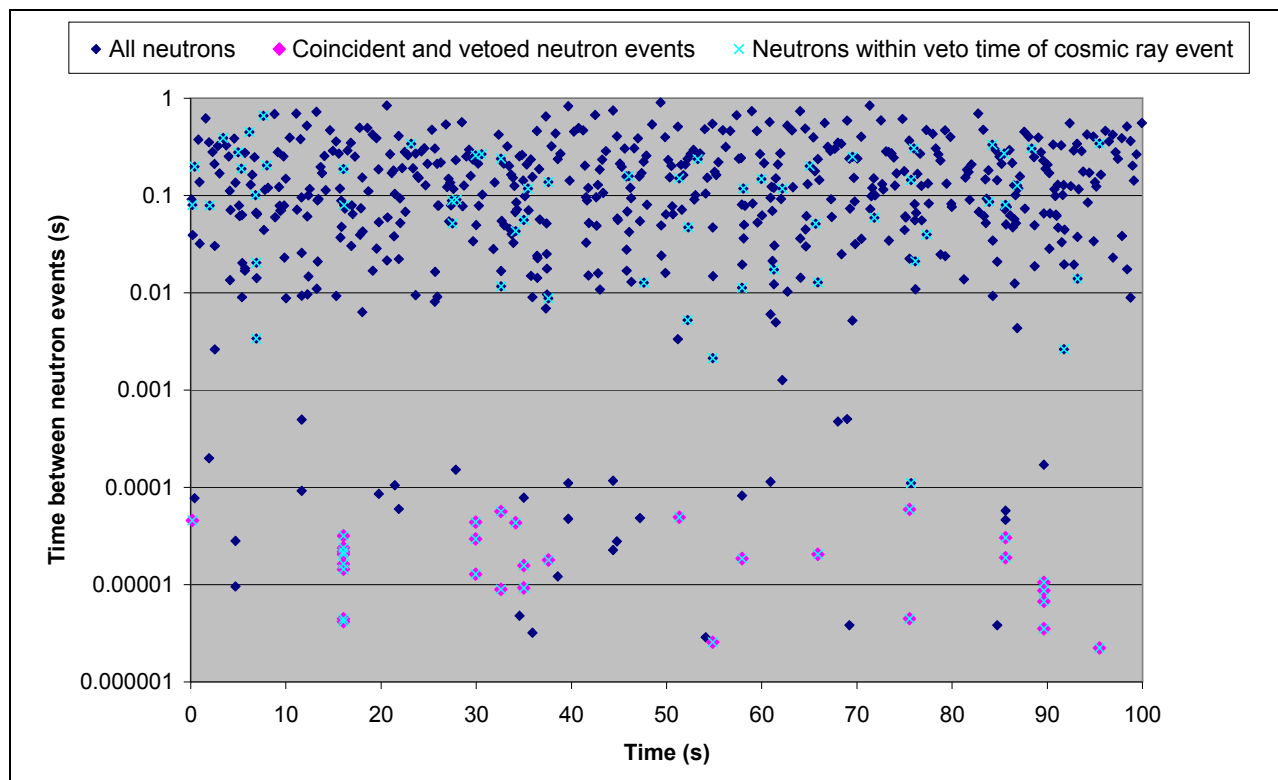
Fig. 2. Time Interval between Neutron Events (100s of Pulse Train Recorded with a Lead Pile).

In the example in Fig.2, approximately 250 cosmic ray events per second were detected in the scintillator detectors. If the neutron events that occur within the "veto" time of 125μs of each cosmic ray event are removed from the pulse train (i.e. the passive neutron counter is effectively switched off for 125μs each time a cosmic ray is detected), this will result in a system dead time of 3%. However, more than half of the coincident neutron events (i.e. in the lower horizontal band in Fig.2) would be removed by the vetoing, thus significantly reducing the Reals neutron background.

Figure 3 shows the effect of changing this veto time for lead and also compares the magnitude of the effect for other materials. Each measurement was performed in the same geometry with the material and four scintillators placed inside the neutron measurement chamber. As this geometry did not provide for full 4π scintillator coverage of the target material it was expected that there would be some cosmic ray interactions which would not be detected by the scintillators.

The background corrected response for each material obtained is normalised to 100 kg and the magnitude of the induced neutron coincidence signal shows a strong correction with the Z number of the material but in each case the residual reals signal (at long veto times) is reduced by a similar fraction. For the low Z measurements the applicability of the background used to correct these results becomes important as the background subtracted is also subject to the same veto analysis. This accounts for the coincident neutrons arising from cosmic ray events within the body of the measurement chamber however this residual empty chamber background was also found to fluctuate with air pressure.
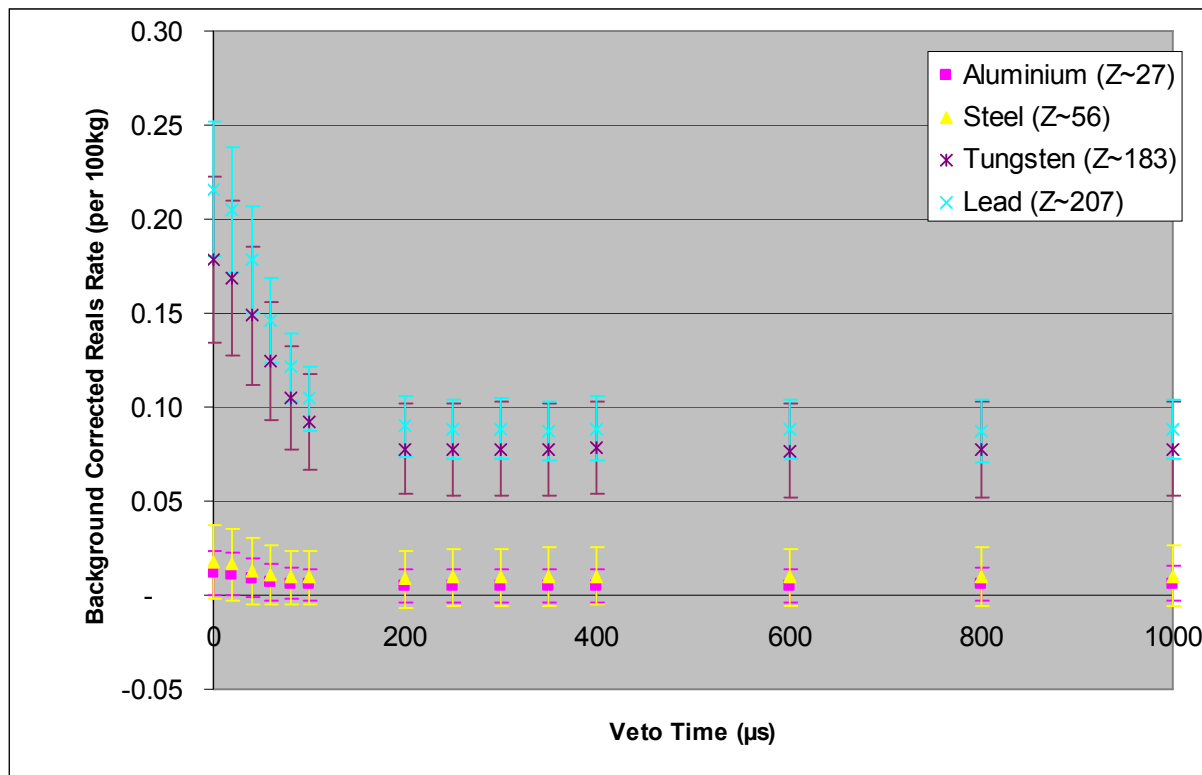
Fig. 3. Effect of changing Veto Time for Various Materials

These initial results demonstrate that a significant proportion of the neutron background can be identified as correlated with detected cosmic ray events, and that by removing these events from the neutron analysis, a considerable reduction in the coincident neutron background is possible.

A detailed study was then undertaken to determine the optimum configuration of plastic scintillator detectors to implement this methodology on the TRU-D® Drum Monitor. Initially the plastic scintillator detectors were placed on top of the measurement chamber to cover the whole surface. This arrangement, the performance of which is described in detail in the next section, allowed some 25% of the background coincident neutron count rate to be correlated to the detected cosmic ray flux. (Note that this is 25% of those that remained after a segment filter had been applied to remove the high multiplicity neutron bursts). Trial measurements indicated that adding detectors to the sides of the hexagonal measurement chamber would increase the overall cosmic ray veto efficiency to greater than 80%, but limitations in the number of detectors available meant that it was not possible to test this arrangement.

It is noted that additional scintillator coverage will increase the cosmic ray detection efficiency which in turn increases the system dead time. However the highest incident cosmic ray flux comes vertically down[1] and will pass through the scintillators on the top of the chamber, those particles incident at lower angles are likely to pass through more than one scintillator. Although these will generate separate events in the pulse stream, the veto time generated will be concurrent (i.e. if a cosmic ray is detected in more than one scintillator, then only one veto time will be applied), therefore the effect on the system dead time will be lessened.

If a very high (>90%) fraction of the cosmic ray signal responsible for the induced neutron signal can be detected by the plastic scintillators, then the simple veto approach described above can be applied. The cosmic ray events are contained within the neutron system pulse stream, and the analysis of this pulse stream can be modified to remove any neutron signals seen within a short "veto" time period after each cosmic ray event. The acquisition would keep track of the amount of time the system was "switched off" in order to ensure the correct total live time is used in subsequent calculations. This would lead to a single data acquisition from which the majority of the cosmic induced background coincidence signal has been removed. As the fission neutron signal from any plutonium within the waste item is not correlated with the random cosmic ray signal, there would be no effect on the plutonium measurement result. The resulting segmented acquisition could then be analysed as normal in order to provide a background corrected plutonium mass.

Utilising this approach to minimising the neutron background reals signal and therefore improving the limit of detection of a passive neutron system involves maximising the detection of cosmic ray induced neutron events. This requires both high detection efficiency for the incident cosmic rays and a veto time several times the chamber die-away time in order to ensure the highest fraction of cosmic induced events are eliminated from the pulse stream. However maximising these two parameters will also result in a significant dead time and an increase in the overall measurement times is then necessary to maintain the same measurement precision.

This led to the development of an alternative approach which does not rely on such a high detection efficiency of the cosmic ray flux. This alternative cosmic ray background correction uses a covariance analysis of both the raw and vetoed reals rates to determine the total cosmic ray induced signal. The measured difference between the raw and vetoed signal is multiplied by a constant factor and subtracted from the raw signal. The factor is determined by calibration using a range of inactive test drums, and is calculated from the fraction of the observed reals which are correlated with cosmic ray events and the assumption that that all observed background coincident events are due to cosmic ray interactions.

Note that in applying this correction, constant cosmic ray veto fraction is assumed across the whole volume of the measurement region and care must be taken in the arrangement of the plastic scintillator and neutron detectors to ensure that this is achieved as closely as possible.

External sources of background neutrons will not produce any coincident neutron signal in a well shielded neutron chamber, therefore this technique does not need to reference any previous background as the full background correction is determined from within the measurement itself, and no prior knowledge of the waste matrix constituents is required. The correction accounts for the coincident background components arising from cosmic ray interactions within the waste item and within the body of the chamber.

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[1] Note that the cosmic ray flux is expected to vary with $\cos^2(\varphi)$, where φ is the angle from the vertical [10]. Therefore the highest component of the flux will be coming straight down – i.e. the shortest path through the atmosphere.

The measurement can be viewed as consisting of two parallel segmented acquisitions on the same pulse stream. In addition to a normal multiplicity acquisition of the neutron events in the pulse stream, a second vetoed acquisition is performed where the scintillator pulses are processed and used to "switch off" the neutron acquisition for a short period after each cosmic ray event is detected. The two segmented multiplicity acquisitions are then processed to obtain the segment coincident (or Reals) neutron count rates. A segment filter is applied to each acquisition and the segments accepted in both the normal and vetoed acquisitions are then subject to covariance analysis. The segment filter is required to reject the high multiplicity bursts of neutrons that are seen infrequently in the pulse streams, thereby providing a stable result allowing the neutron signal arising from the lower multiplicity bursts to be accurately determined.

Since the two Reals rates were obtained from the same original pulse stream, all of the Reals events in the vetoed data will also be in the normal (un-vetoed) data, although a number of events will have been removed by vetoing (i.e. the neutron events found to be coincident with a cosmic ray event). Therefore, the Reals rates calculated from the two pulse streams will be strongly covariant.

The cosmic ray background corrected Reals count rate, R_{CORR}, is given by the following expression:–

$$R_{CORR} = R_{NORM} - F \cdot (R_{NORM} - R_{VETO})$$ (Eq.1)

Where,

R_{NORM} = Reals count rate derived from normal (un-vetoed) data acquisition.
R_{VETO} = Reals count rate derived from vetoed data acquisition.
$1/F$ = Fraction of the cosmic ray induced background events identified in the vetoed pulse stream.

The uncertainty associated with the cosmic ray background corrected Reals count rate, σR_{CORR}, is given by the following expression:–

$$\sigma R_{CORR} = \sqrt{(F-1)^2 \cdot \sigma R_{NORM}{}^2 - 2 \cdot (F-1) \cdot F \cdot \mathrm{cov}(R_{NORM}, R_{VETO}) + F^2 \cdot \sigma R_{VETO}{}^2 + (R_{NORM} - R_{VETO})^2 . \sigma F^2}$$ (Eq.2)

The fraction, $1/F$, describes the efficiency with which the Reals caused by cosmic ray interactions are identified. In the case where all cosmic ray induced neutron events are detected, F=1 and $R_{CORR} = R_{VETO}$, however as discussed above such an arrangement requires perfect scintillator coverage, a long veto time and would therefore exhibit a considerable dead time.

This factor will be dependent on a number of factors including the geometry of the cosmic ray detector and the method by which outlying segments are rejected. In order to yield a useful correction, the correction factor must be representative of the entire waste item volume.

MEASUREMENT RESULTS

To evaluate the performance of the cosmic ray background correction technique described in the previous section, a series of test measurements were performed using a development version of the TRU-D® Drum Monitor system. A total of seven 60 cm by 60 cm plastic scintillator detectors were placed on the top surface of the measurement chamber (i.e. giving total surface area coverage of 2.5 m^2). Further optimisation of scintillator operating voltage and discriminator level lead to a total cosmic ray count rate of around 400 cs^{-1} which, combined with a conservative veto time of 250 μs, gave a dead time of approximately 10%. Typically acquisitions were performed continuously over a 17 hour period, recording the pulse streams in a continuous sequence of 10s segment files. In the data analysis these were processed as a rolling 60 minute acquisition each consisting of 360 segments.

This development system has a reduced number of 1 m He-3 neutron detectors, giving a total neutron detection efficiency of 25%, whereas the production system has 1.2 m detectors yielding a detection efficiency of 35%. As the detectors were shorter than in the production design, this resulted in a reduction in the neutron detection efficiency with height within the measurement chamber. This counteracted the solid angle effect of having scintillators only on the top of the chamber which lead to a higher cosmic ray detection efficiency for material at the top of the chamber than seen at the bottom.

Trials with 200 kg lead target place at the base of the chamber, the top of the chamber and along the vertical axis of the chamber gave consistent results. With this arrangement, $25 \pm 2\%$ of the background Reals count rate was found to be coincident with the detected cosmic ray flux ($F = 4 \pm 0.3$).

Background measurements were then performed for a wide range of different simulated waste matrices, ranging from low mass, low atomic number materials such as an empty drum, filters, paper and plastics, to high mass, high atomic number materials such as concrete, ferrous metals and lead. The performance of the cosmic ray background correction technique described in the previous section was compared against the standard background correction technique, which is based upon an empty chamber background measurement performed immediately prior to the waste drum measurement. The background corrected Reals neutron count rates have been converted to a detection limit in terms of Pu-240 equivalent mass, m_{LOD}, using the following equation (based on [11]):–

$$m_{LOD} = \frac{k^2 + 2 \cdot k \cdot \sigma R_{CORR} \cdot t}{A \cdot t}$$ (Eq.3)

Where,

$k =$ Factor relating to the degree of confidence in the detection limit (a factor of 2.326 is appropriate for 99% confidence (required for compliance with the current UK limits).

$\sigma R_{CORR} =$ Uncertainty on the background corrected Reals count rate.

$A =$ Calibration factor relating the Reals count rate to Pu-240 equivalent mass (i.e. $cs^{-1} \, g^{-1}$ Pu240eq)

$t =$ Measurement time

In addition to the measured performance using the TRU-D® Drum Monitor with 25% veto fraction for cosmic ray induced neutrons, the predicted performance for a system with enhanced performance is also quoted. The enhanced system would have the full quota of He-3 neutron detectors and hence higher and flatter neutron detection efficiency, plus additional coverage of plastic scintillator detectors (on the sides as well as top surface of the measurement chamber) will increase the detection efficiency for cosmic ray induced neutrons to 70% or higher. Note that the predicted performance is based upon experimental data from a previously supplied TRU-D® Drum Monitor with 35% detection efficiency, combined with data from trial measurements with the available plastic scintillator detectors in different configurations on the development system. The detection efficiency for cosmic ray induced neutrons on the production system has been conservatively estimated as 70%, this accounts for the practicalities of mounting scintillators and allows for a reduction in veto time in order to minimise the overall dead time.

The increased coverage provided by the scintillators on the sides should account for the effects of angular variations in cosmic ray flux and local effects on this flux due to nearby structures, providing consistent cosmic ray detection efficiency for interactions throughout the volume of the measurement chamber. The applicability of the covariance correction at higher detection efficiencies was determined by analysis of the trial measurement data.[2].

The detection limit results for a range of simulated waste matrices are shown in Fig. 3. The calibration factor A, is defined as the calibration value for the plutonium content of a non-interfering matrix. This is most appropriate for high Z materials such as steel and lead and matrices such as filters. For more interfering matrices such as concrete or high density plastics the actual detection limit would be slightly higher. In the production system this would be identified and corrected for by a suitable matrix correction technique.

The detection limit acquisitions were performed continuously over a 17 hour period and the data analysis processed this as rolling 60 minute samples each consisting of 360 segments. The resulting uncertainty associated with the $\sigma R_{CORR,}$ for each sample was calculated using Eq.2 and the mean value of $\sigma R_{CORR,}$ showed good agreement with observed standard deviation in the cosmic ray background corrected reals count rate $R_{CORR.}$
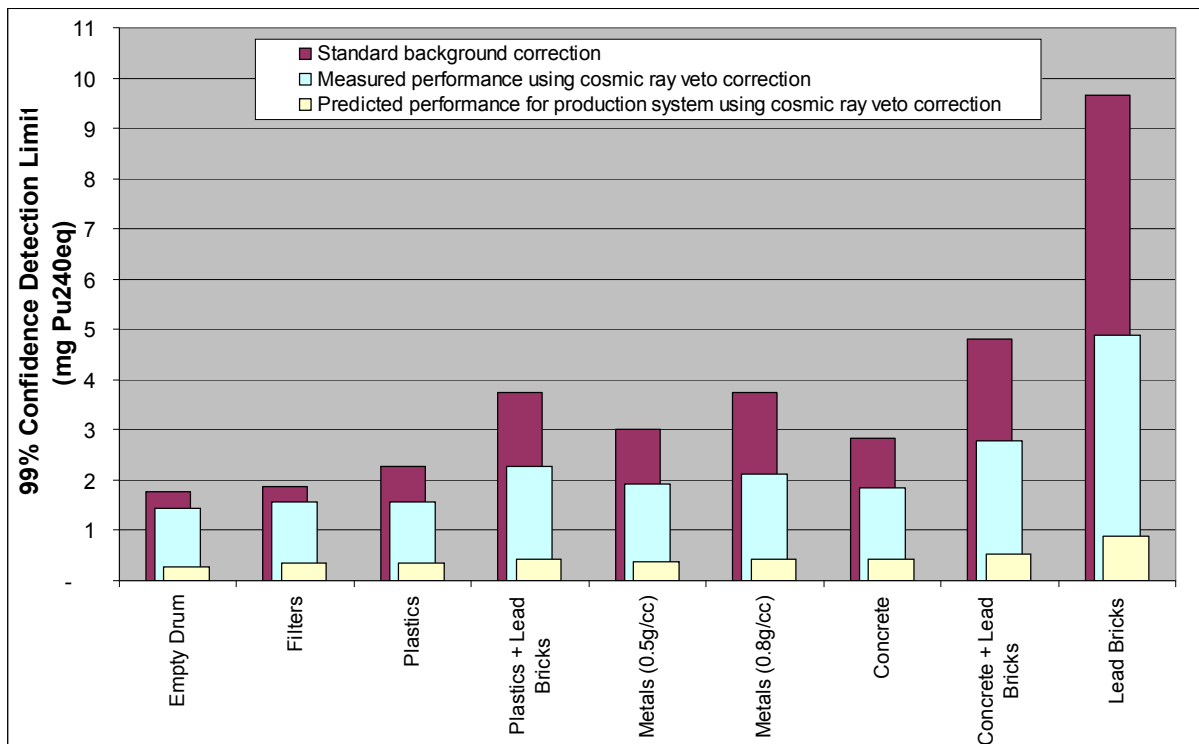

Fig. 3. Measured and Predicted Detection Limit Performance using Cosmic Ray Background Correction.

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[2] During initial trials with scintillators surrounding a lead target within the measurement chamber the effect of increasing the detector voltage and discriminator values was examined. At high scintillator voltages it was found that high cosmic induced neutron detection efficiency could be achieved. Although these high results were determined as being due to the detection of secondary prompt gammas resulting from the cosmic ray interaction rather than direct detection of the incident cosmic rays, the mathematics of the covariance analysis remains valid. This examination of the covariance behaviour at higher detection efficiencies allows the performance achieved by full scintillator coverage to be estimated.

As expected, the cosmic ray background correction gives the greatest reductions in detection limit for the waste matrices that contain high atomic number materials such as lead. However, even in the low density matrices considerable improvement is gained. The measured results using the development system clearly demonstrate that the correlation between cosmic ray events and the coincident neutron background can be used to provide a background correction that is derived from the measurement itself, and that this significantly reduces the effect of cosmic ray interactions. The predicted performance for the higher detection efficiency production system indicates that 99% confidence detection limits of approximately 0.5mg Pu-240 equivalent are achievable across the range of waste matrices that were tested.

The considerable improvements in detection limit gained from applying this cosmic ray background correction methodology mean that the TRU-D® Drum Monitor is capable of segregation of LLW from PCM. This is illustrated in Table I where the (99% confidence) Pu-240 equivalent mass detection limits have been converted to a plutonium alpha activity concentration for comparison against LLW disposal limits. A pessimistic default isotopic composition that assumes 6% Pu-240 has been used to convert the Pu-240 equivalent mass to plutonium alpha activity.

Table I. TRU-D® Drum Monitor 99% confidence detection limit performance.

Waste Matrix	Standard background correction (with development system)		Measured performance (with development system) using cosmic ray background correction		Predicted performance (for production system) using cosmic ray background correction	
	Pu-240 Equivalent Mass Detection Limit, mg	Plutonium alpha activity concentration, GBq/t	Pu-240 Equivalent Mass Detection Limit, mg	Plutonium alpha activity concentration, GBq/t	Pu-240 Equivalent Mass Detection Limit, mg	Plutonium alpha activity concentration, GBq/t
Plastics (50 kg)	2.27	2.04	1.58	1.42	0.36	0.33
Metals (120 kg)	3.00	1.12	1.91	0.72	0.38	0.14
Concrete (266 kg)	2.83	0.48	1.85	0.31	0.43	0.07
Lead (100 kg)	9.65	4.34	4.89	2.20	0.88	0.40

These results demonstrate that the development system would be capable of segregation of LLW at a plutonium alpha activity concentration of 2 GBq/t. The performance of the production system is predicted to be capable of LLW segregation at the 0.4 GBq/t level.

Measurements were also carried out to confirm that the cosmic ray background correction technique would not bias the measurement performance when there is plutonium present in the waste drum. If the scintillators were sensitive to prompt neutron or gamma emissions emanating from plutonium within the chamber then plutonium mass could be significantly underestimated. A short series of trials (of varying measurement time) were performed with a range of plutonium masses located inside a simulated waste matrix comprising of concrete. A concrete matrix was selected to ensure that the cosmic ray induced neutron background component was relatively large. The results are tabulated in Table II.

Table II. Test Measurements with Plutonium Sources.

Plutonium Mass, g	Pu-240 Mass, g	Uncorrected Reals Count Rate, cs^{-1}	Cosmic Ray Background Corrected Reals Count Rate, cs^{-1}
25	5.85	200.78 ± 1.16	200.40 ± 1.40
50	11.70	410.50 ± 7.28	408.48 ± 7.31
80	18.72	662.07 ± 4.75	659.43 ± 5.13

These measurements show a linear plutonium response of 0.035 Reals s^{-1} mg^{-1} Pu240 and indicate that the cosmic ray background correction does not significantly affect the signal from plutonium. As the scintillators appear to be relatively insensitive to radiation emanating from these high plutonium masses any affect on measurements of plutonium at the milligram level will be negligible. Additional testing indicated that the scintillators were insensitive to both external and internal gamma and neutron sources due to the high discriminator setting used.

CONCLUSIONS

VT Group has developed a neutron counting technology based upon the timestamping of pulses from detectors in a counting system. The timestamping concept has been extended by additionally identifying each detected event with the detector of origin. This recording of detector information permits different detector types to be installed in the same counting system, contributing events to a single system pulse stream. This capability has been used to develop a cosmic ray background correction technique that significantly improves the detection limit of passive neutron counting systems.

The coincident (or Reals) neutron background in a passive neutron counting system is dominated by neutrons generated by cosmic ray interactions with the materials used to construct the measurement chamber and those present within the waste item. Experimental results indicate that there are two components of this flux: large neutron bursts from the interactions with the nucleon component of the cosmic ray flux; and smaller bursts of neutrons mainly due to interactions with the muon component of the flux. Conventional segment filtering can be used to remove the larger bursts, but the low order multiplicity bursts from the muon interactions remain and it is assumed that almost all of the coincident neutron background (after segment filtering) is from this component.

By surrounding the top and sides of the neutron counting chamber with plastic scintillator detectors, it is possible to measure the cosmic ray flux incident on the measurement chamber. Experiments have shown that the coincident neutron background is correlated to detected cosmic ray events, and by vetoing (i.e. removing) neutron events detected within a short "veto" time of a cosmic ray event, the coincident neutron background is considerably reduced. Using this approach, 25% veto fraction for cosmic ray induced neutrons was demonstrated with a TRU-D® Drum Monitor development system, and in a full production system with higher neutron detection efficiency and increased plastic scintillator coverage, this should exceed 70%.

The development system showed a significant improvement in the detection limit of the passive neutron measurement for all waste matrices, including those containing low density soft waste. The predicted performance for the higher detection efficiency production system indicates that 99% confidence detection limits of approximately 0.5mg Pu-240 equivalent is achievable for all waste matrix types. Converting these mass detection limits into an activity concentration, a production system would be capable of LLW segregation at the 0.4 GBq/t level. This level of performance would normally require active neutron interrogation, but can now be achieved with simple, reliable passive counting technology.

REFERENCES

[1]   "Improvements in and Relating to Signal Handling and Processing", International Patent Publication Number WO 00/67044, Granted as US6912485, EP1175627, KR679707, CN1175281. Priority date 4th May 1999.

[2]   "Improvements in and Relating to Monitoring of Radioactive Emissions", Patent Publication Numbers; GB2424703, EP1707992, US2006219518, JP2006284589. Priority date 31st March 2005.

[3]   M. WILSON, J. RACKHAM, J. SHARPE, "Improvements to Neutron Counting System Data Acquisition and Processing", Proc. 31st ESARDA Symp. on Safeguards and Nuclear Material Management (2009).

[4]   S. CROFT, ET AL, "The Estimation of the Minimum Detectable Activity from Measured Passive Neutron Coincidence Counter Data", Proc. 46th Int. Symp. on Nuclear Material Management (INMM) (2005).

[5]   S. CROFT and L.C.A. BOURVA, "The Specific Total and Coincidence Cosmic-Ray-Induced Neutron Production Rates in Materials", Nucl. Instr. and Meth. A 505 (2003) 536.

[6]   H. MENLOVE, et al., "The Design of a High-Efficiency Neutron Counter for Waste Drums to Provide Optimised Sensitivity for Plutonium Assay", Proc. 5th Nondestructive Assay and Nondestructive Examination Waste Characterisation Conf. (1997), Los Alamos National Laboratory document LA-UR-96-4585.

[7]   "Improvements in and Relating to Assaying of Waste", Patent Application Number GB817703.2, Priority date 26th Sept 2008.

[8]   G. CHAPLINE, et al., "Cosmic Ray Induced Neutron and Gamma-Ray Bursts in a Lead Pile", Lawrence Livermore National Laboratory document UCRL-TR-230895 (2007).

[9]   "Large Cosmic Ray Plastic Scintillation Detector for Fast Counting Applications with Built in HV Supply and Single Channel Analyser", SCIONIX Model R600*25 B 600/1-HV-E3-P-X, SCIONIX Holland BV.

[10]   P. K. F. GRIEDER, "Cosmic Rays at Earth: Researcher's Reference Manual and Data Book", Elsevier Science BV, 2001, ISBN 0-444-50710-8.

[11]   L.A. CURRIE, "Limits for Qualitative Detection and Quantitative Determination: Application to Radiochemistry, Anal. Chem. 40, 586-593 (1968).