Effect of Cosmic-ray Shielding in Passive Neutron Coincidence Counting

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ABSTRACT

The minimum detectable Pu-240 effective mass for a passive neutron coincidence counter (PNCC) in a given measurement situation is ultimately set by the background neutron rate. Assuming that there is no significant source of neutron emission in the proximity of the system, the background rate is usually dominated by cosmic ray induced neutrons. In order to improve the detection limits overhead cosmic ray shielding should be considered. In this paper, we present results from an experimental assessment and calculations of the effect of overhead shielding on the cosmic ray induced neutron events. Background data were taken with a pair of active-well coincidence counters in different locations under different thicknesses and configurations of concrete to provide shielding from cosmic rays. Comparisons are made to historical performance data and to published work. These results will be useful when considering the location and shielding of PNCC systems.

INTRODUCTION

In passive neutron counting the Pu detection limit for a given measurement protocol is ultimately governed by the background rate. If there are no neutron emitting sources in the surroundings of the counting chamber then the background is dominated by cosmic-ray induced neutrons.

Shielding of the counting chamber can help to reduce the cosmic-ray induced background. Concrete is a convenient construction material that can be used as an effective cosmic-ray shield. It provides a relatively straightforward way of supplying a high stopping power medium to energetic cosmic rays.

In this work, we present experimental data from a pair of Active Well Coincidence Counters (AWCCs) operated in passive mode in the presence of different amounts of overhead concrete shielding. Most of the measurements reported here were made with a lead-lined AWCC that was designed to be used in a shielded hot cell for the active measurement of items irradiated in a reactor; the lead was included to reduce the gamma-ray dose rate striking the He-3 filled proportional counters.

This counter was characterized as a passive neutron multiplicity counter using shift-register neutron correlation analysis including determination of multiplicity dead-time parameters. Because of the high efficiency, high sensitivity to cosmic radiation (because of the lead liner), and characterization history of this detector, it was considered to be a good choice to use for study the background reduction due to overhead shielding.

We present results for measurements taken in different levels of a multi-storey parking lot at the Meriden shopping mall, CT, USA and the corresponding scaling rules developed to estimate the degree of background reduction achieved in certain configurations.

In order to determine whether there could be a coupling effect between the concrete shielding and the assay system, additional background measurements were taken in a shielded cell at different heights to vary the distance between the counter and the overhead shielding. These measurements were done with a standard AWCC, CANBERRA Model JCC-51 filled with 65 kg of lead bricks inside the cavity to serve as the cosmic ray target.

EXPERIMENTAL ARRANGEMENT

The lead-lined AWCC contains 56 He-3 tubes arranged in two rings inside an annular moderator of high-density polyethylene. The measurement cavity is lined with 0.076 m thick lead. It weighs about 545 kg and consequently the ambient background rates are considerably enhanced due to cosmic ray interactions in the lead annulus. The lead-lined AWCC stands approximately 1.2 m (including the wheels) and has a diameter of approximately 0.7 m. The top plug stands 0.25 m tall including handles. Fig. 1 shows top and side view drawings of the counter.

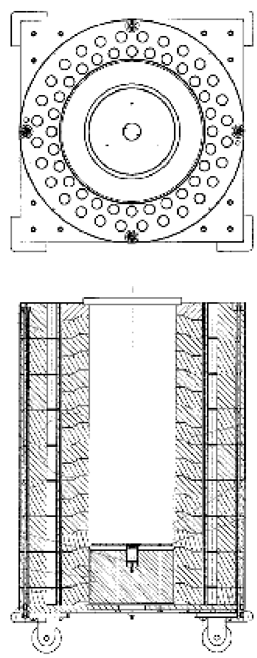

Fig. 1. Lead-lined AWCC top and side views

To test the effects of concrete shielding, the background Totals and Reals rates in the AWCC were measured when the counter was placed in turn on three levels of the shopping mall parking lot. The Meriden mall is located approximately 50 meters above sea level. When the measurements were performed, 8 out of the 56 He-3 tubes, although physically present, were disconnected from the counting circuit. The Cf-252 efficiency in this configuration was 28.1% for source at the center of the cavity.

In some configurations, when the concrete shield is closely coupled to the assay system, there is a potential trade-off to be struck between the concrete attenuating the incoming fluence rate of high energy cosmic ray particles and being a source of high multiplicity spallation neutrons that can themselves impinge of the detector and add to the ambient background of time correlated events. Additional measurements were done in order to evaluate this effect using the second system.

RESULTS

The parking building is comprised of three levels; two concrete floors/ceilings of approx. 0.15m (15cm) and an uncovered top floor. The estimated thickness is based on visual inspection; a 20% uncertainty in the thickness has been used in the calculations presented. The results of these measurements are summarized in Table I. Singles is the Totals or Gross count rate, Reals is the pairs or Doubles rate from shift register analysis and Triples rate is the next higher associated order. We use thickness to quantify the amount of shielding material present although we caution that the density and composition of the concrete (particularly the amount of any reinforcement steel bar present) has not been explicitly checked.

Table I. Measured Background Rates with the Lead-lined AWCC in the Presence of Different Amounts of Overhead Shielding

Location	**Overhead shielding (cm)**	**Singles rate (cps)**	**Doubles rate (cps)**	**Triples rate (cps)**
Mall 3rd level (Open air/No ceiling)	0	22.244±0.066	15.332±0.108	26.401 ± 0.446
Mall 2nd level	15.2± 3.1	16.168±0.077	10.470±0.125	18.358 ± 0.493
Mall 1st level	30.5± 6.1	13.411±0.071	8.640 ± 0.115	15.432 ± 0.487

The attenuation due to the shielding is assumed to follow exponential behaviour over the thickness range covered. Therefore the attenuation factor, *f*, may be written as per Eq. 1.:

$$f = \frac{R_b(t)}{R_b(0)} = e^{-t/L} \qquad \text{(Eq. 1)}$$

where t is the thickness of concrete, $R_b(t)$ is the Rate at thickness t and L is the 1/e attenuation length. For an individual case we therefore have:

$$L = \frac{t}{\ln\left(R_0 / R_t \right)} \qquad \text{(Eq. 2)}$$

where we have introduced the simplified notation $R_x = R_b(x)$.

Treating all the variables as independent we can propagate the experimental uncertainty in *L* for the individual case using the following expression for the standard deviation, $\sigma(L)$:

$$\sigma(L) = \sqrt{(L \cdot \sigma(t)/t)^2 + (L^2/t)^2 \cdot \left[(\sigma(R_0)/R_0)^2 + (\sigma(R_t)/R_t)^2\right]} \qquad \text{(Eq.3)}$$

The data presented in Table I allows three estimates for *L*, one for Totals, Reals and Triples Rates respectively, to be made; the results are summarized in Table II.

Table II. 1/e Attenuation Length, L, for Totals, Reals and Triples Counting

Thickness (cm)	**L_{Totals} (cm)**	**$\sigma(L_{Totals})$ (cm)**	**L_{Reals} (cm)**	**$\sigma(L_{Reals})$ (cm)**	**$L_{Triples}$ (cm)**	**$\sigma(L_{Triples})$ (cm)**
30.5	60.2	12.1	53.1	10.7	56.8	12.0
15.2	47.8	9.8	40.0	8.3	41.9	9.3
	Totals		Reals		Triples	
Mean L ± Std. Err. (cm)	54.0 ± 6.2		46.5 ± 6.6		49.4 ± 7.4	
Weighted Average L (cm)	52.7		44.9		47.5	
Int. Std. Err. (cm)	7.6		6.5		7.3	
Ext. Std. Err. (cm)	6.1		6.4		7.2	

The L values show a high degree of variability although they are broadly consistent within the assigned uncertainties, the unweighted mean of the L-values being (54 ± 6) cm for Totals, (47 ± 7) cm for Reals and (49 ± 7) cm. for Triples. Inverse variance weighting shifts the mean to about 53 cm with a internal standard error estimate of about ± 8 cm and an external standard error estimate of about ± 6 cm for Totals, (45 ± 6) cm for Reals and (48 ± 7) cm for Triples.

In order to determine whether there could be a coupling effect between the shielding and the assay system, additional background measurements were taken in a shielded cell at Harwell, UK, using a JCC-51 AWCC. The system contains 42 Al-wall He-3 tubes with a central Cf-252 efficiency of approximately 30%. In order to increase the target material for cosmic rays the system was filled with 65 kg of lead bricks. The cell ceiling consists approximately of 150 cm of sand and 61 cm of concrete, and the overall distance from the floor to the ceiling was approximately 250 cm. Data was taken in the center of the cell raising the counter at different heights. The results of these measurements are presented in Table III.

Table III. Measured Background Rates at Different Heights from the Ceiling in the Hot Cell of Hangar 10

Height from top of counter to ceiling (cm)	**Overhead shielding concrete (cm)**	**Overhead shielding sand (cm)**	**Totals rate (cps)**	**Reals rate (cps)**	**Triples rate (cps)**
Outside irradiation cell	0	0	7.18 ± 0.05	1.94 ± 0.04	2.28 ± 0.11
143 ± 1	61 ± 10	150 ± 15	1.48 ± 0.02	0.19 ± 0.01	0.15 ± 0.02
115 ± 1	61 ± 10	150 ± 15	1.58 ± 0.02	0.24 ± 0.01	0.17 ± 0.02
86 ± 1	61 ± 10	150 ± 15	1.58 ± 0.02	0.22 ± 0.01	0.19 ± 0.02

ANALYSIS

These new experimental data can be compared with historical performance data from various neutron systems that we have set to work in the past. In order to compare the data, only the Reals rate is taken into consideration since the specific Totals rate from raw radioactive waste is usually more variable and the Triples rate typically has low statistics under actual assay conditions close to the detection limit. Table IV summarizes the systems and shielding main characteristics and the associated 1/e attenuation length for Reals associated with each set of data.

Table IV. Summary of Data Sets and Reals 1/e Attenuation Length Associated with Them

System	**Overhead shielding (cm)**	**Thickness of walls (cm)**	**1/e attenuation length for Reals (cm)**
(a)	60 ± 10 105 ± 15 150 ± 20	-	37.5± 8.0
(b)	183 ± 18.3	60 ± 6	56.3 ± 5.6
(c)	140 ± 5	140 ± 5	54.1 ± 2.0
(d)	20 ± 2 35 ± 2	- 18	28.7 ±2.3

(a) 205 liter drum neutron coincidence counters with 60 He-3 tubes, approximate Cf-252 efficiency 19%.
(b) Passive/active neutron multiplicity counter for 220 liter drums comprising three concentric rings of He-3 tubes. Approximate Cf-252 central counter efficiency 55%.
(c) Small portable PNCC of the HLNCC-II design was used. The counter was filled with approx. 47 kg of lead shot.
(d) An Active Well Coincidence Counter (AWCC), JCC-51 filled with 65 kg of lead bricks. Efficiency ~30% with 42 Al-wall He-3 tubes.

The values show quite a large spread, presumably reflecting the importance of local geometry, composition and density of the shielding. If all the data sets are combined to calculate an unweighted average for the 1/e attenuation length, L, a value of (44 ± 5) cm is obtained, for an inverse variance weighting the mean is again 44 cm with a internal standard error estimate of about ± 1 cm and an external standard error estimate of about ± 6 cm. A value of (44 ± 6) cm therefore seems reasonable. Fig. 2 shows the exponential fit and the individual data for the different counters. The shielding for these measurements are considered *infinite,* since in all the cases either the overhead shielding area was considerably larger than the characteristic dimensions of the counter or there was additional shielding on the sides of the counter so that it was fully enclosed.

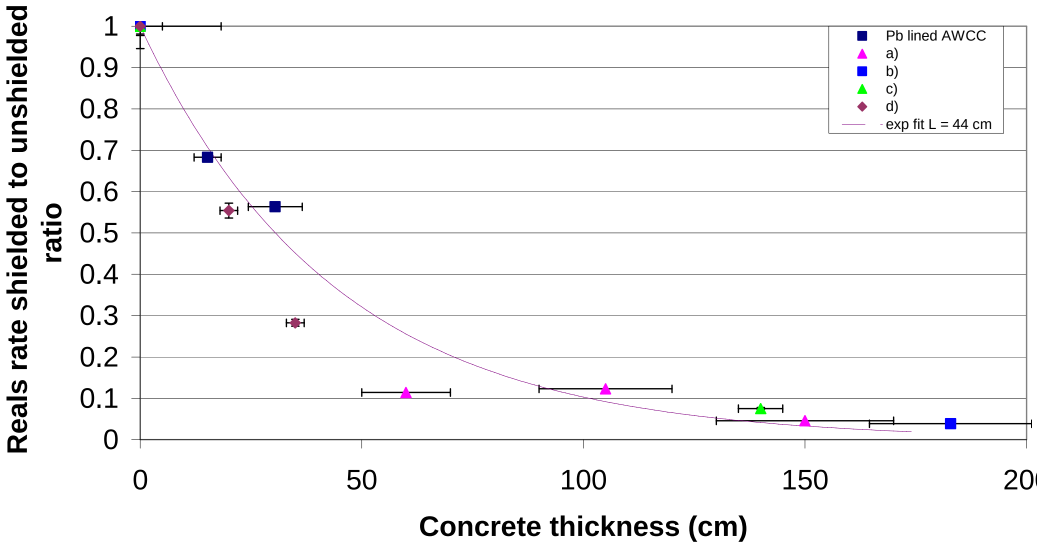

Fig. 2. Coincidence rate attenuation factor in concrete

In Ref. [1], results were presented for measurements using a PNCC chamber of 22.7% Cf-252 efficiency to estimate the effect of concrete shielding. An exponential was fitted for both Totals and Reals counting modes, finding that:

$$\text{Attenuation Factor, } f = e^{-bt} \quad \text{(Eq. 4)}$$

where t is the concrete thickness in m and b= (1.611±0.053) m^{-1}.

Based on this finding the 1/e attenuation length is approximately (62 ± 2) cm, which in rough agreement with the independent results presented here. Similar results were found in Ref. [2], which deals with measurements of concrete shielding on cosmic ray nucleons. Measuring the low energy neutron component (E_n=0.001-10 MeV) these authors obtained an attenuation length of 170 $g.cm^{-2}$, this corresponds to a 1/e length of approximately 70 cm for a nominal concrete density of 2.4 $g.cm^{-3}$.

The Reals 1/e attenuation length for the measurements reported here taken with the second counter (Pb filled JCC-51) is about (90 ± 9) cm. This is much larger than expected for the same thickness of only concrete as overhead shielding, this is probably due to the lower content of hydrogen in sand than in concrete, but there is also significant uncertainty in the effective thickness of the total over burden of material. There is at least a 15% increase in the Reals rate when the system is closer to the ceiling. The effect may be more visible, however, using a detector without the lead. This observation supports the idea that in some situations the shield may act as a local source of correlated neutrons. Distance (to reduce geometrical coupling efficiency to spallation events) and external neutron shielding (e.g. borated high density polyethylene) around the counter to provide neutronic decoupling can help in this regard. The relative importance of neutrons from the shield compared to neutrons produced in the measurement system depends on the specific situation – including the mass and geometry of the target material.

CONCLUSIONS

New experimental and historical data for the effects of cosmic ray shielding have been presented here and assessed. The new measurements carried out with a lead-lined AWCC give a 1/e attenuation length for correlated Reals counting of about (45 ± 6) cm for overhead concrete shielding. This is consistent with reviewed historical data for infinite or 4π shielding, a weighted average of the different data sets gives (44 ± 6) cm.

If the shield is very close to the assay system an increase in coincidence rate can take place due to the production of neutrons in the shield streaming into the counter. Additional measurements resulted in an increase of the coincidence rate of at least 15% for the configuration explored.

The results presented provide generic guidance on the potential benefits of using concrete shielding to suppress the cosmic ray induced neutron signal. The actual composition, density and geometry of a given shield in relation to the counter design clearly exert a significant influence. In future work we aim to explore methods for evaluating shield designs from first principle taking into account these factors.

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