

## **Design and Operating Characteristics of a Lead-lined Hexagonal Neutron-Multiplicity Counter**

W.F. Mueller, S. Croft, R.D. McElroy, R. Venkataraman, H. Zhu  
Canberra Industries, Inc.  
800 Research Parkway, Meriden, Connecticut 06450  
USA

### **ABSTRACT**

A high-efficiency Hexagonal Neutron-Multiplicity Counter (HNMC) has been developed for measurement of non-contact handleable power plant decommissioning and dismantling wastes. The HNMC counter was originally designed for nuclear stockpile safeguards measurements, but the unique challenges of the present application required significant adaptations to the design. The counter consists of six detector modules, each containing two parallel rows of 11 He-3 tubes embedded in high-density polyethylene and arranged in a hexagonal pattern around a central cavity. Graphite reflectors are located above and below the cavity to improve the axial linearity of the response and increase the overall efficiency, which is measured to be 39% for a centrally located Cf-252 source. The HNMC also includes an add-a-source feature by which a known Cf-252 source can be introduced near the bottom of the cavity. The perturbation of the count rate due to the Cf-252 is used to estimate the efficiency loss due to the moderator content of the drum matrix. Unusual to similar large volume multiplicity counters is the addition of a 6.4 mm lead lining on the inner walls of the cavity. This addition results in a suitably low value for the minimum detectable Pu-240-effective mass in drums with as much as  $10 \text{ mSv}\cdot\text{h}^{-1}$  gamma-ray dose rates when operated in a properly shielded bunker to suppress the background production of neutrons in the lead by cosmic rays. The details of the design and operating characteristics of the HNMC are presented and discussed.

### **INTRODUCTION**

The quantified analysis of plutonium and uranium-bearing materials by the detection of fission neutron multiplicity is a well-established non-destructive assay (NDA) technique [1]. This technique takes advantage of the fact that a multitude of neutrons are typically produced in the spontaneous fission of materials such as Pu-240 and Cf-252. By detecting coincident neutrons one can quite accurately and relatively quickly (compared to destructive analysis techniques) quantify the amount of fissioning material within a waste container with moderate alpha-induced (alpha-n) and spontaneous-fission (SF) neutron production rates.

Recently, drum-sized neutron multiplicity counters (NMC's) with efficiencies over 55% have been brought to bear for safeguards and accountancy problems allowing multiplicity analysis to be applied when extra accuracy in difficult to measure cases is needed. Examples of difficulties include highly moderating matrices, multiplying fissile materials and high alpha-n to SF-n rates.

In this paper, we present results from a variant multiplicity counter designed specifically to address the unique features of waste containers in the decommissioning and dismantling of nuclear power plants. In particular, a medium efficiency neutron counter design with suitable energy independence was achieved with an internal lead liner. The lead liner was introduced to reduce the gamma ray exposure rate at the He-3 tubes coming from the non-contact handleable waste drums.

General features of neutron multiplicity counters are high detection efficiency (typically greater than 35%) and granularity (typical counters can have dozens of individual detectors and electronic channels), which allows the effective detection of high multiplicity events with “minimal” electronic dead-time losses. Because the detailed information of drum contents are typically unavailable, the counters are necessarily designed assuming that the material being assayed is homogeneously distributed within the containment vessel, and because of this NMC's are constructed so that the radial and axial efficiency profiles within the counter cavity are as constant as reasonably possible to minimize the effects of the spatial distribution of the source location.

In a typical application for NMC's, the exact composition of the waste drums is not known. The fission material is often unevenly distributed within a matrix of unknown moderating potential. It is also possible that other radioactive products are within the vessel that could produce a significant gamma-ray flux. The effects of an unknown matrix can be estimated by the introduction of an external neutron source to measure the moderation due to the drum matrix. This is called the “add-a-source” technique [2].

Because most of the mass of NMC's is low atomic number (Polyethylene and He-3), these counters tend to be relatively insensitive to gamma rays; however, the gamma rays can interact with the (stainless steel or aluminum) walls of the He-3 detectors and subsequently stream through the fill gas, and produce a measurable signal. This signal tends to be relatively low, and consequently, easy to discriminate from the large signals produced by the desired He-3(n,p) $\gamma$  reaction. However, very large gamma-ray fluxes can eventually produce sufficient secondary electrons such that the pile-up of these signals can be comparable to the (n,p) signal and trigger the He-3 counter. In these situations it is necessary to reduce the gamma-ray flux incident on the He-3 detectors.

The present counter is a hexagonally designed neutron multiplicity counter with “add-a-source” capability and the ability to operate in the presence of large gamma-ray activities. We demonstrate the efficiency uniformity within the cavity, the “add-a-source” calibration, and the counter resistance to gamma ray flux from the assay containers.

In the discussions to follow the terms, Totals, Reals, and Accidentals, refer to the total neutron count rate, the count rate in the prompt time gate minus the rate in the delayed time gate, and the count rate in the delayed time gate respectively. The terms, Singles, Doubles, and Triples, correspond to the first three factorial moments of the Reals multiplicity distribution multiplied by the sample trigger rate.

## **GENERAL DESIGN**

The hexagonal neutron multiplicity counter (HNMC) utilizes 132 He-3 proportional tubes placed in six modules each containing two parallel rows of 11 detectors embedded in high-density polyethylene. The six modules are arranged hexagonally around the assay cavity. Graphite reflectors are located above and below the cavity to improve the axial linearity of the response and increase the overall efficiency. This counter is designed to function in the presence of a large soft gamma-ray flux. To decrease the flux incident on the He-3 detectors, the inner walls of the cavity are lined with 6.4 millimeters of lead. The assay cavity is large enough to accommodate one standard 208-liter drum.

The counter incorporates the add-a-source option in which a Cf-252 source can be introduced at the bottom of the assay chamber. The perturbation of the count rate of the Cf-252 is used to estimate the “Reals efficiency” loss due to the moderator content of the drum matrix.

The output signals are processed in groups of 3 or 4 He-3 detectors per JAB-01 module that contains an Amptek A-111 based preamplifier, primary amplifier, and discriminator circuit. The discriminated signals are then passed through a derandomizing input circuit (to reduce the overall counter dead time) and daisy chained to produce a TTL signal chain corresponding to the output from all the detectors. This signal is then input to a Canberra JSR-14 multiplicity shift register. The JSR-14 analyzer is accessed and controlled via Canberra’s NDA-2000 non-destructive assay software package on a standard personal computer. The present design builds on previous counters in which the total measurement uncertainties have already been estimated in detail [3]. A photograph of the counter is presented in Fig. 1.

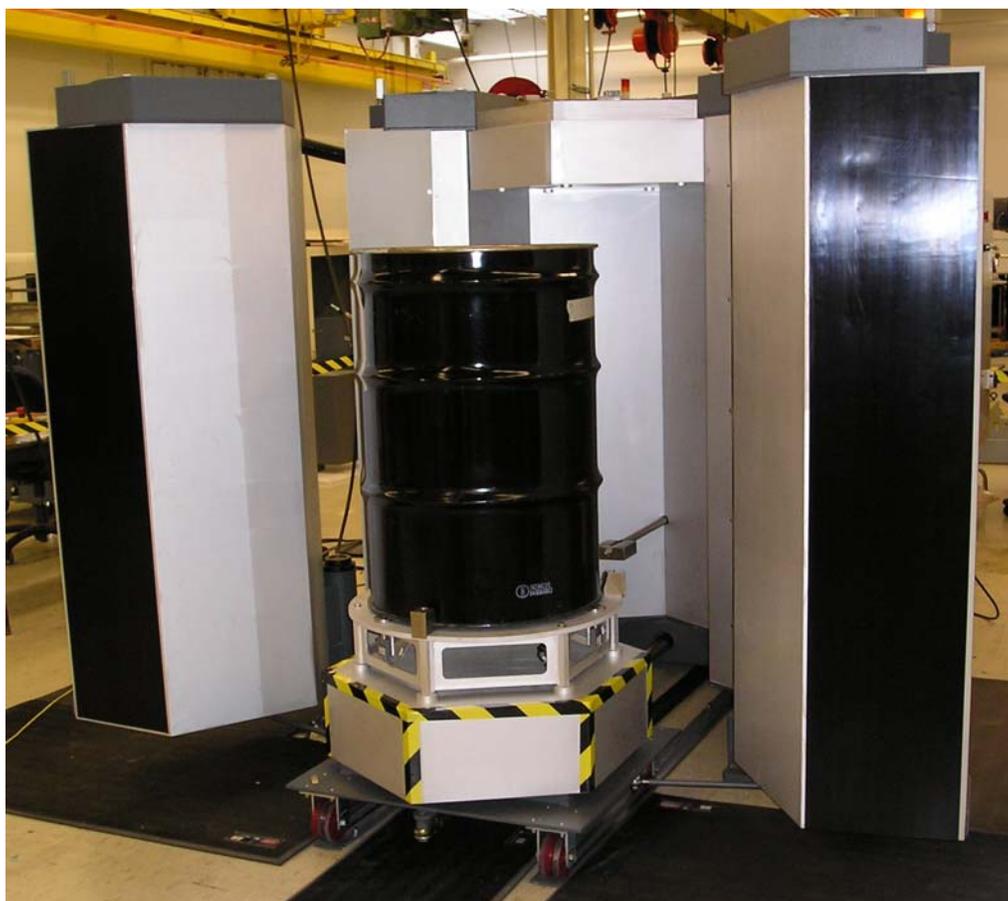


Fig. 1. The automated HNMC with the doors open and a 208-liter waste drum on the platform ready to be inserted into the assay cavity. The drum is centered in the cavity on an open lightweight pedestal. The He-3 proportional counters extend above and below the drum to improve the axial uniformity when the bogey moves into the cavity the add-a-source tube (visible in the back corner along with the graphite reflector) pass close to the bottom of the drum. No rotation is used because there is azimuthal symmetry.

Table I. Calibration Parameters for the HNMC. The details for each of these parameters are described in the main body of text.

	1680 V
	4.5 $\mu$ s
High Voltage	46.1 $\mu$ s
Pre-delay time	128 $\mu$ s
Dead-time Parameters (NCC)	a = 86.43 ns      b = 0 ns <sup>2</sup>
Characteristic Dead-time parameter ( $\delta$ )	23.19 ns
Doubles Dead-time Parameter (c)	14.84 ns
Triples Dead-time Parameter (d)	14.84 ns
Efficiency (Pu point source)	0.4015 $\pm$ 0.0087
Doubles Gate Fraction	0.624 $\pm$ 0.013
Triples Gate Fraction	0.4393 $\pm$ 0.0095
Cf-252 $\rho_0$	0.3921 $\pm$ 0.0010
Pu-240 $\rho_0$ (estimated)	0.2210 $\pm$ 0.0020
Pu-240 mass calib. parameter (estimated)	90.5 $\pm$ 3.7 cps / g Pu-240 effective

## OPERATING PARAMETERS

The neutron counter is characterized by several basic operating parameters. These parameters are determined by the neutron response characteristics of the assay cavity and signal processing electronics. These parameters are differentiated from more typical calibration parameters as they are obtained without the need for actual plutonium samples. Some of operational parameters determined for this counter are summarized in Table I.

The He-3 tubes are proportional counters and the optimal high voltage setting was determined in the traditional fashion. A Cf-252 source with a neutron emission rate of 5.1E+04 neutrons per second was placed within the counter. The voltage was incremented and at each step the Totals count rate was recorded. When the plateau region had been identified the count rate versus voltage was plotted and the correct setting was obtained by choosing a value between 20 and 40 volts above the knee (that is the point where the count rate does not change with bias, yet is also far away from the high voltage breakdown zone). More details regarding the bias setting are presented in following sections.

The counting chain suffers from electronic transient biases when two events occur close in time (in the same preamp). The coincidence rate is difficult to predict during this period so the pre-delay is used to avoid counting these initial events. Additionally, the shift register input buffer introduces a positive bias into the ratio of Reals to Accidentals for very high-count rates. These artificial coincidences are created as the input buffer places randomly distributed counts into a distribution defined by the module's clock. So instead of opening the coincidence window immediately following the start pulse it is started after an interval called the pre-delay has elapsed. The higher the count rate, the longer the optimal pre-delay setting. If the pre-delay is set too small, then the artificial coincidences increase, if the pre-delay is set too high then real

coincident events are needlessly discarded. For the HNMC a pre-delay time of 4.5  $\mu\text{sec}$  was chosen. This is a conventional value – a lower value could have been used.

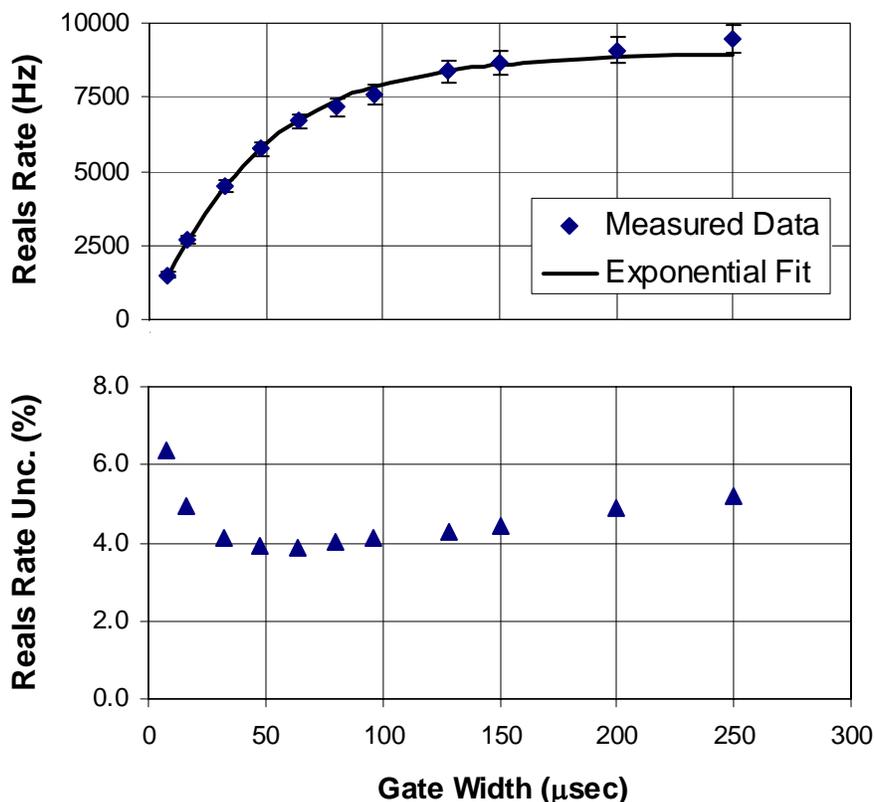


Fig. 2. Top panel: Reals rate plotted as a function of the coincidence gate width. Bottom panel: The relative uncertainty of the Reals rate plotted versus the coincidence gate width.

The characteristic die-away time is the  $1/e$  time difference of correlated thermalized neutrons. The die-away time is typically measured by varying the gate width and measuring the Reals rate. The Reals rate as a function of gate width is given by

$$R(t_g) = R_0 \cdot (1 - e^{-t_g/\tau}), \quad (\text{Eq. 1})$$

where  $\tau$  is the Die-Away time and  $t_g$  is the gate width setting for the detector. The Die-Away time was obtained by placing a small Cf-252 source in the detector and measuring the coincidence rate as the gate width was incremented, and then fitting Eq. 1 to the resultant data by optimizing the parameters  $R_0$  and  $\tau$  using chi-squared minimization. The resulting measurements and fit to the data are presented in Fig. 2.

Since the real coincidence events fall off as a function of time while the random events do not, there is an optimal window width which minimizes the uncertainty in the Reals rate. Typically, the gate width is chosen such that the error in the Reals rate is at a minimum or at a point where significant gains are no longer achieved. When low rates of accidental correlations are expected,

a larger gate width value is preferred to increase the amount of Reals data. For the HNMC an optimal gate width of 128  $\mu$ sec was determined (see Fig. 2).

The dead-time parameters for the standard neutron coincidence counting (NCC) are determined by the measurement of multiple Cf-252 sources. Ideally the sources should span a range in activity such that the smallest introduces only negligible deadtime into the system and the largest causes a Totals rate in excess of the largest expected Totals rate, typically greater than  $10^5$  n.s<sup>-1</sup>.

The NCC deadtime corrections for the Totals and Reals rates take the form:

$$CF_T = e^{(a+bT)T/4} \quad (\text{Eq. 2})$$

and

$$CF_R = e^{(a+bT)T}, \quad (\text{Eq. 3})$$

where  $T$  is the measured Totals rate. The method for determination of the deadtime parameters involved the assay of several Cf-252 sources and fitting the corrected Reals to Totals ratios to a constant value. For the HNMC, seven Cf-252 sources were utilized. Each source was placed at the center of the cavity. For each source measurement, the ratio of Reals/Totals is determined. Ideally this ratio should have a constant value regardless of the Cf-252 source strength. In reality, there are losses due to pulse pileup at very high rates that result in a decreased Reals-to-Totals ratio. Examination of the data indicated that the best fit was achieved if the parameter  $\mathbf{b}$  was allowed to become vanishingly small. A chi-squared minimization technique was used to adjust parameter  $\mathbf{a}$  to minimize the variation between the set of Reals/Totals ratios.

The multiplicity dead-time corrections use three parameters. The first is called simply the “dead-time parameter”, denoted by  $\delta$ . The other two dead-time parameters are  $c$  and  $d$ , the Doubles and Triples dead-time coefficients, respectively. The dead-time corrected multiplicity count rates (Singles, Doubles, and Triples) are given by the following equations:

$$S_d^{\&} = S_f^{\&} \cdot e^{\delta \cdot S_f^{\&}}, \quad (\text{Eq. 4})$$

$$D_d^{\&} = (1 + c \cdot S_f^{\&}) \cdot D_{f'}^{\&} \cdot e^{\delta \cdot S_f^{\&}}, \quad (\text{Eq. 5})$$

and

$$T_d^{\&} = (1 + d \cdot S_f^{\&}) \cdot T_{f'}^{\&} \cdot e^{\delta \cdot S_f^{\&}}. \quad (\text{Eq. 6})$$

Quantities with a subscript  $f$  refer to the statistically filtered (essentially observed) count rates and quantities with a subscript  $d$  referring to the corresponding dead time corrected count rates. The  $f'$  quantities refer to multiplicity rates evaluated using the  $\alpha$ ,  $\beta$  coefficients which are a function of  $\delta$  as explained elsewhere [4].

The dead-time parameters have been determined using the same Cf-252 sources detailed above, placed in the center of the assay chamber. For each source measurement, the ratios of

Doubles/Singles, Triples/Doubles and Triples/Singles is determined. Each of these ratios should have a constant value regardless of the Cf-252 source strength, being characteristic of the californium spontaneous fission process. The dead-time parameters are given in Table I.

The Doubles and Triples gate fractions are used only for the multiplicity calculations and not the standard coincidence method. The Doubles gate fraction may be obtained from measured rates via

$$f_d = \frac{2 D v_1}{\varepsilon S v_2}, \quad (\text{Eq. 7})$$

where  $f_d$  is the Doubles gate fraction,  $D$  is the measured Doubles rate,  $S$  is the Singles rate,  $\varepsilon$  is the Cf-252 neutron detection efficiency for the counter, and  $v_1$  and  $v_2$  are the 1st and 2nd spontaneous fission moments for Cf-252. The corresponding equation for the Triples gate fraction is

$$f_t = \frac{6 T v_1}{\varepsilon^2 S v_3}, \quad (\text{Eq. 8})$$

where  $f_t$  is the Triples gate fraction,  $T$  is the measured Triples rate,  $S$  is the Singles rate,  $\varepsilon$  is the Cf-252 neutron detection efficiency for the counter, and  $v_1$  and  $v_3$  are the 1st and 3rd spontaneous fission moments for Cf-252 [5].

The neutron detection efficiency is given in terms of the counter response to Cf-252 neutrons emitted from a source located in the center of the empty assay cavity. The measured Singles rate was corrected for dead-time losses and for background. The counter efficiency was then determined by dividing the measured rate by the output neutron rate. The information provided on the source certificates was evaluated carefully to determine the uncertainty estimates on the neutron emission rates. The Cf-252 sources used in this work have been purchased from different vendors and may have different pedigrees. As a result, the isotopic content can vary considerably. The Cf-252 isotope has a half-life of 2.645 years and decays at a faster rate when compared to Cf-250 which has a half-life of 13 years. Therefore, over a period of several years the ratio of Cf-250 / Cf-252 tends to increase. The decay correction applied to a given certified Cf-252 emission rate includes a correction factor to account for the change in the Cf-250 / Cf-252 isotopic ratio. The associated uncertainties in the Cf-250 and Cf-252 half-lives have been propagated.

The quantity  $\rho_0$  is used to calculate the multiplication correction in the standard NCC (known  $\alpha$ ) method. This parameter is the expected ratio of Reals to Totals events for a non-multiplying sample of representative material. It is given by the relationship

$$\rho_0 = (1 + \alpha_0) \frac{R_0}{T_0} \quad (\text{Eq. 9})$$

where  $R_0$  and  $T_0$  are the values for the Reals and Totals rates respectively for the non-multiplying sample.  $\alpha_0$  represents the ratio of uncorrelated (random) neutrons to spontaneous fission neutrons and for the plutonium sample is given by,

$$\alpha_0 = \frac{k_1 f_{238} + k_2 f_{239} + k_3 f_{240} + k_4 f_{241} + k_5 f_{242} + k_6 f_{Am241}}{k_7 (k_8 f_{238} + f_{240} + k_9 f_{242})}, \quad (\text{Eq. 10})$$

where the values of  $k_i$  and  $f_m$  are the relative abundance's and neutron emission constants for the sample. The value of  $\rho_0$  may be determined by directly measuring a small non-multiplying sample of metallic Pu for which  $\alpha$  is small; however, no well defined Pu samples were available for this calibration. The value of  $\rho_0$  was determined for Cf-252 which is then used to determine  $\rho_0$  for Pu-240.

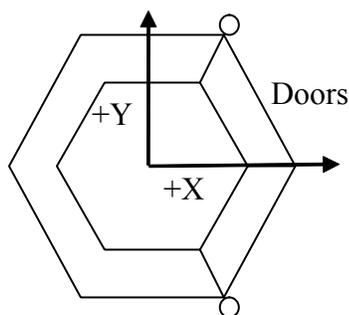


Fig. 3. Schematic overhead drawing of the HNMC. Also shown are the axes along which the radial measurements were performed.

For typical Cf-252 sources  $\alpha_0$  is zero so  $\rho_0$  is given simply by the ratio of Reals to Totals. The average value for the corrected ratio of Reals/Totals ratios for NCC analysis is used to provide the value of  $\rho_0$  for Cf-252.

$$\rho_{0(\text{Cf})} = 0.3921 \pm 0.0010 \quad (\text{Eq. 11})$$

This value is adjusted for the differences between Cf-252 and Pu-240;

$$\rho_{0(\text{Pu})} = \rho_{0(\text{Cf})} \frac{\nu_{240}(\nu_{240} - 1)}{\nu_{252}(\nu_{252} - 1)} \cdot \frac{\nu_{252}}{\nu_{240}} \cdot 1.02 = 0.2210 \pm 0.0020 \quad (\text{Eq. 12})$$

where the subscripts 240 and 252 correspond to the spontaneous fission moments for Pu-240 and Cf-252. The factor of 1.02 is to adjust the Cf-252 efficiency to that for Pu-240. This is a calculated value that will be confirmed once the counter enters operation.

## CHAMBER MAP

The radial and axial response of the empty counter was mapped out by measuring a Cf-252 source at various locations within the assay cavity. Fig. 3 shows a schematic drawing of the counter with coordinate axes labeled X and Y. The HNMC was mapped by placing the source at known locations along the two axes and at known heights (Z-axis position).

The radial response along the short (Y) axis was performed by recording the Totals rate from 300 second assays measured at 8 locations from the center of the counter (the origin) to approximately 1 cm from the cavity wall. The response along the long (X) axis was measured at 9 locations. At each of these radial positions, the response at 9 different heights (Z) were measured.

The results of these measurements are presented in Fig. 4. These data show that the total variation in point-wise efficiency throughout the cavity is less than  $\pm 4\%$ . It is also interesting to note that there is a less than 2% deviation in efficiency (at the surface of a waste drum) between a source on a radius approaching the center of a wall (where the He-3 detectors are located), and a radius approaching a corner (where there is a detector void).

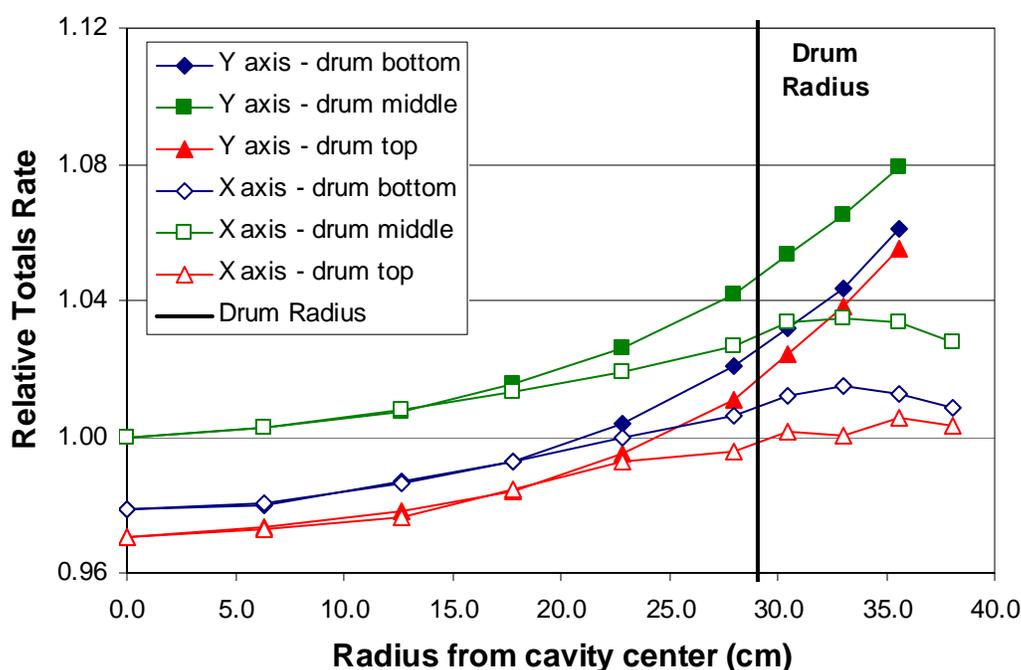


Fig. 4. Totals rates from a Cf-252 placed at several locations in the HNMC assay cavity. The rates are relative to the rate when the source is in the center of the assay cavity. The results at three different heights in the cavity (corresponding to the bottom, middle, and top of the drum) are plotted. The filled symbols correspond to radial positions that approach the middle of one of the walls. The open symbols are measurements along a radius approaching a corner. Marked at 29.1 cm is the typical radius of a 208-liter waste drum.

### ADD-A-SOURCE CALIBRATION

The Add-A-Source (AAS) technique provides a means of measuring the impact of the waste matrix on the neutrons emitted within the drum. A small Cf-252 source (about  $10^5$  n.s<sup>-1</sup>) is introduced into the assay cavity with an empty drum in the counter to provide a reference measurement. The measurement is repeated when the waste drum is loaded and the results

compared. The difference in the measured count rates can be used to correct the measured sample rate.

For the HNMC, the AAS Cf-252 source is placed in a remotely controllable transfer line located directly beneath the drum assay platform. The interrogation position for the source is about two inches below the bottom center of the drum.

To calibrate the AAS response to different matrices, a series of measurements are made using a point source placed in various positions within the representative matrix drums. A volume-weighted average measurement is determined for each drum from these measurements. That is each unit volume of the drum (which is also an equal matrix mass element) is assigned an equal proportion of activity. An additional measurement is made for each of the matrix drums using the AAS Cf-252 source. These data are used to generate a calibration curve that relates the AAS

Table II. Calibration Drum Descriptions Including the Matrix Type, Net Weight, and Actual Contents of the Drum

Matrix	Net Weight (kg)	Contents
Reference Drum	0	Empty 17H drum
Concrete	229	Dry concrete rubble
Combustibles	60.5	Paper, plastics, wood
Soft Board	83	0.4 g/cc cellulose type material
Particle Board	158	0.76 g/cc cellulose type material
100% Poly Beads	21	High Density Polyethylene beads and vermiculite

Cf-252 measurement to the effect of the drum's matrix on the detection of neutrons emitted uniformly within the drum.

The AAS matrix correction approach treats the drum contents as a perturbing influence on the response from an empty drum. The AAS Perturbation factor,  $P_{AAS}$ , is defined as

$$P_{AAS} = \frac{R_{AAS\_reference}}{R_{AAS\_sample}} - 1, \quad (\text{Eq. 13})$$

where  $R_{AAS\_reference}$  is the AAS rate measured with the empty reference drum (decay corrected to account for the difference between measurement dates) in the cavity and  $R_{AAS\_sample}$  is the AAS rate measured with the sample drum in the cavity. Similarly, the volume perturbation factor,  $P_{volume}$ , is defined as

$$P_{Volume} = \frac{R_{volume\_reference}}{R_{volume\_sample}} - 1, \quad (\text{Eq. 14})$$

where  $R_{volume\_reference}$  is the volume average rate measured for the empty reference drum in the cavity and  $R_{volume\_sample}$  is the volume average rate measured for the sample drum in the cavity.

The AAS matrix correction factor is a function of the AAS perturbation factor has the form

$$CF = 1 + f(P_{AAS}), \quad (\text{Eq. 15})$$

where  $f$  is a polynomial function. A separate calibration curve is required for the Totals and Reals rates.

The AAS correction is based on the assumption of uniform source and matrix distributions. Deviations from the assumptions of uniformity will introduce errors that are not accounted for by the AAS calibration. The matrices used in the calibration include highly reflective matrices such as 229 kg of dry concrete rubble through highly moderating matrices such as high-density polyethylene beads. The matrices included in the calibration are listed in Table II.

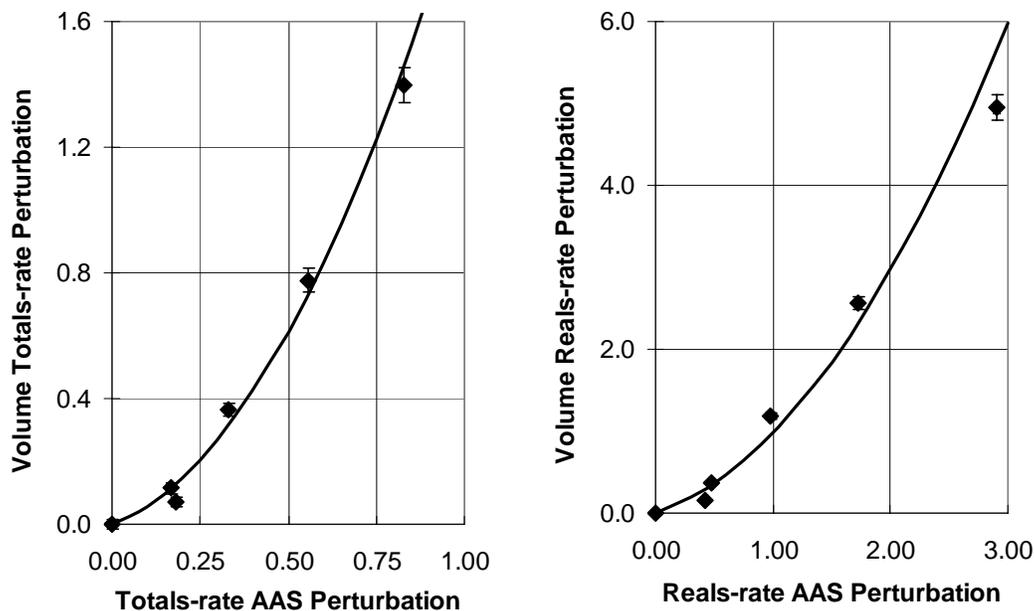


Fig. 5. Plot of volume averaged Totals rates (left panel) and Reals rates (right panel), normalized to the empty drum reference. The dotted bars represent the measured values within different matrices. The grey bars are the measured rates after the add-a-source perturbation correction.

The volume perturbation for a variety of drum matrices was determined by making a series of measurements of the Totals and Reals rates with a Cf-252 point source within each matrix and taking the volume weighted average. This number was compared to the add-a-source rate with the drum matrix in place. A quadratic polynomial relationship was determined between the Volume perturbation Totals and Reals rates and the corresponding add-a-source measurements. Fig. 5 shows the measured volume weighted perturbation values plotted versus the AAS perturbation values for the Totals and Reals rates. The Totals and Reals rates dependences were both fit to quadratic polynomials, and the resulting fits are also displayed in the figure.

To illustrate the quality of the calibration, the measured Cf-252 rates in each of the drum matrices are shown in Fig. 6 together with the perturbation corrected rates. One can observe that for highly moderating matrices that the uncorrected rates can result in significantly reduced count rates compared to the empty drum rate. The application of the perturbation correction brings the corrected values to close comparison with the unmoderated (empty) drum measurement.

## GAMMA-RAY ATTENUATION WITH INTERNAL SHIELDING

One uncommon feature of the present counter compared to other neutron multiplicity counters is the addition of an internal lead shield to suppress the gamma-ray flux from a waste drum on the He-3 detectors. For NMC's, it is common design practice to minimize the amount of high-Z material. This is because the largest source of background in NMC's comes from spallation neutrons from cosmic-ray interactions in these materials. Consequently, the addition of a lead shield in an NMC can significantly increase the background in a counter that is not shielded from cosmic radiation.

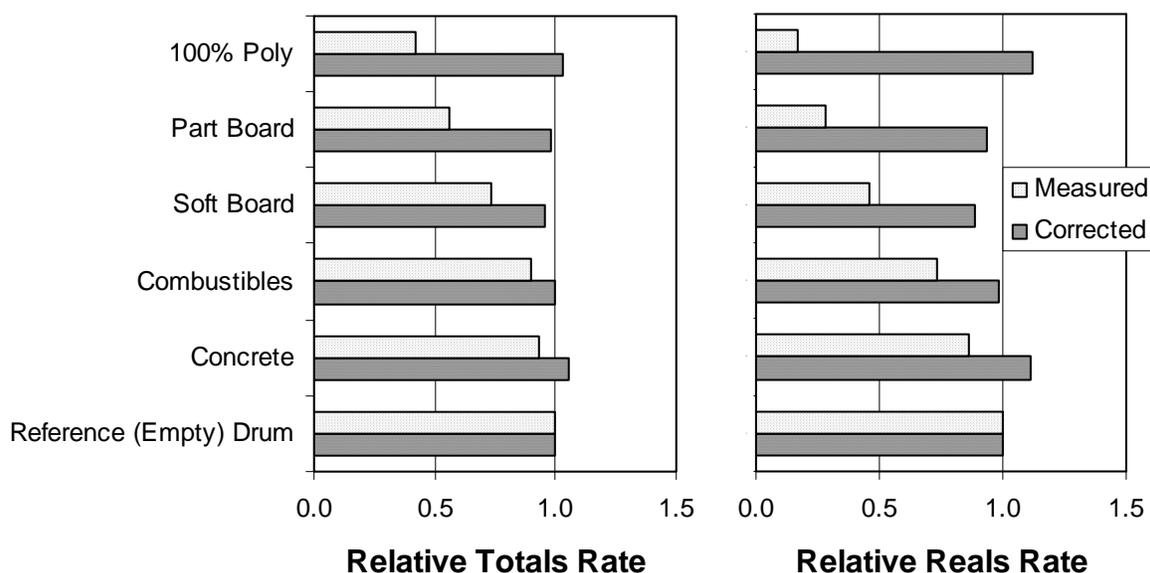


Fig. 6. Plot of volume averaged Totals rates (left panel) and Reals rates (right panel), normalized to the empty drum reference. The dotted bars represent the measured values within different matrices. The grey bars are the measured rates after the add-a-source perturbation correction.

While NMC's are generally insensitive to electromagnetic radiation, gamma rays can produce high-energy electrons in the steel or aluminum casing of the He-3 counters, which can in turn stream through and ionize the He-3 within the detectors. The energy deposited by electrons is on the order of 10 keV or less (compared to a minimum 191 keV for He-3(n,p)T reactions). These are normally well separated, and can be easily discriminated, but in cases where the gamma ray flux is significant these electron events can add up and breakthrough to the neutron channel and trigger the counter. In these situations it is critical to attenuate the gamma-ray flux to allow a normal operation of the counter.

The HNMC is designed to measure Pu-Cm waste in the presence of gamma-ray exposures up to  $1 \text{ R}\cdot\text{hr}^{-1}$ . In order to estimate the gamma-ray breakthrough limit, a 60 mCi Cs-137 source was placed in the HNMC cavity. This test source has an air kerma rate of about  $0.204 \text{ rad}\cdot\text{hr}^{-1}$  at 30 cm. The 662 keV gamma-ray energy from this source produces a harder spectrum than is typical of Pu waste (i.e. Am-241 and degraded fission products). The source was placed at several locations within the cavity (both in the center and near the walls), and in each position the

detector Voltage was incremented in steps of 20 volts and the Totals and Reals rates measured at each step. The averaged results of these measurements are presented in Fig. 7.

It can be seen from these results that the gamma-ray breakthrough begins at just above 1700 V. Consequently, this break away occurs above the optimal Voltage setting of the counter (1680 V). Also plotted in the figure is the Reals rate in the presence of the Cs source. While the Totals rate is significantly affected by the breakthrough at 1700 V, no effect is observed on the Reals rate up to 1800 V, which illustrates that the gamma-ray breakthrough is a random effect.

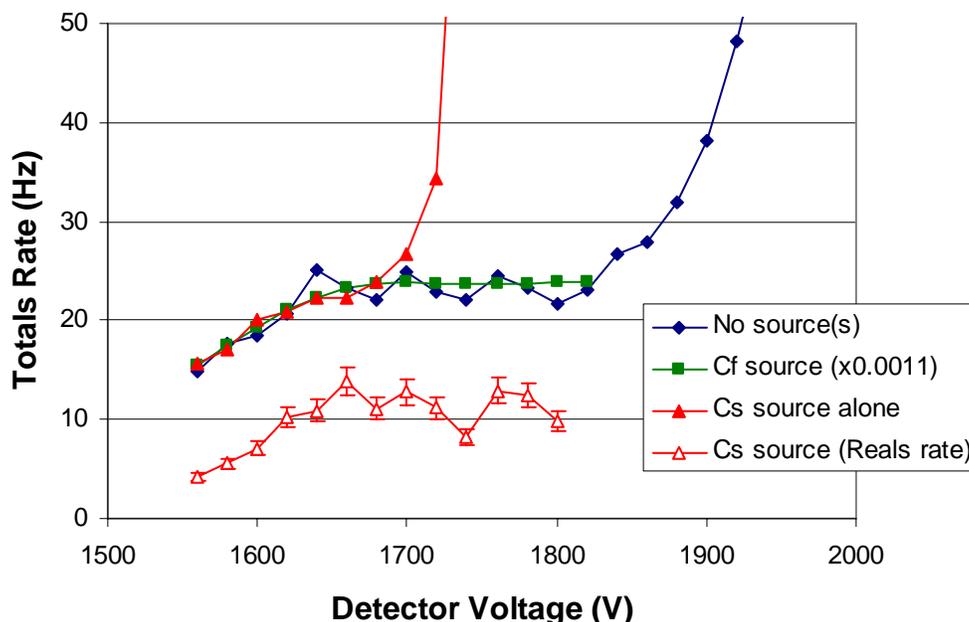


Fig. 7. Measured Totals rates as a function of detector voltage in the presence of no source, a Cf-252 source (scaled by 0.0011), and a 60 mCi Cs-137 source. Also included in the figure are the measured Reals rates for the Cs-137 source.

### BACKGROUND RATES IN THE HNMC

As was mentioned in the previous section, the consequence for placing high-Z material in the HNMC is the increased background rate due to cosmic-ray interactions. The measured background Totals and Reals rates for the HNMC and a non-Pb hexagonal counter (with an inner cadmium liner) [6] are presented in Table III. The measurements for both of these counters were made at the Canberra Industries Meriden Facility.

Table III. Measured background rates for the HNMC compared to a non-lead lined hexagonal counter (non-Pb HNMC) of similar design [6].

	HNMC	non-Pb HNMC
Totals	$25.93 \pm 0.25$ Hz	$12.32 \pm 0.09$ Hz
Reals	$12.95 \pm 0.18$ Hz	$1.13 \pm 0.06$ Hz

One can see that the addition of the lead liner increases the background rate by more than a factor of 10 in the Reals rates (and a factor of 2 in the Totals). It should be emphasized that both of these measurements were made in an unshielded location. Thus, while the lead liner offers significant resistance to gamma-ray flux from a waste container, the penalty is increased background from cosmic radiation; however, because the cosmic-rays are external this issue can be controlled by the placement of this counter in a well shielded bunker. A detailed study of cosmic ray shielding is addressed by Alvarez *et al.* [7].

## SUMMARY

A high-efficiency hexagonal neutron multiplicity counter has been designed for use in the decommissioning and dismantling of nuclear power plants. It includes an add-a-source feature to correct for neutron moderation in the waste drum matrix, and an internal lead liner to attenuate the gamma-ray flux from the container. The data shows that a single Cf-252 source introduced at the bottom of the drum can be used for the add-a-source correction. The hexagonal design of the counter does not introduce significant spatial dependence on the detection efficiency within the volume of a 208 liter waste drum. The introduction of a lead liner on the surface of the neutron counter is shown to allow the counter to be run in an environment with a  $0.2 \text{ R}\cdot\text{hr}^{-1}$  exposure with no recordable effect on the Totals rate (when the system is run at the nominal 1680 V for the He-3 counters). For the lower-energy gamma rays typically observed in Pu-Cm waste drums, the counter will be resistant to even higher exposures. The Reals rate is shown to be significantly less affected by high gamma-ray flux.

## REFERENCES

1. N. Ensslin, W.C. Harker, M.S. Krick, D.G. Langner, M.M. Pickrell, and J.E. Stewart, *Application Guide to Neutron Multiplicity Counting*, Los Alamos National Laboratory Report, LA-UR-98-4090.
2. H.O. Menlove, J. Baca, J.M. Pecos, D.R. Davidson, R.D. McElroy, and D.B. Brochu, *HENC Performance Evaluation and Plutonium Calibration*, Los Alamos National Laboratory Report, LA-13362-MS (October 1997); P.M.J. Chard and S. Croft, *Plutonium Measurements with a Reconfigurable Passive Neutron Coincidence Slab Counter*, In proceedings of 19<sup>th</sup> Annual Symposium on Safeguards and Nuclear Material Management, Montpellier, France (May 1997), pg 575.
3. R.D. McElroy, S. Croft, B. Gillespie, and B. Young, *Total Measurement Uncertainty Analysis for an Integrated Waste Assay System*, In proceedings of 44<sup>th</sup> Meeting of the Institute for Nuclear Materials and Management, Phoenix, AZ, USA (July 2003).
4. N. Dytlewski, M.S. Krick, and N. Ensslin, *Nucl. Instr. and Meth. A* **327**, 469 (1993).
5. S. Croft and L.C.-A. Bourva, *Nucl. Instr. and Meth. A* **453**, 553 (2000).
6. R.D. McElroy, M. Koskelo, S. Kadner, M. Ondrik, and M. White, *Mobile High Efficiency Multiplicity Counter for Uranium Measurements*, In proceedings of 41<sup>st</sup> Meeting of the Institute for Nuclear Materials and Management, New Orleans, LA, USA (July 2000).
7. E. Alvarez, S. Croft, R.D. McElroy, W.F. Mueller, S. Philips, V.F. Villani, and C.G. Wilkins, *Effect of cosmic ray shielding in passive neutron coincidence counting*, WM'06, abstract number 6284.