

## 8. FAST AND EPITHERMAL NEUTRON MULTIPLICITY COUNTERS

Mark M. Pickrell, Kevin Veal, and Norbert Ensslin

### I. Introduction and Problem Statement

This chapter will discuss the designs and motivation for the most modern of neutron multiplicity counters. These are the Epithermal Neutron Counters and the Fiber-Based Fast Neutron Counters. Both systems are addressing the same measurement issue: items that are difficult to measure by neutrons because the coincidence and multiplicity accidentals rate is too high. The high accidentals rate causes a large uncertainty in the counting statistics, which degrades the measurement precision. Traditionally, these measurement problems have been so severe that, in some cases, neutron assay by multiplicity or coincidence counting became impractical.

The first section of this chapter will be a review and inventory of the types of measurement cases that have suffered from this problem. We will review and discuss the range of neutron measurement cases that have been difficult or impractical to address with neutron multiplicity counting. These will be disparate in their apparent measurement difficulty, but will have a common thread: they will all have a high accidentals rate.

The following section will discuss the underlying physics of these neutron measurements. First, we will consider the common aspect of all the measurement cases and show that all have a high accidentals rate. Second, we will show that the high accidentals rate does indeed vitiate the measurement precision. Third, we will discuss the counter parameters that can mitigate the problem of high accidentals. Again, this section will be quantitative: we will show the relative improvement as a function of detector efficiency and die-away time, which leads immediately to the basic design parameters of an improved neutron detector.

The last section will discuss detectors that were designed specifically to address these counter parameters, namely a high efficiency and a low die-away time. We will discuss a survey of these instruments and describe the physics and engineering trade-offs that lead to particular designs. Two general types of detector will be discussed: the epithermal neutron multiplicity counter (ENMC) and the fiber-optic-based neutron detector. The ENMC is based on and is an extension of existing neutron counters. It is predicated on traditional neutron counting technology, but extends that technology based on the need for mitigating the specific problems of high accidentals measurements. The fiber-optics systems are a radically different type of neutron detector. The essential benefit is that it extends the potential capability of neutron detectors significantly beyond what conventional designs might be capable of. However, this improvement has a cost of degraded performance in other parameters and also it is less robust because it is a newer technology. These new approaches may indicate the future of neutron detector development, though.

The underlying logic of this chapter follows a direct progression: 1) address and inventory the spectrum of neutron assays that are difficult-to-measure, 2) show that these measurement challenges have a common basis, namely the high accidentals rate, 3) show that the accidentals rate can be improved by improving certain detector parameters, namely the efficiency and die-away time, and 4) discuss the new detectors that achieve improvement in efficiency and die away time.

## **II. Measurement Problems Addressed by Epithermal Neutron Counting**

The ENMC and the new generation of neutron counters (HLNCC10, ENMC/INVS, SuperHENC, Collar, KAMS NMC, etc.) designed with closely-packed high-pressure  $^3\text{He}$  tubes make it possible to effectively address a number of measurement problems for the first time. These measurement problems cannot be solved in a timely, cost-effective manner with the older generation of thermal neutron counters. The problem categories include passive multiplicity measurements of impure plutonium items with moderately-high alpha values, active/passive measurements of HEU/Pu, and active multiplicity assay of many forms of HEU.

### **A. Impure Plutonium**

The combination of the new ENMC and the Advanced Multiplicity Shift Register (which reduces count times by an additional factor of 2) enables passive multiplicity measurements of impure plutonium metals and oxides ranging in mass from milligram to kilogram quantities. The ENMC may also enable passive assays of U-238 in quantities greater than 1 kg. For multiplicity measurements of impure Pu, the increase in  $\alpha$  with increasing impurities hurts the counting precision on triple coincidences, eventually making the required counting time too long. The ENMC's higher efficiency and shorter die-away time leads to dramatic reductions in counting time. At an  $\alpha$  value of 1, the ENMC is about 10 times faster than a thermal neutron multiplicity counter for the same 1% precision. At an  $\alpha$  value near 8 (very impure Pu), the ENMC is about 20 times faster for the same 1% precision. But the practical limit of the ENMC is around  $\alpha$  values of 10 to 12, where the counting time for 1% precision begins to exceed one hour. It should also be noted that the ENMC counter design has a relatively flat detection efficiency profile as a function of neutron energy, providing an essentially bias-free assay for  $\alpha$  values from 0.1 to 0.3 (impure metal) to 7 to 12 (very impure oxide).

### **B. HEU Materials**

The DOE Complex contains many metric tons of excess HEU materials including mixed HEU/Pu, U weapons components in shielded storage drums, high-density HEU scrap/waste, remote-handled waste, and non-self-protecting irradiated fuels. DOE/NNSA nuclear facilities often need the capability to do fast, timely accountability, shipper/receiver verification, vault inventory verification, or waste characterization measurements of SNM materials. Identified validated needs include the following material categories: HEU metal, HEU metal and oxide pieces, pure HEU oxide, impure HEU oxide, high-density HEU scrap/waste, low-density HEU scrap/waste, remote-handled waste, and U-233 oxide. Shipper/receiver or inventory verification measurements of some of these materials need to be done in shipping containers. These are often shielded for personnel dose reduction, making the measurements very difficult. Large volume epithermal neutron multiplicity counters outfitted with active interrogation sources may provide a practical approach to these measurement problems.

### **C. Mixed HEU/Pu**

The ENMC will provide new capabilities for accountability or verification of the U mass in mixed HEU/Pu materials, including metal scrap in irregular shapes, U/Pu oxide, high-density

U/Pu waste, or un-irradiated, non-self-protecting U/Pu fuel assemblies. The measurement of mixed HEU/Pu items requires that the neutron counter be used for both an active and a passive measurement. The passive measurement is usually made by multiplicity counting to determine the  $^{240}\text{Pu}$  content with minimal bias. The active measurement is made by doubles coincidence counting to determine the  $^{235}\text{U}$  content with sufficient precision. Because the active measurement also induces fissions in  $^{239}\text{Pu}$ , this contribution needs to be subtracted from the total observed doubles rate to obtain a difference doubles rate that is related to the  $^{235}\text{U}$  content.

Calculations of the expected precision for the HEU portion of mixed HEU/Pu measurements made with the ENMC outfitted with active end caps were carried out. The Figure of Merit calculations assumed 1000s counting times for 93% enriched HEU and Pu with 10%  $^{240}\text{Pu}$ . For a mixture of 1500g HEU and 500g Pu, the ENMC measurement had a total statistical uncertainty on the difference doubles rate of 2%, whereas the AWCC was 4%. For a mixture of 500g HEU and 1500g Pu, the ENMC measurement had a total statistical uncertainty on the difference doubles rate of 3%, whereas the AWCC was 26%. This example shows that the ENMC can provide much better measurement capability for mixed HEU/Pu, especially if the Pu component is large.

#### **D. Additional Applications for Fast Neutron Counters**

A future generation of fast neutron counters based on liquid scintillators or other technology may provide another order of magnitude improvement in performance over the ENMC. The expected counting precision for such counters is described in Chapter 7, Section 7.4.4. The most important potential benefit is the capability to do active multiplicity counting with 1% or better assay precision over nearly the entire  $^{235}\text{U}$  mass range. Thus, liquid-scintillator-based neutron counters could provide active multiplicity results for almost all DOE facility inventory materials with reasonable counting times. Potential applications would also include fast scintillator detector arrays for active/passive measurements of some forms of domestic research reactor fuel, foreign research reactor receipts fuel, and remote-handled transuranic waste. These materials often do not have high enough radiation doses to be self-protecting, and, therefore, require safeguards measurements.

### **III. The Physics of High Accidentals Multiplicity Counting**

There is a common physics feature to all of the “difficult” problems discussed in section II. All of these measurements have a high neutron accidentals rate. The accidentals rate applies to either doubles (coincidence) counting or triples (multiplicity) counting. In both cases, it refers to those cases where by sheer probability; multiple (either two, three, or more) neutrons are detected and counted within the time window of the multiplicity shift-register gate. These counts appear as correlated, but are indeed merely chance coincidence. The multiplicity formalism separates out the chance coincidences (accidentals) from the true coincidences (called reals), using a statistical model. In the mathematics of neutron multiplicity counting, described in chapter 6, the accidentals counts are called the background distribution. The notation is either  $b(i)$  or  $Q(i)$ , depending on the reference. For conventional shift-register-based neutron coincidence counting, the accidentals are counted in the Accidentals or “A” gate.

In this chapter, we will use two approaches to illustrate the effects of the accidentals on the multiplicity precision. The first method will be to use a numerical calculation of the neutron

multiplicity rates (for singles, doubles, and triples) and their associated variances, as well as the resultant multiplicity assay precision which considers the combined variances of all of the measured quantities and the inversion of the point model equations. This numerical calculation follows the theoretical formalism developed by Ensslin, et.al. The second approach will be analytical with an approximate calculation for the expected variance of the doubles counts. The mathematics for the triples variance is more complicated, and does little to elucidate the underlying physics. For that, we will rely on the Ensslin Figure of Merit (FOM) numerical calculations. However, for the doubles, the analytical result does illustrate the basic dependence of variance on the accidentals.

It is the effect of accidentals that substantially changes the variance behavior for neutron multiplicity counting compared to, say, counting individual neutrons or counting any individual, uncorrelated particle or event. From classical probability, if a measurement is made of any system that satisfies the conditions for a Poisson process, then relative error of the count (percent error) scales as  $\frac{1}{\sqrt{n}}$ , where n is the number of counts. Therefore, if singles, doubles, and triples counts in multiplicity all obeyed Poisson statistics, we would expect the relative standard deviation to scale the same way for all of them. However, that is not the case. The singles do indeed follow this relationship, nearly, but the behavior of the doubles and triples are quite different.

Figure 1 below illustrates some of these points. Using the Ensslin FOM code we calculate the variance for the singles, doubles, triples, and multiplicity assay. In order to vary the accidentals rate strongly, we varied the assay mass over a large range, from 0.01 grams to 100,000 grams. The parameter alpha (alpha is the ratio of alpha-n neutrons to fission neutrons) is fixed at zero. The sample leakage multiplication is fixed at unity. The detector efficiency is 35%, the die away time is 50  $\mu$ sec, the predelay is 3  $\mu$ sec, and the gate width is 50  $\mu$ sec, and all of these are fixed.

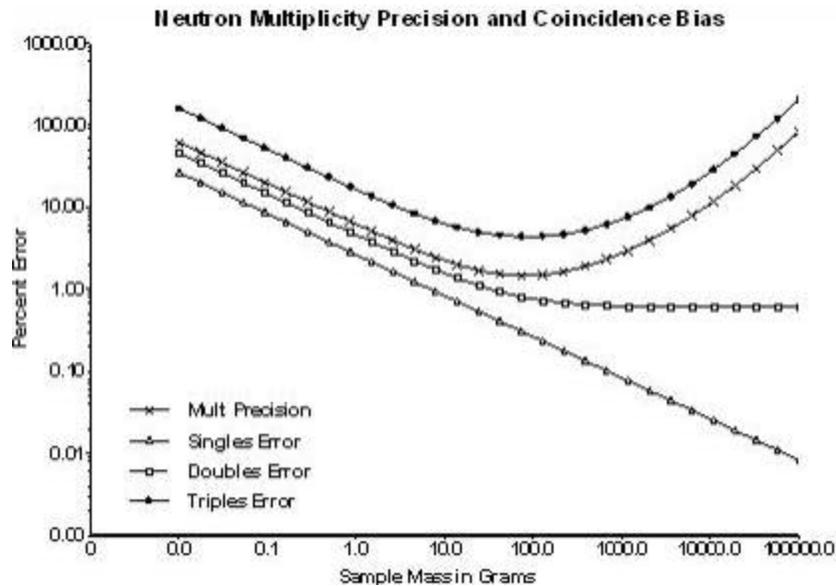


Fig. 1. Measurement variance versus sample mass for different multiplicity orders.

The results of Figure 1 demonstrate the effects on variance from the accidentals. The singles relative standard deviation does indeed scale as  $1/\sqrt{n}$ , as is expected, (note the graph is a log-log plot). However, the behavior of the doubles and triples relative standard deviation (RSD) is quite different. At low masses the doubles RSD scales as  $1/\sqrt{n}$ , but at modest mass values the scaling stops and the doubles RSD remains nearly constant. By contrast, the triples RSD scales as  $1/\sqrt{n}$  for low masses, but above about 100 grams, for this particular case, the triples RSD actually increases at a rate that is nearly proportional to the count rate. The total multiplicity assay RSD depends on the variances of singles, doubles, and triples, and it also increases after about the 100 gram level.

This general behavior can also be addressed analytically, using the point model equations. We repeat the point model equations derived earlier.

$$S = Fm_{240}\varepsilon M v_{s1} (1 + \alpha) \quad (1)$$

$$D = \frac{Fm_{240}\varepsilon^2 f_d M^2}{2} \left[ v_{s2} + \left( \frac{M-1}{v_{i1}-1} \right) v_{s1} (1 + \alpha) v_{i2} \right] \quad (2)$$

$$T = \frac{Fm_{240}\varepsilon^3 f_t M^3}{6} \left\{ v_{s3} + \left( \frac{M-1}{v_{i1}-1} \right) [3v_{s2}v_{i2} + v_{s1}(1 + \alpha)v_{i3}] + 3 \left( \frac{M-1}{v_{i1}-1} \right)^2 v_{s1}(1 + \alpha)v_{i2}^2 \right\} \quad (3)$$

where,

F = spontaneous fission rate, 473 fission/s-g <sup>240</sup>Pu, so that m<sub>240</sub> = effective <sup>240</sup>Pu mass,

ε = neutron detection efficiency,

M = neutron leakage multiplication,

α = (α,n) to spontaneous fission neutron ratio,

f<sub>d</sub> = doubles gate fraction,

f<sub>t</sub> = triples gate fraction,

v<sub>s1</sub>, v<sub>s2</sub>, v<sub>s3</sub> = first, second, and third reduced moments of the spontaneous fission neutron distribution,

v<sub>i1</sub>, v<sub>i2</sub>, v<sub>i3</sub> = first, second, and third reduced moments of the induced fission neutron distribution.

Consider first the case of the singles, which are simply the total number of neutrons detected. There are no accidentals to subtract from the totals, because there are no coincidences, accidentals or otherwise. Using the point model equation for the singles, we note that the singles variance scales approximately as:  $1/\sqrt{n}$ , because there are no accidentals to change this scaling.

Next consider the variance for the doubles, which are also classical coincidences. These equations are best understood in two limiting cases: the case where the plutonium mass (m<sub>240</sub>) is low and the other case where it is high. “Low” and “high” will be defined in the equations. For the case of coincidence counting (doubles only), an excellent measure of the variance is:

$$\sigma = \sqrt{(R + A) + A} . \quad (4)$$

where  $(R+A)$  is the total count in the “reals plus accidentals” gate (the signal triggered gate) and  $A$  is the total count in the “accidentals” gate (the random triggered gate). In a multiplicity shift register these values are calculated as the factorial moment summations over the foreground,  $f(i)$ , distribution and the background,  $b(i)$ , distribution. The value for  $R$  is simple the doubles rate from the multiplicity equations above times the count time:

$$R = D \cdot t \quad . \quad (5)$$

The accidentals rate can be calculated from the totals rate. The total accidentals value is the accidentals rate times the count time:

$$A = GtS^2 \quad . \quad (6)$$

where  $G$  is the shift register gate width and  $S$  is the singles rate from the multiplicity equations above. Note that the singles rate and the doubles rate are proportional to the plutonium mass, but the accidentals rate is proportional to the mass squared:

$$\begin{aligned} S &\propto m_{240} \\ A &\propto m_{240}^2 \\ D &\propto m_{240} \end{aligned} \quad (7)$$

Combining these equations and solving for the Relative Standard Deviation we obtain:

$$\sigma_{rel} = \frac{\sqrt{Dt + 2GtS^2}}{Dt} \quad . \quad (8)$$

Now, consider the two limiting cases. In the case of low mass, the second term in the numerator,  $2GtS^2$ , which depends on the square of the mass, becomes arbitrarily smaller than the first term, which is linear with the mass. Therefore, at sufficiently low mass, the second term is negligible, and the equation for the RSD simplifies to:

$$\sigma_{rel} \propto \frac{1}{\sqrt{t\epsilon m_{240}}} \quad (9)$$

which scales as  $1/\sqrt{n}$ , just as the FOM calculations show in Figure 1, for masses less than 100 grams of plutonium. The variance is limited by the statistical precision of the reals counting. The triples behave in the same fashion.

By contrast, consider the case of large mass, namely  $m_{240}$  is sufficiently large that the second term in the numerator is much larger than the first term:  $2GtS^2 \gg Dt$ . Then, the equation for the RSD scales as:

$$\sigma_{rel} \propto \frac{\sqrt{\tau}}{\epsilon\sqrt{t}} \quad . \quad (10)$$

In this case, the total variance is dominated by the accidentals, and the scaling of the variance with efficiency, die-away time, and plutonium mass is quite different than for the low mass case. We have also assumed that the system is optimized so that the gate fraction is proportional to the die-away time,  $\tau$ . Indeed, there is no change in variance with mass! The usual benefit of improved statistics is lost. Note also that the RSD improves with short die-away time and large detection efficiency. A similar (but more complicated) calculation can be done for the triples measurement, which shows that the triples RSD actually increases with mass, just as the FOM calculation illustrated in Figure 1.

The clear result is that in the case of a high accidentals rate, the variance induced by the accidentals can be the dominant contribution to the measurement variance. In the limit of large masses, therefore large accidentals, the variance contribution from the Poisson statistics of the real rate is negligible compared to the variance contribution of the accidentals. Other measurement problems that also have a high accidentals rate will be affected in the same way.

Another example of a high-accidentals-rate measurement problem is active neutron multiplicity counting. Active neutron counting uses a neutron source to interrogate a fissile sample that has a low spontaneous fission rate. Enriched uranium is a common example. The significance of active multiplicity counting is that the interrogating source provides a high level of total neutrons (but no real coincidence or triples counts). Because the accidentals rate (for doubles) scales as  $A = G T^2$ , where  $G$  is the shift register gate width and  $T$  is the total rate, the accidentals rate is very high as well. Figure 2 illustrates this point. For a nominal set of active measurement conditions:  $^{235}\text{U}$  range from 100 to 10,000 grams, doubles rate of 10 counts per gram, interrogation neutron rate of  $10^6$ , and the same detector parameters as before. Figure 2 illustrates that the high accidentals rate caused by the interrogating source has substantially increased the doubles and triples precision. By contrast, the singles variance is not affected as much. These RSD values are much higher than for the passive multiplicity case, where no interrogating source is used.

Another example is the case of materials with a high alpha. The affect of alpha is similar to

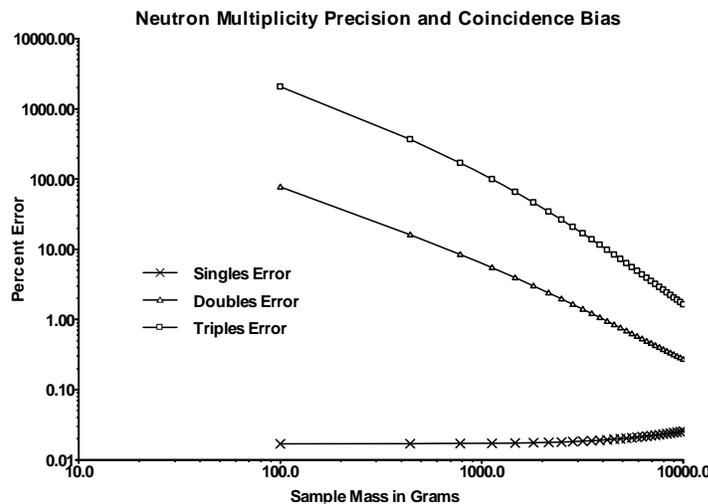


Fig. 2. Multiplicity error components versus sample mass.

that of an interrogating source. The alpha-n neutrons appear as singles, but they increase the total rate, which increases the accidentals rate. We consider a nominal case that is similar to the calculation plotted in Figure 1, (the detector parameters are identical). We hold the mass fixed at

1000 grams and vary the alpha from 0.1 (essentially zero) to 5. The results are plotted in Figure 3. Note that the RSD for the doubles and triples increases, because the totals rate increases and therefore the accidentals rate increases. However, the RDS for the singles decreases, because the totals rate increases and this improves the statistical precision.

In all of these cases, the neutron measurement problem is made challenging by a high accidentals rate for the doubles and triples counts. In these instances, the variance contribution of the accidentals dominates the variance of the measurement. Knowing that the accidentals have such a profound impact, we can consider design changes in the neutron detectors that can reduce the variance contribution from accidentals. The evaluation proceeds from the equations derived above which approximates the doubles variance in the limit of high accidentals, (we do not need to consider the case of low accidentals for this part of the discussion).

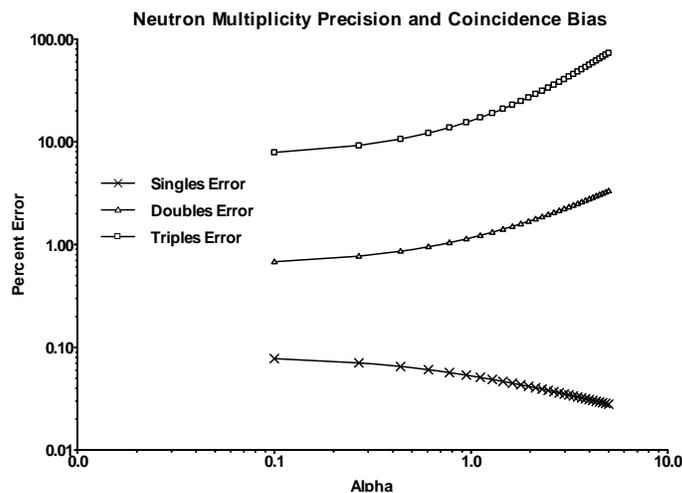


Fig. 3. Multiplicity precision versus alpha ( $\alpha$ )

An increase in efficiency improves the precision of the multiplicity and coincidence measurements, which we demonstrate with a figure of merit calculation. In Figure 4, we plot the case that efficiency is increased. The other detector parameters are the same as for Figure 1,

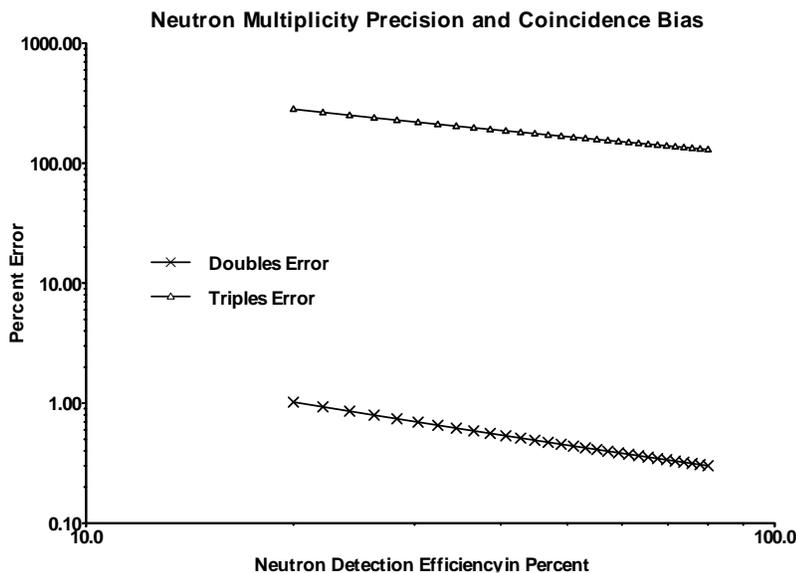


Fig. 4. Figure of Merit calculation: varying efficiency.

however, the mass value is chosen to be 100,000 grams, which (from Figure 1) is well into the regime of accidentals-dominated variance for the doubles and triples. In this calculation, the efficiency varies from 20% to 80%. Figure 4 shows, consistent with equations 9 and 10, that the efficiency improves the variance for multiplicity counting in both the low mass (limited by real coincidence counting statistics) and the high mass (limited by the accidentals rate) cases.

For completeness, we also note that the variance for the opposite case, when the mass is low is also improved as efficiency is increased. Die away time has little effect, though. The significance is that a counter with high efficiency and low die away time will improve the variance over the entire spectrum of measurement cases: from the limiting case where accidentals are the dominant contribution to variance at the high end, to the limiting case where counting statistics of the real coincidences at the low end. These effects can also be seen from the FOM calculations. Figure 5 is identical to Figure 4 except that the mass value is 1 gram instead of 100,000 grams of plutonium. Again, the efficiency is varied from 20% to 80%.

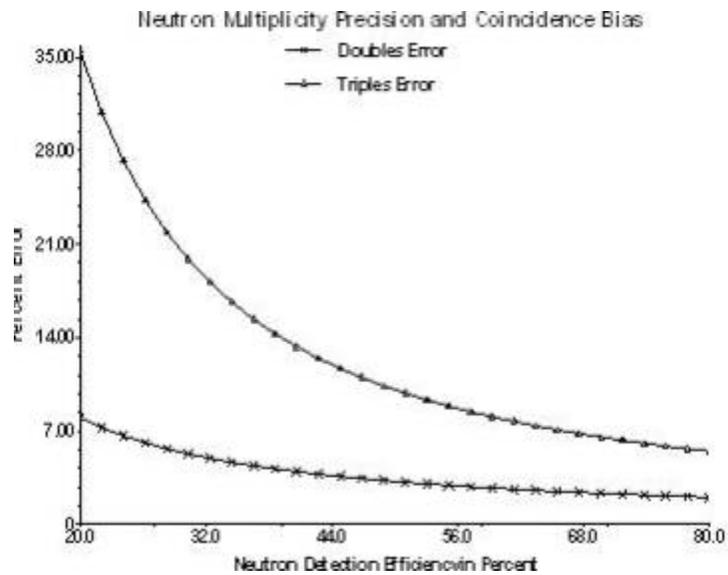


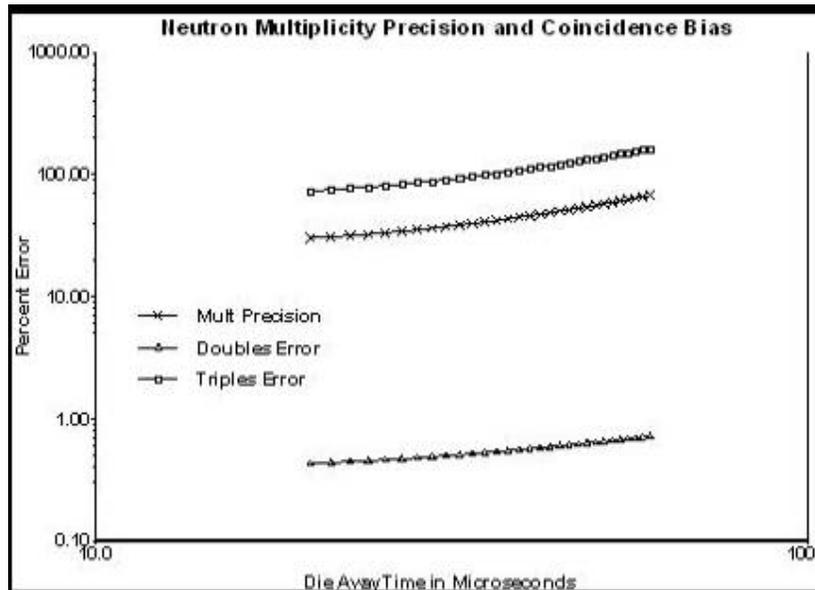
Fig. 5. Figure of Merit calculation: varying efficiency

Finally, we calculate, using the FOM code, the improvement in detector performance (i.e. reduction in variance) when the die-away time is decreased. Figure 6 plots the same case as Figures 4 and 5, except that the efficiency is held constant at 35%, the mass is 100,000 grams, the gate width is reduced to 35  $\mu$ sec, and the die away time is varied from 20  $\mu$ sec to 60  $\mu$ sec. For the case of doubles and triples, the variance is improved when the die-away time is reduced and the efficiency is increased. Although we did not develop the analytical expressions for triples, the effect is more pronounced.

These effects can be understood from the basic physics. The correlated gate in a shift register, which is the signal triggered gate, measures both the reals and the accidentals. In order to measure the correlated neutron moments (the real doubles and triples), the accidentals rate must be subtracted off. The accidentals are measured by opening up a second gate, the random-triggered gate for a second measurement. The random triggered gate measures only uncorrelated neutrons. Because these two numbers are subtracted, their variances must add. Therefore, the total variance includes contributions from both the reals and the accidentals. When the die-away time is reduced, the gate width is reduced proportionately. As the gate width is reduced, the

amount of accidentals that are counted is reduced, and the contribution to the variance is correspondingly reduced.

Fig. 6. Figure of Merit  
Calculation: Vary Die Away Time



The conclusions from this discussion are that high accidentals, caused by high mass, high alpha, or active interrogation significantly degrade the precision of multiplicity measurements. However, a neutron detector that has a high efficiency and a low die away time can significantly mitigate this problem.

#### IV. Fast and Epithermal Neutron Multiplicity Counters

In this section we will discuss the designs of modern neutron counters, which were specifically developed to address the class of measurement problems described above, and which are characterized by a high accidentals rate. There are two systems we will consider: the Epithermal Neutron Multiplicity Counter (ENMC) and the Fiber-Optic-Based Fast neutron counter. The ENMC is an existing design, which has been built and field tested. In experimental and numerical tests, the instrument has proven to be considerably more precise (all other measurement parameters being equal) than previous state-of-the-art instruments. By contrast, the fiber optic fast neutron detector is an experimental device that is intended to extend the basic measurement parameters beyond what is practical for  $^3\text{He}$ -based neutron detectors. In particular, this fast neutron system has a neutron die-away time of 3.8  $\mu\text{sec}$ , compared to a nominal 22  $\mu\text{sec}$  for an ENMC and a 47  $\mu\text{sec}$  die-away for a Plutonium Scrap Multiplicity Counter (PSMC). Both systems will be discussed in this section.

##### A. Epithermal Neutron Multiplicity Counter

The design of the ENMC follows largely from the existing technological base of thermal neutron counters, namely, it is a well-type counter that uses polyethylene to moderate neutrons and  $^3\text{He}$  tubes to detect the neutrons. The pulse amplification, discrimination, and pulse counting electronics are identical to conventional neutron well counters. The ENMC differs from more

conventional counters in that it has a much higher efficiency and a lower die away time. Table 1, below, summarizes the operation parameters of the ENMC compared to an AWCC and a PSMC. The ENMC has an efficiency of 65%, which is significantly larger than the PSMC, which has an efficiency of 53%. It also has a much shorter die away time compared to the PSMC, 22  $\mu$ secs compared to 47  $\mu$ secs.

**Table 1: Design Parameters for an ENMC and PSMC**

<b>Parameter</b>	<b>AWCC</b>	<b>PSMC</b>	<b>ENMC</b>
<b>He-3 Tubes</b>	<b>4 atm</b>	<b>4 atm</b>	<b>10 atm</b>
<b>Efficiency</b>	<b>33%</b>	<b>53%</b>	<b>65%</b>
<b>Die-Away Time</b>	<b>51 <math>\mu</math>s</b>	<b>47 <math>\mu</math>s</b>	<b>22 <math>\mu</math>s</b>
<b>High Voltage</b>	<b>1680 V</b>	<b>1680 V</b>	<b>1720 V</b>
<b>Pre-Delay</b>	<b>3 <math>\mu</math>s</b>	<b>3 <math>\mu</math>s</b>	<b>1.5 <math>\mu</math>s</b>
<b>Gate</b>	<b>64 <math>\mu</math>s</b>	<b>64 <math>\mu</math>s</b>	<b>24 <math>\mu</math>s</b>
<b>Deadtime</b>	<b>225 ns</b>	<b>120 ns</b>	<b>37 ns</b>

There are three essential design features of the ENMC that enabled the improvement in die-away time and efficiency. These are:

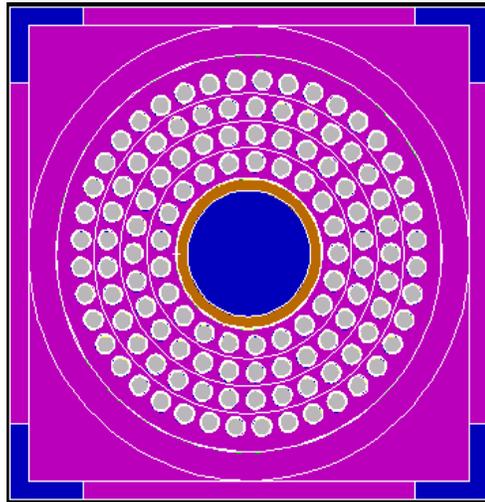
1. The ENMC uses 10 atm  $^3\text{He}$  detection tubes rather than the more typical 4 atm tubes. The higher pressure  $^3\text{He}$  captures more of the thermalized and epithermal neutrons. Higher pressure  $^3\text{He}$  detectors have also been used to upgrade existing neutron counters, and have improved detection efficiency and reduced die-away time.
2. The ENMC uses less polyethylene moderator than conventional designs. With less moderator, the neutrons may not become fully thermalized (hence the name).
3. The ENMC uses multiple rings of detectors embedded in polyethylene. Other modern neutron well counters have also used this design, but for the ENMC it is particularly important.

The significance of the ENMC design features is understood best in the context of how a neutron counter actually detects neutrons. The general process has three basic steps:

1. The neutron impinges on the polyethylene moderator and is thermalized (principally by the hydrogen). The thermalization occurs because the high energy neutron collides with (typically) a hydrogen atom and loses much of its energy. After (generally) several collisions, the neutron energy is about the same as the thermal energy of the moderator (room temperature).
2. After the neutron is thermalized, it typically undergoes several more collisions with the moderator material and moves (essentially by diffusion)

- through the detector until it is lost by one of several processes. Ideally, a conventional neutron detector would work best if the neutron became thermalized immediately adjacent to a  $^3\text{He}$  detector so that it could be instantly captured. However, more commonly the neutron becomes fully moderated in the polyethylene some distance from a detector tube and must transport (by a random walk process of several collisions) to the  $^3\text{He}$  tube.
3. The neutron is lost. There are three basic loss processes:
    - a) The neutron is captured and detected by the  $^3\text{He}$  gas in one of the detector tubes.
    - b) The neutron transports outside of the detector and is lost.
    - c) The neutron is absorbed by the hydrogen in the polyethylene.

The goal of the detector design is to optimize these processes so that the efficiency is as large as possible and the die-away time is as short as possible. Efficiency is increased when the fraction of neutrons lost by  $^3\text{He}$  capture is large compared to the competing lost processes (e.g. hydrogen absorption). Die away time is made shorter by reducing the time between thermalization and capture. The ENMC achieves these objectives by using high pressure  $^3\text{He}$  tubes and a minimum of polyethylene moderator. The detector tubes are closely spaced in the



*Fig. 7. MCNP plot of cross section of ENMC detector.*

polyethylene moderator. When a neutron impinges on the detector, there is just barely enough polyethylene to moderate it (because of the close spacing of the  $^3\text{He}$  tubes). Once the neutron is moderated or partially moderated, it will be in close proximity to a detector tube. Therefore, the neutron will not remain in the moderator material for a long period of time and the die-away time is kept short. Because the detector tube pressure is high, the neutrons have a high probability of being captured, so the efficiency is high. The multiple rings of detectors ensures that most of the neutrons are captured, even though the moderator density is low. Figure 7 plots the cross sectional view of the ENMC detector and Figure 8 shows a cut-away side view.

The ENMC was designed using the MCNP neutron transport code. The detector geometry and spacing was optimized for best efficiency and die-away time. The optimal design point differs from other MCNP-optimized designs because the detector tubes had 10 atm of  $^3\text{He}$  rather than the conventional 4 atm. That, and the 4-layer design shepherded the design optimization toward the minimal polyethylene design.

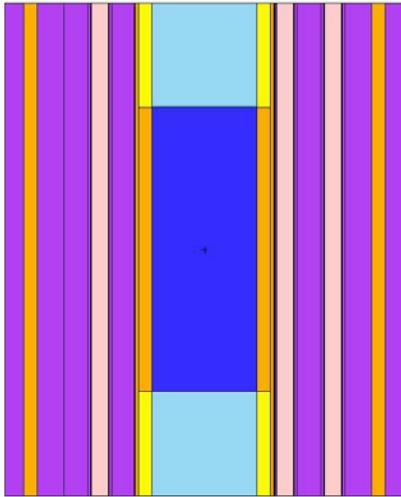
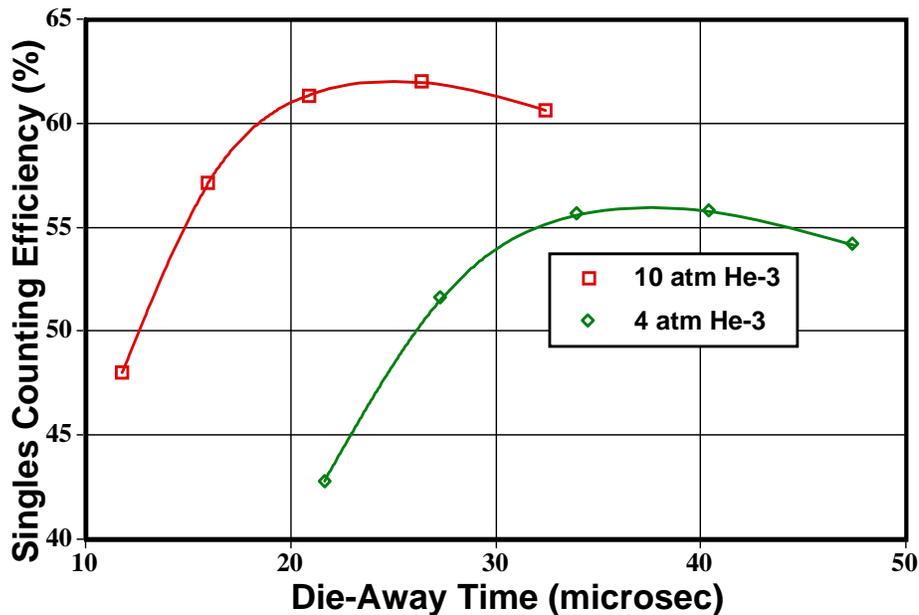


Fig. 8. MCNP plot of ENMC detector. Side cut-away view.

Figure 9 below shows the relative trade off between improved efficiency and die-away, calculated using the MCNP code. As the moderator is increased, the efficiency does improve until it plateaus. However, as the moderator is increased, the die-away time also increases. The ENMC design was optimized to achieve the best combination of die-away time and efficiency possible. The figure of merit was the reduction of the variance due to the accidentals, as also described in equations 9 and 10.



The mechanical design of the ENMC detector groups the 127 detector channels into 4 axial rings and 27 electrical channels. Each channel has an AMPTEC preamplifier-amplifier-discriminator attached. A de-randomizing buffer is also included in the intrinsic counter electronics. The output of the counter is connected to any standard neutron multiplicity shift register. A picture of the ENMC counter is shown in Figure 10.

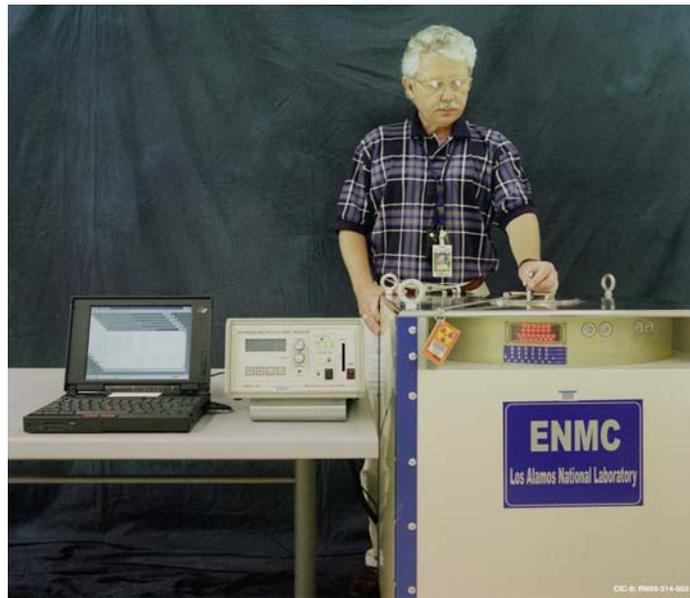


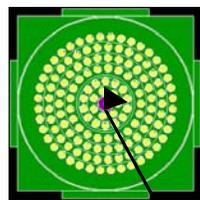
Fig. 10. Picture of ENMC detector.

A variation of the ENMC includes a counter insert, called the Inventory Sample Counter (INVS). Inserting the INVS counter adds an additional 21 detector tubes in two rings to the counter system. The addition of the INVS increases the over all efficiency to 80%, and the die-away time remains 22  $\mu$ sec. The MCNP design for the modified ENMC is shown in Figure 11.

The ENMC (with and without the INVS insert) has been extensively tested. The experimental results confirm that figure-of-merit analysis described above. For a given sample type and count time, the ENMC provides assays with better precision than earlier neutron counter designs. We compare measurements taken with the ENMC to the Plutonium Scrap Multiplicity Counter (PSMC), which had been the state-of-the-art instrument. Table 2 below lists the relevant performance characteristics of the ENMC and the PSMC.

**Table 2: Operational Parameters for an ENMC and a PSMC Counter**

Detector	Efficiency (%)	Pre-delay ( $\mu$ s)	Gate Width ( $\mu$ s)	Doubles Gate Fraction	Triples Gate Fraction	Die-Away Time ( $\mu$ s)
PSMC	53	3	64	.651	.441	47
ENMC	65	1.5	24	..621	.404	21.8
ENMC/INVS	80	1.5	24	.605	.399	18.8



**INVS Booster Insert**  
 21 Tubes (2 rings)  
 20 in. Active Length

**ENMC/INVS**  
 $\epsilon = 80.0\%$ ,  $\tau = 22 \mu$ s

**Sample Chamber**  
 2 in. (.08 cm) Diam.  
 X 6 in. 15.2 cm) High

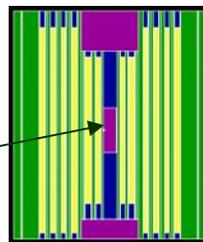


Fig. 11. MCNP plots of ENMC detector with INVS module inserted.

**Table 3: Count time comparisons between different counters**

Detector	Working Reference Material				
	LANL STD-ISO3,6,9,12	LANL STD-11	LANL STDSRP12-1	Hanford PFP 41-86-03-240	LANL LAO261C10
PSMC	7.3	170	34	1,352	27
ENMC	1.6	36	5.6	64	2.7
Ratio PSMC / ENMC	4.6	4.7	6.1	21	10

The ENMC can be compared to previous multiplicity counters either by comparing the assay time required to achieve a particular precision, or by comparing the measured precision for a fixed count time. These two methods are physically equivalent but illustrate the improved performance in different ways. Table 3 below compares count times (in minutes) and the count time ratios between the ENMC and the PSMC for various different reference standards. The standards were chosen to test the limits in precision induced by a high accidentals rate: both high mass and high alpha are represented. The samples were counted for a time sufficient to achieve a 1% RSD precision. This comparison clearly shows that for all other parameters equal, the ENMC achieves significantly better multiplicity precision than the PSMC detector (or conversely, a shorter count time for the same precision).

Multiple measurements of reference standards were also made to evaluate the accuracy of the ENMC. These included a broad range of materials, plutonium masses, alphas and multiplication. The masses varied from 0.691 grams of plutonium to 1,500 grams of plutonium, a range of alpha from 0.1 to 12, and a multiplication of 1 to 1.2. The results are plotted in Figure 12 against the known values for these reference standards. The results of Figure 12 show that the ENMC has achieved a high level of operational accuracy, over a broad range of test cases. In all cases a full multiplicity assay was performed.

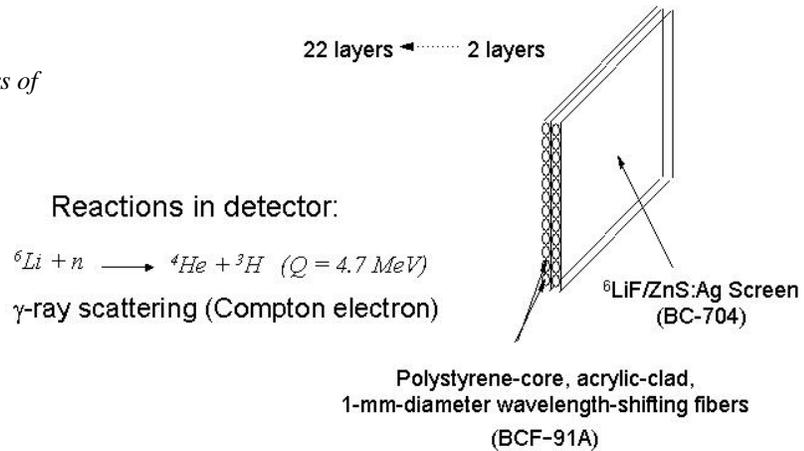
## **B. Fast Neutron Counters**

The ENMC has proven to be a significant advancement in the capability of neutron multiplicity counters. Research is being conducted to extend the capabilities even further. The intent of this research is to advance the improvement by reducing die away time and increasing detection efficiency, beyond that of the ENMC. Again, the design approach has been motivated by the die away time and efficiency scaling discussed earlier. Although these new methods are not yet operational, this discussion provides a snap shot into the current directions and state of neutron multiplicity counter research.

Experiments to develop very fast neutron counters approach the problem of neutron detection from an entirely different technological perspective, which do not build on the general designs of existing, conventional neutron detectors. The “fiber” Neutron Capture Counter for Residues (NCCR) is a prototype neutron multiplicity counter with a very short die-away time. The neutron sensor uses a ZnS:Ag scintillator loaded with <sup>6</sup>Li (as fluoride), which captures thermal and epithermal neutrons. The energetic alpha particle and triton released in the capture reaction produce light in the scintillator. The light is transported by 1-mm-diameter wavelength-shifting optical fibers to the photomultiplier tubes at opposite ends of the <sup>6</sup>Li-scintillator/fiber assembly.

Figure 13 illustrates the alternating layers of  $^6\text{Li}$ -scintillator and fiber ribbon that make up these neutron detector elements, consisting of 22 layers each of fiber and  $^6\text{Li}$ -scintillator.

Fig. 13. The sketch shows two layers of the 22-layer sensor elements of the NCCR.



The moderator consists of the plastic fiber and hydrogenous binder in the LiF-ZnS mixture. These are intimately combined with the  $^6\text{Li}$  capture material. The relatively high density of capture nuclides contributes to epithermal capture, which results in a shorter neutron die-away time. The intimate mix of moderator and capture media also contributes. Thus, the NCCR has a neutron die-away time of 4  $\mu\text{s}$ .

Figure 14 is a photograph of three of 12 detector elements of the NCCR. These make up one side of the four-sided neutron well counter.



Fig. 14. Three of 12 NCCR detector elements are assembled to form one side of the four-sided neutron well counter. PMTs are coupled optically at the ends of each element. Signals from opposite ends of each element are combined into a single preamplifier. Note meter stick in foreground.

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