NEW SHIFT-REGISTER ELECTRONICS FOR IMPROVED PRECISION OF NEUTRON COINCIDENCE AND MULTIPLICITY ASSAYS OF PLUTONIUM AND URANIUM MASS

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ABSTRACT

Active and passive neutron-coincidence counting (NCC) is used routinely for nondestructive assay (NDA) of uranium and plutonium, in many forms. Passive neutron multiplicity counting (PNMC) is used routinely for NDA of plutonium scrap and waste. We've developed and extensively tested new electronics that significantly improves precision of double and triple coincidences, and multiplicity assays. Using both a time-correlated pulser and neutron sources, we've simulated PNMC assays (PNMAs) for a wide variety of plutonium samples. Plutonium-240-effective masses ranged from 0.1 to 200 g. The important parameter α [ratio of (α,n) to spontaneous-fission neutrons] varied from 0 to 10. We've also tested one circuit (Fast Accidentals Sampling or FA) on Pu-oxide standards. For sources and standards measurements, representative the majority of NCC and PNMC applications, FA precision reductions relative to conventional multiplicity shift-register (CMSR) circuits, are 20-29% for doubles, and 24–31% for multiplicity assays. For ^{240}Pu-effective masses of 50–100 g, FA gains are roughly independent of α. For α =0, FA gains are roughly independent of ^{240}Pu-effective mass. FA sampling has been implemented in the Advanced Multiplicity Shift Register (AMSR). The AMSR, relative to CMSRs, reduces doubles measurement times by factors of 1.6 to 2.0. The reduction for PNMC assays is by factors of 1.7 to 2.1. Testing of FA sampling on plutonium was done using an integrated system: the Epithermal Neutron Multiplicity Counter (ENMC), the commercial AMSR-150, and the general-purpose international NCC software package, INCC ver. 4.00. FA sampling also significantly improves measurement precision for active NCC assays of uranium. The new electronics reduces the need for high efficiency, and therefore cost, of neutron coincidence and multiplicity counters.

I. INTRODUCTION

Radioactive decays of plutonium and uranium, statistical processes, produce characteristic-signature neutrons and gamma rays that are measured in various radiation detectors for the purpose of nondestructive assay (NDA). Because of their high penetrability, neutron methods are used primarily to measure isotopic masses. Gamma-ray methods typically measure isotopic ratios. Both these measurements are essential to modern systems of nuclear material control and accountability, and also nuclear waste characterization for materials disposition. Many NDA methods count electronic pulses, produced by neutrons and/or gamma rays. These measurements are also statistical processes. Time-correlation analysis of neutron pulse streams is commonly used to unfold signals from spontaneous fission (SF), induced fission (IF), and (α,n) reactions produced in, for example, a plutonium item. This unfolding is required for determination of isotopic masses. Such analysis methods are called neutron coincidence counting (NCC) and neutron multiplicity counting (NMC). A review of NMC is given in reference 1. NCC and NMC assay precisions are largely determined by the level of accidental coincidence pulses (A). With higher A, assay precision worsens. Many NCC and NMC assays are precision-limited, and require long count times for acceptable results. Attempts to improve precision have been focused primarily on detector design (see, for example reference 2), and large gains have been achieved. This paper describes significant improvements in measurement precision over conventional methods using new digital-signal-processing circuits. These circuits can be used with all current and advanced NCCs and PNMCs, to improve precision over and above the recent improvements made by detector design.[2]

The Advanced Multiplicity Shift Register (AMSR)[3] is now available commercially. It is designed for use with the general-purpose international NCC software package, INCC v. 4.00.[4] The Epithermal Neutron Multiplicity Counter (ENMC)[2] is the current state-of-the-art NMC, with count times lower by factors of 5 – 20, compared to the Plutonium Scrap Multiplicity Counter (PSMC).[5] representative of the previous generation of Thermal Neutron Multiplicity Counters (TNMCs). The AMSR is matched to the performance capabilities of the ENMC. Figure 1 shows he integrated, operating ENMC/AMSR/INCC system, and some of the authors of this paper.

Figure 1. Photograph showing the integrated, operating ENMC/AMSR/INCC system, and, left-to-right, Jim Stewart, Steve Bourret, Merlyn Krick, and Martin Sweet.

II. DESCRIPTION OF THE NEW PULSE PROCESSING TECHNIQUES

The conventional multiplicity shift register (CMSR)[6] samples both the real-plus accidental (R+A), or foreground, coincidence gate and the accidental (A), or background, coincidence gate at the rate of incoming pulses, and in only one direction in time. Fast Accidentals Sampling (FA) samples the A gate much faster, at the clock speed, in this case, 4 MHz. This improves the precision of the A measurement, and, in turn the R measurement, because R is obtained by unfolding R from R+A. Forward/Backward Sampling (F/B) samples R+A at the pulse rate, but looks both forward and backward in time, changing the effective gate width, and thus changing R+A. Here, R, R+A, and A, can be either simple sums, in the case of conventional neutron coincidence counting (NCC), or pulse multiplicity distributions (0s, 1s, 2s, etc.) NMC.

A. Conventional, Pulse-Triggered, Time-Correlation Neutron Pulse Counting

For a fission at time zero, the probability of detecting a fission neutron at time **t** decreases exponentially with time [$P(t)=(1/\tau)\exp(-t/\tau)$, where τ is the neutron "die-away time"]. After a long delay, Δ, the probability of detecting a neutron from a fission at **t** = 0, is negligible. Therefore, upon detecting a neutron at time **t**, CMSRs count real coincidences R (neutron pulses from the same fission) plus accidental coincidences A [neutron pulses from other fissions plus time-random neutron pulses, e.g., from (α,n) reactions], in the time interval t+p to t+p+G, where G is the gate length, and p is the predelay. The predelay p removes bias due to electronic dead time effects. Upon detecting a neutron at time **t**, CMSRs also tally accidental coincidences A in the interval t+p+G+Δ to t+p+2G+Δ. At the end of the counting interval, one quantity of interest is the number of real coincidence pairs, or doubles (D), one NDA signature for fissile material mass. For doubles, the unfolding of R from R+A is simple,

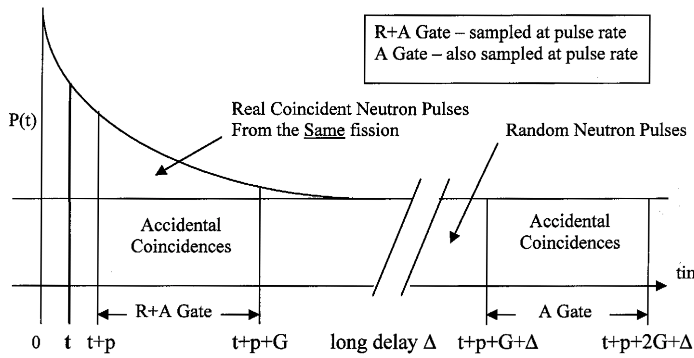

Figure 2. Detection probability distribution and gate timing/sampling – conventional method.

$$D = (D+A_D) - (A_D), \quad \text{Eq. (1)}$$

Where D is the real doubles and A_D is the accidental doubles. The statistical error in D (precision) is given approximately by

$$\sigma_D \sim [(D+A_D) + A_D]^{1/2} \quad \text{Eq. (2)}$$

In most actual cases, $D << A_D$, and the D error is approximately

$$\sigma_D \sim (2A_D)^{1/2} \quad \text{Eq. (3)}$$

The error model in Eq. 2 is based on the assumptions of independent errors in ($D+A_D$) and A_D as well as Poisson statistics. Neither of these assumptions is valid for coincidence counting. However, this simple error model agrees with doubles sample standard deviation measurements to within a few tens of percent, depending on the item measured.

FA sampling and F/B sampling were implemented to measure and compare their individual and combined effects on doubles, triples, and passive-neutron assay (PNMA) precision, and thus, measurement time for a fixed precision.

B. Pulse-Triggered Time-Correlation Neutron Pulse Counting with Fast-Accidentals Sampling

With FA sampling, the R+A gate is sampled conventionally, at the pulse rate, but the A gate is sampled at the clock rate. In Figure 3, n is the clock cycle and δt is the time increment per cycle, in this case, 0.25 μs. Sampling of the 2 gates is decoupled, compared with the conventional approach. Because the clock rate (4 MHz here) is usually very much larger than the pulse rate, measurement precision of accidental coincidences is very much better than that of signal-triggered real-plus-accidental coincidences. This results in a decrease in σ_D by a factor of approximately $2^{1/2}$, or

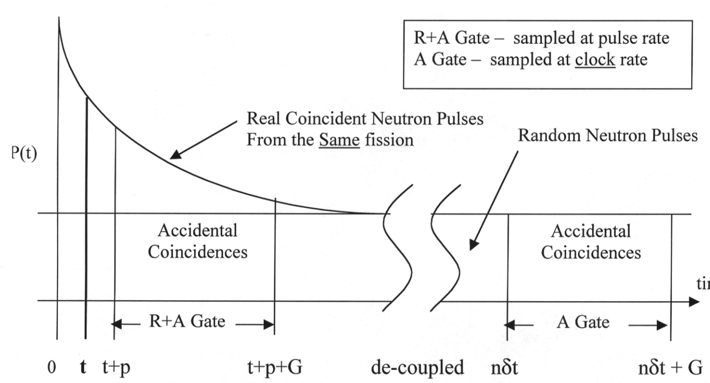

Figure 3. Detection probability distribution and gate timing/sampling – fast accidentals sampling.

$$\sigma_{D\text{-}FA} \sim A_D^{1/2} \qquad \text{Eq. (4)}$$

The resultant reduction in doubles measurement time to reach a fixed precision is a factor of 2, according to the simple error model.

The quantity D, measured by CMSRs, is simply the number of pulse-triggered time-correlated pulse pairs in a counting interval. CMSRs accumulate all multiplets of neutron pulses (0s, 1s, 2s, 3s, etc.) separately from the R+A and A gates. The R+A and A-pulse multiplicity distributions are unfolded to produce the R-multiplicity distribution. Moments of the R distribution are formed that can yield the rates of double, triple, quad, etc., real coincidences. In practice, the doubles rate is usually determined by simply summing the pulse-triggered contents of the R+A and A gates, subtracting the two, and dividing by the count time. The triples rate is determined by an equation involving moments of the R+A and A distributions. Exact, analytic, and point-model equations have been developed for the singles, doubles, and triples rates.[7, 8] These equations contain detector parameters, nuclear fission data, and assay-sample unknowns. For a plutonium item, the unknowns are the neutron source intensities from SF, IF, and (α,n) reactions. The SF rate is directly related to the effective mass of ^{240}Pu in the item, the assay quantity of interest. Exact expressions for the multiplicity assay mass precision have not yet been developed, but theoretical/empirical estimates are available for CMSRs.[9]

C. Pulse-Triggered Time-Correlation Neutron Pulse Counting with Forward/Backward Sampling

With F/B sampling, two R+A gates are sampled, one before and one after a pulse at τ, both at the pulse rate. In stand-alone F/B mode, two A gates are sampled, one long before and one long after a pulse at t, both also at the pulse rate. This process is depicted in Figure 4. FA and F/B can be run in combined mode, with a single A gate, sampled at the clock speed. We attempted to isolate the effect of F/B on measurement precision, using gate width G/2, and predelay p/2. For the conventional case, the doubles rate is proportional to the "doubles gate fraction," f_D , the fraction of pulse pairs counted relative to the total possible, where

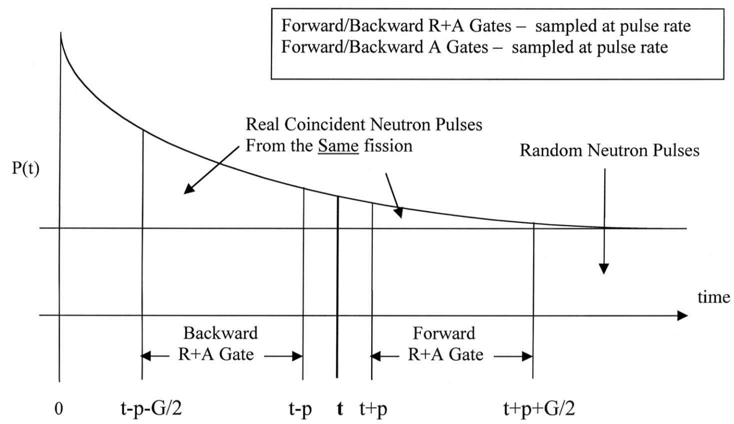

Figure 4. Detection probability distribution and gate timing/sampling – Forward/Backward Sampling (F/B.)

$$f_D\,(p,G,\tau) = \exp(-p/\tau)[1-\exp(-G/\,\tau)]. \qquad \text{Eq. (5)}$$

For p=3 μs, G=64 μs, and τ=50 μs, f_D = 0.68. For F/B, the doubles gate fraction is twice f_D , for the same detector parameters, i.e.,

$$f_{D,\,F/B}\,(p,G,\tau) = 2\,f_D\,(p,G,\tau) \qquad \text{Eq. (6)}$$

It is easily shown that F/B sampling, compared to conventional sampling, merely multiplies the measured D value by two, without improving precision, because no new information is collected. However, with stand-alone F/B using G=64 μs, the A gate is being sampled at twice the rate as that of conventional mode. This alone results in an improved measurement precision for doubles. With G/2, A gate sampling is equivalent to conventional sampling for doubles. For p=1.5 μs, G=32 μs, and τ=50 μs, $f_{D,F/B}$ = 0.92, 35% higher than for the conventional method but without new information. Similarly, it can be shown, the F/B triples gate fraction is 60% higher than that of the conventional method. It is as yet not entirely clear whether or not F/B sampling adds new information for triples measurements, to improve precision. For PNMA, the measured singles, doubles, and triples rates are used to compute the effective mass of ^{240}Pu. Therefore, changes in the precision of doubles and triples, affect the PNMA mass precision.

Our doubles measurements to date indicate that the F/B sampling with p/2 and G/2 is not equivalent to conventional sampling with p and G. It appears that these cases have different optimum gate widths, G_{opt}, (value of G that minimizes measurement precision) depending on sample parameters for fixed detector parameters. Determination of G_{opt} for doubles, triples, and PNMA mass for a wide range of sample parameters and sampling methods is beyond the scope of this paper. Here, we do, however, report extensive measurement data for F/B(p=1.5, G=32), F/B(p=3, G=64), both FA and F/B(p=1.5, G=32), and both FA and F/B(p=3, G=64).

III. EVOLUTION OF ADVANCED SHIFT-REGISTER TIME-CORRELATION ELECTRONICS

Our first efforts were directed towards reducing precision of the measured doubles rate for a fixed count time. This was done by simply increasing the width of the A gate, thus improving the precision of A_D, hence that of D. This work was done using the Dual-Gated Shift Register (DGSR).[10] A maximum count-time (variance) reduction factor of 1.72 was observed from DGSR measurements of ^{252}Cf and AmLi sources. The maximum gain was seen for $D/A_D = 1/4$, or less, as to be expected. The prototype DGSR is shown at far left in Figure 5 below. We extended this concept to multiplicity counting by increasing the A-gate sampling rate from the pulse rate (conventional) to the clock speed (4 MHz), while keeping the same gate widths for R+A and A. At the same time, we implemented F/B sampling on the R+A gate, a suggestion from A. Gorobets[11] from the Research Institute of Atomic Reactors in Dimitrovgrad, Russia. The capability to combine FA and F/B sampling was also implemented. The test bed for these studies is the Experimental AMSR, shown second from left in Figure 5. Next we fabricated a unit for testing at Dimitrovgrad, the experimental multiplicity shift register (EMSR) shown second from right in Figure 5. At this time, FA sampling has been implemented in one commercial unit, the AMSR-150, shown at far right in Figure 5.

Figure 5. Photograph showing evolution of the Advanced Multiplicity Shift Register (AMSR). Left to right: the Dual-Gated Shift Register (DGSR), the Experimental AMSR (test-bed), the EMSR, and a commercial AMSR (AMSR-150)

IV. MEASUREMENT RESULTS COMPARING CONVENTIONAL, FAST-ACCIDENTALS (FA), FORWARD/BACKWARD, AND COMBINED FA AND F/B SAMPLING CIRCUITS

An extensive series of measurements was performed using the time-correlated/random pulser[12] to simulate actual measurements of a wide range of plutonium items in a fictitious thermal-neutron multiplicity counter (TNMC). The assumed TNMC has an efficiency of 50%, and a die-away time of 50 µs. A CMSR used with the TNMC is normally set with a pre-delay of 3 µs, and a gate of 64 µs. These detector and electronics parameters are close to those of the PSMC. Several pulse-sampling cases were tested for each item, using the Experimental AMSR. These cases are described in Table I.

Table I. General Description of Pulse-Sampling Methods: Pulser-Simulated TNMC Measurements

Case	Pulse-sampling method	Description	Predelay, p µs	Gate, G µs	Doubles gate fraction, f_D	Triples gate fraction, f_T
A	Conventional	C(3,64)	3	64	0.6799	0.4623
B	Fast Accidentals	FA(3,64)	3	64	0.6799	0.4623
C	Forward/Backward	F/B(1.5,32)	1.5	32	0.9175	0.7392
D	Both Together	Both(1.5,32)	1.5	32	0.9175	0.7392
E	Forward/Backward	F/B(3,64)	3	64	1.3598	1.5096
F	Both Together	Both(3,64)	3	64	1.3598	1.5096

We also tested pulse-sampling methods using combinations of AmLi and ^{252}Cf neutron sources, measured with the 5-Ring Multiplicity Counter (5RMC).[13,14] The 5RMC has an efficiency of 54%, and a die-away time of 55 µs, similar to the TNMC. Both types of tests (sources and pulser) produced time-correlated and random pulse streams characteristic of real plutonium items. For each measurement, 1000 repeat cycles were acquired, and standard deviations of the means of measured parameters were determined. For 1000 repeats, the relative error in the standard deviation of the mean is $2000^{-1/2}$, or 2.24%.

A. Item Parameters: $^{240}Pu_{eff}$ Mass (m) = 50 g, Multiplication (M) = 1.05, Variable α; Sources (5RMC) and Pulser Measurements (TNMC)

For three sampling methods (B, C, and D in Table I), Figure 6 shows ratios of measured D precisions relative to those for the conventional method. For these cases, the pulser was programmed to simulate medium-sized plutonium items with a $^{240}Pu_{eff}$ mass (m) of 50 g, a multiplication (M) of 1.05, and 2 values of α, 0 and 4. TNMC detector parameters were used. Results of these cases are plotted with results of 5RMC measurements using combinations of ^{252}Cf and AmLi sources, approximating m and M programmed for the pulser, with α ranging from 0 to ~7. The pulser results are in good agreement with the sources results. Figure 6 shows the FA(3,64) and both(1.5,32) cases to be nearly equivalent in performance, with D precision ratios of ~0.8 for α = 0, to ~0.72 for αs greater than 4. Here, FA(3,64) means FA with p=3, and G=4. The F/B(1.5,32) cases were set up in an attempt to isolate the effects of F/B sampling on D precision. Theoretically, F/B(3,64) produces a doubles rate that is exactly twice that of the C(3,64) case, with no improvement in D precision, except for the gain derived from sampling the A gate at twice the rate of C(3,64)[15]. The F/B(1.5,32) gate fraction is 35% higher than that of the C(3,64) case, but should not improve doubles precision at all[15]. However, the data of Figure 6 show the F/B(1.5,32):C(3,64) precision ratio to be uniformly less than unity and vary from ~0.89 to ~0.93, for α ranging between 0 and 7. This result likely due to a more optimum effective gate width of F/B(1.5,32) vs. that of C(3,64), for D.

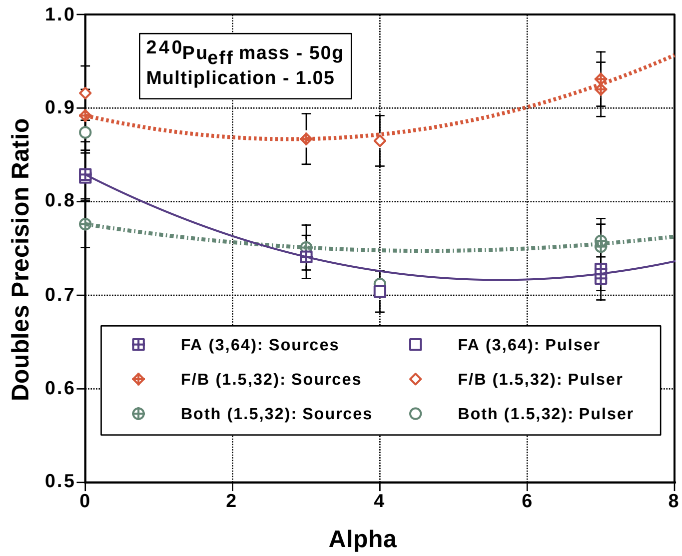

Figure 6. Precision of doubles (D) measurements for the AMSR (FA, F/B, and Both sampling schemes) relative to a CMSR, using Cf + AmLi sources and the pulser to simulate medium-sized plutonium items, with variable α, measured with the 5RMC and the pulser(TNMC), resp.

Figure 6 shows D precision ratios to be only weakly dependent on α for the 50-g item.

Figure 7 is similar to Figure 6 for PNMA precision ratios. As with Figure 6, results are shown for 5RMC/sources and TNMC/pulser measurements. The pulser results are not in good agreement with the sources results, probably due to the greater sensitivity of PNMAs, (relative to doubles), to small differences in detector and item parameters between 5RMC/sources and TNMC/pulser measurements. Figure 7 shows the FA(3,64) and both(1.5,32) cases to be nearly equivalent in performance, with PNMA precision ratios of ~0.77 for α = 0, to between 0.70 and 0.76 for αs greater than 4. Again, the F/B(1.5,32) cases were set up to isolate the effects of F/B sampling on PNMA precision. The F/B(1.5,32) triples gate fraction is 60% higher than the C(3,64) case. The data of Figure 7 show the F/B(1.5,32):C(3,64) precision ratio to vary from ~0.80 to ~0.85, for α ranging between 0 and 7. The relative

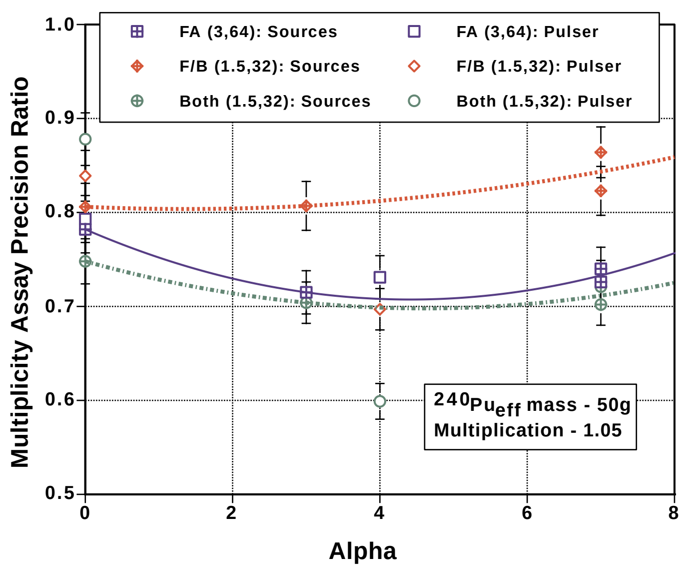

Figure 7. Precision of passive, neutron multiplicity assays (PNMAs) for the AMSR (FA, F/B, and Both sampling schemes) relative to a CMSR, using Cf + AmLi sources and the pulser to simulate medium-sized plutonium items, with variable α, measured with the 5RMC and the pulser(TNMC), resp.

precision gains of F/B(1.5,32) compared to C(3,64) are significantly greater for PNMA than doubles. This could be due to a more optimum effective gate width and/or additional information collection of F/B(1.5,32) relative to C(3,64), for PNMA.

Figure 7 shows PNMA precision ratios to be only weakly dependent on α for the 50-g item.

B. Item Parameters: $^{240}Pu_{eff}$ Mass (m) = 1 g, Multiplication (M) = 1, Variable α; Pulser Measurements (TNMC)

For five sampling methods (B, C, D, E and F in Table I), Figure 6 shows ratios of measured D precisions relative to those for the conventional method. Figure 8 is similar to Figure 6 for smaller mass and multiplication. The pulser was programmed to simulate small plutonium items with a $^{240}Pu_{eff}$ mass (m) of 1 g, a multiplication (M) of 1, and 5 values of α, 0, 1, 2, 5, and 10. TNMC detector parameters were used. Figure 8 shows the FA(3,64) and both(3,64) cases to be nearly equivalent in performance, with D precision ratios of ~0.92 for α. = 0, to ~0.72 for α greater than 6. The F/B(1.5,32):C(3,64) D precision ratio exceeds unity for α less than ~1.5, but reaches ~0.91 for α greater than 6. The improved performance of F/B(3,64) relative to F/B(1.5,32) is partially due to twice the rate of A-gate sampling, compared to C(3,64) and partially due to the wider effective gate of F/B(3,64). The FA(3,64) and Both(3,64) precision ratios should be identical for D, but Figure 8 shows slight differences, probably due to the wider effective gate of Both(3,64).

Figure 8 shows D precision ratios to be strongly dependent on α for the 1-g item, for α less than 5.

Figure 9 is similar to Figure 8 for PNMA precision ratios. Figure 9 shows the FA(3,64) and Both(3,64) cases to be nearly equivalent in performance, with PNMA precision ratios of ~0.93 for α = 0, to ~0.71 for α greater than 6. The improved performance of F/B(3,64) relative to F/B(1.5,32) is partially due to twice the rate of A-gate sampling, compared to C(3,64) and partially due to the wider effective gate of F/B(3,64). The both(3,64) PNMA precision ratios are slightly lower than for those of FA(3,64). Because PNMA uses both doubles and triples, several effects are possible. These could include the larger effective gate width of Both (3,64), and possible new information on real triples (T) being collected by F/B, relative to FA on the R+A distribution.

Figure 9 shows the PNMA precision ratios to be strongly dependent on α for the 1-g item, for α less than 5.

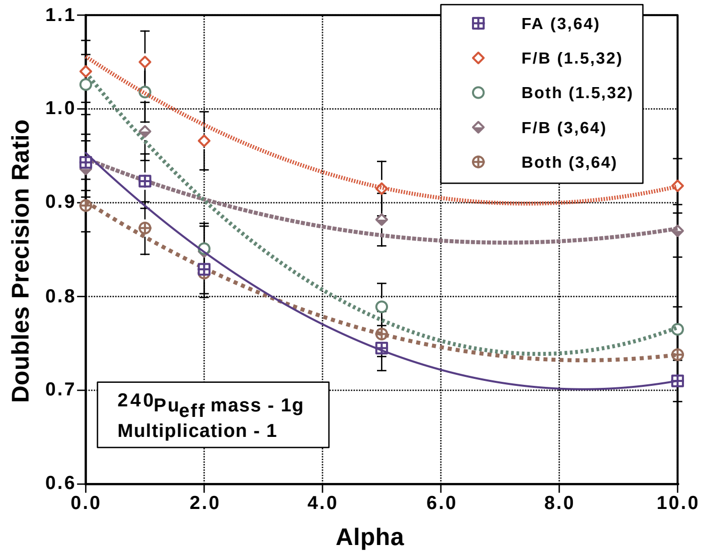

Figure 8. Precision of doubles (D) measurements for the AMSR (FA, F/B, and Both sampling schemes) relative to a CMSR using the pulser to simulate small, variable-α plutonium items measured with TNMC detector parameters.

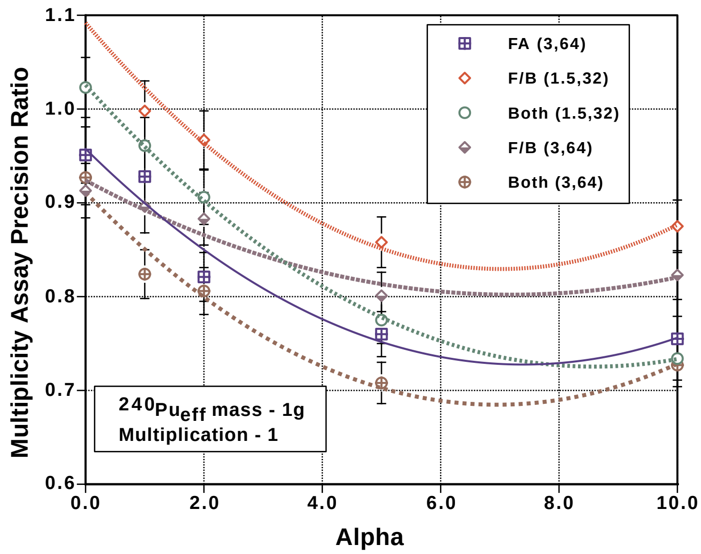

Figure 9. Precision of passive, neutron multiplicity assays (PNMAs) for the AMSR (FA, F/B, and both sampling schemes) relative to a CMSR, using the pulser to simulate small, variable-α plutonium items measured with TNMC detector parameters.

C. Item Parameters: Multiplication (M) = 1, α = 0, $^{240}Pu_{eff}$ Mass (m) - Variable; Pulser Measurements (TNMC)

For five sampling methods (B, C, D, E and F in Table I), Figure 10 shows ratios of measured D precisions relative to those for the conventional method. For these cases, the pulser was programmed to simulate plutonium items with a multiplication (M) of 1, α = 0, and variable $^{240}Pu_{eff}$ mass (m = 0.1, 0.2, 0.5, 1, 2, 5, 10, 20, 50, 100, and 200). TNMC detector parameters were used. Figure 10 shows FA(3,64) and both(3,64) to be essentially the same for the chosen mass range. This indicates F/B(3,64) alone, with a wider effective gate, has no effect on D precision. Above m = ~30, both(1.5,32) is slightly better than FA(3,64) and both(3,64), with the precision ratio dropping below 0.7. This slight improvement is likely from a more optimum effective gate width of F/B(1.5,32) relative to C(3,64), for m greater than ~30. Both(1.5,32) is better than F/B(1.5,32), because of FA, but both exceed unity for m less than ~0.7. This is possibly due to a less-optimum effective gate width of F/B(1.5,32) relative to C(3,64) for small masses. F/B(3,64) is better than F/B(1.5,32) up to m = ~20 g, where F/B(1.5,32) is better. F/B(3,64) and F/B(1.5,32) have different rates of A-gate sampling and different effective gate widths.

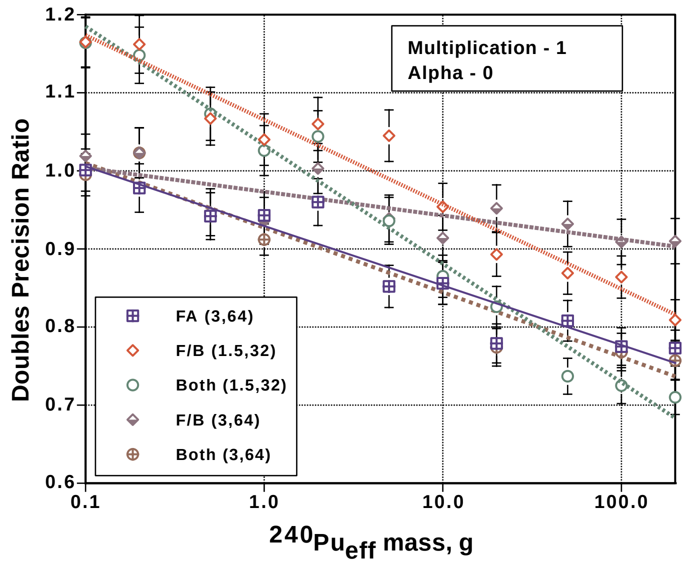

Figure 10. Precision of doubles (D) measurements for the AMSR (FA, F/B, and Both sampling schemes) relative to a CMSR, using the pulser to simulate variable-mass plutonium items measured with TNMC detector parameters.

Figure 11 is similar to Figure 10 for PNMA precision ratios. Figure 10 shows FA(3,64) and Both(3,64) to be essentially the same for the chosen mass range. Above m = ~20, both(1.5,32) is better than FA(3,64) and Both(3,64), with the precision ratio dropping below 0.7. Once again, this improvement is likely from a more optimum effective gate width of F/B(1.5,32) relative to C(3,64), for m greater than ~20. Both(1.5,32) is better than F/B(1.5,32), because of FA, but both exceed unity for m less than ~0.5. This is possibly due to a less-optimum effective gate width of F/B(1.5,32) relative to C(3,64) for small masses. F/B(3,64) is better than F/B(1.5,32) up to m = 10 g, where F/B(1.5,32) is better. F/B(3,64) and F/B(1.5,32) have different rates of A-gate sampling and different effective gate widths.

D. Fast Accidentals (FA) Testing Using The ENMC/AMSR/INCC System and Pu-Oxide Standards

Earlier this summer, a prototype commercial AMSR was modified to include FA sampling. At the same time, a version of the INCC code, compatible with FA sampling, became available. We integrated components to make the ENMC/AMSR/INCC system, shown in Figure 12.

We used the ENMC/AMSR/INCC system to remeasure items that had been measured earlier this year using the ENMC, a CMSR, and INCC ver. 3.

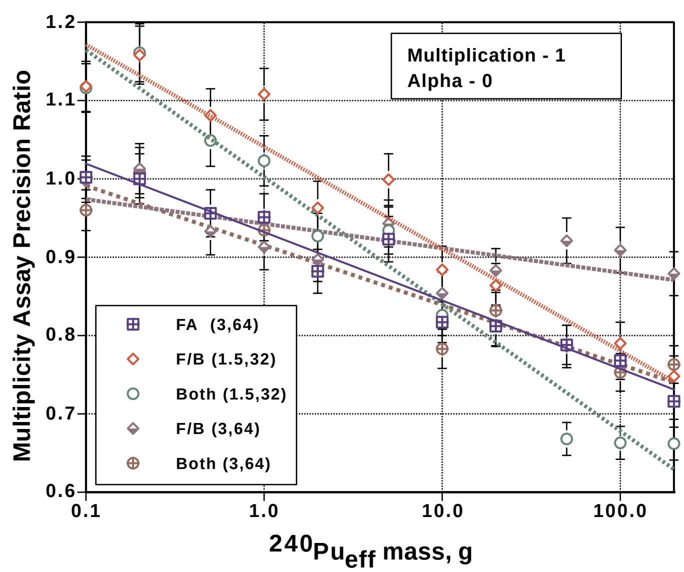

Figure 11. Precision of passive, neutron multiplicity assays (PNMAs) for the AMSR (FA, F/B, and both sampling schemes) relative to a CMSR, using the pulser to simulate variable-mass plutonium items measured with TNMC detector parameters.

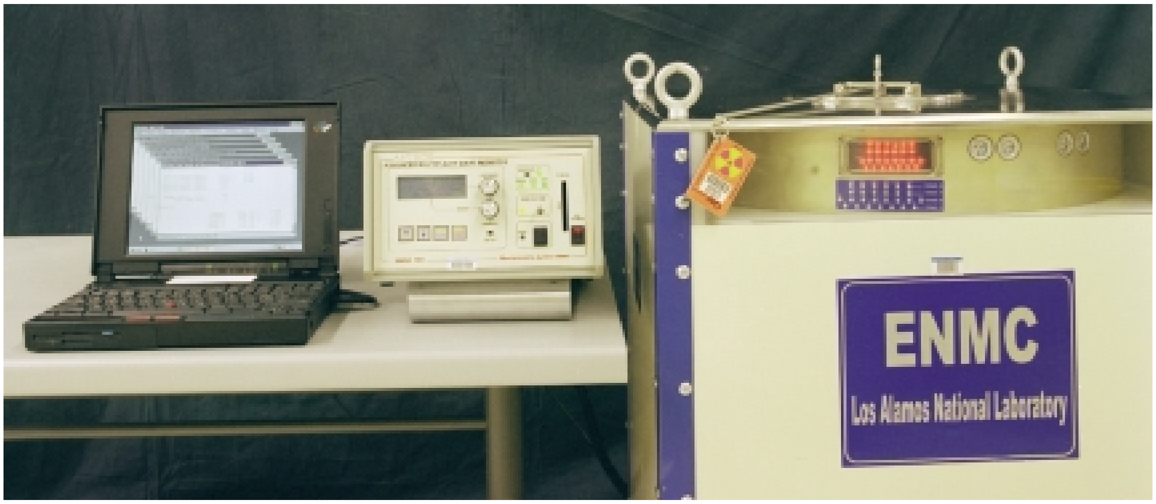

Figure 12. Photograph showing the integrated, operating ENMC/AMSR/INCC system components, left-to-right, a laptop PC running INCC version 4, a commercial AMSR (AMSR-150), and the ENMC.

Table I gives measurement-precision performance comparisons of the AMSR (FA sampling) and CMSR for four plutonium oxide standards spanning a range of Pu mass, %240Pu_{eff}, multiplication, and α. Note that standard LAO252C10 is very similar to an item in Figures 6 and 7, with an α of ~0.5.

The results of Table II show significant precision and/or count time improvements for all but the smallest standard, CBNM Pu61. FA sampling is not effective for samples with low-accidental coincidence rates. However, for measurements of very small masses, e.g., in large waste containers, real coincidence rates can be dominated by accidentals from background neutrons. In this case, FA sampling could show a significant benefit.

For the three largest standards (LAO261C10, STDSRP12-1, and STD-11), gains from FA sampling are greater for passive neutron multiplicity assay (PNMA) than doubles (D). This is because multiplicity assays are based on measurements of the singles, doubles and triples. FA gains for PNMA precision result from a combination of FA gains for doubles (D) and triples (T) precisions.

Table II also shows that FA gains are greatest for STD-11, with a Pu mass of only 60 g, but with an α of 4.9. For the first 2 standards, the FA gains are slightly greater for the higher mass and α. In general, the measured gains in count times are lower than a factor of two, estimated only approximately by the simple error model described Section B. above. Note that the LAO252C10 FA precision ratios are in excellent agreement with Figures 6 and 7.

TABLE II. Comparison of Precisions and Count Times for ENMC/AMSR and ENMC/CMSR Measurements of Standards					
	Standard	Standard ID			
	Parameter	LAO252C10	STDSRP12-1	STD-11	CBNM Pu61
	Pu, g	319.6	874.3	59.81	5.556
	$^{240}Pu_{eff}$, g	54.3	108.4	4.58	2.02
	Multiplication	1.045	1.117	1.004	1.026
	α	0.499	1.039	4.852	0.985
Multiplicity Shift Register					
Advanced (AMSR)	Cycle Time	30	50	30	20
	Cycles	996	965	998	997
	Doubles	15793.1	47869.9	1138.6	552.65
	Doubles precision	2.842	6.478	0.649	0.324
	PNM Assay - Pu,g	319.1	873.6	59.57	5.547
	Assay precision	0.144	0.543	0.116	0.00456
Conventional (CMSR)	Cycle Time	100	60	100	20
	Cycles	120	95	466	998
	Doubles	16250.7	48588.0	1146.9	551.67
	Doubles precision	5.588	24.89	0.651	0.334
	PNM Assay - Pu,g	318.0	874.2	59.92	5.53 6
	Assay precision	0.300	2.111	0.128	0.00467
AMSR/CMSR Precision Ratios: 1000 s Counts	**Doubles**	0.826 ± 0.056	0.769 ± 0.058	0.805 ± 0.032	0.968 ± 0.031
	Multiplicity Assay	0.765 ± 0.052	0.754 ± 0.057	0.731 ± 0.029	0.978 ± 0.031
CMSR/AMSR Count Time Ratios: Fixed Precision	**Doubles**	1.466 ± 0.113	1.693 ± 0.117	1.543 ± 0.064	1.068 ± 0.061
	Multiplicity Assay	1.710 ± 0.234	1.758 ± 0.267	1.873 ± 0.149	1.046 ± 0.066

SUMMARY AND CONCLUSIONS

New methods for processing mixed time-correlated and random digital pulse sequences have been developed. These methods (FA, F/B, and Both) are intended for improvement of the precisions of nuclear-material-assay signatures obtained using NCC and NMC. NCC and NMC are used routinely in many countries for identification, verification, and accountability of uranium and plutonium masses. Thus, improvement in assay precision can yield large dividends in the costs associated with material control and accountability (MC&A). These costs are shared by the facility and the safeguards authority. Included are NDA system costs, but are often dominated by facility-operations costs, which are very time-sensitive.

FA sampling is being commercialized, while F/B sampling is still being investigated. Most testing of the new methods has been done using the pulser. The pulser produces only an approximation to the real pulse stream, in that it produces multiplicities of 1, 2, and 3, 4, but none higher. In limited comparisons we've made for pulser-simulated samples, the results of actual measurements using ^{252}Cf and AmLi sources and plutonium oxide standards are in good agreement for FA. However, for high values of ^{240}Pu-effective masses (m), multiplication (M), and/or α, we have observed biases. These have not been thoroughly investigated, nor has the influence of effective gate width. Also, first-principles Monte Carlo simulations are in progress to better understand F/B sampling of the R+A multiplicity distribution.

In summary, using the pulser and neutron sources, we've simulated PNMC assays (PNMAs) for a wide variety of plutonium samples. ^{240}Pu-effective masses ranged from 0.1 to 200 g. The important parameter α varied from 0 to 10. We've also tested FA sampling on Pu-oxide standards. For sources and standards measurements, representative of the majority of in-facility NCC and NMC applications, FA precision reductions relative to conventional multiplicity shift-register (CMSR) circuits, are 20–29% for doubles, and 24–31% for multiplicity assays. For sources measurements, F/B sampling produces gains of 7–13% for doubles, and 16–20% for PNMAs. For pulser measurements, the combined FA and F/B circuit performs similarly to FA alone. For ^{240}Pu-effective masses of 50 – 100 g, FA gains are roughly independent of α. For α=0, FA gains are roughly independent of ^{240}Pu-effective mass. FA sampling has been implemented in the Advanced Multiplicity Shift Register (AMSR). The AMSR, relative to CMSRs, reduces doubles measurement times by factors of 1.6 to 2.0. The reduction for PNMA is by factors of 1.7 to 2.1. Testing of FA sampling on plutonium was done with an integrated system: the Epithermal Neutron Multiplicity Counter (ENMC), the commercial AMSR-150, and the general-purpose international NCC software package, INCC ver. 4.00.

FA sampling also significantly improves measurement precision (by a factor of ~$2^{1/2}$) for active NCC assays of uranium. The new electronics reduces the need for high efficiency, and therefore cost, of neutron coincidence and multiplicity counters.

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REFERENCES:

1. N. Ensslin, W. C. Harker, M. S. Krick, D. G. Langner, M. M. Pickrell, J. E. Stewart, "Application Guide to Neutron Multiplicity Counting," Los Alamos National Laboratory report LA-13422-M (November 1998).

2. J. E. Stewart, H. O. Menlove, D. R. Mayo, K. E. Kroncke, F. A. Duran, B. S. Cordova, D. G. Langner, and C. D. Rael, "The Epithermal Neutron Multiplicity Counter - Faster Plutonium Assays by Factors of 5 - 20," Los Alamos National Laboratory paper presented at the Institute of Nuclear Materials Management 40th Annual Meeting, Phoenix, AZ, July, 1999 (LA-UR-99-3791).

3. M. E. Abhold, M. R. Sweet, S. C. Bourret, W. J. Hansen, J. Audia, M. S. Krick, S. D. Salazar, and J. E. Stewart, "Advanced Multiplicity Shift Register with Networking Capability," Los Alamos National Laboratory paper presented at the Institute of Nuclear Materials Management 40th Annual Meeting, Phoenix, AZ, July, 1999 (LA-UR-99-512).

4. W. C. Harker and M.S. Krick, INCC Software Users Manual," Versions 3.20 and 3.21, Los Alamos National Laboratory report, Copyright 1998 by the Regents of the University of California, July 21, 1998, Los Alamos National Laboratory document LA-UR-99-1291.

5. H. O. Menlove, J. Baca, M. S. Krick, K. E Kroncke, and D. G. Langner, "Plutonium Scrap Multiplicity Counter Operation Manual," Los Alamos National Laboratory report LA-12479-M (ISPO-349) (January 1993).

6. J. K. Halbig, S. C. Bourret, P. R.Collinsworth, W. J. Hansen, and M. S. Krick "Recent Developments in Multiplicity Counting Hardware at Los Alamos," Los Alamos National Laboratory Unclassified Release LA-UR-91-3571, in Proceedings of the 1991 IEEE Nuclear Science Symposium and Medical Imaging Conference, Santa Fe, NM, November 1991.

7. K. Boehnel, "The Effect of Multiplication on the Quantitative Determination of Spontaneously Fissioning Isotopes by Neutron Correlation Analysis," Nuclear Science and Engineering **90** 75-82 (1985).

8. D. M. Cifarelli and W. Hage, "Models for a Three Parameter Analysis of Neutron Signal Correlation Measurements for Fissile Material Assay," *Nucl. Inst. Meth*. A251, 550 (1986)

9. N. Dytlewski, M. S. Krick, and N. Ensslin, "Measurement Variances in Thermal Neutron Coincidence Counting," *Nucl. Inst. Meth*., A327, 469-479 (1993).

10. J. E. Stewart, S. C. Bourret, M. S. Krick, W. J. Hansen, and W. C. Harker, "A 2-Fold Reduction in Measurement Time for Neutron Assay: Initial Tests of a Prototype Dual-Gated Shift Register (DGSR)," Los Alamos National Laboratory paper presented at the Institute of Nuclear Materials Management 37th Annual Meeting, Naples, FL, July, 1996 (LA-UR-96-2462).

11. A. Gorobets, personal communication, Los Alamos National Laboratory, December 1996.

12. M. S. Krick, M. R. Sweet, and S. C. Bourret, "A Correlated Pulse Generator for Thermal Neutron Coincidence and Multiplicity Counting Applications," Los Alamos National Laboratory paper presented at the Institute of Nuclear Materials Management 40th Annual Meeting, Phoenix, AZ, July 1999 (LA-UR-99-5849).

13. M. S. Krick and J. E. Swansen, "Neutron Multiplicity and Multiplication Measurements," *Nucl. Inst. Meth.*, **219**, 384, 393 (1984).

14. D. G. Langner, M. S. Krick, N. Ensslin, G. E. Bosler, and N. Dytlewski, "Neutron Multiplicity Counter Development," Los Alamos National Laboratory paper presented at the ESARDA conference, Avignon, France, May 14-16, 1991.

15. M. S. Krick, personal communication, Los Alamos National Laboratory, February 1999.