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Extension of ESARDA NDA Multiplicity Benchmark Simulations to Validate Dead Time Correction Algorithms

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Abstract:

Dead time correction algorithms are being evaluated at Los Alamos National Laboratory (LANL) as part of a strategic R&D program to advance correlated neutron analysis. Such algorithms have an immediate impact on currently and soon to be deployed neutron detection systems. The Monte Carlo N-Particle eXtended radiation transport code (MCNPX) can be used to generate a pulse train file that can be post-processed by bespoke analysis software that includes the simulation of dead time effects. This simulation methodology is known as Monte Carlo pulse train generation. Further analysis of the simulated pulse trains with multiplicity shift register (MSR) algorithms can be used to study the dead time perturbed Singles, Doubles and Triples counting rates. MSR analysis is being included in the scope of work since many currently deployed counters cannot benefit from pulse trains acquired using list mode data acquisition, because they are constrained by hardware.

In February 2006 the ESARDA non-destructive assay (NDA) working group published multiplicity benchmark (phases I and II) results in the ESARDA bulletin number 34. This benchmark compared the codes and analysis algorithms used for the simulation of neutron multiplicity counters. The basis for comparison was a series of neutron pulse trains generated by LANL using MCNPX. This paper will present the Monte Carlo pulse train methodology developed for this benchmark exercise and the simulation of dead time effects. The original benchmark simulations have been re-visited to explore the effects of dead time and extended in an attempt to validate dead time correction algorithms. The simulation work in this study accounted for the total dead time in the detection system, based on an extending (or paralyzable) model.

Keywords: NDA; Monte Carlo; dead time; neutron multiplicity; nuclear safeguards

1. Introduction

Temporally correlated neutron emission, from both spontaneous and induced fission, provides a unique signature for the detection of special nuclear material (SNM). Passive neutron multiplicity counting based on multiplicity shift register (MSR) electronics uses signal triggered and (what amounts to) randomly triggered gate inspection to record the number of occurrences of multiplicity i to generate MSR histograms and thus derive correlated neutron event rates. This technique is commonly used in international safeguards measurements for the non-destructive assay of plutonium (Pu) mass.

Denoting the signal triggered and randomly triggered histograms by N_i and B_i and the assay time by t the observed or measured Singles, S_m, Doubles, D_m and Triples, T_m, rates may be expressed by Equations 1, 2 and 4, respectively.

$$S_m = \frac{1}{t} \cdot \sum_{i=0}^{\infty} N_i = \frac{1}{t} \cdot \sum_{i=0}^{\infty} B_i \tag{1}$$

The Singles rate is also referred to as the Totals rate or Gross neutron rate and importantly can also be thought of as the MSR trigger rate, which is the rate of inspection interval or coincidence gate openings.

$$D_m = \frac{1}{t} \cdot \sum_{i=1}^{\infty} i \cdot (N_i - B_i) \tag{2}$$

The expression for the Doubles is formed by the difference between the genuine (or Real) plus chance (or Accidental) pairs tallied with the trigger and the Accidentals. It therefore follows that the Accidentals coincidence (or pairs) rate for Doubles counting, is derived from the random triggered histogram, and takes the form given by Equation 3.

$$A_m = \frac{1}{t} \cdot \sum_{i=1}^{\infty} i.B_i \tag{3}$$

$$T_m = \frac{1}{t} \cdot \sum_{i=2}^{\infty} \frac{i \cdot (i-1)}{2} \cdot (N_i - B_i) - A_m \cdot \frac{D_m}{S_m} \tag{4}$$

The last term in the Triples expression reduces to the product of the Singles, Doubles and gate width; thus may be thought of as Doubles randomly promoted to Triples.

1.1. Dead time

Currently deployed neutron multiplicity counting systems utilize ^{3}He proportional counters for neutron detection, served by dedicated electronics which include amplifier-discriminator boards (~ 3-10 tubes per board) followed by an OR gate or derandomizer circuit. Only signals which exceed the discriminator threshold are counted (generate a digital pulse). The next signal cannot be counted reliably until the trace has returned to a value below the threshold, otherwise pulse pile-up is encountered. This is considered to be one of the main sources of dead time in a neutron multiplicity counting system. The action of the discriminator explains one aspect of counting losses and provides justification for the use of an extending dead time model in this work. In simulation we are able to recreate this ideal model, however real life is more complex. In reality, the system dead time may resemble a combination of extending and non-extending dead times, or indeed some other manifestation.

1.2. Dead time mitigation by design

Dead time effects may (to some extent) be mitigated by design; by distributing the counts between many ^3He proportional counters with a single amplifier-discriminator board per counter. However, this is a costly approach, which extends the current methodology to higher count rates but does not solve the problem. It would be especially costly to retrofit new electronics to all the neutron multiplicity counters deployed in the field. Mitigation by design also has the drawback that the system dead time has a fundamental lower limit dictated by the collection time of the electrons from gas ionization and amplification. Given these limitations, there is still a need for accurate dead time correction methods during analysis of the measured neutron multiplicity data.

1.3. Review of traditional Singles rate dead time correction

Dead time correction algorithms, or correction factors, are applied to measured neutron counting rates to correct for counting losses and thus derive estimates of the true counting rates i.e. the counting rates expected in the absence of dead time. As will be described, correction factors have traditionally been applied solely to the measured neutron counting rates (Singles, Doubles and Triples) using formalisms based on the assumptions of an extending (paralyzable) dead time and Poisson source. In this paper, we consider the correction of the MSR histograms with the advantage that the histograms are assay item specific and corrections are therefore not reliant on the same assumptions.

The Singles rate dead time correction factor CF_S is the ratio S_c/S_m of the dead time corrected Singles rate to the measured (uncorrected) Singles rate. This correction factor should be unity in the absence of dead time. The traditional Singles rate dead time correction factors that we will consider in this paper are herein known as (1) the Poisson Singles rate dead time correction factor, (2) the Empirical Singles rate dead time correction factor, and (3) the Dytlewski Trigger Singles rate dead time correction factor. (4) A fourth alternative histogram-dependent Singles rate dead time correction factor will also be proposed and referred to as the Croft-Dytlewski Singles rate dead time correction factor.

1.3.1. Poisson Singles rate dead time correction factor

The exact Singles rate dead time correction factor for a random (Poisson) neutron source subjected to extending dead time would be of the form given by Equation 5.

$$CF_S = e^{d \cdot S_c} \tag{5}$$

where d is the multiplicity dead time parameter (value of the fixed extending dead time) [1]. AmLi sources approximate the Poisson condition, whereas ^{252}Cf and Pu items have correlated neutron pulse trains.

1.3.2. Empirical Singles rate dead time correction factor

In traditional neutron coincidence counting (Singles, Doubles), the extending dead time correction factor is applied as an empirical two-parameter approximation, given by Equation 6, which is the Doubles dead time correction factor raised to the fourth root in the exponent.

$$CF_S \approx e^{\frac{1}{4}\delta \cdot S_m} = e^{\frac{1}{4}\cdot(A+B\cdot S_m)\cdot S_m} \tag{6}$$

where δ is distinct from d and is referred to as the effective Doubles dead time parameter. For equality with the Poisson model at low rates, we can define A and B in terms of d (although normally A and B are chosen as free parameters).

$$A = 4 \cdot d, \text{and } B = \frac{A^2}{4} \qquad (7), (8)$$

Through experience [2], the inclusion of a higher order term in the exponent is beneficial. Currently, the safeguards software INCC makes use of the semi-empirical correction for the Singles and Doubles rates, and the Dytlewski [3] method for the Triples rate. In addition, a consistent dead time treatment could also be developed for both neutron coincidence and multiplicity counting (Triples).

1.3.3. Dytlewski Trigger Singles rate dead time correction factor

Dytlewski [3] proposes a Singles rate dead time correction factor, based on the correction for the loss of the trigger event rate due to dead time i.e. the lost number of gate inspection intervals. This correction factor is given by Equation 9.

$$CF_S \sim e^{d \cdot S_m} \qquad (9)$$

where d is the system dead time parameter. The approximation is expected to be suitable at low rates $(d \cdot S_c << 1)$ and when the pulse train is not highly correlated. The level of correlation on the neutron pulse train can be formally quantified in terms of the ratio $(D_c / f_d) / S_c$, where f_d is the Doubles gate utilization factor [4]). D_c / f_d is the true (dead time corrected) Doubles event rate on the pulse train with 'perfect' gating so that no pairs are missed due to the pre-delay and gate width being of finite duration.

1.4. The need for improved dead time correction algorithms

As described, traditional dead time correction factors for neutron multiplicity counting are based on an extending (paralyzable) system dead time. Both the Singles and Doubles rate dead time correction factors are approximated by an exponential dependence similar to those for a pure random (Poisson) source. However, the pulse trains are not random for fission sources. There is a need to develop alternative dead time correction factors for the Singles, Doubles and Triples rates derived from the MSR histograms, to extend their application to correlated neutron sources. There is also a need to extend the application to higher order rates e.g. quads (quadruple correlations) etc. to enable a greater number of reliable correlated neutron rates to be obtained in order to reduce dependence upon calibration. Typically neutron multiplicity is used when the detection efficiency is known via the measurement of a number of calibration standards, but this requirement could perhaps be eliminated for complex items.

Evolving counter designs and safeguards applications also dictate a need for more rigorous analysis methods. Since the development of the first neutron multiplicity counters, detector designs have evolved to produce significant increases in efficiency and reductions in effective die-away time. In addition, the range of items being measured has expanded so that large masses of impure items in multiplying form are now routinely encountered. Shielded items may also pose a challenge. As a consequence of these changes, a greater concentration of correlated events appear on the neutron pulse train and management for the correction of dead time losses is being re-visited with a renewed focus.

1.5. Our Research Approach

Here, we extract a new alternative histogram-dependent Singles rate dead time correction factor and present this theoretical approach. The performance of this alternative correction factor is then compared to the three traditional Singles rate correction methods using the simulated neutron pulse trains created for the ESARDA NDA benchmark, perturbed for dead time in post-processing software. Conclusions are drawn as a first step towards developing and implementing advanced dead time correction algorithms. Conclusions regarding the simulation method can also be drawn and will be published elsewhere.

2. Croft-Dytlewski alternative histogram-dependent Singles rate dead time correction

Dytlewski [3] derives expressions for the dead time corrected Singles, Doubles and Triples counting rates, which themselves are derived from the MSR histograms. It can therefore be found that implicit within the Dytlewski dead time correction factors is an alternative form of the Singles rate dead time correction factor, based on the correction of the MSR histogram. The alternative form is beneficial because it is assay item specific in that it derives from the histogram. By identifying this alternative form, we aim to produce a set of self-consistent dead time correction factors so that dead time treatment for Singles (and in some implementations, Doubles) can be made within the same set of assumptions, model and calibration.

The Singles neutron counting rate can also be thought of as the MSR trigger rate. The trigger rate is the number of events that trigger the MSR coincidence gate structure to open and count correlated neutron events, which are then tallied as the MSR histograms. Since the Singles counting rate is perturbed due to counting (or dead time) losses, the number of trigger events is therefore reduced. The new alternative form of the Singles rate dead time correction factor compensates for the impact of counting losses on the trigger rate i.e. it compensates for the gates that did not open and thus did not contribute to the MSR histogram. This alternative form is given by Equation 10.

$$CF_s = \frac{S_c}{S_m} = \frac{\left(\sum_{i=1}^{\infty} \alpha_i \cdot B_i \Big/ \sum_{i=0}^{\infty} B_i\right)}{S_m \cdot T_g} \tag{10}$$

where T_g is the width of the coincidence gate (duration of the inspection interval). The ratio $B_i \Big/ \sum_{i=0}^{\infty} B_i$ is the normalized randomly triggered inspection interval multiplicity histogram. B_i is the number of events recorded in the randomly triggered (also called the Accidental or A-) histogram of multiplicity order i, t is the assay duration, and α_i are the dead time correction functions defined by Dytlewski [3] in terms of the extending dead time parameter d and the order of the histogram bin i. This form is inspired by the multiplicity dead time treatment introduced by Dytlewski [3] and implemented by Dytlewski, *et al.* [5] for Triples. Equation 10 does not collapse to Equation 5 for a Poisson source, but is a close approximation.

3. Simulation method

Three benchmark exercises have been carried out by the ESARDA Working Group on techniques and standards for Non-Destructive Analysis (NDA-WG) since 2003 in order to assess the capabilities of Monte Carlo modeling to reproduce experimental data and the capabilities of analyzing pulse trains. The ESARDA multiplicity benchmark is one such exercise, carried out to compare the different algorithms and codes used in the simulation of neutron multiplicity counters. The published ESARDA multiplicity benchmark exercise modeling data is used here to quantitatively test and compare the performance of four dead time correction schemes using simulated data that conforms to the constant extending dead time assumption.

The counter used to make measurements for the ESARDA multiplicity benchmark, and also used as the basis for the simulations, was the Active Well Coincidence Counter (AWCC) [6] in the fast configuration (Cd liner inside the cavity) in the passive mode (with both discs removed). This is a widely deployed and well known safeguards counter. This active well comprises a cavity height of 35 cm and utilizes 42 ^{3}He tubes for neutron detection. The performance characteristics of the AWCC include an efficiency of 28 % in the fast mode, and a die-away time of 50 microseconds [7]. An MCNPX model of the AWCC was produced by JRC Ispra.

3.1. Pulse train generation

As part of this benchmark exercise, Swinhoe [8] simulated thirteen neutron pulse trains, to represent a range of assay items and counting rates. Table 1 shows the cases that were simulated.

Case	Item
Case 1a	Random neutron source (AmLi) 10 kcps
Case 1b	Random neutron source (AmLi) 100 kcps
Case 1c	Random neutron source (AmLi) 1000 kcps
Case 2a	Spontaneous fission source (252Cf) 10 kcps
Case 2b	Spontaneous fission source (252Cf) 100 kcps
Case 2c	Spontaneous fission source (252Cf) 1000 kcps
Case 3a	Pu metal 10 g (90 % 239Pu)
Case 3b	Pu metal 1000 g (90 % 239Pu)
Case 4a	Pu oxide 10 g (reactor grade)
Case 4b	Pu oxide 1000 g (reactor grade)
Case 5a	Pu oxide 10 g (reactor grade) with AmLi source to give α = 10 (α = ratio of (α,n)/spontaneous fission neutrons)
Case 5b	Pu oxide 10 g (reactor grade) with AmLi source to give α = 20
Case 5c	Pu oxide 10 g (reactor grade) with AmLi source to give α = 100

Table 1: Simulated assay items

3.2. Dead time perturbation of pulse trains

The ESARDA NDA-WG did not extensively consider the simulation of dead time effects. Here, an extending dead time of fixed value was applied to each neutron event in the pulse train and the resulting dead time perturbed train was recorded and output to file. Several values of dead time were initially simulated, but the dead time parameter value of 180 ns closely represents the overall dead time of the AWCC (note that each preamplifier has a greater dead time). Dead time parameter values a factor of two above and below this value were also used for the final performance comparison.

3.3. Software MSR

An in-house software MSR known as VB-Tap6 was used to mimic the action of the MSR and apply dead time to the pulse train. This took the form of a fixed (rectangular) extending dead time after each pulse. The code was used to calculate the measured count rates for both the original pulse trains (without dead time losses) and the resulting dead time perturbed pulse trains.

4. Results

4.1 Effects of dead time on the MSR histograms

The effects of dead time on the MSR (R + A)- and A-histograms can be observed for a ^{252}Cf source with extending dead time values of 22.5 ns, 45 ns, 90 ns, 180 ns, and 360 ns, in Figure 1 below. The effect on both histograms is similar, the width becomes narrower and the mean of the histogram shifts to a lower neutron multiplicity value as the dead time increases. The actual dead time of the AWCC is ~ 180 ns, so we span a range.

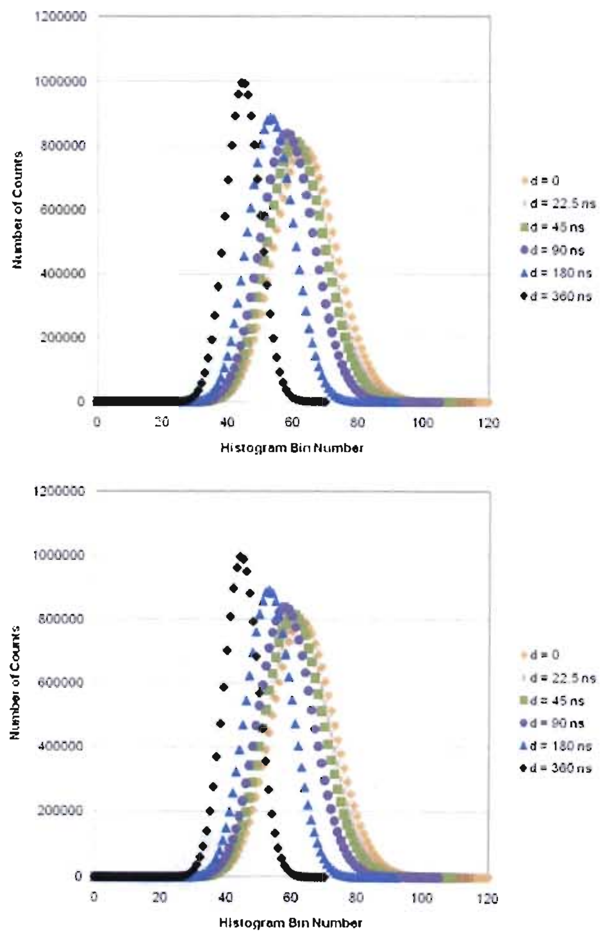

Figure 1: Case 2c ^{252}Cf. Top: (R + A)-histogram. Bottom: A-histogram.

The difference between these two histograms ((R + A) – A) can be observed in Figure 2 below, together with the effects of dead time on this quantity. The difference histogram is a measure of the number of correlated events and Figure 2 shows how the number of correlated events being detected decreases with increasing system dead time.

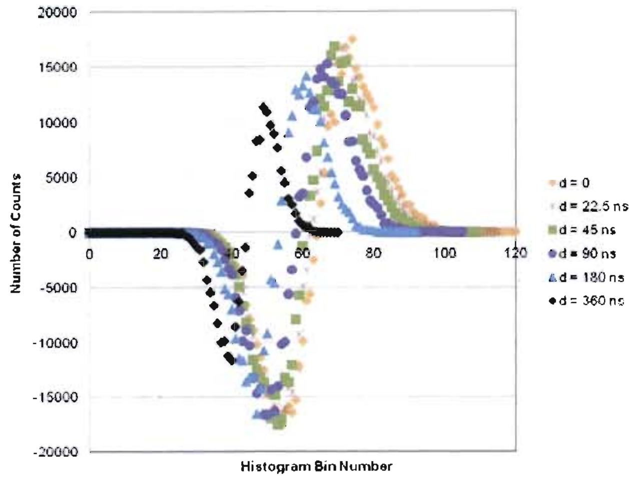

Figure 2: Case 2c ^{252}Cf. Difference ((R + A) – A) histogram

4.2. Performance comparison of selected cases

The Singles rates were corrected using the four "traditional" Singles dead time correction approaches, as well as the new Croft-Dytlewski histogram-dependent Singles rate dead time correction factor. All corrections were made using the fixed dead time value that was applied to make the pulse train i.e. parameters A and B were determined by d. The Doubles rates were also corrected using an empirical Doubles rate dead time correction factor, as well as an extension of the new histogram-dependent Singles rate dead time correction factor to derive a Doubles correction factor.

The % Recovery, given by Equation 11, was used as the performance comparison metric i.e. how well did the each of the Singles rate dead time correction factors back-correct the measured rates to the true rates. A positive result, for example, a 1 % recovery meant that the correction factors over-corrected the rates by 1 %, resulting in a corrected Singles rate 101 % of the true Singles rate value. A negative value, for example, a -1 % recovery meant that the correction factors under-corrected the rates by 1 %, resulting in a corrected Singles rate 99 % of the true Singles rate value. A zero value meant that the correction factors were able to perfectly reproduce the original true Singles rate value.

$$\%\,\text{Recovery} = \left(\frac{S_c}{S_{True}} - 1 \right) \times 100 \qquad (11)$$

The % Recovery for each of the Singles rate dead time correction approaches is shown in Figure 3 as a function of the value of dead time applied. Note the relative scales: the data for the Poisson and Histogram Singles rate dead time correction factors are displayed on the same expanded scale, indicating that these two correction methods have similar performance. In the worst case, the % Recovery is -0.7 %. Similarly, the data for the Empirical and Dytlewski Trigger Singles rate dead time correction factors are also displayed on the same scale. Here the performance is worse; the % Recovery is -10 % in the worst case, which corresponds to a 10 % under-correction.

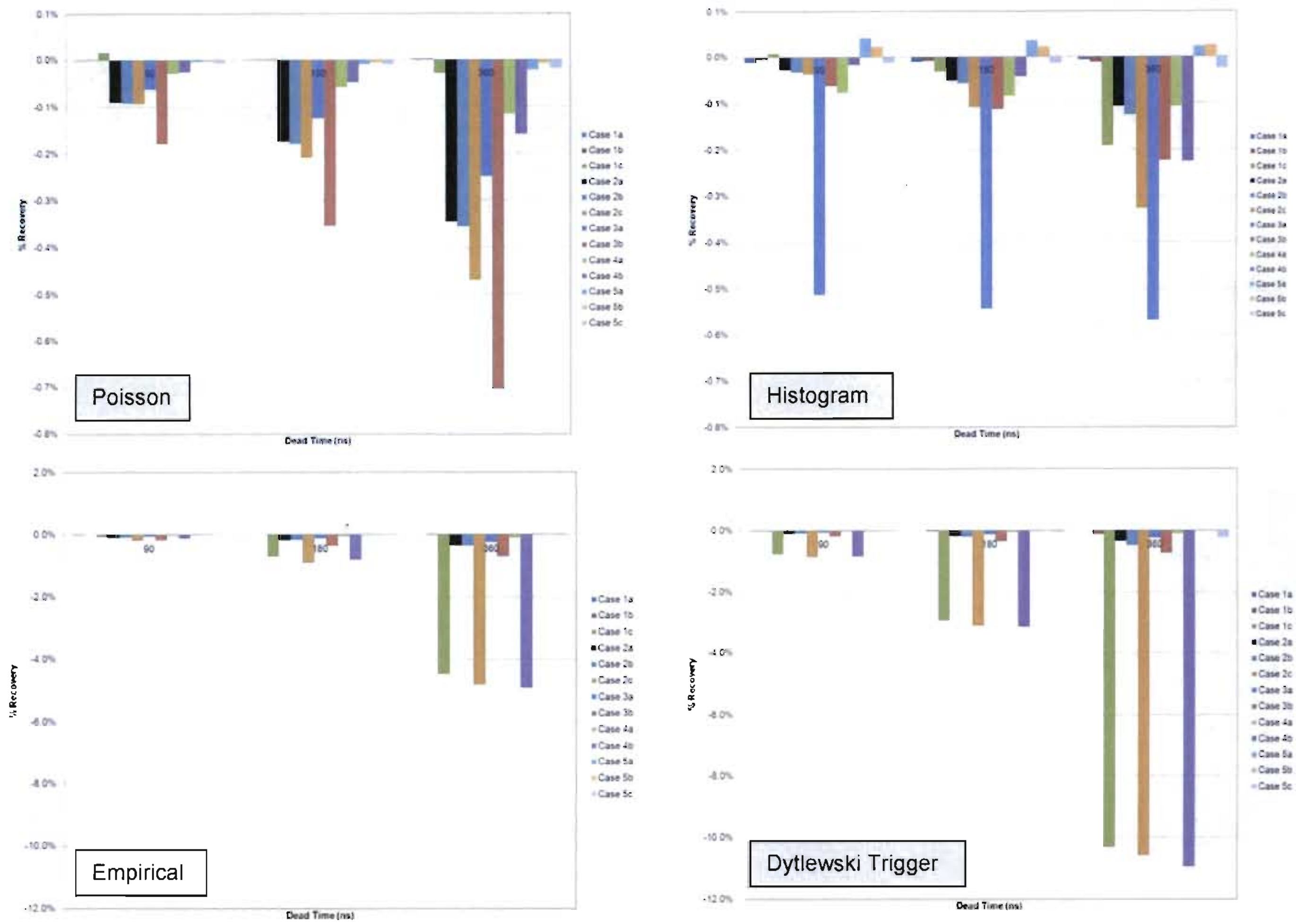

Figure 3: % Recovery performance metric for each of the four Singles rate dead time correction approaches being compared. Data is shown for all thirteen source cases at three values of input extending dead time: 90 ns, 180 ns, and 360 ns.

The % Recovery for two Doubles rate dead time correction approaches is shown in Figure 4. The top of Figure 4 shows the % Recovery for the Empirical and Histogram Doubles rate dead time correction factors. The bottom of Figure 4 shows the "Modified Histogram' Doubles rate dead time correction, which is the same correction factor but using a higher dead time value of 220 ns in the correction factor itself (instead of 180 ns). The input extending dead time in the simulation remained at 180 ns, so the same data was re-analyzed.

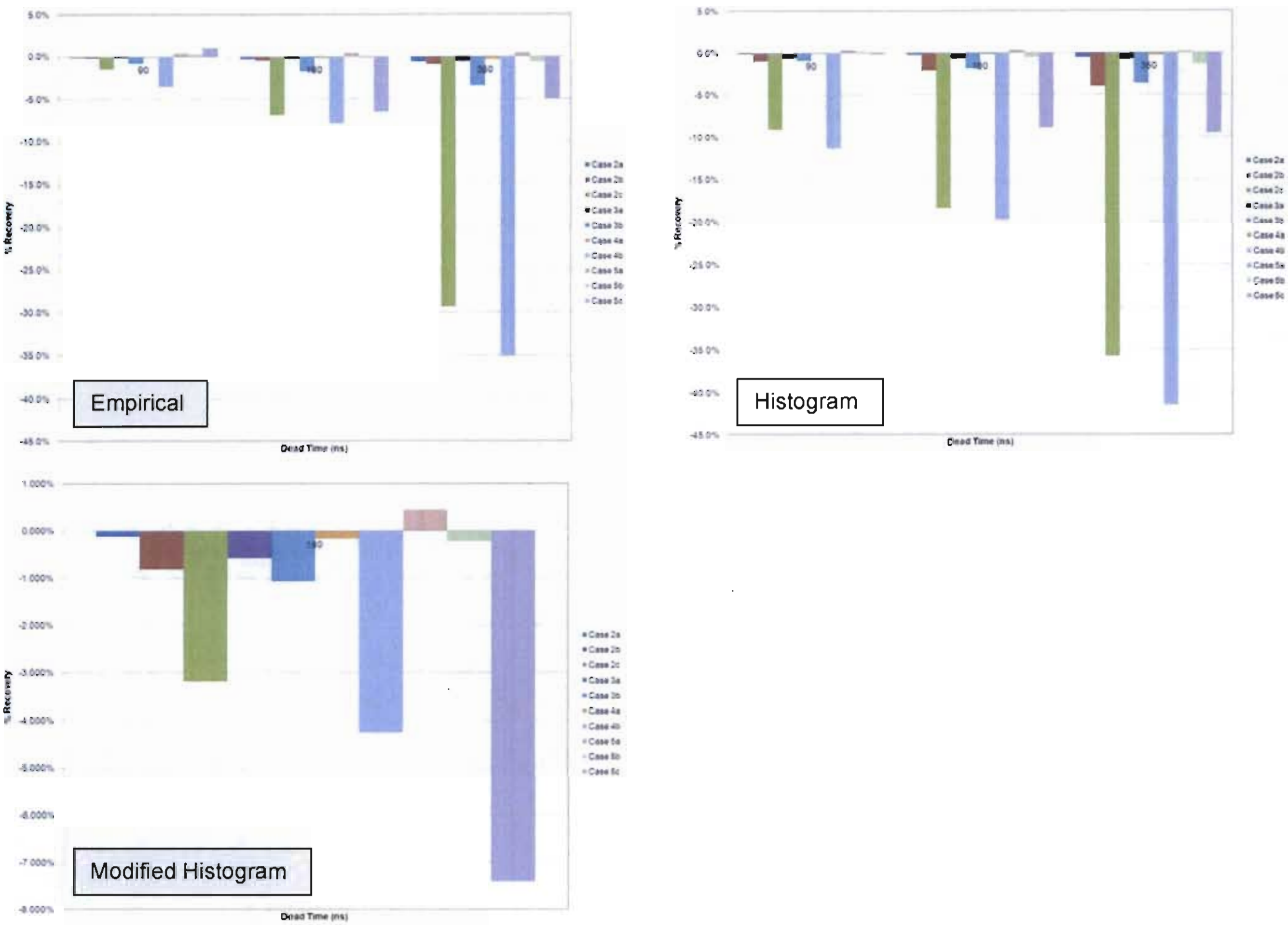

Figure 4: (Top) % Recovery performance metric for two of the Doubles rate dead time correction approaches being compared. Data is shown for ten source cases (AmLi yields only a Singles rate) at three values of input extending dead time: 90 ns, 180 ns, and 360 ns. **(Bottom)**

5. Conclusions and Future Work

We have derived alternative an alternative histogram-dependent Singles rate dead time correction factor, inspired by the Dytlewski approach. This Croft-Dytlewski dead time correction factor was tested using dead time perturbed simulated neutron pulse trains, based on the ability of the correction to recover dead time losses from the resulting histogram. All of the applied Singles rate dead time correction factors perform well for each of the AmLi source cases. This shows that the simulations of dead time effects are correct in that they truly represent an extending dead time system with a random (Poisson) neutron source. However inadequacies emerge for correlated sources. For this counter, the Poisson Singles rate dead time correction factor works well, as does the Croft-Dytlewski approach. However, the other two methods are relatively poor. Doubles corrections based on the multiplicity dead time parameter d are also poor. This emphasizes how empirical parameters are often needed to improve the correction.

Any correction method based on the correction of the MSR histograms will be item specific, since the histograms are item specific. Correction of the MSR histograms is not therefore constrained by the traditional assumptions of a true random or Poisson source. Another alternative to applying algebraic correction factors to the derived rates at the analysis stage would be to determine a method for the correction of dead time effects within the histograms themselves. Dead time corrected rates could then be derived directly from the dead time corrected histograms. This ought to allow dead time corrected correlated rates of any order to be calculated. One key research aspect of this method would be to determine the best way to "re-populate" the neutron pulse train from which the MSR histograms are derived i.e. to replace events in the pulse train that had otherwise been lost due to dead time or counting losses.

In practice, the true value of the fixed dead time is not known. It is determined by making experimental measurements and choosing a value that makes the dead time corrected count rates 'correct' at some particular counting rate. (There are several ways to determine this correct rate: twin sources, adding random counting rates to a known Doubles rate etc.) Thus it is the size of the correction that is chosen, rather than the dead time value. This approach makes a crude compensation for limitations of the chosen correction method in the range of count rates of the dead time measurement. This has worked reasonably well in many cases, but extrapolation to dissimilar counting rate regimes cannot be relied upon. The data presented here demonstrates this effect in that greatly improved results can be achieved by using the dead time corrections with a larger value for the 'dead time' than that which was applied (Figure 4). One follow-up study would be to re-create a dead time measurement (such as the twin source method) using the simulated pulse trains. The ^{252}Cf and AmLi pulse trains could be combined and the combined result re-analyzed. This would provide an indication of whether current dead time measurement methods enable the input parameters to be extracted and would expose the weaknesses in the correction methods.

The authors are preparing a more complete description of the simulation method and a "lessons learned" follow-up paper to record the potential biases in the simulation method. This paper will provide advice regarding best practice for Monte Carlo neutron pulse train simulation and post-processing in software. We shall also extend the present work to Doubles in more detail and Triples.

Acknowledgements

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