A Physics Investigation of Deadtime Losses in Neutron Counting at Low Rates with ^{252}Cf - 10444

Louise G. Evans* and Stephen Croft**

*Nuclear Nonproliferation Division, Los Alamos National Laboratory, Los Alamos NM 87545, USA
lgevans@lanl.gov
**Canberra Industries, Inc., 800 Research Parkway, Meriden, CT 06450, USA
now at Los Alamos National Laboratory
scroft@lanl.gov

ABSTRACT

^{252}Cf spontaneous fission sources are used for the characterisation of neutron counters and the determination of calibration parameters; including both neutron coincidence counting (NCC) and neutron multiplicity deadtime (DT) parameters. Even at low event rates, temporally-correlated neutron counting using ^{252}Cf suffers a deadtime effect. Meaning that in contrast to counting a random neutron source (e.g. AmLi to a close approximation), DT losses do not vanish in the low rate limit. This is because neutrons are emitted from spontaneous fission events in time-correlated 'bursts', and are detected over a short period commensurate with their lifetime in the detector (characterised by the system die-away time, τ). Thus, even when detected neutron events from different spontaneous fissions are unlikely to overlap in time, neutron events within the detected 'burst' are subject to intrinsic DT losses. Intrinsic DT losses for dilute Pu will be lower since the multiplicity distribution is softer, but real items also experience self-multiplication which can increase the 'size' of the bursts.

Traditional NCC DT correction methods do not include the intrinsic (within burst) losses. We have proposed new forms of the traditional NCC Singles and Doubles DT correction factors. In this work, we apply Monte Carlo neutron pulse train analysis to investigate the functional form of the deadtime correction factors for an updating deadtime. Modeling is based on a high efficiency ^{3}He neutron counter with short die-away time, representing an ideal ^{3}He based detection system. The physics of deadtime losses at low rates is explored and presented. It is observed that new forms are applicable and offer more accurate correction than the traditional forms.

INTRODUCTION

The detection of temporally-correlated neutrons from spontaneous fission (SF) provides a unique time signature for the non-destructive assay of spontaneously fissile nuclides such as plutonium (Pu). Temporal correlations arise from the fact that prompt neutrons are emitted from spontaneous fission events in groups or time-correlated 'bursts'. Each 'burst' of prompt neutrons is emitted within 10^{-14} seconds of the initial fission event. These neutrons are therefore closely correlated in time.

Correlated event rates determined from results of passive neutron coincidence counting (PNCC) (Totals and Reals) and passive neutron multiplicity counting (PNMC) (Singles, Doubles and Triples) are potentially limited in accuracy by traditional deadtime correction methods. Measured correlated count rates are reduced due to deadtime thus, if not performed accurately, deadtime correction itself may lead to uncertainties in derived total Pu mass values. For safeguards measurements, target accuracies of less than 0.25% may be needed in demanding cases to maintain material balance areas and, even with careful item specific calibration, variations between items mean that deadtime corrections are significant. This is discussed in a recent paper by Croft, *et al.*[1].

Motivation

Conventionally, pulse pile-up and the effects of deadtime are associated with high count rates. However, it has been observed in work presented in Evans, *et al.* [2] that, even at low event rates, correlated neutron counting using ^{252}Cf suffers a deadtime effect. In contrast to counting a random neutron source (e.g. AmLi to a good approximation), deadtime losses do not vanish in the low rate limit. In other words, deadtime corrected count rates are not equivalent to true count rates. This is because neutrons are emitted from spontaneous fission events in time-correlated 'bursts', and are detected over a short period commensurate with their lifetime in the detector (characterised by the system die-away time, τ). Thus, even at low event rates when spontaneous fission events themselves are unlikely to overlap, neutrons within the detected 'burst' are subject to intrinsic deadtime losses since within the group there is a high instantaneous rate.

It is our aim to better understand the physics of deadtime losses. There is also a cost benefit to extending traditional deadtime correction methods. It is costly to retrofit new hardware to existing assay systems to reduce the effects of deadtime, therefore it is advantageous to develop and implement new deadtime correction algorithms as an alternative approach to ameliorate this problem. There has been a general trend to field neutron instruments with higher efficiencies and shorter die-away times and hence these designs also present the need for improved deadtime treatments.

Thought Experiment

The concept that deadtime losses can occur even in the limit that the Singles rate tends to zero can be illustrated by the example of a spallation 'burst' of high multiplicity, $\nu \sim 50$ say. Spallation neutrons can arise as a result of a cosmic ray interaction with a high Z material such as lead (Pb) counter shielding. The next event could, for the sake of argument, occur one day later. Assuming 100% detection efficiency, this single event would result in 50 neutrons being observed in a 24 hour observation period, the assay time in this example. This can be thought of as a pulse train of maximum period 24 hours, with just a single pulse consisting of a burst of 50 neutrons.

The 50 neutrons would be detected over a time scale of the order of a few μs in a counter with short die-away time, and therefore would appear as a high instantaneous rate within a short coincidence gate. Overlapping events within the burst will result in the pulse train being subject to a large deadtime effect. Since the next event occurs one day later, this scenario does not correspond to a high sustained event rate. From this illustration, there is a clear need to build the effect of correlations into the correction factors for deadtime losses, event at low ($\sim$ zero) average event rates.

Mathematical Illustration

The average (sustained) count rate for a single neutron burst of multiplicity, $\nu = 50$ in a 24 hour observation period can be calculated using the following:

$$Average\ count\ rate = \frac{50\ neutrons}{3600 \times 24s} = 5.79 \times 10^{-4} n/s \tag{1}$$

Within a single coincidence gate width of 4.5 μs (which is commensurate with the capture time characteristic of a sea of ^{3}He), however, the instantaneous rate is calculated from:

$$Instantaneous\ count\ rate = \frac{50\ neutrons}{4.5 \times 10^{-6} s} = 1.11 \times 10^{7} n/s \tag{2}$$

The instantaneous count rate in this case is a factor of $\sim 10^{10}$ larger than the average count rate.

Deadtime Losses in Neutron Counting at Low Rates with ^{252}Cf

For ^{252}Cf the effect is less severe because the multiplicity distribution is softer than in the cosmic ray thought experiment, but nevertheless in Evans, *et al* [1] it has been demonstrated that a deadtime effect can be observed even at low count rates. The effect was emphasised by modeling a neutron counter with high efficiency and short die-away time. This led to extending present deadtime correction formalisms in an attempt to quantify this effect. In this work, Monte Carlo simulation and subsequent numerical calculation were used to address this problem, as opposed to assuming an empirical correction factor as has been the tradition in the past.

Here, new solutions are presented as to how the equations for the deadtime correction factors may be modified. Empirical results from simulation, quantifying the magnitude of the effect for different deadtimes and covering a range of gate fractions, are then presented.

TRADITIONAL NCC DEADTIME CORRECTION

Traditionally, the count rates obtained from neutron coincidence counting (NCC) are corrected for deadtime using parameters extracted based on the expectation that the Reals-to-Totals ratio, $\frac{R}{T}$ for ^{252}Cf will be constant. This ratio will herein be referred to as the Doubles-to-Singles ratio, $\frac{D}{S}$. The Reals-to-Totals ratio, $\frac{R}{T}$ and Doubles-to-Singles ratio, $\frac{D}{S}$ are numerically equivalent. However, during an assay, the Reals and Totals rates are obtained directly from the shift register hardware while Doubles and Singles are derived from the measured multiplicity histograms.

The traditional form of the deadtime correction factors (DTCFs) for the Singles and Doubles rates obtained from standard NCC are based on a simple paralyzable model. The traditional deadtime correction formalism for NCC Singles counting relates the deadtime corrected Singles rate, S_c to the measured Singles count rate, S_m through the following transcendental expression:

$$S_c \approx S_m.\exp(\delta.S_c) \tag{3}$$

The simple paralyzable form of the Singles deadtime correction factor is therefore defined as:

$$DTCF_S \approx \frac{S_c}{S_m} \approx \exp(\delta.S_c) \tag{4}$$

Practically, this is normally applied as:

$$DTCF_S \approx \exp(\frac{a + b.S_m}{4}.S_m) \tag{5}$$

This exponential form of the deadtime correction factor is referred to in a discussion by Swansen [3]. The current form of the NCC deadtime parameter is empirical. By extension, the traditional deadtime correction formalism for NCC Doubles counting relates the deadtime corrected Doubles rate, D_c to the measured Doubles count rate, D_m through the following expression:

$$DTCF_D \approx \frac{D_c}{D_m} \approx \exp(4.\delta.S_c) \tag{6}$$

The factor 4 in the exponential is empirical. The theoretical basis, drawn on by Swansen [3], of the factor 4 is unknown and currently no formal discussion in literature exists. By analogy to equation (5), this correction factor is normally applied as:

$$DTCF_D \approx \exp((a + b.S_m).S_m) \tag{7}$$

NEW THEORETICAL APPROACH

Developing an alternative formalism for the Singles DTCF

Applying equation (4) for the Singles DTCF is straightforward when simulated data is analysed because S_c is known. The existing expression for the Singles deadtime correction factor is dominated by the Singles rate with no treatment for correlation within the pulse train. For a correlated neutron source, however, correlated events within the fission burst itself can also lead to deadtime losses, as previously described. The deadtime correction factor for Singles should therefore include terms for correlations. Empirically it is proposed here that additional exponential terms may be added to the the correction factor, to account for deadtime arising from higher order correlations. The Singles deadtime correction factor would therefore, to first order in S, D and T_r, take the following form:

$$\frac{S_c}{S_m} = DTCF_S = \exp(\delta.S_c + \text{“}s_1.D + s_2.T_r + 0\text{”}) \tag{8}$$

where “s_1” and “s_2” are constants to be determined. The terms enclosed in quotations relate to the correlations and have been determined by Croft [4]. The additional term $\exp(\text{“}s_1.D'')$ is added to take into account the effect of correlations on the pulse train analysis i.e. the effect of Doubles on the Singles rate deadtime in this case. Quotations " " are used to emphasise that the above discussion is not quantitative, but indicates that some dependence of the kind should exist. In equation (9) Triples and higher terms are neglected since T rates are often low in practical applications due to low detection efficiency ($\epsilon \ll 100\%$) and low Triples gate fractions ($< \frac{1}{2}$):

$$DTCF_S \approx \exp(``s_1.D''). \exp(\delta.S_c).1 \tag{9}$$

PHYSICS OF DEADTIME LOSSES

Croft [4] has proposed an alternative form for the Singles deadtime correction factor:

$$DTCF_S \approx [1 + \frac{(D_c/f_d)}{S_c}.\frac{\delta}{\tau_{eff}}]. \exp(\delta.S_c) \tag{10}$$

in the limit where $\frac{\delta}{\tau_{eff}} \ll 1$ and $\frac{\delta}{\tau_{eff}}$ is roughly constant for a given system. This was inspired by the work of Matthes & Haas [5], Haas [6], Haas & Swinhoe [7], Pederson, *et al.* [8], and Srinivasan [9]. Equation (10) may be recognised as the quantified first order development of equation (9). The terms in equation (10) are justified by the following arguments:

- The Singles deadtime correction factor should have a direct dependence on deadtime to first order and is therefore linearly related, in the multiplier, to a single system deadtime parameter, δ.

- The form of the deadtime correction factor is thought to include a direct dependence on deadtime yet be independent of gate fraction. That is the deadtime affects the pulse train and not the processing overlaid on top of it. Since deadtime effects are manifest in the pulse train itself, deadtime is thought to be independent of gate fraction, f_d i.e. independent of pre-delay and coincidence gate width.

- The deadtime imposed by correlated events is expected to depend on parameters related to the proportion of correlation in the pulse train (which will in turn depend on the source multiplicity distribution). The level of correlation in the pulse train can be characterised by the ratio $\frac{D}{S}$. The Doubles-to-Singles ratio, $\frac{D}{S}$ can therefore be thought of as the "volume control" on the level of correlation in the pulse train.

- The deadtime correction is inversely proportional to a single exponential dieaway, τ_{eff}. τ_{eff} is the effective dieaway time of the detection system, approximated to a single exponential. The ratio $\frac{1}{\tau_{eff}}$ therefore determines the timescale over which events are detected i.e. how concentrated events from an individual burst are or how close together in time.

- The in-burst deadtime correction factor (which in equation (10) is the term in square brackets before the exponential factor) is independent of mass (i.e. "rate") except through multiplication, M.

- Equation 10 is also dimensionally correct. Dividing $\frac{D}{S}$ also eliminates the rate (non-multiplying mass) dependence for a given fissioning system. Likewise $\frac{\delta}{\tau_{eff}}$ is dimensionless.

Equation (10) can be expressed as:

$$DTCF_S \approx K_S.\exp(\delta.S_c) \tag{11}$$

where K_S is defined as the vanishing (Singles) rate DTCF multiplier i.e. this parameter determines the deadtime in the limit where the event rate tends to zero. K_S is given by the following expression:

$$K_S \approx [1 + \frac{(D_c/f_d)}{S_c}.\frac{\delta}{\tau_{eff}}] \tag{12}$$

For a given system, K_S is a constant for ^{252}Cf. Values for this constant have been derived for a range of system deadtime parameters and gate fractions from empirical results presented. For actual Pu assays, K_S will depend on the leakage self-multiplication, M_L and random to spontaneous fission neutron production rate, α. That is on the item dependent $\frac{(D_c/f_d)}{S_c}$ value.

Developing an alternative formalism for the Doubles or Reals DTCF

By analogy to equation (11), the Doubles correction factor can be expressed as:

$$DTCF_D \approx K_D.\exp(4.\delta.S_c) \tag{13}$$

where K_D is defined as the vanishing (Doubles) rate DTCF multiplier. Again, K_D is a modifier to the traditional NCC Doubles DTCF. Initially, the factor 4 has been retained from the original expression. K_D is also item dependent and will be discussed further.

SIMULATION

Deadtime correction factors have been simulated over a range of source intensities for ^{252}Cf. Simulation provides a means to:

- **Investigate the functional form** of the revised Singles and Doubles DTCFs for PNCC.
- **Evaluate performance** of revised DTCFs, relative to traditional NCC DTCFs.

Simulated measured Singles and Doubles rates were recorded at a range of values of system deadtime parameter (for a constant gate fraction) and range of gate fractions (for a constant system deadtime parameter). By this method, the proposed alternative formalisms for the Singles and Doubles DTCFs, in equations (11) and (12), were evaluated.

Ideal neutron pulse trains were generated for ^{252}Cf using the simulation method published in Evans, *et al* [10]. A ^{252}Cf source was modelled as a point isotropic source positioned at the centre of an idealised ^{3}He detector. Thirteen pulse trains were generated in total. An assay time of 600 s was chosen in each case, with 10 counting cycles for statistical analysis. A range of ^{252}Cf source intensities were simulated, between 6.262×10^{3} ns^{-1} (6.262 kHz) and

2.505×10^5 ns^{-1} (0.251 MHz). The detection efficiency was $\sim$ 99.4% and the die-away profile could be approximated by a double exponential with die-away times 3.06 μs and 4.41 μs, with relative intensities 74% and 26%.

The shift register settings of pre-delay, T_p, coincidence gate width, T_g, and long delay, T_l, were fixed at values of 0.3 μs, 4.5 μs and 200 μs, respectively in the main results presented. Hence the Doubles gate fraction, f_d remained constant whilst the deadtime was varied. Simulated measured S and D rates were recorded at zero deadtime (corresponding to true count rates). Ideal pulse trains were then perturbed by overlaying the effect of a paralyzable deadtime model. Simulated measured S and D rates were recorded at the following range of system deadtime parameters: 0.010 μs, 0.050 μs, 0.075 μs, 0.100 μs and 0.150 μs. Empirical simulation results could be used to determine the following:

- Dependence of vanishing Singles rate DTCF multiplier, K_S on system deadtime parameter, δ
- Dependence of vanishing Doubles rate DTCF multiplier, K_D on system deadtime parameter, δ

Simulated measured rates were then recorded for a range of gate fractions between 0.141 and 0.743. Gate fractions were varied by fixing the multiplicity shift register (MSR) pre-delay, T_p at a constant value of 0.3 μs and varying the coincidence gate width, T_g between 0.5 μs and 6.0 μs in increments of 0.5 μs. The system deadtime parameter was also held constant at a value of 0.01 μs for these simulations to determine the dependence of deadtime correction factors on gate fraction. In this case, empirical simulation results could then be used to determine the following:

- Dependence of vanishing Singles rate DTCF multiplier, K_S on gate fraction, f_d
- Dependence of vanishing Doubles rate DTCF multiplier, K_D on gate fraction, f_d

SIMULATION RESULTS

Empirical simulation data were fit to the form of the deadtime correction factors proposed in equations (11) and (12) to extract K_S and K_D. Curve fitting was performed using the Deming non-linear weighted least-squares fitting method [11] as implemented in the DEM4_27 code [12] which was available in the BASIC programming language. Fits to the data were found to improve by allowing the multipliers in the exponential to vary, as opposed to using 1 in the case of Singles and a factor 4 in the case of Doubles. Simulated data were therefore fit to the following forms of the Singles and Doubles deadtime correction factors:

$$\frac{S_c}{S_m} = DTCF_S \approx K_S.\exp(n_S.\delta.S_c) \tag{14}$$

where n_S is a free parameter derived from the data itself.

$$\frac{D_c}{D_m} = DTCF_D \approx K_D.\exp(n_D.\delta.S_c) \tag{15}$$

where n_D is again a free parameter derived from the data itself. From equations (11) and (13), n_D is expected to vary with n_S as follows:

$$n_D \approx 4 \cdot n_S \tag{16}$$

$$\frac{n_D}{n_S} \approx 4 \tag{17}$$

Table 1 shows the ratio $\frac{n_D}{n_S}$ calculated from the fitting method, together with the calculated uncertainty on this ratio. Evans [13] performed an independent uncertainty analysis to place uncertainties on the parameters being discussed and they were found to be well defined and stable. However for the present discussion a detailed uncertainty analysis is not given because we want to convey the concept of the new approach and the actual system simulated will not be used for practical measurements. Also, as noted τ_{eff} is dependent on the choice of fitting range therefore the fit is somewhat empirical.

Table 1: Ratio $\frac{n_D}{n_S}$ derived from fitted simulation data, expected to be close to 4.

δ (μs)	$\frac{n_D}{n_S} \pm \sigma(\frac{n_D}{n_S})$
0.010	4.022 $\pm 1.469\times10^{-10}$
0.050	3.982 $\pm 4.080\times10^{-10}$
0.075	3.972 $\pm 4.431\times10^{-10}$
0.100	3.959 $\pm 5.412\times10^{-10}$
0.150	3.945 $\pm 7.344\times10^{-10}$

Figure 1 shows n_S and n_D against system deadtime parameter, δ. Values of n_S and n_D are seen to be close to 1 and 4, respectively, and remain approximately constant over the range of simulated source intensities. Uncertainties in n_S and n_D are plotted, but are small.

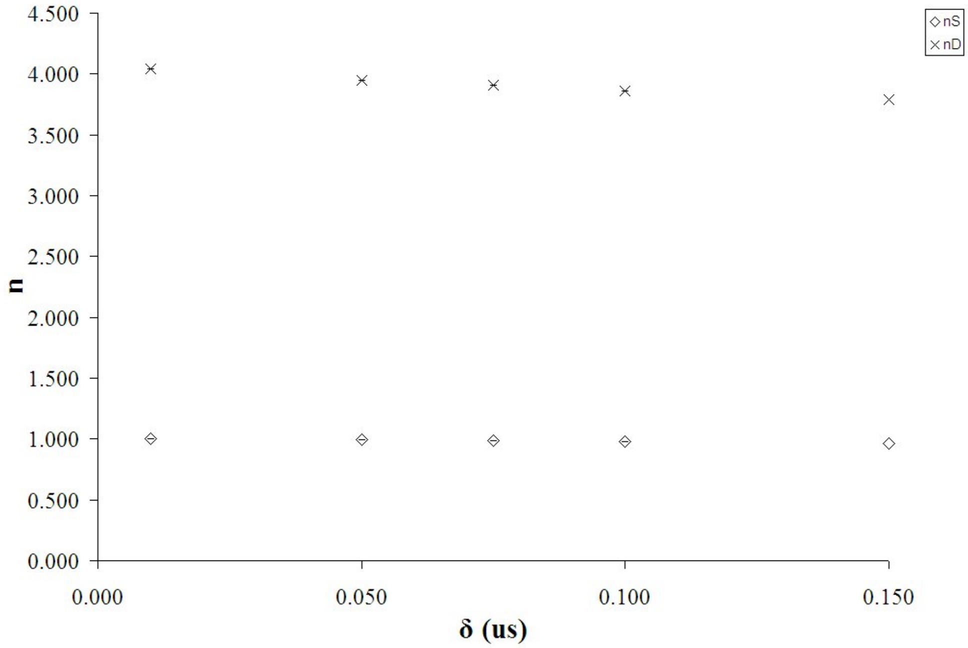

Figure 1: n_S and n_D vs. system deadtime parameter, δ.

Dependence of Singles and Doubles DTCFs on System Deadtime Parameter

The empirical results demonstrate the Singles DTCF to be dependent on system deadtime parameter and independent of gate fraction in the functional manner expected. This analysis supports the proposed form of the Singles DTCF given by equation 10.

Figure 2(a) shows a linear dependence of the vanishing Singles rate DTCF multiplier, K_S on system deadtime parameter, δ.

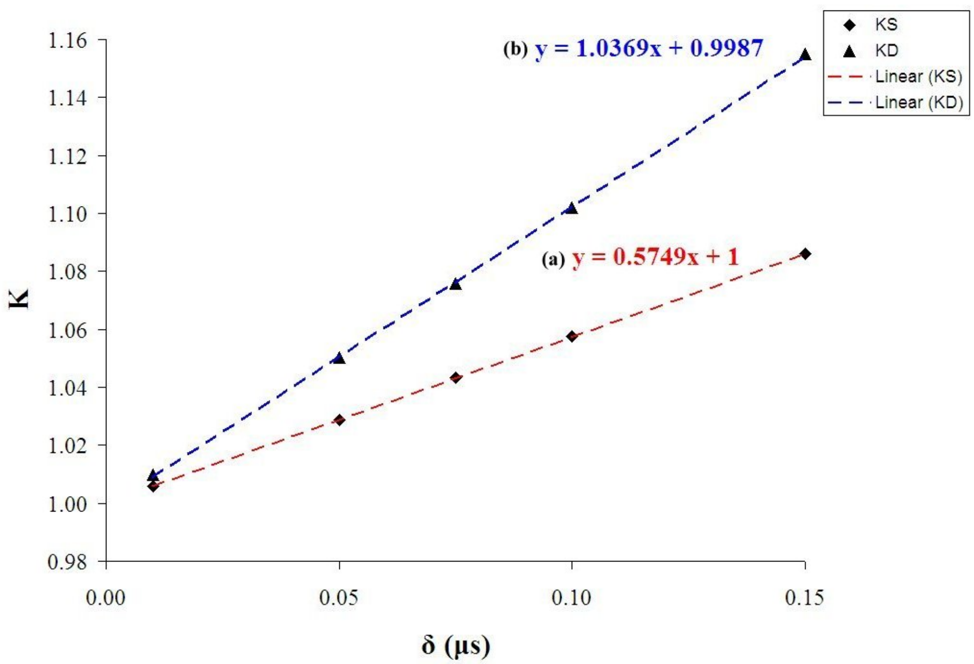

Figure 2: (a) Vanishing Singles rate DTCF multiplier, K_S vs. system deadtime parameter, δ (b) Vanishing Doubles rate DTCF multiplier, K_D vs. system deadtime parameter, δ ($K \rightarrow y$; $\delta \rightarrow x$) Uncertainties in K are plotted, but are small.

The following function was derived from a standard linear fit to the data in figure 2(a):

$$K_S = 1 + 0.5749.\delta \tag{18}$$

where 1 corresponds to the intercept on the graph and 0.5749 is the gradient. A generalisation of equation (10) for the linear fit to the data is given by:

$$K_S \approx [\theta_1 + \theta_2.\frac{(D_c/f_d)}{S_c}.\frac{\delta}{\tau_{eff}}] \tag{19}$$

where θ_1 is the intercept on a plot of K_S vs. δ, and the gradient is given by $\theta_2.\frac{(D_c/f_d)}{S_c}.\frac{1}{\tau_{eff}}$. The intercept θ_1 is expected to be unity, but was allowed to be a free parameter. Note that τ_{eff} is used on the basis of the understanding that the die-away of real systems do not follow a single exponential.

Dependence of Singles and Doubles DTCFs on Gate Fraction

Figure 3(a) shows the vanishing Singles rate DTCF multiplier, K_S to be independent of Doubles gate fraction, f_d. The slight downward trend in figure 3(b), indicated by the negative gradient of magnitude 0.0044, shows that the vanishing Doubles rate DTCF multiplier is, however, dependent on gate fraction. Results show a similar trend for system deadtime parameter values: 0.050 μs, 0.075 μs, 0.100 μs and 0.150 μs. Results for the highest value of system deadtime parameter 0.150 μs are presented in figure 4. To account for this dependence, the vanishing Doubles rate DTCF multiplier can therefore be written as the following:

$$K_D \approx [\lambda_1 + \lambda_2 . \frac{(D_c/f_d)}{S_c} . \frac{\delta}{\tau_{eff}} . f_d] \tag{20}$$

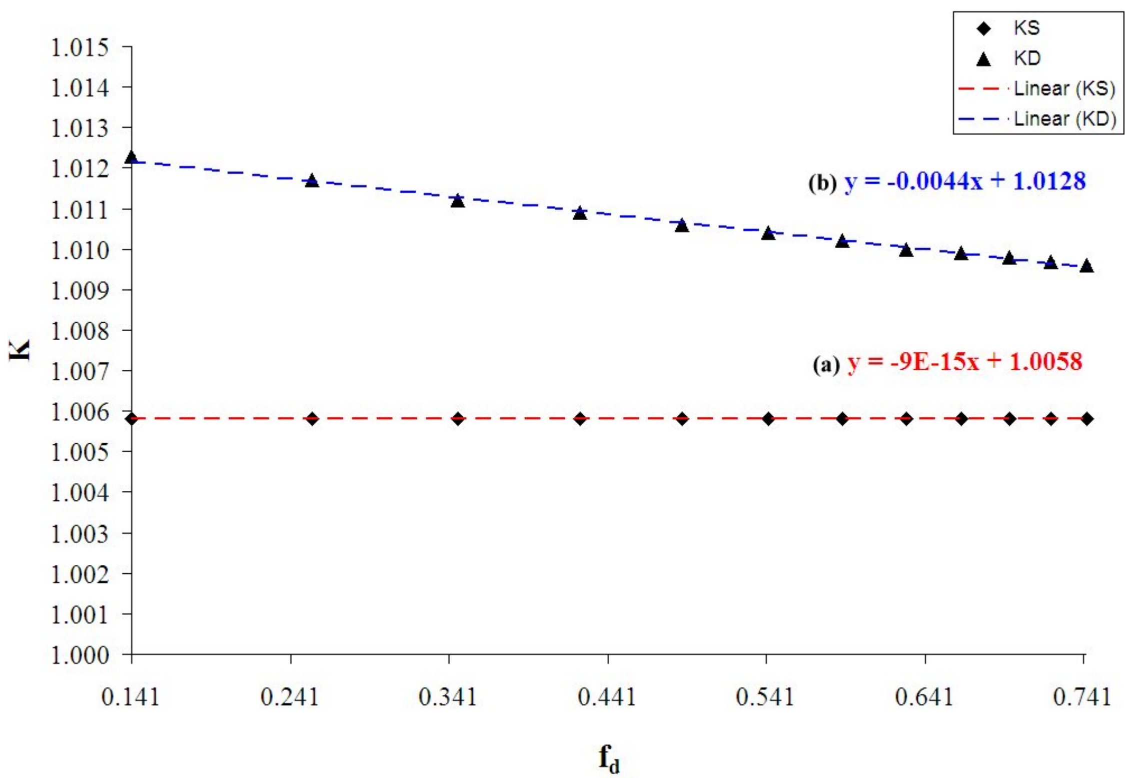

Figure 3: (a) Vanishing Singles rate DTCF multiplier, K_S vs. Doubles gate fraction, f_d (b) Vanishing Doubles rate DTCF multiplier, K_D vs. Doubles gate fraction, f_d. System deadtime parameter, $\delta = 0.01$ μs. Uncertainties in K are plotted, but are small.

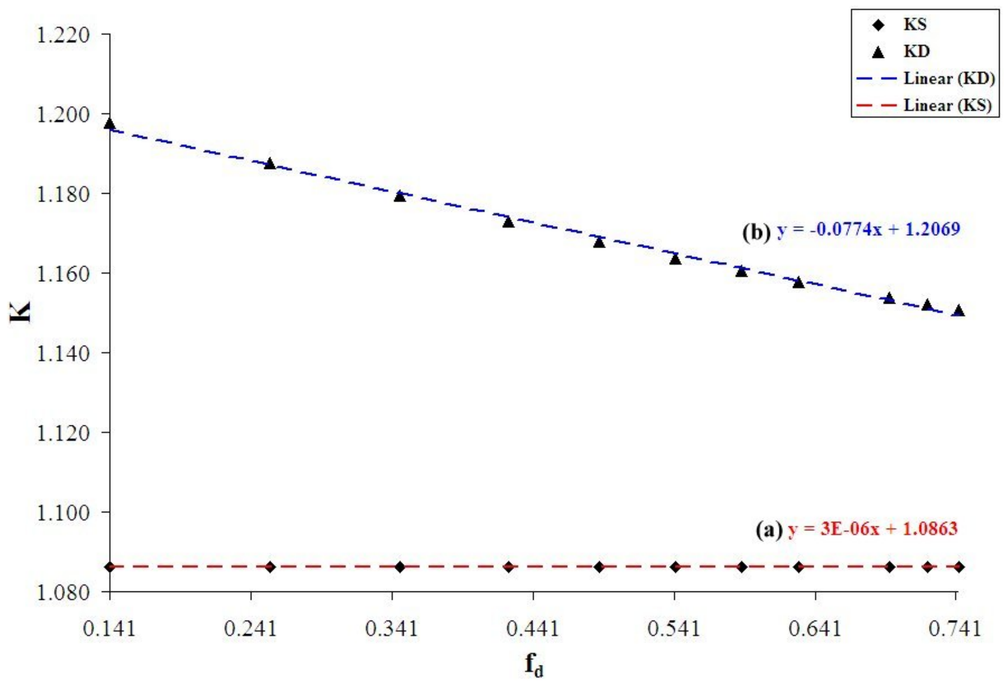

Figure 4: (a) Vanishing Singles rate DTCF multiplier, K_S vs. Doubles gate fraction, f_d (b) Vanishing Doubles rate DTCF multiplier, K_D vs. Doubles gate fraction, f_d. System deadtime parameter, $\delta = 0.150$ μs.

COMPARISON

Here, both the traditional form and revised form of the deadtime correction factors are applied to the simulated measured Singles and Doubles rates (acquired over a range of δ values) and compared. Singles and Doubles deadtime correction factors should correct the measured rates to obtain a constant $\frac{D}{S}$ ratio. In other words, the following ratio should be unity across the range of count rates simulated:

$$\xi = \frac{\frac{D_c}{S_c}|_{\delta}}{\frac{D_c}{S_c}|_{\delta=0}} = 1 \tag{21}$$

Deadtime Corrected Doubles to Singles Ratios using the Traditional Theoretical Approach

When traditional NCC DTCFs are applied, figure 5 provides an illustration that the $\frac{D}{S}$ ratio does not correct to a constant value in the limit that the Singles tends to zero. This figure therefore shows the deviation from unity (where unity is the expected value for Cf). A 0.5% deviation in the $\frac{D}{S}$ ratio can be calculated (at the lowest count rate, at the lowest value of δ) compared to the true value (at $\delta = 0$), when performing deadtime correction using the traditional NCC DTCFs. This is significant compared to the small 0.1% statistical uncertainty in the true $\frac{D}{S}$ ratio at this count rate. The deviation of this ratio from unity is just 0.01 % when performing deadtime correction using the revised NCC DTCFs. The magnitude of this effect is emphasised by the extreme efficiency of the chamber modeled and the choice of δ.

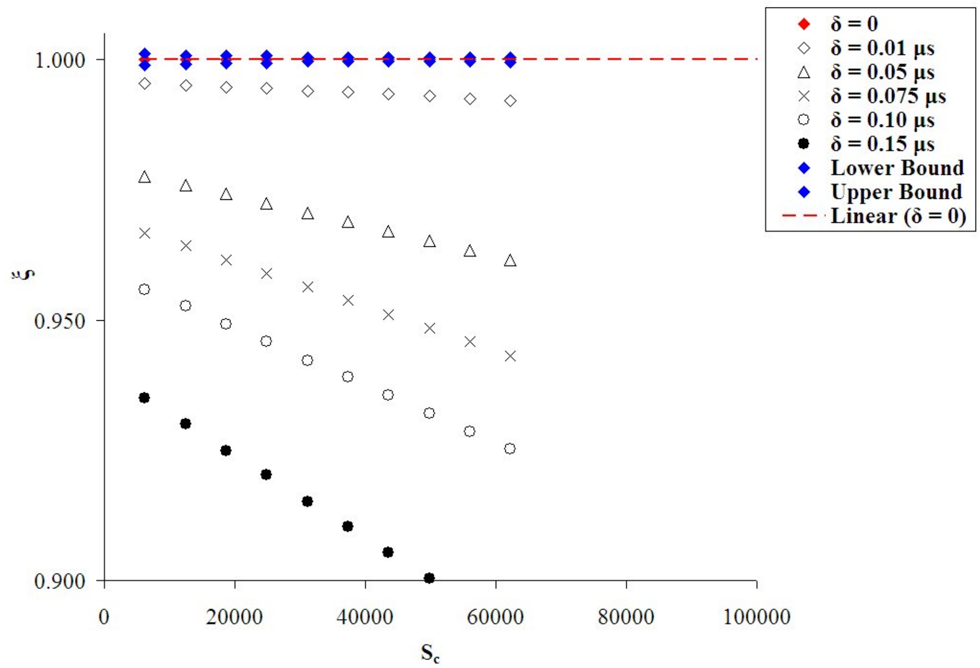

Figure 5: Ratio ξ using traditional NCC deadtime correction factors vs. S_c

Deadtime Corrected Doubles to Singles Ratios using the New Theoretical Approach

Figure 6 shows that the ratio ξ is consistent with unity and the revised approach is able to correct the measured $\frac{D}{S}$ ratio within the statistical uncertainties in the true $\frac{D}{S}$ ratio. The blue solid diamonds on the curve illustrate the lower and upper bounds for the statistical uncertainties in the true $\frac{D}{S}$ ratio i.e. the simulated $\frac{D}{S}$ ratio when δ with $\delta = 0$. All corrected rates lie within these bounds.

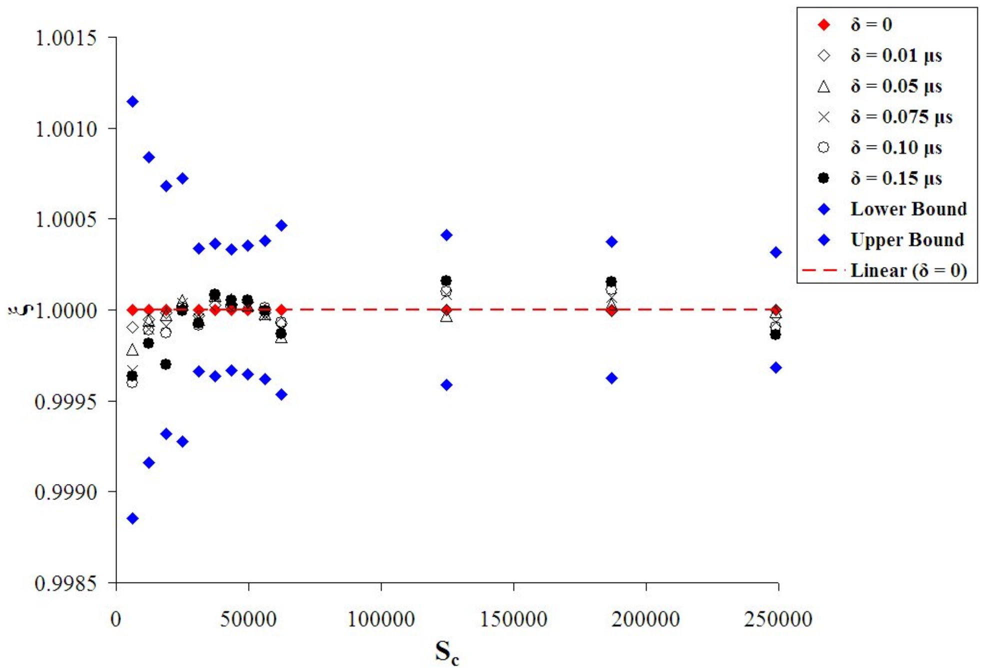

Figure 6: Ratio ξ using revised NCC deadtime correction factors vs. S_c. The $\delta = 0$ case lies on the unity line.

CONCLUSIONS

We have presented new forms of the Singles and Doubles deadtime correction factors for PNCC and empirical simulation data in support of the functional form of these correction factors. Data has shown that these formalisms are applicable to correlated neutron sources. In addition, the new deadtime correction factors have improved performance compared to the traditional NCC deadtime correction factors, when correcting for deadtime based on a constant $\frac{D}{S}$ ratio. The revised deadtime correction formulae explicitly make allowance for "within burst losses" at low sustained rates. This allows the small biases to parameters such as ρ_0 to be corrected and also provides the appropriate allowance in switching between fission sources.

The effect of multiplication on these deadtime losses can also be considered. As the multiplication, M, becomes greater than one, the pulse train becomes more correlated i.e. the term $\frac{D_c}{S_c}$ in the vanishing (Singles or Doubles) rate deadtime correction factor multiplier increases. As a result, the deadtime correction factor becomes larger due to the greater probability of neutrons being detected closer together in time.

We have considered ^{252}Cf for which K_S and K_D are constant because the characteristics of the fissioning source are fixed. In a real assay situation the general form needs to be used since the self-multiplication and the (α, n)-to-SF-n ratio can change item to item as may the detection efficiency.

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