Monte Carlo Studies of the Neutron Detector Dead Time Effects on Pulsed Neutron Experiments

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Abstract – *This paper purposes a Monte Carlo procedure to study the effect of neutron detector dead time in the pulsed neutron source experiments. It is simple and easy to be implemented. It can be used for different type of neutron sources. In this paper, numerical simulations are performed with different type of neutron sources to validate the Monte Carlo procedure. The neutron count losses predicted by the Monte Carlo procedure is compared with the neutron count losses calculated by the simple mathematical model which is usually used to correct the neutron count losses due to the detector dead time.*

I. INTRODUCTION

The Accelerator-Driven Subcritical (ADS) systems have been considered for disposing of the Minor Actinides (MAs) for closing the nuclear fuel cycle of fission power reactors. In an ADS system, a high amount of MAs can be loaded without concern about their small delayed neutron fractions [1, 2]. To insure the safe ADS system operation, the Pulsed-Neutron Source (PNS) experiments are often used to measure the reactivity of the subcritical core [3]. In the PNS experiment, the subcritical core is driven by a repeated pulsed neutron source. The neutron flux is measured by neutron detectors placed inside and around the subcritical core.

Any neutron detector requires a minimum amount of time for distinguishing between two different events to be recorded separately. This minimum time is called the detector dead time [4]. It is determined by the detector intrinsic process such as ion charge collection time and the speed of the associated electronics. During the measurement, a neutron event can be lost (not registered by the neutron detector) if it follows too close to the previous event. With more neutrons arriving to the detector about the same time, more neutrons will be lost due to the detector dead time.

Typically, the detector dead time behavior can be described by one of two models: non-paralyzable and paralyzable [4]. Fig. 1 illustrates the two models.

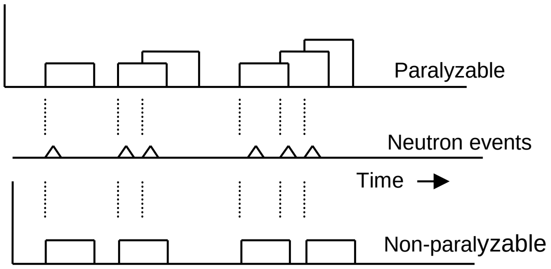


Fig. 1. Illustration of paralyzable and non-paralyzable detector dead time models.

For the non-paralyzable detector, any neutron which arrives to the detector during the dead time period of the previous recorded event will be lost. Then, the detector recovers after the dead time. For the paralyzable neutron detector, the neutrons which arrive to the detector dead time period are lost and the detector dead time period starts again after the lost neutron event. Therefore, the paralyzable neutron detector may recover after a longer time period relative to the non-paralyzable detector. Compared with the non-paralyzable detector, the paralyzable detector will have more neutron losses.

In the PNS experiments, to measure the reactivity of the subcritical system accurately, the lost neutrons due to the neutron detector dead time have to be considered [5, 6]. The detector dead time losses were previously calculated using simple mathematical models as shown in Fig. 2 [6] for the PNS experiments performed in the Yalina booster facility.

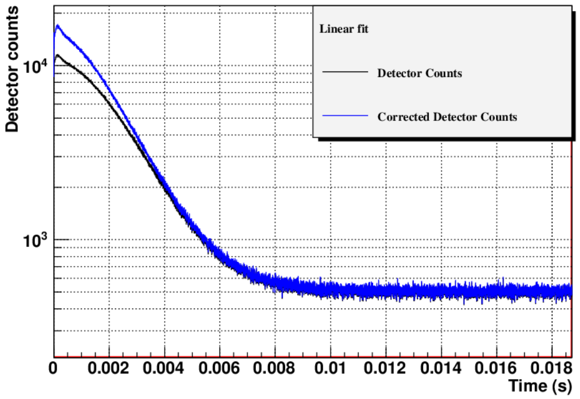


Fig. 2. Correction of the neutron detector count losses in the PNS experiments performed in the YALINA booster facility.

The correction model assumes that during the counting period, the neutron flux value is a constant. However, as shown in the above figure, the neutron fluxes vary since the subcritical core is driven by an external pulsed neutron source. The neutron pulse width is in the order of microseconds. Those external source neutrons are scattered and multiplied in the subcritical core. The prompt neutron mean generation time is about few hundred or thousands nanoseconds for a fast subcritical core, and is about few tens or hundreds of microseconds for a thermal subcritical core.

The dead time for a neutron detector is often unknown and needs to be measured. The methods to measure the detector dead time are not discussed in this paper and it can be found in textbooks and other papers [4, 7]. For He-3 detectors, the dead time is about few microseconds. To examine the detector dead time effects, this paper proposes a new procedure simulating the detector dead time effects in a PNS experiment. It can also be treated as a general procedure to study the detector dead time effects in other similar experiments, and to test the applicability of simple mathematical models used for correcting the counting loss in those experiments.

Specifically, in this paper, the simple mathematical models for constant flux measurements accounting for the detector dead time loss are examined. Then the proposed Monte Carlo procedure is discussed. It is followed by numerical test cases to examine the proposed procedure for the constant flux measurements. Then the proposed procedure is applied to transient fluxes. Three test cases are examined, a pulse source experiment, a slowly varying linear source experiment, and a PNS experiments performed at the YALINA Thermal facility.

II. ANALYTICAL MODELS FOR ESTIMATING DETECTOR DEAD TIME LOSSES

With a steady state neutron flux, the neutron count loss due to the detector dead time can be analytically calculated. For the non-paralyzable detector, if the true neutron event rate is denoted by *n*, the detector counting rate is denoted by *m*, and the detector dead time is denoted by τ, the detector count loss can be simply calculated as:

$$n - m = nm\tau \qquad (1)$$

Where $m\tau$ is the total dead time period due to *m* detected neutron events, and $nm\tau$ is the number of true neutron events arrived during the total dead time. Thus, with equation (1), the true event rate can be calculated as:

$$n = \frac{m}{1-m\tau} \qquad (2)$$

For paralyzable detector, the detector dead time is not a fixed time interval during the counting time. The relationship between the detector count rate and the true event rate is setup by counting the number of intervals among the true events which exceeds τ:

$$m = \int_T^\infty ne^{-nT}dT = ne^{-n\tau} \qquad (3)$$

Where $ne^{-nT}dT$ is the probability of detecting the second event within dT after interval time T from the first detected event. The true event rate *n* is then calculated by solving the above non-linear equation.

III. MONTE CARLO PROCEDURE FOR SIMULATING THE DETECTOR DEAD TIME LOSSES

A procedure is proposed to simulate the neutron detector count losses as shown in Fig. 3. In this procedure, first, the neutron events arriving to the detector are sampled using Monte Carlo methods. The arrival time to the detector is recorded and sorted as a sequence of events. Second, the detector dead time is applied on the sampled event sequence.

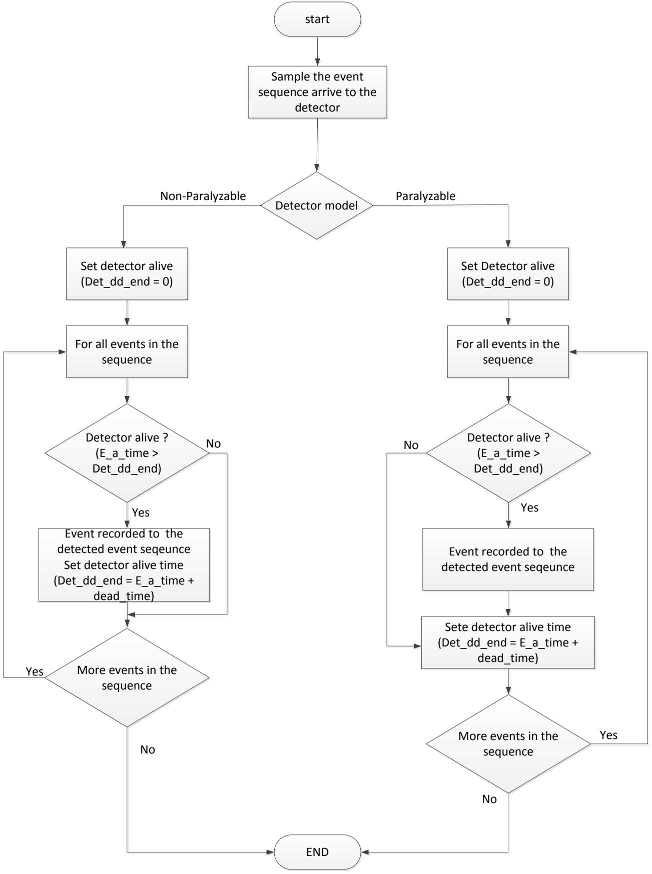


Fig. 3. Illustration of the procedure simulating the detector dead time losses.

As shown in Fig. 3, "Det_dd_end" denotes the time when the detector is recovered from a dead time period and is ready to record another event. "E_a_time" denotes the time that next even arrives at the detector. To apply the detector dead time, the event arrival times at the detector are sorted in ascending order. For every event in the sorted event sequence, the event arrival time "E_a_time" is compared with "Det_dd_end". The event is only recorded if "E_a_time" is greater than "Det_dd_end".

During the process, the "Det_dd_end" is updated from event to event. For non-paralyzable detector, the "Det_dd_end" is reset to a new value only when the event is recorded. It is equal to the recorded event arrival time plus the detector dead time τ. For paralyzable detector, the "Det_dd_end" is reset to a new value whenever an event is arrived to the detector. Its new value is equal to the current event arrival time plus the detector dead time τ.

The above procedure is general and can be applied to many experiments for analyzing detector dead time losses. For different measurements, different Monte Carlo sample techniques at the beginning are required to generate the event sequence.

IV. NUMERICAL VALIDATIONS

1. Detector Dead Time Losses for Steady State Sources

First, the procedure is used with a steady state source for validation purpose. The simulated detector count rate *m* is compared with the detector count rate calculated using the analytical models.

The event sequence for the steady state source is generated by sampling the arrival time to the detector directly. The MATLAB random function was used to sample the steady state source. Different total number of events is uniformly sampled within one second to represent the different source rates *n*. The sampling period is extended to multiple seconds to reduce the statistical errors in the Monte Carlo count losses. For low source rates, more sampling periods are needed relative to the high source rates in order to reduce the statistical errors in the Monte Carlo sampling. The sampled true event sequences at each source rate *n* are sorted in the time domain. The procedure shown in Fig. 3 is applied to the sampled event sequences.

For every source rate, the generated counting event sequence assumes that the detector dead time is 3.4 μs. In addition, the detector count rate *m* is also calculated using the simple analytical models shown in equation (2) and (3) for both detector types.

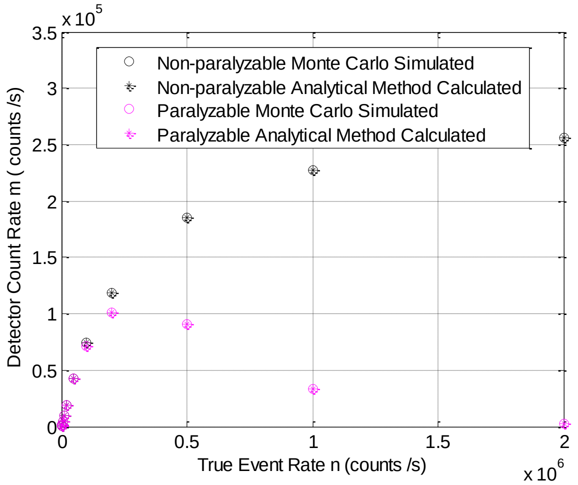


Fig. 4. Comparison of the neutron detector counting simulated by the Monte Carlo procedure with the results calculated by the analytical models for steady state sources.

The detector counting results obtained from the proposed Monte Carlo procedure and the results obtained from the analytical models are compared in Fig. 4 at each source rate. The comparison shows that for both non-paralyzable and paralyzable detectors, the proposed procedure accurately simulated the detector count losses for different source rates. The Monte Carlo results and the analytical calculations perfectly agree as shown in Fig. 4.

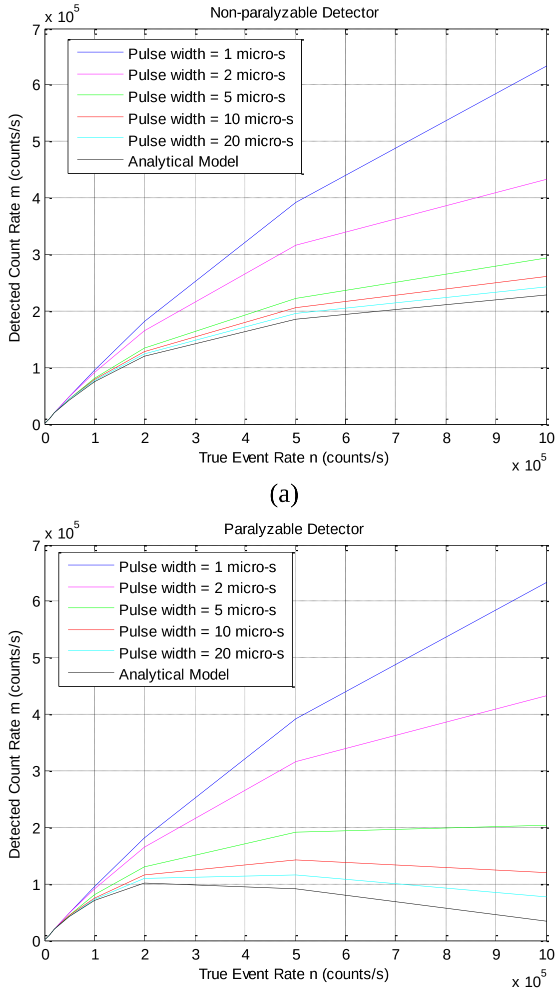
2. Detector Dead Time Losses for Pulsed Sources

The Monte Carlo procedure is utilized to study the neutron detector losses with pulsed sources. A square pulse with constant rate within the pulse width is used. The event sequence is generated by uniform sampling within the pulse width. Similarly, different total number of events sampled within the pulse period representing different source rates. For pulse source, the event rate per time interval within the pulse width depends on the length of the pulse. For the same source rate and same pulse period, a narrower pulse width means that the same amount of events will be packed within a shorter time period. In other words, for the same source rate and pulse period, the event rate at the pulse plateau is higher for narrower pulses.

To study the impact of the pulse length on detector counting losses, and to compare the detector losses simulated with the Monte Carlo procedure and the losses calculated with mathematical models, different event rates within the pulse width are examined. The pulse repetition period is 2 ms. The detector dead time is 3.4 μs. The pulse width is varied from 1 μs to 20 μs. Similar to the numerical simulation performed for the steady state source, the event sequence is generated by the MATALB using its random function. Multiple pulse periods were sampled to reduce the statistical error. The sampled event sequence is sorted in the time domain.

Fig. 5 shows the simulated counting rates *m* corresponding to the event rates *n* on the pulse plateau for the two types of detectors. Clearly, the pulse width is an important factor in calculating the detector losses. The analytical models are only valid for the cases where the pulse width is much larger than the detector dead time. Based on the Monte Carlo simulations, when the pulse width is comparable or even smaller than the detector dead time, the detector counting losses are much smaller than the losses calculated from the analytical method. Thus, this test case suggests that the Monte Carlo procedure or other analytical model shall consider the pulse width to correct the neutron count losses [8].

Fig. 6 plots the neutron counts for the case with the 20 μs pulse width and 10^4 neutron/s during the pulse width. The time bin is 2 μs. For the first two time bins, the Monte Carlo results show smaller neutron losses compared with the analytical model results. It is because the detector is always fully recovered from the dead time effect at the beginning of each pulse if the pulse period is larger than the detector dead time. The Monte Carlo procedure simulated this behavior honestly. On the contrary, the analytical models assume a steady state source. Thus, it is assumed that the detector may suffer from the dead time effect at the beginning of the pulse.



(a)

(b)

Fig. 5. Comparison of the counting events obtained from the Monte Carlo simulations and the calculated counting events from the analytical models for a pulsed source with different pulse widths: (a) non-paralyzable detector and (b) paralyzable detector.

In addition, for pulse source, the maximum count rate depends on the pulse period and the pulse width. If the pulse width is smaller or equal to detector dead time, as the two cases with pulse width of 1 μs and 2 μs in Fig. 6, the maximum detected counts will be equal to the pulse frequency [4]. In other words, for the pulsed source at each pulse period, only maximum one event can be counted during each pulse period. Fig. 7 shows the Monte Carlo simulation accurately predicted this behavior.

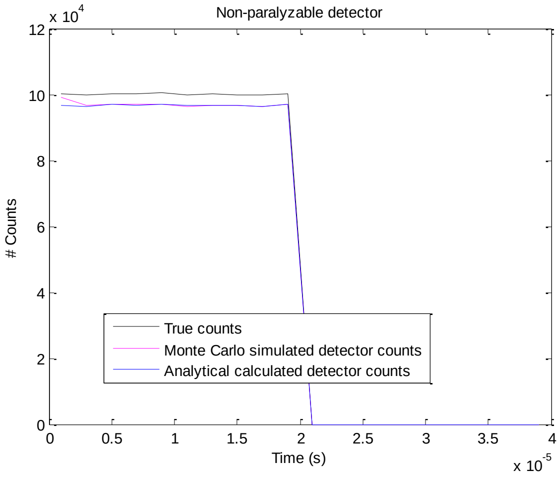


Fig. 6. Comparison of the detector counts per 2 μs obtained from the Monte Carlo simulation and the analytical model with the true counts for the test pulsed case. The pulse width is 20 μs and the true event rate is 10^4 c/s, results are accumulated from multiple periods.

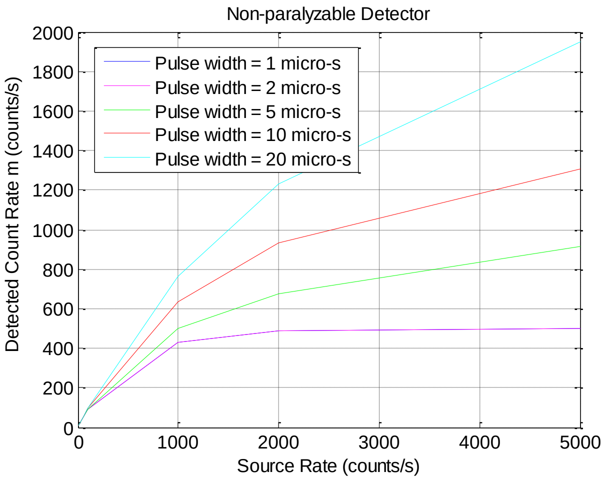


Fig. 7. The detector count rate as a function of the pulsed source rate with different pulse widths from 1 μs to 20 μs.

3. Detector Dead Time Losses for a Linear Source

The Monte Carlo procedure is also used to study the detector losses with a slowly varied transient source. In this test case, a hypothetical periodic source with linear variations in the source period is used as shown in Fig. 8.

The pulse period of this repetitive linear source is 2 ms. The detector dead time is 3.4 μs. The true event sequence shown in Fig. 8 is generated using the MATLAB random function, with about 50000 events sampled in every period. The counting curve is accumulated after 10000 periods to reduce the statistical error. The sampled event sequence is sorted in the time domain. The detected events are obtained with the Monte Carlo procedure applied on the event sequence. The count losses are also calculated using the Monte Carlo simulation and the analytical models.

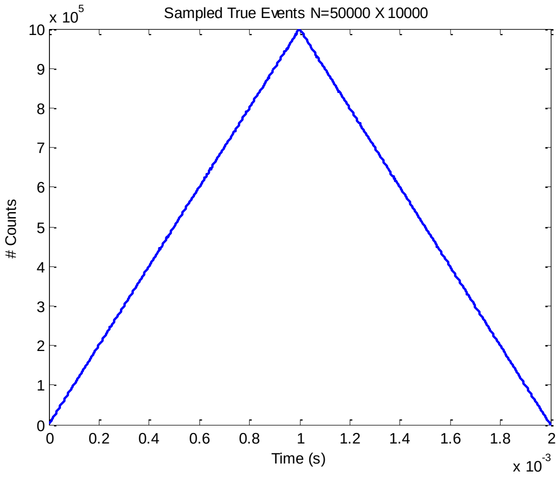


Fig. 8. Monte Carlo sampled true events for a slowly varied pulsed source, results are accumulated from 10000 pulses.

Fig. 9 shows the losses obtained by the Monte Carlo simulation and the analytical models for each 2 μs count bin within the pulse period for both detector models. Fig. 10 compares the results of Fig. 9 for each time bin. For this test case, as shown in the figures, the count losses for this slowly varied transient source can be corrected accurately by the simple mathematical model.

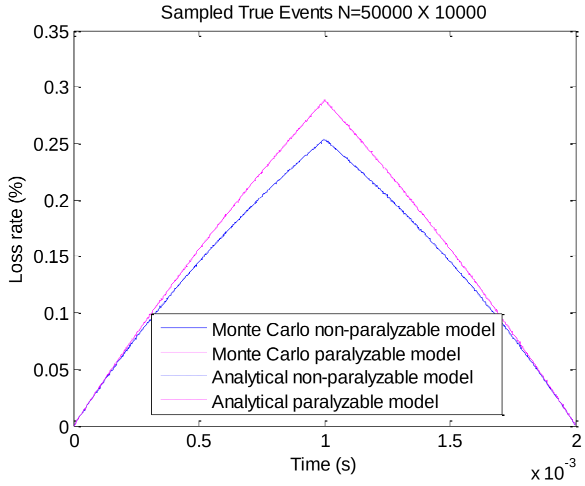


Fig. 9. Comparison of the detector counting losses calculated by the Monte Carlo simulations and the analytical models for the repetitive linear source at each 2 μs count bin within the pulse period.

However, compared with the Monte Carlo simulation results, the analytical model slightly over-corrects the count losses at the first half of the pulse and slightly under-corrects the count losses at the second half of the pulse. This discrepancy is due to the steady state source assumption used in the analytical models. In every time bin, the analytical model assumes the source rates in the previous time bin are the same as the rates in the current time bins. Actually for a transient source, the source rate at the current time bin is higher than the source rate at the previous bin when the source tends to increase , i.e., in the first half of the test pulse, and it is lower when the source tends to decrease, i.e., in the second half of the test pulse. The differences among the two consecutive bins are less significant when the source rates are high. It becomes more important at lower source rates. Thus, the discrepancies at the beginning and end of the pulse become larger as shown in Fig.10. The larger statistical errors are due to the low source rates, which permit only a few samples. This results in large statistical errors in the Monte Carlo simulations.

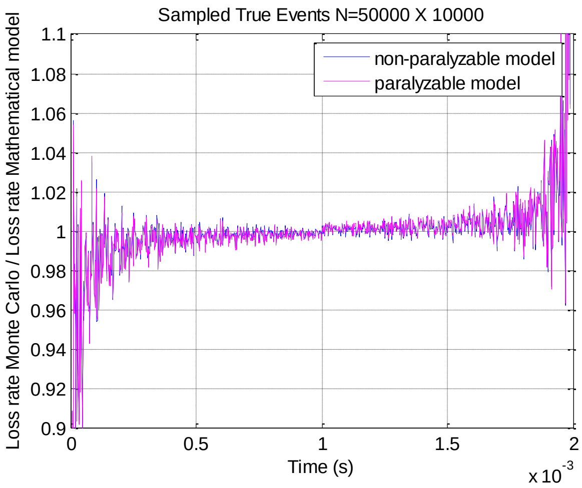


Fig. 10. The comparison of counting loss results calculated by the Monte Carlo simulation and the analytical models for the repetitive linear source at each 2 μs count bin within the pulse period.

4. Detector Dead Time Losses in PNS Experiment

To examine the neutron detector loss in a PNS experiment, Monte Carlo simulations are performed to simulate the PNS experiment of the YALINA thermal facility [9]. Fig. 11 shows the horizontal view of the facility, with the neutron detector locations labeled in the core map.

The YALINA subcritical assembly is driven by an external pulsed neutron source with a pulse period of 20 ms and a pulse width of 20 ns. In the MCNP simulations, all the external neutrons are born during the first 20 ns of the period. The delayed neutrons are ignored. The MCNP PTRAC function is used to record the neutron arrival time to the MC1 detector, which is located in the left upper corner of the reflector zone [9], and other detectors as its positions illustrated in Fig. 11. The neutron flux is tallied by MCNP F4 tally. Fig. 12 shows the normalized neutron flux obtained by the F4 track-length tally and the event sequence obtained by the PTRAC function at the MC1 detector. As shown in the figure, the event sequence obtained from the

PTRAC file preserves the time characteristics of the neutron flux variation in the PNS experiment.

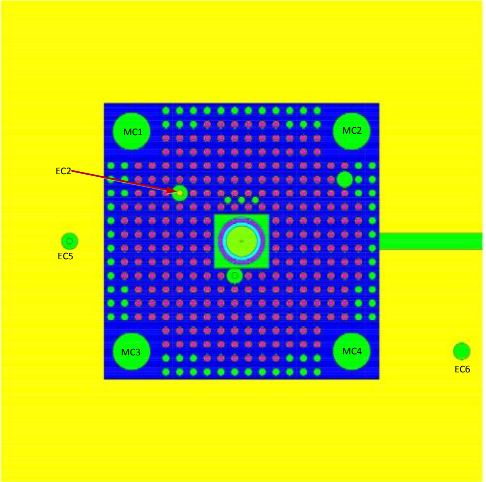


Fig. 11. Horizontal view of the Yalina thermal facility with neutron detector locations illustrated.

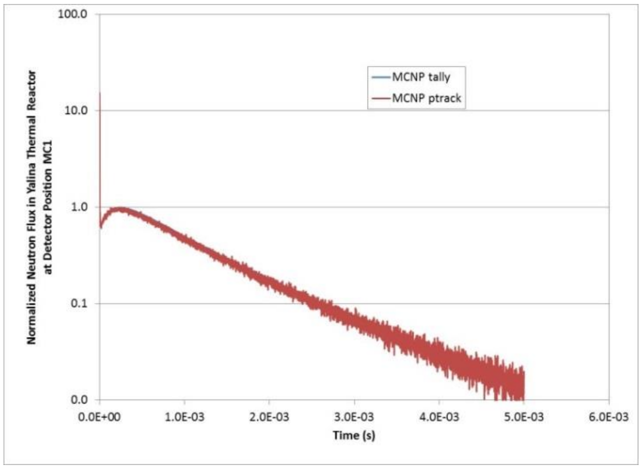


Fig. 12. Comparison of the neutron fluxes obtained from the F4 tally with the event sequence obtained from the PTRAC function in the Yalina thermal facility at MC1 detector.

As shown in Fig. 12, the tallied neutron flux has a relative large component in the first few times bins. The MCNP simulations were performed to examine the time structure of this large component. The neutron fluxes were tallied using the MCNP f4 tally with a fine time structure at MC1, EC2 and EC5 detector locations, respectively. The results are shown in Fig. 13 and all the results are normalized per source per time shake. As shown in Fig. 11, the detector EC2 is the closest of the three detectors to the external source, and the detector MC1 and EC5 are at the same distance away from the source. Fig. 13 shows that the EC2 detector channel observes the neutron fluxes earlier than the MC1 and EC5 detector channels. The large values of Fig. 12 in the first few time bins are indeed contributed directly from the external neutron source.

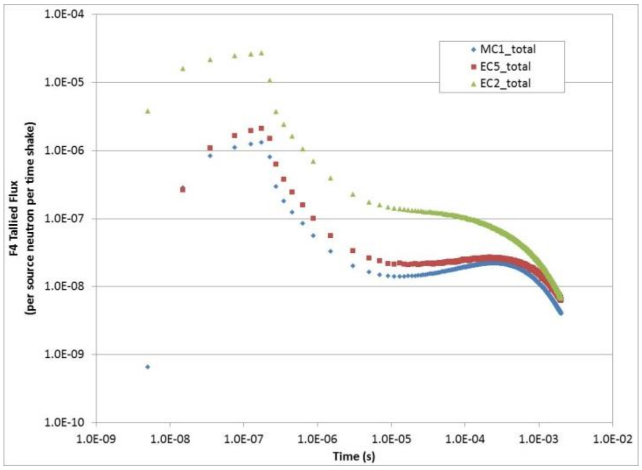


Fig. 13. Comparison of the neutron flux using fine time structure obtained from the F4 tally at EC2, MC1 and EC5 of the YALINA thermal facility.

The event sequence plotted in Fig. 12 is accumulated through multiple pulse periods. For the events recorded in the PTRAC file, different numbers of source particles were sampled within one pulse period representing the different source rates in the PNS experiments. In the Monte Carlo simulations to generate the true event source sequence, rather than to simulate the actual neutron interactions within the detector (collision or absorption), the neutron arrival time to the detector zone is recorded. Since only a small fraction of these neutrons will be recorded, these neutrons arriving to the detectors are sampled with an assumed detector efficiency of 0.1%.

The sampled event sequence is sorted in the time domain. The assumed detector dead time is 3.4 μs. The neutron detector type is assumed to be nonparalyzable. The Monte Carlo procedure is applied on the event sequence obtained from the MCNP simulations. Fig. 14 shows the accumulated detected counts simulated with the Monte Carlo procedure denoted as "MC" for different source rates. The time bin width is 1 μs. Three external neutron source rates are plotted in Fig. 14 with the maximum even rate at the pulse peak as $1.46\text{x}10^4$, $2.92\text{x}10^4$, and $1.46\text{x}10^5$ count/s respectively.

The analytical model was also used to calculate the neutron detector losses based on the event rate at each time bin. The accumulated detector counts with the analytical calculation within each time bin are denoted as "MM" in Fig. 14.

Overall, Fig. 14 showed that for the PNS experiment of the YALINA thermal facility using the MC1 detector, the Monte Carlo simulated neutron detector losses are very close to the neutron detector losses predicted by the simple analytical model for the three source rates. Thus, this numerical test demonstrates that the analytical model can be utilized to correct the neutron detector counts obtained from this PNS experiment.

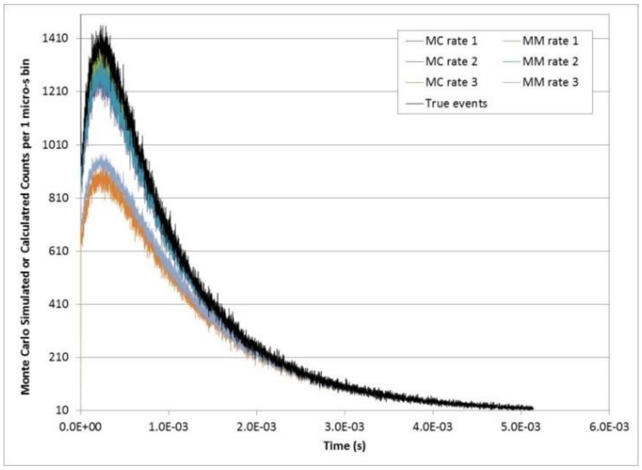


Fig. 14. Comparison of the neutron detector count curves obtained from the Monte Carlo simulations and the results calculated with the analytical model for the PNS experiment

In addition, Fig. 14 shows that the analytical model slightly under estimates the neutron losses when the counting rates are high. This is different from the previous test case as shown in Fig 10. In this test case, the analytical model tends to under calculate the count losses at the pulse peak on both sides when the source increases or decreases. This depends on the detector efficiency used in the Monte Carlo simulations.

Fig. 15 shows the same comparison as Fig. 14, except that the detector has a perfect efficiency of 100% for generating the events using the MCNP simulation data. As can be seen from the figure, the difference between the Monte Carlo simulated detected counts and the detected counts calculated from the analytical model increased significantly. This difference is mainly because the counted fission neutrons are correlated. In any fission media, about two neutrons are born from the fission event near the detector and both neutrons may reach the detector. The time stamps of these two correlated neutrons may be very close to each other. Thus, the latter neutron will have a larger probability to be lost than two random uncorrelated events reaching the detector. Neutron detector with a low counting efficiency significantly reduces this probability of such two correlated neutrons to be counted. Therefore, the event sequence generated with a low efficiency detector is closer to the random uncorrelated source as assumed in the analytical model. In PNS experiment, i.e., PNS experiments performed in the YALINA thermal facility or future ADS facilities, the neutron detector efficiency is very low as 0.1% or even smaller.

This test case shows that the analytical model is accurate and it can be used to correct neutron losses for the low efficiency neutron detectors. For PNS experiments using the area-ratio method to measure the reactivity of the ADS subcritical assembly, if the analytical model is used to correct the neutron detector count for losses, a small prompt neutron area as well as a small reactivity in absolute value will be obtained.

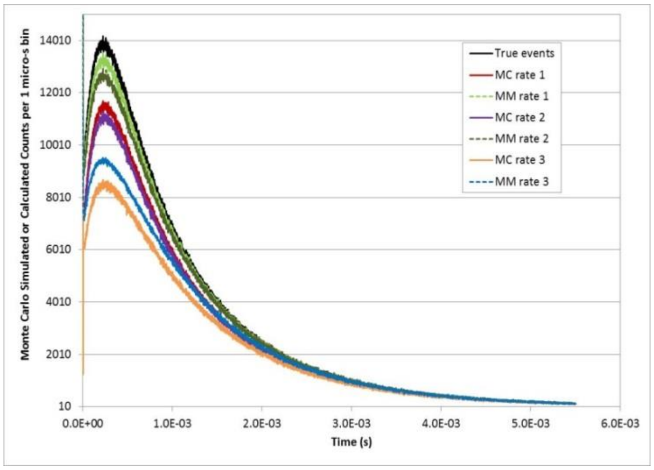


Fig. 15. Comparison of the neutron detector count results from the Monte Carlo simulations and the results calculated with the analytical model for the PNS experiment in the YALINA thermal facility at MC1 for hypothetical neutron detector with 100% efficiency.

V. SUMMARY

A Monte Carlo procedure was developed to study the neutron detector dead time effects in a PNS experiment. The procedure itself is simple and is easy to be implemented. It can be used for different neutron sources, steady state and transient sources. The sequence of the detector events can be faithfully simulated.

In this paper, the Monte Carlo procedure was first validated for a steady state source. The detector counting losses obtained from the Monte Carlo procedure were verified against the analytical results. Then the Monte Carlo procedure was used to study the detector dead effects with transient sources. It showed that for a pulsed transient source, the analytical model is only valid when the transient pulse width is much larger than the detector dead time. The counting losses are much smaller than the traditional analytical model predicted when the pulse width is comparable or even smaller than the detector dead time. For the transient source with slow variations, the Monte Carlo procedure shows that the analytical model can be used to predict the neutron count losses accurately.

The Monte Carlo simulation of the neutron detector counting losses for the YALINA thermal PNS experiment is performed by simulating the neutron arrival time to the MC1 detector using the MCNP PTRAC file. The detector count losses obtained from the Monte Carlo procedure is very similar to the losses predicted by the analytical model. In addition, the numerical simulations shows that the analytical model is accurately estimating the neutron counting losses for the YALINA thermal PNS experiment using real neutron detectors.

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