



Article

Pulsed-Neutron Experiments at the Inherently Safe Subcritical Assembly[†]

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Abstract

The pulsed neutron technique is a powerful, dynamic method to assay the reactivity of a multiplying system. This work presents the novel application of the pulsed neutron technique to the Inherently Safe Subcritical Assembly, an experimental configuration accepted by the International Criticality Safety Benchmark Evaluation Project Handbook. The experiments were replicated with COG11.3, a continuous-energy Monte Carlo code. The pulsed neutron data were analyzed using the Sjöstrand and Gozani area-ratio methods and by extracting the prompt neutron decay constant. Subsequent static k-eigenvalue and α -eigenvalue simulations were also performed for the same configurations. Neutron detector dead-time effects from the experiments were corrected using the Backwards Extrapolation Method and shown to have a negligible impact on the estimated reactivities. The results highlight that capturing time-dependent effects like delayed neutron precursor buildup are essential to accurately reproduce experimental results. They also highlight the importance of shielding the detectors from generator source neutrons in deeply subcritical configurations.

Keywords: pulsed neutron; subcritical reactivity; area-ratio; experimental reactor physics

1. Introduction

The Inherently Safe Subcritical Assembly (ISSA) is an educational and research facility used to study neutron noise, criticality safety, and reactor kinetics. In 2019, ISSA's neutron noise experiments were recognized as a fundamental benchmark by the Nuclear Energy Agency's International Criticality Safety Benchmark Evaluation Project (ICSBEP) [1,2]. A new experimental campaign was conducted at ISSA using the pulsed-neutron method [3]. It probed the physics of dynamic subcriticality which affects applications like medical isotope production [4], reactor startup monitoring [5], and waste transmutation in accelerator-driven systems [6]. The technique has had significant interest over many experimental campaigns, including a recent study at VR-1 and VR-2 reactors [7]. Unique to this campaign is that it extends to deeper subcriticality than usually presented in the literature, and that it builds off a previous neutron noise benchmark.

To better understand how this method can be for validation, this work presents the new experiment at ISSA and explores modeling techniques specific to pulsed neutron systems. Simulations of subcritical experiments require bespoke techniques and algorithms



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to evaluate their integral parameter, in comparison to well-established k -eigenvalue calculations for critical experiments. For instance, neutron noise benchmarks stimulated the integration of event-by-event fission simulators into Monte Carlo codes [8] and event tracking in OpenMC [9].

This paper documents the experiments and approaches to model it. The analysis used area-ratio methods [10,11] and the Prompt Decay Constant (PDC) method [12] to calculate reactivity and to derive effective multiplication for both experimental and simulated data. Importantly, the effect of different levels of subcriticality on determining k_{src} are explored. Most work modeling subcritical assemblies involves systems at high levels of multiplication ($k_{src} \geq 0.9$) with deeply subcritical states being ignored [7,13–15]. Some studies have looked at intermediate states of subcriticality [16], however important source biasing effects are revealed at k_{src} of less than 0.4. Others have investigate machine learning techniques to estimate reactivity with pulsed neutrons [17].

Previous studies focused on simulating pulsed neutron experiments with time-dependent Monte Carlo codes like MCNP [18–20], MONK [20,21] and Serpent [7]. The literature presents specific approaches to simulate pulsed neutron experiments like the pulse superimposition method [22] or the single pulse convolution method [23]. The former simulates thousands of individual pulses and superimposes the individual responses upon each other, while the latter takes a single pulse response and evenly distributes the delayed neutron response across the pulse. Modeling the source term, including its angular, geometric, energetic, and timing properties, is the primary challenge for pulsed neutron experiments.

In this study, we implemented two types of pulsing models in the COG11.3 Monte Carlo radiation transport code [24]: a single pulse and a series of periodic pulses. The periodic pulsing model is different from the previously outlined simulation methods. It involves simulating a pseudo-continuous experiment with multiple discrete pulses occurring to capture delayed neutron effects on the seconds-to-minutes timescale. Additional comparisons were made with simulations using beam-type and isotropic point source definitions. The dead time effects from the detectors used in the experiments were corrected to ensure that simulations and experiments were properly compared. The results show that the direct and dynamic simulation approaches have not yet fully captured all experimental effects, but do provide valuable insights for future experimental design and the algorithms needed to properly simulate pulsed neutron measurements.

2. Theory

This work estimates subcritical reactivity through the analysis of a pulsed neutron die-away curve seen in Figure 1. This curve can be analyzed either through the area-ratio method or by calculating the prompt neutron decay constant. The area-ratio method compares the prompt and delayed neutron areas (A_p and A_d , respectively) of the curve. In Figure 1, the neutron generator pulse occurs from 0 to ~ 0.66 ms, consisting primarily of prompt and source neutrons; the prompt neutrons are primarily detected from ~ 0.66 to 3 ms, and the delayed neutrons are primarily represented from 3 ms onward. The die-away curve changes with the level of subcriticality, which will modify the initial rise in neutron population in the generator pulse region, the decay in the prompt neutron region, and the plateau in the delayed neutron region.

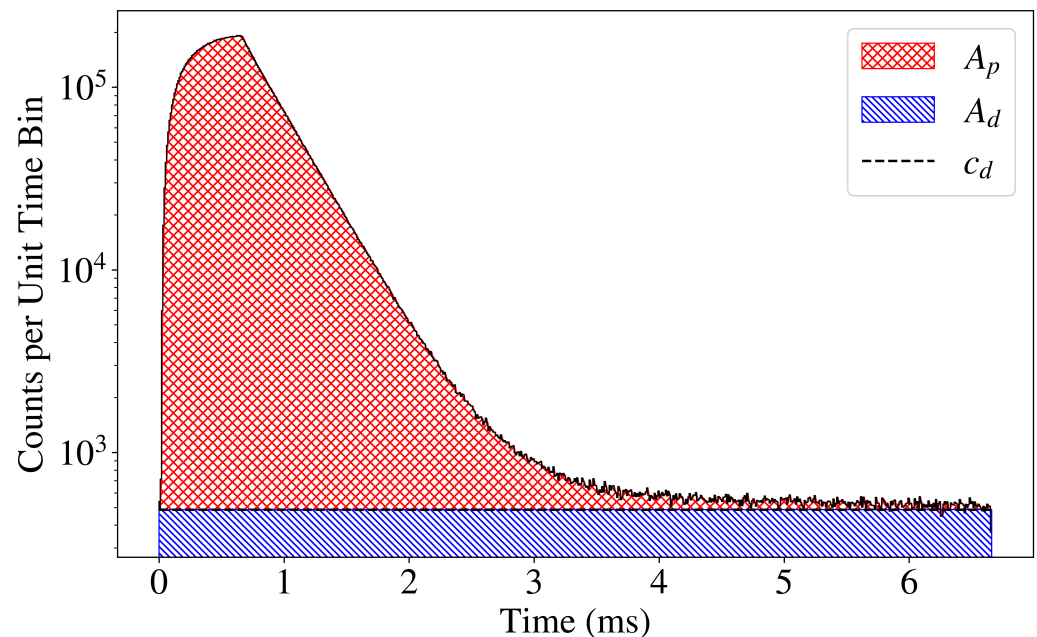


Figure 1. A measured die-away curve in ISSA highlighting the prompt area (A_p) and the delayed area (A_d) estimated from the delayed neutron plateau (c_d).

The reactivity of the system, ρ , can be estimated (in dollars) with Equation (1). Using the definition of reactivity [25], we can estimate the k_{src} of the system and relate it to the A_p and A_d with Equation (2). β_{eff} is known either from *a priori* knowledge or from running a separate simulation of the system. Prior knowledge can be as simple as assuming all fission occurs at a certain energy and a certain dominant isotope. Simulations typically involve adjoint-weighted quantities [26]. Finally, Equation (3) is the propagated variance of k_{src} . Two approaches to the area-ratio method are used in this paper: Sjöstrand's method [10] and Gozani's extrapolated area-ratio method [11].

$$\frac{\rho}{\beta_{eff}} = -\frac{A_p}{A_d} \quad (1)$$

$$k_{src} \approx \frac{1}{1 + \beta_{eff} \frac{A_p}{A_d}} \quad (2)$$

$$\sigma_{k_{src}}^2 = \left(\frac{-A_p A_d}{(\beta_{eff} A_p + A_d)^2} \right)^2 \sigma_{\beta_{eff}}^2 + \left(\frac{-\beta_{eff} A_d}{(\beta_{eff} A_p + A_d)^2} \right)^2 \sigma_{A_p}^2 + \left(\frac{\beta_{eff} A_p}{(\beta_{eff} A_p + A_d)^2} \right)^2 \sigma_{A_d}^2 \quad (3)$$

The k_{src} extracted from the area-ratio methods is *not* a k-eigenvalue solution but rather a k-source solution. Gandini and Salvatores [27] outline how reactivity measurements from accelerator driven subcritical systems are k-source solutions, which include effects from the source spectrum, position, and the importance of fission neutrons versus source neutrons. Only COG results from inverse power iteration simulations are k-eigenvalue solutions and thus referred to as k_{eff} . As a system approaches criticality, the k_{src} solution converges to that of the k_{eff} solution.

The area-ratio method assumes the fundamental mode is dominant, the prompt and delayed neutron flux have the same shape, and the prompt and delayed eigenfunctions are the same. These assumptions make the method depend on spatial effects that change the importance of high-order harmonics. Furthermore, area-ratio methods require that the experiment is conducted over a period long enough to build up a delayed neutron population. Given that the longest half-life for a delayed neutron precursor group is

~ 55 s [12], several minutes or half-lives are necessary to allow all delayed neutron precursors to accumulate. All of these effects suggest that subcriticality estimates with this method may have biases that depend on detector and source effects—and modeling and analysis approaches. Therefore, direct simulations of the time-dependent neutron source are likely the best approach for validation studies. Spatial correction techniques exist to correct for detector effects (sensitivity and location) [5,11]. The methods require some modeling of the system to develop the correction factors. Because we sought to investigate the experiment for validation, we decided to avoid as much as possible modeling in the analysis of experimental data.

2.1. Sjöstrand Method

The Sjöstrand area-ratio method calculates reactivity in dollars by using the ratio of A_p to A_d as in Equation (4). Here, $N_p(\mathbf{r}, t)$ [$\text{n}/\text{cm}^3 \cdot \text{s}$] is the number of prompt neutrons per unit volume at position $\mathbf{r}$ and time t , $N_d(\mathbf{r}, t)$ [$\text{n}/\text{cm}^3 \cdot \text{s}$] is the number of delayed neutrons per unit volume, and T is the period of the pulsed neutron generator. Evaluating these integrals leads to the prompt area A_p and the delayed area A_d needed to estimate reactivity.

$$\rho(\$) = \frac{\int_0^T N_p(\mathbf{r}, t) dt}{\int_0^T N_d(\mathbf{r}, t) dt} = -\frac{A_p}{A_d} \quad (4)$$

Calculating A_p and A_d first requires estimating the region of the die-away curve where delayed neutrons dominate. Section 3.1 describes in more detail how to estimate this delayed neutron plateau c_d , seen as the horizontal line in Figure 1. Once c_d is found, Equation (5) calculates A_d by integrating c_d over T . A_p is calculated by subtracting the delayed neutron area from the total area A_t , where the total area is calculated by summing the counts (C_i) per time bin i over all N time bins, as in Equation (6). This method assumes the uncertainty in the counts per time bin ($\sigma_{(C_i)}$) obeys Poisson statistics, or $\sigma_{(C_i)} = \sqrt{C_i}$, and that counts in each time bin are statistically independent [28].

$$A_d = T \cdot c_d \quad (5)$$

$$A_p = A_t - A_d = \sum_{i=1}^N C_i - A_d \quad (6)$$

The uncertainty of A_p is propagated from the total area A_t with linear error propagation, assuming that A_t and A_d are uncorrelated. Finally, to derive k_{src} from the estimated reactivity, Equation (3) propagates the uncertainty in A_p , A_d , and β_{eff} . For the delayed neutron area, the variance of c_d is denoted as $\sigma_{(c_d)}^2$. The resulting propagated error of A_d and A_p are found in Equations (7) and (8), respectively.

$$\sigma_{(A_d)}^2 = T \cdot \sigma_{(c_d)}^2 \quad (7)$$

$$\sigma_{(A_p)}^2 = \sum_{i=1}^N \sigma_{(C_i)}^2 + T^2 \cdot \sigma_{(c_d)}^2 \quad (8)$$

2.2. Gozani Method

The Gozani method solves some theoretical limitations of the Sjöstrand method by calculating A_p without the influence of non-fundamental mode harmonics [11]. To do so, the die-away curve is fit to the exponential of Equation (19) via subtracting c_d from the total die-away curve, as seen in Figure 2. Then, a variably-sized fitting window is used to find the fundamental mode. Finally, Equation (9) is evaluated over T to calculate A_p by back extrapolating the fitted curve to time $t = 0$. This approach is highly similar to that of

the prompt fundamental mode fitting method outlined in Section 3.1, and the optimized parameters determined from this method are utilized when calculating A_p . A_d is calculated in the same manner to the Sjöstrand method with Equation (5).

$$A_p = \int_0^T \psi(t) dt = \int_0^T a e^{\alpha_0 t} dt = \frac{a}{\alpha_0} (e^{\alpha_0 T} - 1) \quad (9)$$

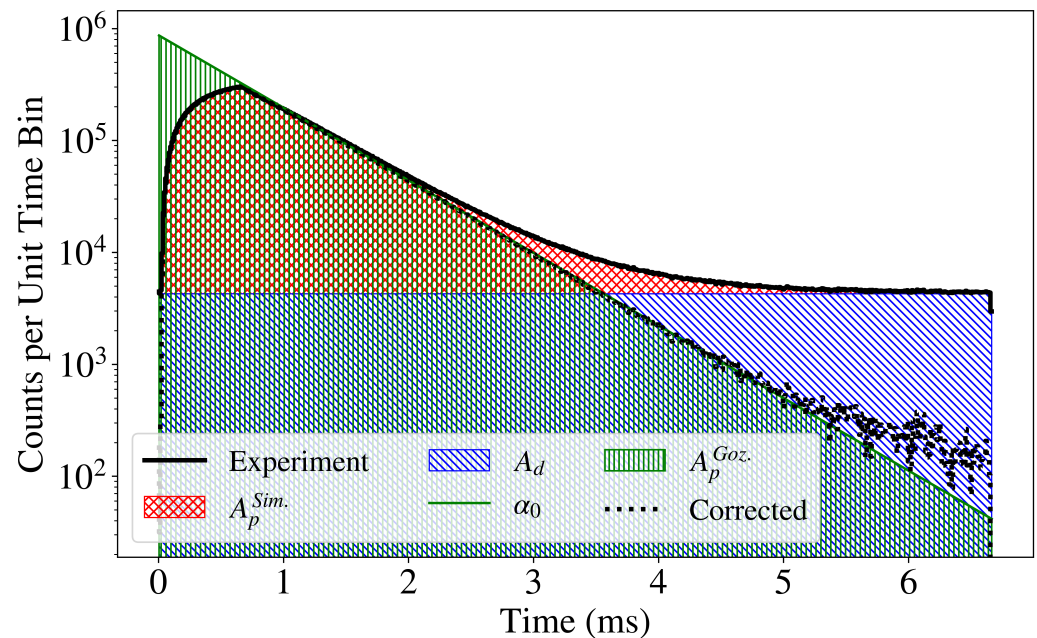


Figure 2. Analysis of the die-away curve in the Gozani method.

The method outlined above is defined for a system that has a narrow pulse. Equation (10) defines a relation to determine if a pulse can be considered narrow [29]. Here, α_0 is the prompt, fundamental mode decay constant in inverse seconds and d is neutron generator pulse width in seconds. d is equivalent to the pulse period multiplied by the duty factor of the neutron generator. If this relation is not true, which is the case in this study, the prompt neutron response must be multiplied by a correction factor, seen in Equation (11) [7,29].

$$\alpha_0 d \ll 1 \quad (10)$$

$$\lambda = \frac{e^{\alpha_0 d} - 1}{\alpha_0 d} \quad (11)$$

The variance in A_p for the Gozani method can be calculated with Equation (12). Generally, the uncertainty in the pulse period (T) is assumed to be zero. The variance of A_d can be calculated with Equation (7). The variance in the pulse correction factor is can be calculated with Equation (13), where the uncertainty on d is assumed to be zero.

$$\sigma_{A_p}^2 = \left(\frac{e^{\alpha_0 T} - 1}{\alpha_0} \right)^2 \sigma_{(a)}^2 + \left[a \left(\frac{T e^{\alpha_0 T}}{\alpha_0} - \frac{e^{\alpha_0 T} - 1}{\alpha_0^2} \right) \right]^2 \sigma_{(\alpha_0)}^2 \quad (12)$$

$$\sigma_{\lambda}^2 = \left(\frac{1 + \alpha_0 d e^{\alpha_0 d} - e^{\alpha_0 d}}{\alpha_0^2 d} \right)^2 \sigma_{(\alpha_0)}^2 \quad (13)$$

2.3. Prompt Decay Constant Method

Another method to estimate subcriticality with the pulsed-neutron technique uses the prompt-neutron decay constant in the fundamental mode (α_0). Here, α_0 is defined to be inherently negative with the relationship $N(t) = N_0 \cdot \exp(\alpha_0 t)$ where $N(t)$ is the time-dependent neutron density in the fundamental mode.

The prompt multiplication k_p of a system can be related to α_0 using Equation (14) [30]. Here, ℓ [s] is the prompt neutron lifetime. The k_{src} of the system can be calculated in Equation (16) via substituting Equation (15) into Equation (14) [30]. The method only requires kinetics parameters to calculate k_{src} for a system. They can be determined by simulation or experiment. This method has certain deficiencies that will be discussed in detail later.

$$k_p = \alpha_0 \ell + 1 \quad (14)$$

$$k_p = (1 - \beta_{eff}) k_{src} \quad (15)$$

$$k_{src} = \frac{\alpha_0 \ell + 1}{1 - \beta_{eff}} \quad (16)$$

This work used the fitting routine outlined in Section 3.1 to determine α_0 in conjunction with kinetics parameters found from simulations of the system. The variance in k_{src} , or $\sigma^2_{(k_{src})}$, uncertainty in the experimental α_0 , or $\sigma^2_{(\alpha_0)}$, and the Monte Carlo simulated ℓ and β_{eff} , or $\sigma^2_{(\ell)}$ and $\sigma^2_{(\beta_{eff})}$, is provided in Equation (17). This equation is derived from linear error approximation and assumes that α_0 , β_{eff} , and ℓ are uncorrelated.

$$\sigma^2_{(k_{src})} = \left(\frac{\ell}{1 - \beta_{eff}} \right)^2 \sigma^2_{(\alpha_0)} + \left(\frac{\alpha_0}{1 - \beta_{eff}} \right)^2 \sigma^2_{(\ell)} + \left(\frac{-(\alpha_0 \ell + 1)}{(1 - \beta_{eff})^2} \right)^2 \sigma^2_{(\beta_{eff})} \quad (17)$$

3. Methods

3.1. Delayed Area and Fundamental Mode Determination

The most important parameters for the area-ratio method are the delayed neutron plateau constant (c_d) used for determining A_d for the Sjöstrand and Gozani methods, and the prompt neutron decay constant in the fundamental mode (α_0) used for the Gozani method and PDC method. We evaluated c_d by averaging the last ten data points of a die-away curve to mitigate statistical variations in the data at those time scales.

An ideal die-away curve will follow an exponential decay of the neutron flux ϕ [n/cm²·s] vs. time t [s] plus a constant, as shown in Equation (18). Die-away curves generally do not perfectly follow this behavior due to external neutron sources biasing detection events, and thus necessitate a more nuanced approach to correctly fit the parameters of Equation (18). The primary concern is ensuring the decay constant α is the fundamental mode decay constant α_0 [s⁻¹].

$$\phi(t) = ae^{\alpha t} + c_d \quad (18)$$

This work applied the following method: first c_d is subtracted from the entire die-away curve, yielding Equation (19), creating data that are assumed to represent only prompt neutrons. Here, we assume that when the measured neutron flux is in the fundamental mode and prompt neutrons dominate, it can be adequately represented by a single exponential. By selectively choosing the data for which the fit is done, this assumption is accurate. Fitting only in the fundamental mode ensures that the higher-harmonics are sufficiently decayed away and the prompt neutrons decay with the single exponential of the fundamental mode. Excluding late data in the curve and performing the subtraction

of the constant background term renders c_d to be a negligible component, shown by the factor of 10^5 difference between the fitted region and the background in Figure 3.

$$\phi(t) = ae^{\alpha t} \quad (19)$$

The prompt neutron die-away curve is subsequently fitted using the Levenberg-Marquardt algorithm within the Scipy Python package, version 1.15.3 [31] in intervals of 25 data points. The data are iterated over, producing a list of α values corresponding to each time bin of the curve. A region of five α values with the lowest change between neighboring values is selected and averaged. Choosing five α values was an arbitrary decision, but provided adequate performance in our analysis in terms of the convergence and uncertainty quantification given the physics of the ISSA system. Other ranges of averages provided equivalent results, while too large ranges would push the averaging outside of the plateaued region of the fundamental mode. This averaged quantity is the resulting α_0 . The uncertainty of each fitted α is propagated to the population standard deviation of the final α_0 . The uncertainty of c_d and the counts in each time bin (C_i) were assumed to follow Poisson statistics. The fit uses the uncertainty in C_i passed as a diagonal covariance matrix, inherently assuming that the counts in each time bin are uncorrelated.

Figure 3 provides a visual interpretation of this process. The vertical dotted lines represent the averaging window for α_0 , the red points represent the calculated α values, and the black plot is the delayed-neutron subtracted (prompt only) die-away curve. This fitting technique has an advantage over just fitting an exponential like Equation (18), as it provides better estimations of the delayed neutron plateau constant for noisy data, removes the susceptibility of overfitting parameters of non-ideal exponential die-away curves (which can be present in deeply subcritical states), and considers only prompt neutrons when fitting.

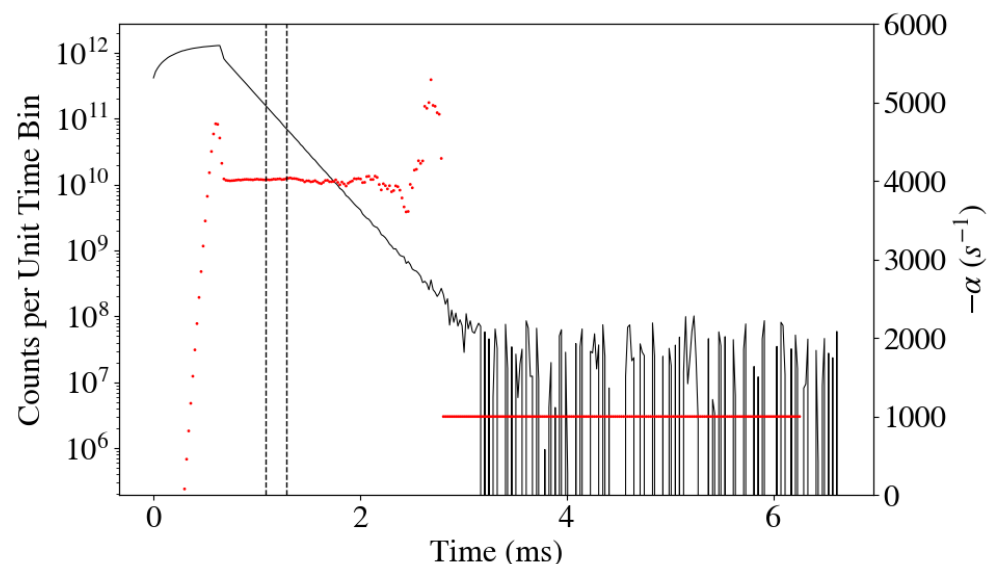


Figure 3. A representation of our approach to estimate the prompt neutron decay constant in the fundamental mode, α_0 . The red dots are the fitted exponential decay constants. The vertical lines represent the averaging window used to estimate α_0 .

3.2. Experiments

The Inherently Safe Subcritical Assembly (ISSA) consists of Materials Test Reactor (MTR) type fuel assemblies of highly enriched uranium (93.16 wt.%). An assembly has nineteen fuel plates, with each plate holding 12.210 ± 0.250 g of ^{235}U . The fuel plates are

a dilution of U_3O_8 in high-purity aluminum powder to $\sim 18\%$ uranium oxide by weight. The plates are arranged in the assembly with gaps that serve as water channels, creating a highly thermalized system. Up to nine assemblies can be loaded into ISSA in one, two, four, six, and nine fuel assembly patterns. These assemblies were tightly packed into a Lucite support structure and submerged in a water tank (101.6 cm in diameter and 182.88 cm in height). The experiment also used four ^3He neutron detectors (5.16 cm in diameter and 100.48 cm in length, at 0.21 MPa) with the distance from the centerline of a detector to centerline of the support structure being 16.5 cm in the horizontal direction and 17.4 cm away in the vertical direction. A detailed description of the experiment can be found in the ICSBEP benchmark, labeled FUND-LLNL-ALPHAN-HE3-MULT-001. Figure 4 shows a photograph of ISSA with a nine-fuel assembly configuration and a 3D rendering of its corresponding COG model.

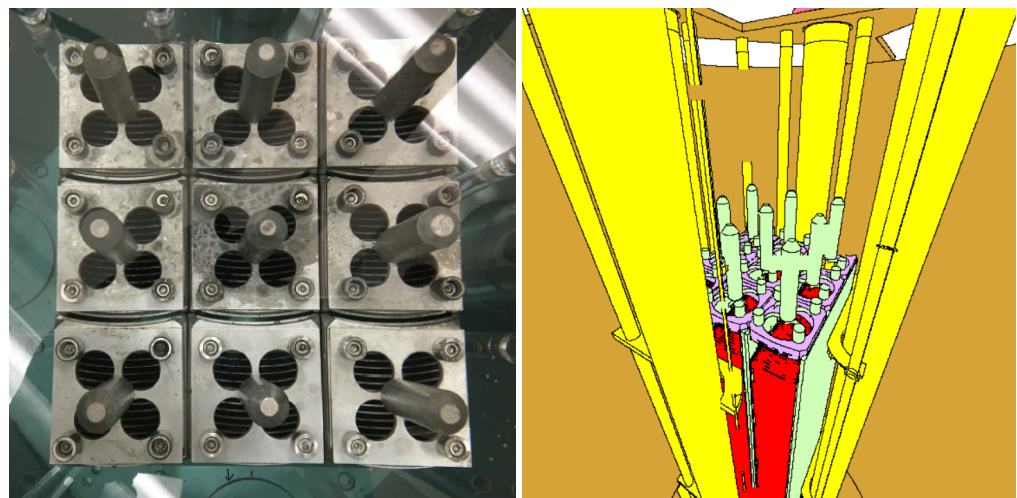


Figure 4. Images of the ISSA benchmark experiment and a COG benchmark model.

The pulsed-neutron experiments replicated the ICSBEP benchmark [1] but included a D-T P 383 neutron generator manufactured by ThermoFisher Scientific in CO, USA [32]. By pulsing neutrons into the system, it is possible to measure the subcritical reactivity of different ISSA configurations. The neutron generator was positioned beneath the ISSA tank, with source neutrons directed upward through an empty pipe that ends below the fuel. The pipe is open to the atmosphere on the bottom of the tank, allowing unmoderated neutrons to reach the fuel. Experiments were carried out on four of the benchmark configurations, where ISSA contained nine, six, four, and two fuel assemblies. The neutron generator was operated at a frequency of 150 Hz with a pulse width of 667 μs for 15 min per experiment, totaling approximately 135,000 pulses per experiment. At 90 kV and 60 μA , the generator produced approximately 10^8 n/s with an average neutron energy of 14.1 MeV. While the pulse width is larger than that which is optimally desired, it is consistent with recent work [7] that uses commercial-off-the-shelf equipment.

3.3. Modeling

This work adapted the benchmark COG model of ISSA to include a pulsed neutron source term. We sought to optimize the modeling strategy of the pulsed neutron experiment to best match its physics in an effort to establish a set of best practices for performing pulsed neutron experiments with matching, time-dependent COG models. To do so, two modeling approaches were taken: a single neutron pulse, and a multi-pulsing neutron source. Figure 5 compares the normalized die-away curves of the experiment to the two simulation strategies. This figure demonstrates how a single pulse cannot capture

the delayed neutron behavior needed for the area-ratio method while the multi-pulsing method does re-create the delayed neutron plateau.

The multi-pulsing technique requires a large number of particles to be simulated to achieve adequate statistics, and yields long computation times and requires large computational resources. For example, the simulations in this study used 50 nodes or 5600 cores per simulation on Lawrence Livermore National Laboratory's supercomputing cluster requiring 900,000 CPU hours for the highest multiplication case. The long simulation times are related to the that configurations high multiplication and the long neutron lifetimes in this highly thermal and reflected system. In comparison, a single pulse simulation only requires a third of the compute time. This decrease in required computation was a point of interest and motivated our use of the PDC method to calculate k_{src} . Modeling a single pulse also has the advantage of creating data that is dominated by prompt neutrons, with no significant effect from delayed neutron needing to be considered.

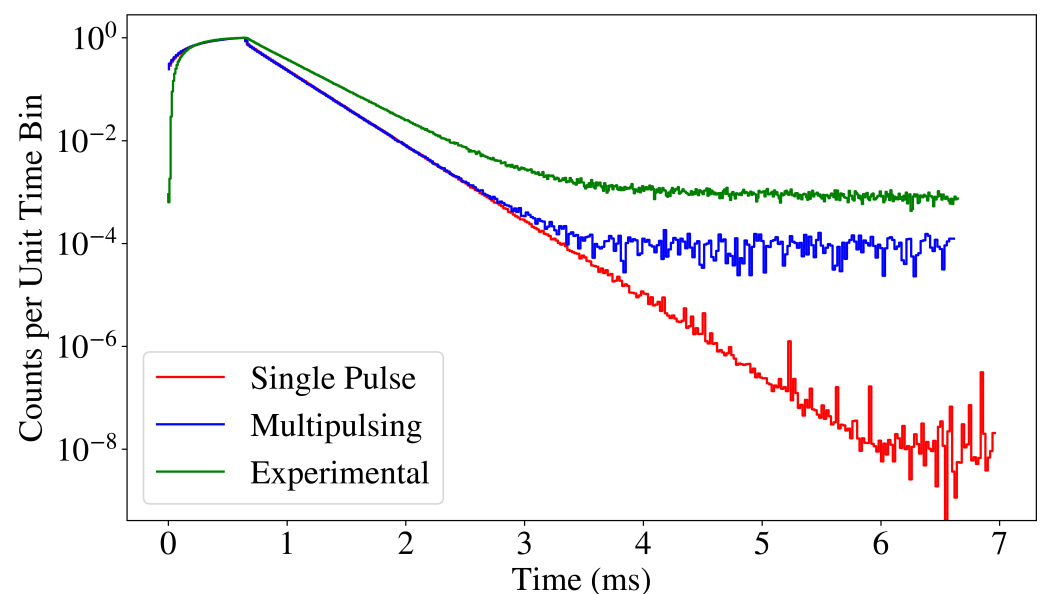


Figure 5. An example of four normalized pulses in the multi-pulsing strategy after 60 s of dynamic simulations. Due to the logarithmic y-axis, the stochastic error of the data from the Monte Carlo method or from counting statistics in experiments is not visible, but present.

For area-ratio methods, this work modifies the inputs of the benchmark model source term such that it behaves as a neutron generator with a periodic frequency, as seen in Figure 6. The prompt neutron contribution is evident by the initial peaks and subsequent die-away of the neutron population. Additionally, the delayed neutron contributions are minimal, with some pulses often having none, demonstrating the difficulty of achieving adequate delayed neutron statistics when running the dynamic multi-pulsing simulations.

The neutron generator was modeled as a beam source, that is, a flat, circular disk placed underneath the tank (see Figure 7). The pulsing neutrons stream up the air-filled tube into the bottom of the fuel array. The beam model assumed that the thick water column beneath the fuel assembly—through which the 72-cm-long tube penetrates—fully collimates the neutrons. This limits D-T source neutrons from streaming directly to the detectors and affecting the die-away curve. Despite this design feature, some water-scattered neutrons do interact with the detector in the experiment, which will be discussed later. All simulations used the ENDF/B-VIII.0 cross section library [33].

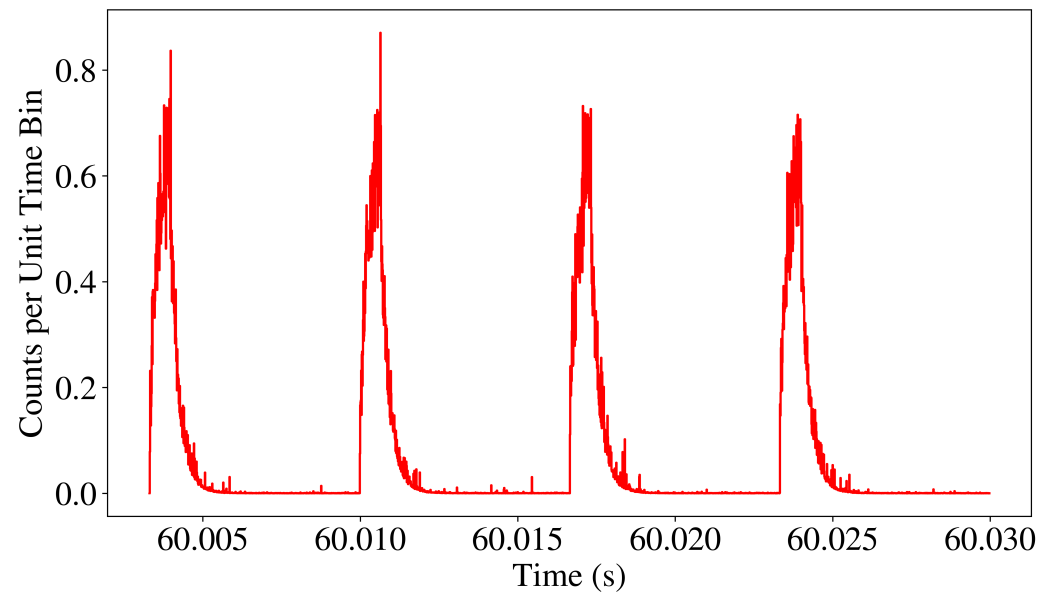


Figure 6. First four tracked normalized, simulated pulses of the six assembly configuration.

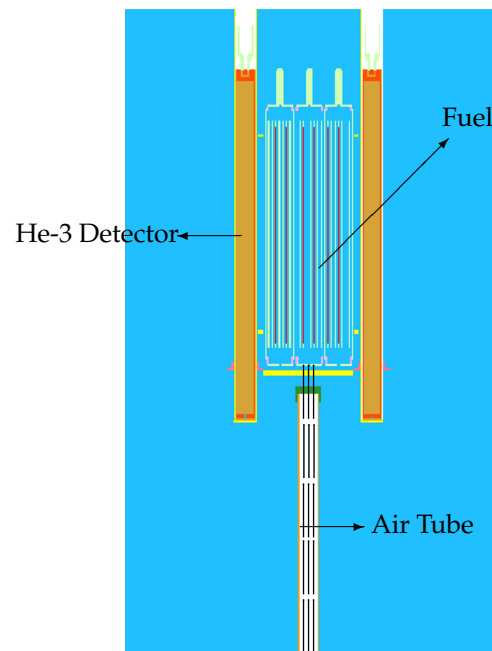


Figure 7. The COG model showing the vertical air-filled pipe and the beam-source model with neutron streaming directly up the pipe.

The neutron generator was operated with a pulse period of 6.67 ms and a 10% duty factor. For the multi-pulsing simulations, this pulse was repeated over an 80-s time window, equaling 11,994 pulses, to accumulate an adequate delayed neutron population. To mimic the processed experimental data, the simulated detector data were binned into 10- μ s time bins. For the single pulse model, this created 701 total bins from 0 to 7 ms. For the multi-pulsing simulations, this created 200,000,001 bins from 60 to 80 s.

The subcriticality of the system was estimated with static k-eigenvalue calculations. These simulations also provided the forward-weighted, effective delayed neutron fraction (β_{eff}) that was used to transform the reactivity in dollars estimated by the area-ratio methods to k_{src} . The simulations also estimated ℓ , which was needed in combination with β_{eff} to convert the prompt neutron decay constants estimated by the PDC method into k_{src} . These values can be seen in Table 1.

Table 1. Simulated effective delayed neutron fractions (β_{eff}), prompt neutron lifetimes (ℓ), and k_{eff} from COG.

Number of Assemblies	β_{eff} (pcm)	ℓ (μs)	k_{eff}
2	908 ± 13	41.645 ± 0.117	0.52606 ± 0.00096
4	859 ± 10	45.971 ± 0.102	0.70434 ± 0.00096
6	821 ± 9	46.706 ± 0.101	0.79030 ± 0.00096
9	822 ± 8	47.373 ± 0.089	0.90089 ± 0.00094

3.4. Dead Time Correction

The detection system of the experiment has an inherent dead time associated with the detectors and electronics. The dead time means that counting events are “lost” and that the prompt or delayed areas may be incorrectly estimated when compared to simulations without dead time effects. To account for this, the experimental data were dead time corrected with the Backward Extrapolation (BEX) method [34], adapted for pulsed neutron measurements [35].

Figure 8 provides an example of the BEX method applied to ISSA data. The approach takes the listmode data from each detector (i.e., individual timestamps associated with each detection event) and sequentially imposes artificial dead times in 100-ns steps from 0 to 20 μs . Depending on the size of the artificial dead time and the spacing between neutron events, neutron counts may be removed from the listmode data and subsequently from the die-away curve. This process can be implemented with both a paralyzable and non-paralyzable method.

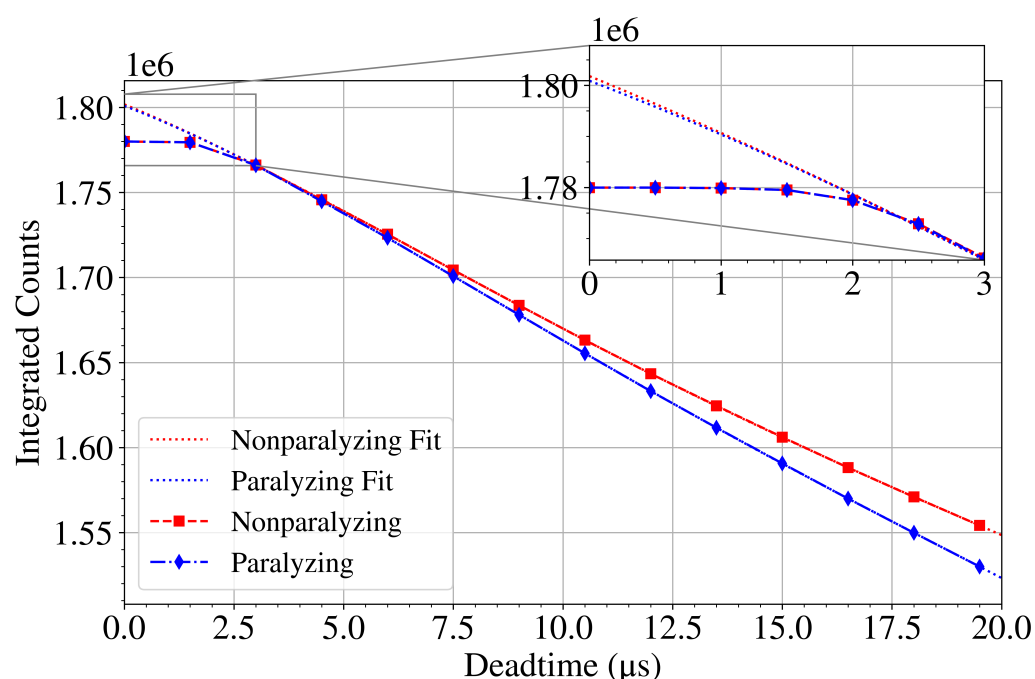
**Figure 8.** Imposed dead time curve of an example He-3 detector of the experiment. The inlayed plot shows the point where the curve asymptotes and the extrapolation to the y-intercept. In this figure, 1e6 means 10^6 .

Figure 9 visualizes the BEX method’s effect on the total number of neutron counts integrated across the whole die-away curve. For a large dead time of 100 μs , $\sim 750,000$ and $\sim 930,000$ neutron counts were lost vs. the uncorrected data (i.e., 0 μs of imposed dead time) for non-paralyzable and paralyzable dead time models, respectively. As the imposed dead

time decreased, the number of total counts increased until it reached an asymptotic point where smaller dead times did not cause any loss of counts. A fourth-degree polynomial was subsequently fit to the curves, and the resulting y-intercept is the corrected, or “true”, counts. This is applied to both paralyzing and non-paralyzing data.

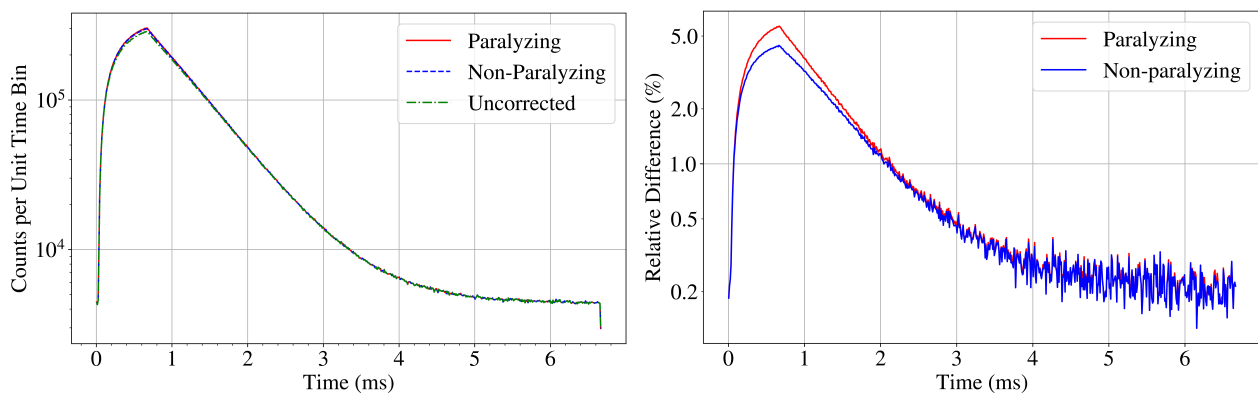


Figure 9. Comparison of dead time corrected and uncorrected experimental data.

In order to account for the non-constant reaction rate of the system caused by the pulsed neutron generator [35], the time series data is split into 10- μ s bins and the BEX method is applied to each time bin using the non-paralyzing and paralyzable dead time models. The data then undergoes the same superimposition routine for creating a die-away curve to create a non-paralyzing and paralyzing die-away curve. Section 4.1 discusses the results of the experimental data after undergoing dead time correction.

4. Results

This section compares the experimental and simulated data for the area-ratio methods and PDC method. It also discusses the applicability and validity of the simulation techniques and discusses future work for further improvements.

4.1. Dead Time Corrections

Section 3.4 presented a technique from the literature to correct pulsed neutron experiments for dead time effects. Figure 9 presents an uncorrected and corrected die-away curves for ISSA with nine fuel assemblies. The nine assembly configuration has the highest neutron multiplication and the highest count rate of any experimental data. Also, the paralyzing dead time model had the greatest effect upon count rate correction.

When the corrected die-away curve is compared to the uncorrected curve, no relative differences greater than 5.65% were observed. The dead time effects were greatest during the neutron pulse and immediately after, and decrease to less than 0.3% during the delayed neutron plateau. After repeating the reactivity analysis, the paralyzing model had the most prominent effect on k_{src} estimates. An average decrease in k_{src} of 462 pcm and 632 pcm across all cases was observed for the Sjöstrand and Gozani methods, respectively. The non-paralyzing dead time model yielded an average decrease of 414 pcm and 609 pcm for the Sjöstrand and Gozani methods, respectively. These k_{src} differences can be seen in Table 2. Note, for all future presentation of experimental results, the uncorrected data is used. Importantly, neither dead-time model showed a statistically significant difference greater than three standard deviations in the derived k_{src} when compared with the uncorrected data.

Table 2. Comparison of corrected and uncorrected k_{src} estimates using paralyzable and non-paralyzable dead time models for Sjöstrand and Gozani.

Assemblies	Uncorrected	Corrected	Δk_{src} (pcm)
Sjöstrand (Paralyzable)			
2	0.29361 ± 0.00938	0.28947 ± 0.00930	414 ± 1320
4	0.56402 ± 0.00608	0.55798 ± 0.00610	604 ± 862
6	0.71078 ± 0.00371	0.70531 ± 0.00375	547 ± 528
9	0.91367 ± 0.00086	0.91083 ± 0.00088	284 ± 123
Gozani (Paralyzable)			
2	0.20510 ± 0.00751	0.19894 ± 0.00736	615 ± 1051
4	0.47399 ± 0.00626	0.46569 ± 0.00624	830 ± 884
6	0.67327 ± 0.00414	0.66521 ± 0.00423	806 ± 591
9	0.90640 ± 0.00106	0.90329 ± 0.00107	311 ± 151
Sjöstrand (Non-Paralyzable)			
2	0.29361 ± 0.00938	0.28979 ± 0.00930	382 ± 1321
4	0.56402 ± 0.00608	0.55853 ± 0.00610	550 ± 862
6	0.71078 ± 0.00371	0.70591 ± 0.00375	487 ± 528
9	0.91367 ± 0.00086	0.91131 ± 0.00088	236 ± 123
Gozani (Non-Paralyzable)			
2	0.20510 ± 0.00751	0.19901 ± 0.00736	609 ± 1051
4	0.47399 ± 0.00626	0.46579 ± 0.00624	820 ± 884
6	0.67327 ± 0.00414	0.66547 ± 0.00422	779 ± 591
9	0.90640 ± 0.00106	0.90354 ± 0.00107	286 ± 151

4.2. Area-Ratio Results

Table 3 gives the estimated k_{src} from the Sjöstrand and Gozani methods with simulated data and Table 2 provides the k_{src} estimates for the uncorrected and corrected experimental data. Table 1 provides the k_{eff} estimates for a static k-eigenvalue solution using COG11.3. The single pulse models are omitted because they largely under-predict k_{src} by approximately 30,000 pcm. The reason for this under-prediction was previously shown in Figure 5; a single pulse produces no delayed neutron plateau, and therefore an accurate delayed neutron area cannot be calculated.

Table 3. Simulated COG multi-pulsing k_{src} estimates using the Sjöstrand and Gozani methods.

Assemblies	Sjöstrand	Gozani
2	0.21657 ± 0.00243	0.10405 ± 0.00135
4	0.47349 ± 0.00290	0.27050 ± 0.00232
6	0.65743 ± 0.00247	0.45288 ± 0.00274
8	0.84051 ± 0.00130	0.71645 ± 0.00202

Table 4 compares k_{src} values derived from simulated die-away curves and k_{eff} results to their respective experimentally derived k_{src} for both area-ratio methods. Across all domains of subcriticality, the Sjöstrand method better estimates k_{src} for the simulated and experimental tests compared to the Gozani method, when using experimental k_{src} as reference values. Additionally, the simulated multi-pulsing model k_{src} results have lower relative differences for the deeper states of subcriticality in comparison to the COG k-eigenvalue simulations, except in the nine-assembly case. The simulated multi-pulsing model using the Sjöstrand method had an average relative difference when compared to the experimental data across the first three cases of 16.6% compared to the 38.4% of the COG criticality code compared to the experimental data. Across all cases, the simulated

multi-pulsing model data averaged 14.5% relative difference compared to the 29.2% with k-eigenvalue simulations.

Table 4. Absolute relative differences of multi-pulsing (MP) k_{src} and COG k_{eff} (COG) simulations to experimental k_{src} results for the Sjöstrand and Gozani methods.

Assemblies	Sjöstrand Method		Gozani Method	
	MP (%)	COG (%)	MP (%)	COG (%)
2	26.24 ± 3.40	79.17 ± 4.09	49.27 ± 4.13	156.49 ± 6.82
4	16.05 ± 1.21	24.88 ± 1.12	42.93 ± 1.52	48.60 ± 1.48
6	7.51 ± 0.63	11.19 ± 0.54	32.73 ± 0.76	17.38 ± 0.64
9	8.01 ± 0.17	1.40 ± 0.14	20.96 ± 0.25	0.61 ± 0.16

The Gozani method showed much greater underestimation of the system's k_{src} in comparison to k-eigenvalue simulations and Sjöstrand method, outside of the nine assembly case. We attribute this to the pulse width of the neutron generator in the experiment and model. The large pulse width of 667 μ s caused the extrapolation of the prompt die-away to time $t = 0$ to overestimate the prompt area even after correction for the pulse width. Meanwhile, the theory typically considers a Dirac delta pulse, and experimentally, a much shorter pulse width is desired. This effect is most prominent in deeper states of subcriticality due to the increased steepness of the die-away curve fundamental mode slope, resulting in extrapolation to a higher point along the y-axis, resulting in the increased prompt neutron area size. Future experiments with a smaller pulse width would allow for better applicability of the Gozani method.

4.3. Prompt Decay Constant Results

Table 5 shows k_{src} for all ISSA configurations using the PDC method. Here, the experiment and simulation α_0 (seen in Tables 6 and 7) values were fitted using the method outlined in Section 3.1, and the single pulses were done with delayed neutron tracking on. This method heavily overestimated k_{src} with reference to the COG k-eigenvalue results in deeper states of subcriticality, but provided more accurate results in the regimes closer to criticality. Additionally, when comparing to the Sjöstrand experimental results, the PDC method overestimated k_{src} across all simulation types. However, the value of this method is that it requires only a single pulse simulation. Table 6 also highlights that dead-time effects were negligible within uncertainties for the α_0 values.

Table 5. k_{src} estimates from the PDC method with the experimental data and the simulated data from multi-pulsing and single pulse.

Assemblies	Experiment	Multi-Pulsing	Single Pulse
2	0.78824 ± 0.00138	0.78604 ± 0.00043	0.78477 ± 0.00047
4	0.85984 ± 0.00049	0.84038 ± 0.00050	0.83991 ± 0.00049
6	0.88146 ± 0.00037	0.85089 ± 0.00039	0.85093 ± 0.00038
9	0.94669 ± 0.00024	0.90882 ± 0.00026	0.90918 ± 0.00026

Table 5 shows the close overlap between the different simulation types, with an average absolute difference between the multi-pulsing model and single pulse simulations of 34 ± 29 pcm. Running a single pulse simulation drastically reduces the required computation time in comparison to the multi-pulsing model simulations, which is powerful if accurate simulations of subcritical systems with k_{src} ranging from ~ 0.9 to just below 1 are desired. The results of Table 7 show that the multi-pulsing model offers no significant advantage over the single pulse model for estimating α_0 , and that COG's method to estimate

α_0 from a k-eigenvalue simulation does not adequately reproduce experimental results for deeply subcritical systems.

Table 6. Fitted prompt neutron decay constants (α_0) for uncorrected, paralyzing corrected, and non-paralyzing corrected experimental data.

Assemblies	Uncorrected (s^{-1})	Paralyzing (s^{-1})	Non-Paralyzing (s^{-1})
2	-4361 ± 44	-4380 ± 47	-4380 ± 47
4	-3555 ± 18	-3569 ± 17	-3569 ± 17
6	-2738 ± 21	-2761 ± 23	-2760 ± 23
9	-1475 ± 19	-1493 ± 18	-1491 ± 18

Table 7. Fitted prompt neutron decay constants (α_0) multi-pulsing, single pulse, and COG criticality (COG) simulation methods.

Assemblies	Multi-Pulsing (s^{-1})	Single Pulse (s^{-1})	COG (s^{-1})
2	-4681 ± 7	-4683 ± 7	$-11,580 \pm 21$
4	-4021 ± 5	-4029 ± 3	-6608 ± 22
6	-3393 ± 3	-3401 ± 5	-4649 ± 24
9	-2080 ± 5	-2103 ± 6	-2302 ± 25

4.4. Discussion

When looking specifically at the Sjöstrand method, the multi-pulsing model simulations underestimated the experimental k_{src} across all ISSA configurations by an average of 7400 pcm. To understand the discrepancies in the die-away curves, three biases in the model were investigated: the neutron generator source modeling, the short pulsing time (80 s), and the short neutron counting window (20 s). Additional contributions to the neutron population from (α, n) reactions in the fuel and the bias from the ENDF/B-VIII.0 cross section library were considered minor.

Figure 10 shows that the simulated die-away curves do not capture the correct generator ramp-up and ramp-down behavior. The simulated data show a sharp drop in the neutron population when the pulse ends that is not present in the experimental die-away curve. Future experimental campaigns could monitor the pulse time profile with a fast neutron detector to include this feature in simulations. In addition, Figure 10 shows that the simulated die-away curve is missing an additional neutron source contribution at later time scales past 2 ms. Currently, it is understood that modeling the neutron source as a beam does not capture the scattering of source neutrons in water, which can then cause fission in the fuel or reach the detectors. This second absent effect biases the die-away curve in comparison to experimental data and deviates from an ideal exponential. This effect would add additional neutrons to the prompt and delayed neutron areas, changing the k_{src} estimates.

To support this hypothesis about the deficiency of the beam source term, Figure 11 displays an additional discrepancy between the simulated and experimental die-away curves. The experimental die-away curve shows a distinctly different slope, or prompt neutron decay constant, and a large delayed-neutron plateau. These discrepancies were initially attributed to differences in the duration of the simulated experiment (80 s) from the experiment, which lasted 15 min. The longer duration of the experiment could explain the larger delayed neutron plateau, thanks to a more significant delayed neutron precursor buildup. Figure 11, however, specifically isolates the experimental data in the 60 to 80-s time window after neutron pulsing began to eliminate this discrepancy, and shows that these differences remain. This points to the detection of neutrons from only the source and not from induced fission as the likely modeling discrepancy between simulation and

experiment. This further confirms that there is a neutron contribution to the die-away curves that is not being considered, which is believed to be from the source approximations.

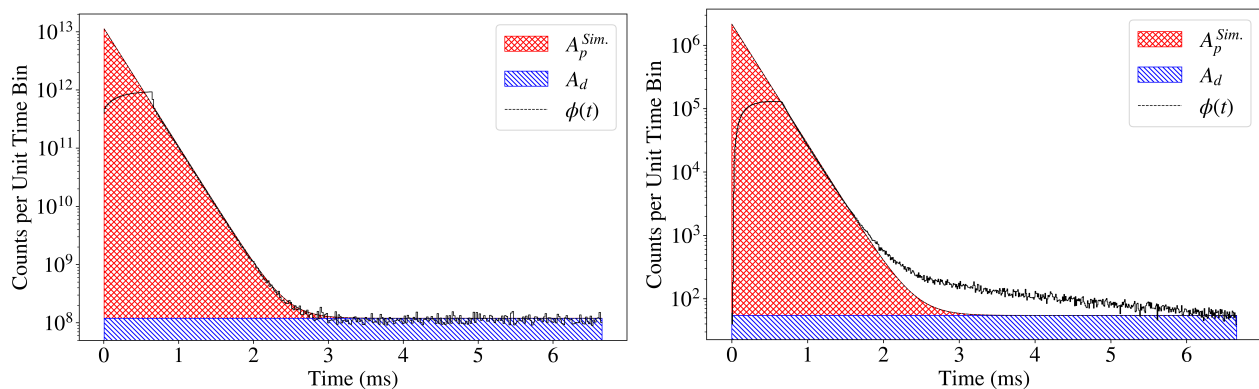


Figure 10. Comparison of simulated (left) and experimental (right) die-away curves with two fuel assemblies.

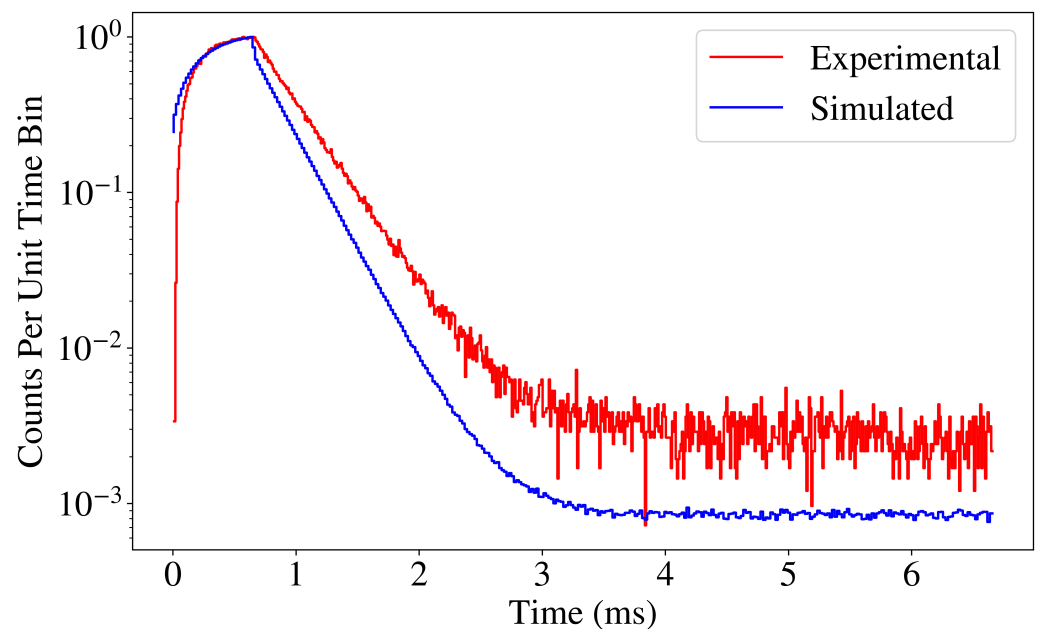


Figure 11. Comparison of normalized 6-assembly experiment die-away to simulation counterpart from 60 to 80 s.

With this evidence, an isotropic source term was investigated in the COG models. Table 8 shows an average underestimation of k_{src} by 27,000 pcm, with a maximum of 50,000 pcm, by the isotropic point source simulations—a decrease in performance relative to the beam source. In theory, this type of simulation is preferred due to the ability to capture the neutrons streaming through the water directly to the detector; however, Figure 12 demonstrates the poor statistics these simulations achieve, even when simulating 10^{12} particles, ten times the amount done for the beam source simulations.

Importantly, the poor statistics manifest the most in the delayed neutron plateau, causing spikes in times bins which contributed excess neutrons to the prompt area, causing the delayed area determination method to over- or under-fit the plateau, resulting in unpredictable k_{src} estimates. COG11.3's lack of dynamic Monte Carlo and delayed neutron variance reduction does not allow for an easy path forward for solving said issue without significant computational resources. Uncertainty quantification practices in experimental reactor physics require dozens to hundreds of perturbation calculations in uncertainty

quantification studies [36], which would be unfeasible with the current approach. This experimental campaign highlighted areas of deficiency for COG11.3 and revealed the need for delayed neutron variance reduction to be added to future versions of the code. Major revisions to the COG codebase are required if further use of it for pulsed neutron validate experiments are desired.

Table 8. k_{src} estimates from isotropic beam simulations using the Sjöstrand and Gozani methods.

Assemblies	Sjöstrand	Gozani
2	0.02915 ± 0.00045	0.03307 ± 0.00059
4	0.39761 ± 0.00281	0.41719 ± 0.00909
6	0.21123 ± 0.00186	0.23361 ± 0.00496
9	0.61738 ± 0.00230	0.65529 ± 0.00482

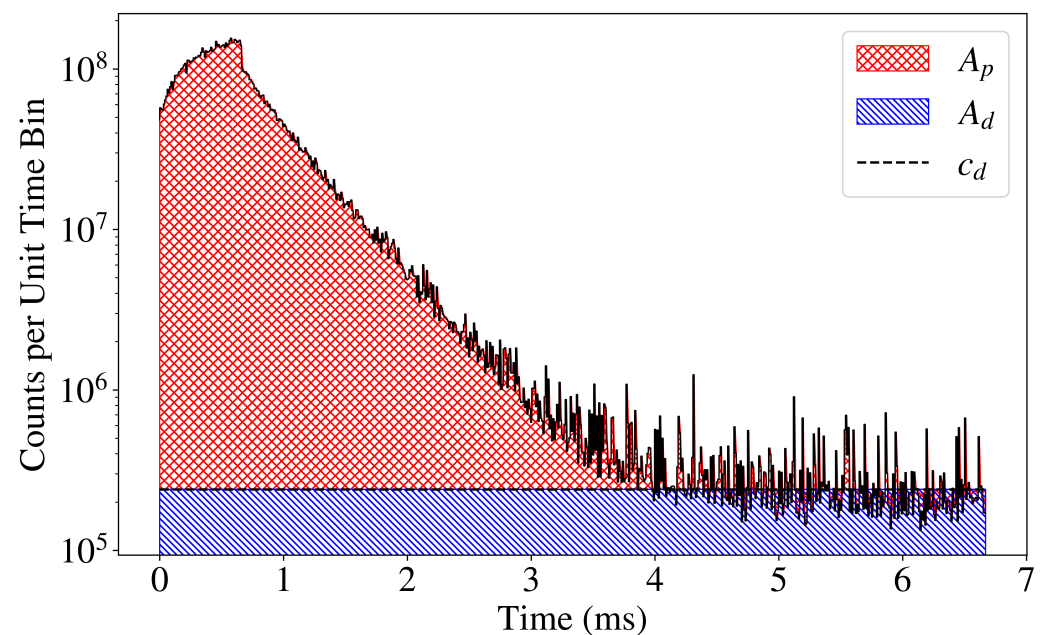


Figure 12. Die-away curve for isotropic point source simulation demonstrating the poor statistics achieved.

Additionally, Table 8 compares the two simulation modes to the experimental die-away curve, and the source term is still biased in the new isotropic simulations. Here, the Sjöstrand isotropic point source simulations underestimate the k_{src} by 30,000 pcm. This demonstrates the necessity to have a well-characterized generator to properly capture the ramp-up and ramp-down time of the neutron generator to model the additional source neutrons after the pulse is over. For this work, a characterization of the DT generator used in the experiments was not possible. Exploration into which factors have the greatest importance in biasing the generator pulse will continue to be explored to understand which approximations are valid in source modeling, but currently it is required to have well a characterized source if high quality simulations are desired.

5. Conclusions

The pulsed neutron technique is a valuable approach to estimate reactivity in sub-critical accelerator-driven systems, for fundamental neutronics experiments, as an in-situ method for emergency response and criticality safety, and during reactor startup. To plan and understand applications of the technique, well-characterized experiments are required. This paper demonstrated the use of simulated pulsed-neutron experiments to estimate

reactivity, and, subsequently, effective multiplication for subcritical systems. Using the Gozani and Sjöstrand area-ratio methods to estimate k_{src} , the results demonstrate the potential viability of using simulated experiments in conjunction with experimental data as alternatives to criticality code for subcritical systems. The Sjöstrand method provided the best results of the tested methods, whereas the Gozani method had poor performance in comparison to this. This result informs future work in the importance of carefully selecting neutron generator operating parameters, but also in the decisions made in purchasing a neutron generator for these types of experiments, mainly a duty factor that is small and a pulse period that is larger. Furthermore, this work demonstrates that certain approximations cannot be made to the source term, and the bias in k -eigenvalue results at deeper levels of subcriticality. However, this work still requires further investigation into experimental variables that were not replicated in the COG simulations if a pulsed neutron validation experiment is to be made, as well as development in dynamic Monte Carlo variance reduction techniques for delayed neutrons that need to be added to the COG code.

Future research into the effects of scattered source neutrons and longer simulation and detection times is required to direct simulations coupled with area-ratio methods to determine k_{src} validation experiments of subcritical systems. Furthermore, if a pulsed neutron validation experiment is to be made, certain criteria must be met, namely, a quantified uncertainty budget. Additionally, using alternative k_{src} estimation methods, like the Garelis-Russel [37] method, are required for a more thorough study of how different system effects change k_{src} , and a comparison with the pulse superimposition method developed by Talamo [22] for methodological validation. Furthermore, an expansion on how to quantify bias of simulated results relative to measurement uncertainty to determine if they are satisfactory for model validation must be conducted.

Alternative to simulation changes, an additional experiment could be used in a pseudo-background subtraction. Here, the experiment is reproduced with dummy assemblies containing no fissile material to produce a water-only die-away curve, which can then be subtracted from the die-away curve with fuel. Finally, the experimental design could be modified, potentially by further collimating the neutron source to prevent source neutrons from diffusing to the target, or by adding an absorber material.

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