

Efficiency Assessment of Implicit Capture in Time-Dependent Monte Carlo Neutron Transport Calculations

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1. Introduction

Transient analysis of a nuclear reactor is important for safety calculations. However, applying Monte Carlo (MC) neutron transport simulations to this analysis has long been challenging. With advances in computing power and the development of reliable methodologies, the Monte Carlo field has been actively investigating time-dependent Monte Carlo (TDMC) neutron transport calculations [1]. Although the physical simulation of neutron transport in TDMC is essentially identical to that of conventional Monte Carlo methods, the effectiveness of variance reduction techniques has not been thoroughly investigated for time-dependent calculations. In this study, we assess the computational efficiency of steady-state TDMC [2], a preparatory step used to obtain initial conditions for transient scenarios, when implicit capture and Russian roulette are applied. We define a suite of cases by varying the time step size and the weight cutoff. For each case, we quantify the statistical uncertainty and computational cost, and we evaluate the computational efficiency using the figure of merit (FOM). We then analyze how the resulting TDMC FOM trends differ from those in conventional eigenvalue calculations.

2. Methods

2.1. Steady-state TDMC algorithm

In TDMC, fission is sampled during the reaction-type sampling process [2], allowing fission neutrons to be generated and transported within the same time step. At the end of each time step, a combing technique [3] can be applied so that the next step begins with a controlled neutron population while maintaining consistency in the total weight. In this study, we employed this combing technique at the time boundaries. Furthermore, newly born fission neutrons explicitly inherit the weight of their parent neutron to preserve the expected fission production

For steady-state TDMC, Shaukat [2] suggested using a fictitious fission multiplicity, ν_f/k , instead of ν_f for the fission neutron generation logic, where ν_f is the average number of fission neutrons produced per fission reaction and k is the fundamental-mode eigenvalue. Under this configuration, histories starting from each time step include within-step fission neutrons, are truncated at time step boundaries, and yield steady-state tallies on the fission neutron basis.

2.2. Implicit capture and Russian roulette settings

In this study, implicit capture and Russian roulette were used as variance reduction techniques, and the case without implicit capture was defined as the analog method. For Russian roulette, we set a lower weight cutoff, W_L . When a neutron enters Russian roulette and survives, its weight is restored to a prescribed value, W_A . Following the FLUKA setup [4], we set $W_A = W_L$, and W_L was varied from 0.0 to 1.0 to examine the variance reduction effect over a wide range of neutron weights.

For comparison, additional calculations were also performed with $W_A = 2W_L$ under the same TDMC calculation conditions but with a different Russian roulette setup. The resulting FOM trends and peak values were similar to those for $W_A = W_L$, indicating that the main observations of this study are not strongly sensitive to this choice. However, when $W_A = 2W_L$ is used, W_L must be limited to the range from 0.0 to 0.5 in order to keep the survival weight W_A below 1.0. This reduces the range over which the overall trend can be examined. For this reason, $W_A = W_L$ was adopted as the default setting in this study.

2.3. Flux tally and performance metric

To compare computational efficiency across test cases, we estimate the cell flux using a track-length estimator under steady-state TDMC conditions. As a performance metric, we use the figure of merit (FOM), which accounts for both the statistical uncertainty of the tally and the computational cost. Following the definition used in MCNP [5], the FOM is defined as

$$\text{FOM} = \frac{1}{R^2 T}, \quad (1)$$

where R is the estimated relative error of the tally of interest, and T is the computing time, measured only as the time spent on neutron transport physics, including neutron flights and collisions.

3. Numerical results

3.1. 0D2G problem

For the 0D2G test problem, calculations are performed using an in-house code. The multi-group cross sections

are obtained by modifying the C5G7 dataset [6,7]. All 0D2G cases are run with the same number of histories and the same number of active time steps to ensure a consistent comparison. The time step size, Δt , is swept over 0.001, 0.01, 0.05, 0.1, and 1.0 ms. For each time step, the weight cutoff W_L is varied from 1.0 down to 0.1 in steps of 0.1, and additional cases are evaluated at $W_L = 0.05, 0.01, 0.005, \text{ and } 0.001$. For each setting, we evaluate the average weight per collision, \bar{W} , and the figure of merit (FOM). The results are compared between the analog case and the cases using implicit capture with Russian roulette.

3.1.1. Effect of implicit capture in an eigenvalue calculation

Implicit capture is expected to reduce tally variance [3]. At the same time, it tends to increase calculation time because more neutrons survive and continue to undergo flights and collisions. When the Russian roulette weight cutoff, W_L , is varied, these competing effects can produce an optimum FOM at an intermediate W_L .

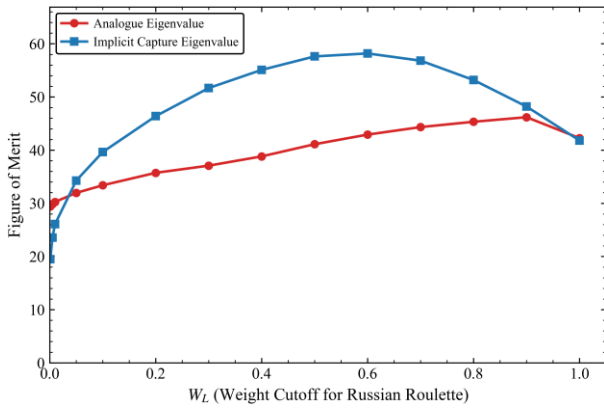


Fig. 1. Track-length flux figure of merit (FOM) with respect to the Russian roulette weight cutoff, W_L , for eigenvalue calculations of the 0D2G problem

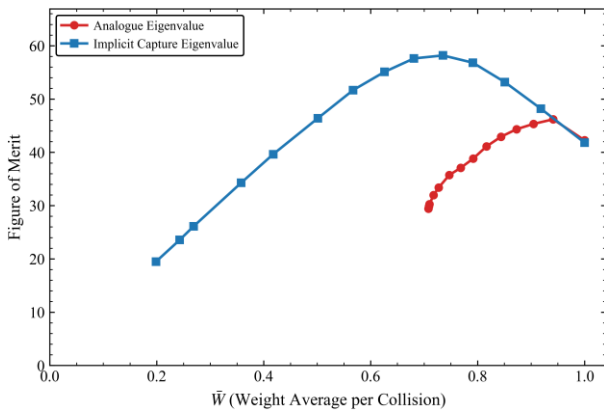


Fig. 2. Track-length flux figure of merit (FOM) with respect to the average weight per collision, \bar{W} , for eigenvalue calculations of the 0D2G problem

Fig. 1 illustrates the FOM as a function of W_L , while Fig. 2 presents the FOM as a function of \bar{W} , which

changes with variations in W_L . In the eigenvalue calculation, the FOM demonstrates an optimal result at a specific W_L point. Furthermore, in the 0D2G problem, employing implicit capture for the eigenvalue calculation improved performance compared to the analog method in most cases, except when W_L became extremely small.

3.1.2. Effect of implicit capture in TDMC calculations

In analog TDMC, no reactions are treated implicitly, so neutron weights do not decrease at collisions. Under this condition, the average weight per collision, \bar{W} , remains 1.0. Therefore, the performance does not change with W_L in analog TDMC.

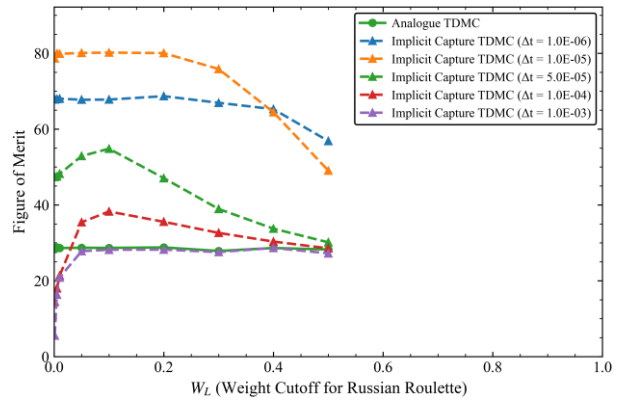


Fig. 3. Comparison of track-length flux figure of merit (FOM) across various time steps with respect to the Russian roulette weight cutoff, W_L , for steady-state TDMC calculations of the 0D2G problem with $W_A = 2W_L$.

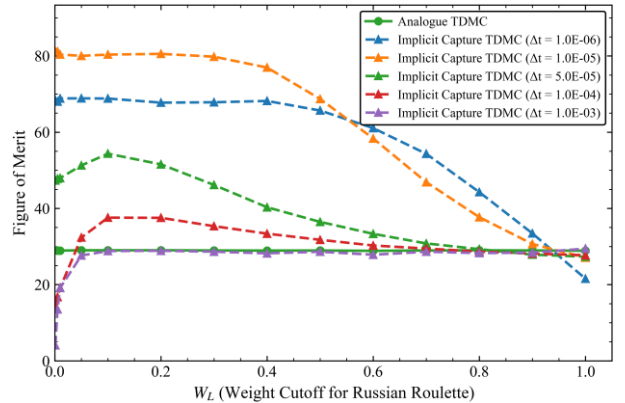


Fig. 4. Comparison of track-length flux figure of merit (FOM) across various time steps with respect to the Russian roulette weight cutoff, W_L , for steady-state TDMC calculations of the 0D2G problem with $W_A = W_L$.

For comparison, Fig. 3 shows the FOM curves obtained with $W_A = 2W_L$. The overall trend and the peak FOM values are similar to those obtained with $W_A = W_L$, although the available range of W_L is limited to the range from 0.0 to 0.5 in order to keep W_A below 1.0, which also narrows the corresponding range of \bar{W} . Fig. 4 and 5 therefore present the results for $W_A = W_L$, which allows the FOM behavior to be examined over the full range

from 0.0 to 1.0. Fig. 4 illustrates the FOM as a function of W_L , while Fig. 5 presents the FOM as a function of \bar{W} . As the time step becomes longer, neutrons undergo more collisions within a step, and their weights can decrease to the Russian roulette cutoff. The range of \bar{W} then expands from 1.0 to lower values. At the same time, the peak FOM decreases, and the FOM curve becomes flatter.

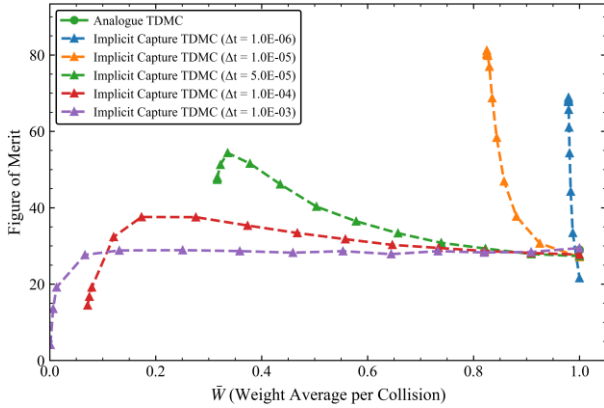


Fig. 5. Comparison of track-length flux figure of merit (FOM) across various time steps with respect to the average weight per collision, \bar{W} , for steady-state TDMC calculations of the 0D2G problem with $W_A = W_L$.

If the time step is long enough, the FOM curve flattens and approaches the level of analog TDMC. In a long time step, neutrons undergo enough collisions for their weights to decrease to the cutoff level W_L . Fission neutrons inherit their parent neutron's weight, so once many neutrons reach W_L , newly born fission neutrons also start near W_L . As a result, most collisions occur with neutron weights close to W_L , and neutrons can enter Russian roulette almost immediately after a collision.

In this regime, the transport behaves almost like an analog simulation, dominated by the tracking of many neutrons with low weights. The reduction in variance is then offset by the increase in calculation time from longer tracking and a higher number of surviving neutrons, and the overall FOM approaches the analog TDMC level.

In the very short time step regime, the FOM decreases again. When the time step becomes shorter than the mean collision time of the slow group, many histories are truncated at the time boundary before a collision and contribute only a short flight length. Because at least one track segment must still be processed for each history, the computational cost does not decrease in proportion to the loss of statistical efficiency. In the 0D2G problem, this effect starts to appear when the time step becomes shorter than the mean collision time of group 2, about 0.0012 ms.

3.2. KUCA-C core problem

KUCA [8] stands for the Kyoto University Critical Assembly. In this study, we analyze the C35G0-4 core,

which is a light-water-moderated and light-water-reflected configuration fueled with highly enriched uranium. To examine whether the same behavior appears in a more practical continuous-energy core problem, the KUCA-C cases are computed using the McCARD [9] code. The KUCA-C cases use the same variance reduction settings and comparison procedure as the 0D2G cases, and only the TDMC results are reported here.

3.2.1. Effect of implicit capture in TDMC calculations

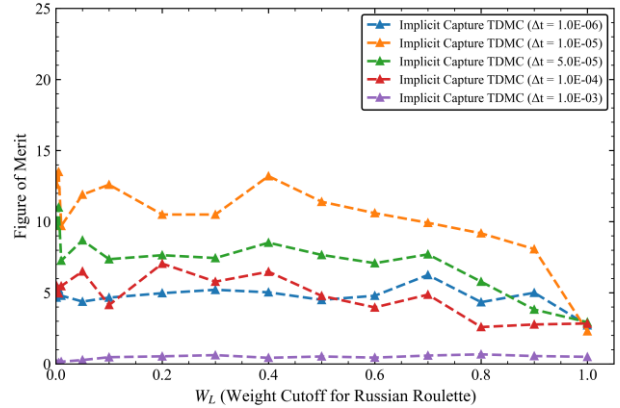


Fig. 6. Comparison of track-length flux figure of merit (FOM) across various time steps with respect to the Russian roulette weight cutoff, W_L , for steady-state TDMC calculations of the KUCA-C core problem

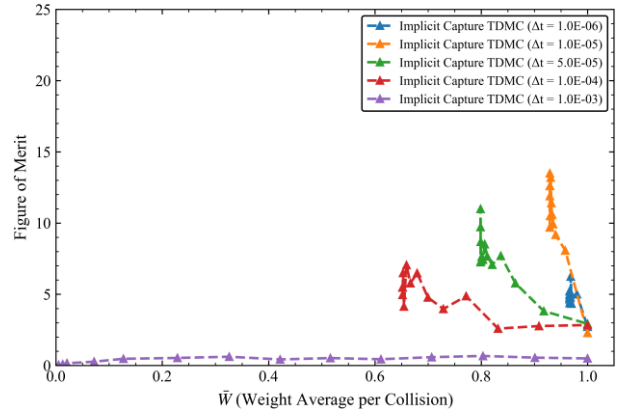


Fig. 7. Comparison of track-length flux figure of merit (FOM) across various time steps with respect to the average weight per collision, \bar{W} , for steady-state TDMC calculations of the KUCA-C core problem

Fig. 6 illustrates the FOM as a function of W_L , while Fig. 7 presents the FOM as a function of \bar{W} . The track-length flux results show the same overall trends as those observed in the 0D2G problem, indicating that the same behavior also appears in the continuous-energy KUCA-C core problem. As W_L varies, the distribution of \bar{W} becomes wider, and the optimum FOM decreases. For the longest time step of 1.0 ms, the FOM becomes nearly constant. The shortest time step case also exhibited lower FOM than the next larger time step case, consistent with the short time step trend observed in the 0D2G problem.

4. Conclusions

This work examined how implicit capture affects computational efficiency in TDMC calculations. We used a steady-state TDMC method with implicit capture and Russian roulette as variance reduction techniques. Performance was evaluated using a track-length flux tally and the figure of merit (FOM) for a 0D2G test problem solved with an in-house code, and for the KUCA-C core problem solved with McCARD.

The numerical results demonstrated that the FOM trends, including the height and location of the peak, depended significantly on the time step size. As the time step increased, the optimum FOM decreased and the overall FOM curve became flatter. When the time step was sufficiently long, the computational efficiency ultimately converged to the performance level of the analog method. Conversely, when the time step was short, neutrons underwent fewer collisions within a single step, resulting in a narrowly distributed average weight per collision, \bar{W} . Furthermore, if the time step was excessively short, the extreme lack of collisions further degraded the computational efficiency. These same performance trends were also observed in the practical KUCA-C core problem. Ultimately, these findings indicate that the FOM trends in steady-state TDMC differ from those in conventional eigenvalue calculations.

These results also suggest that the effectiveness of implicit capture in TDMC becomes limited when the time step is excessively long, and that the optimum Russian roulette weight cutoff depends on the time step size. Therefore, these two parameters should be considered together. As detailed in our methodology, these results are specific to the treatment where fission neutrons inherit their parent's weight. Consequently, adopting alternative treatments, such as the biasing-fission approach proposed by Sjenitzer and Hoogenboom [10] for fixed-source calculations, could lead to distinct performance trends since it assigns weights differently to newly born fission neutrons.

REFERENCES

- [1] S. H. Jang and H. J. Shim, Advances for the time-dependent Monte Carlo neutron transport analysis in McCARD, Nuclear Engineering and Technology, Vol. 55, pp. 2712-2722, 2023.
- [2] N. Shaukat, M. Ryu, and H. J. Shim, Dynamic Monte Carlo transient analysis for the Organization for Economic Co-operation and Development Nuclear Energy Agency (OECD/NEA) C5G7-TD benchmark, Nuclear Engineering and Technology, Vol. 49, pp. 920-927, 2017.
- [3] T. E. Booth, A Weight (Charge) Conserving Importance-Weighted Comb for Monte Carlo, Report LA-UR-96-0051, Los Alamos National Laboratory, 1996.
- [4] A. Ferrari, P. R. Sala, A. Fassò, and J. Ranft, FLUKA: a multi-particle transport code (Program version 2005), CERN-2005-010, INFN TC 05/11, SLAC-R-773, CERN, Geneva, 2005.
- [5] C. J. Werner (Ed.), J. Armstrong, F. B. Brown, J. S. Bull et al., MCNP® Code Version 6.3.0 Theory & User Manual, Report LA-UR-22-30006, Rev. 1, Los Alamos National Laboratory, 2022.
- [6] E. E. Lewis, M. A. Smith, N. Tsoulfanidis, G. Palmiotti, T. A. Taiwo, and R. N. Blomquist, Benchmark Specification for Deterministic 2-D/3-D MOX Fuel Assembly Transport Calculations without Spatial Homogenisation (C5G7 MOX), Report NEA/NSC/DOC(2001)4, OECD Nuclear Energy Agency (NEA), 2001.
- [7] J. Hou, K. N. Ivanov, V. F. Boyarinov, and P. A. Fomichenko, OECD/NEA benchmark for time-dependent neutron transport calculations without spatial homogenization, Nuclear Engineering and Design, Vol. 317, pp. 177-189, 2017.
- [8] C. H. Pyeon, G. Chiba, T. Endo, and K. Watanabe, Reactor Laboratory Experiments at Kyoto University Critical Assembly, Springer Nature Singapore, Singapore, 2025.
- [9] H. J. Shim, B. S. Han, J. S. Jung, H. J. Park, and C. H. Kim, McCARD: Monte Carlo Code for Advanced Reactor Design and Analysis, Nuclear Engineering and Technology, Vol. 44, No. 2, pp. 161-176, 2012.
- [10] B. L. Sjenitzer and J. E. Hoogenboom, Variance reduction for fixed-source Monte Carlo calculations in multiplying systems by improving chain-length statistics, Annals of Nuclear Energy, Vol. 38, pp. 2195-2203, 2011.