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A Study on the Optimal Use of Ramp-up Technique Under Massive Particle Condition with CMFD Acceleration

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1. Introduction

PRAGMA is a GPU-based continuous energy Monte Carlo (MC) code dedicated for power reactor analyses [1]. PRAGMA is capable of carrying out whole-core MC simulations with considerable quantity of particles – at least over 10^8 per cycle – in a reasonable time scale on a small cluster equipped with consumer-grade GPUs.

At this rate of particles, the number of active cycles needed to obtain statistically acceptable solutions drops to dozens. However, the number of inactive cycles only depends on the dominance ratio of the problem. As the result, the number of required inactive cycles still stays at around 20 for typical power reactors, even when the CMFD acceleration is used [2]. It causes drastic increase in the computing time portion of the inactive cycles.

Therefore, additional time-wise acceleration method other than the CMFD acceleration should be introduced to reduce the cost of inactive cycles in massive particle simulations. One of the typical acceleration scheme is the ramp-up scheme, which has been already introduced in several literatures [3, 4, 5, 6]. It gradually increases the number of particles in the inactive cycles such that the amount of histories wasted to reach the converged source distribution is minimized.

Paring CMFD acceleration and ramp-up scheme has not been considered before, as the CMFD acceleration requires sufficient amount of tallies to be stable, while the ramp-up scheme minimizes the number of particles in the inactive cycles. However, as PRAGMA targets to deploy hundreds of millions of particles per cycle, still sufficient amount of histories to keep the CMFD stable is guaranteed with ramp-up.

Thus, in this paper, we will examine various ramp-up schemes, perform sensitivity tests, and find the optimal scheme under the massive particle condition paired with CMFD acceleration. By employing the optimal scheme, we will demonstrate a full-core simulation with massive number of particles achieving feasibility on a practical GPU cluster.

2. Statistical Impacts of Ramp-up Schemes

2.1. Ramp-up Schemes

The fundamental principle to increase the number of particles is identical for all ramp-up schemes. First of all, the ramp-up factor, which is the ratio between the initial and the target population, should be determined. At each cycle, weights of the neutrons are adjusted appropriately to a value larger than unity such that the population is naturally increased by artificially upraised fission yields. What distinguishes the ramp-up schemes is the ramp-up mode; namely, in which trend the population is increased. **Figure 1** shows the change of the number of particles in each cycle of several ramp-up modes.

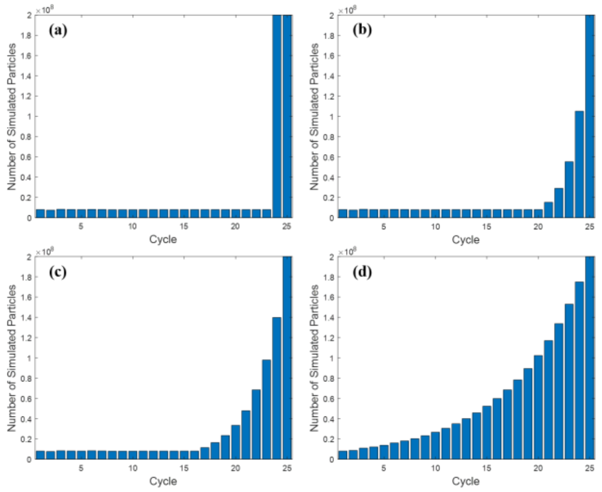

Figure 1. Ramp-up modes: (a) step, (b) step-exponential (4 steps), (c) step-exponential (8 steps), and (d) full exponential.

2.2. Apparent Variance Analysis

A sensitivity test on the ramp-up schemes is performed for an APR1400 full-3D initial core problem [7] at HFP condition. The detailed specification of the computing cluster that will be used is presented in **Table 1**.

Table 1. Computing cluster specification.

# of Nodes	3
CPU / Node	2 × Intel Xeon E5-2630 v4
GPU / Node	4 × NVIDIA GeForce RTX 2080 Ti
RAM / Node	8 × 16GB DDR4 RAM
Interconnect	Mellanox Infiniband (56Gbps)

Calculation conditions are shown in **Table 2**. All the conditions except the ramp-up scheme itself are identical. STEP denotes the step ramp-up scheme, and EXP is the full exponential ramp-up scheme. S-E(4) and S-E(8) are the step-exponential hybrid ramp-up schemes that differ by the number of exponential increase steps indicated in the parentheses. STANDARD is the reference case that only employs CMFD acceleration without ramp-up. For each case, the total number of histories that are simulated is presented. Note that the S-E(4) scheme has the largest reduction; it reduces the number of inactive histories by about 90% compared to the STANDARD case. Even the EXP scheme which is the most expensive one among the ramp-up schemes provides about 70% reduction.

Table 2. Calculation conditions.

Case Name	STEP	S-E(4)	S-E(8)	EXP	STANDARD
# of Particles per Cycle	200,000,000				
# of Inactive Cycles	25				
# of Active Cycles	50				
# of Inactive Histories	5.84E8	5.15E8	7.16E8	1.54E9	5.00E9
CMFD	On (Assembly-wise)				
Ramp-up	On (Factor of 25)				Off

Figure 2 illustrates the Shannon entropy behavior as a function of the cumulative number of simulated histories for above cases. The vertical dash-line indicates the end of the inactive cycle for each case. It is noticed that the Shannon entropy converges normally in all cases, and no significant difference is observed after the convergence; all the schemes show very steady Shannon entropy trend.

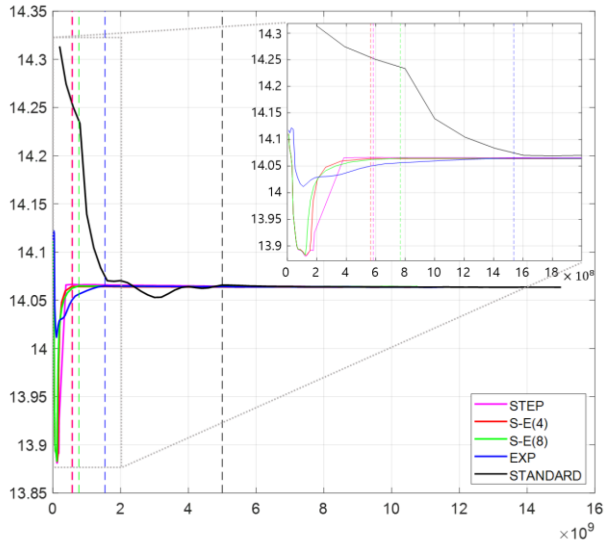

Figure 2. Shannon entropy behavior.

Table 3 compares the apparent standard deviations of pin and unit cell (axial sub-volume in a pin) power tallies of different ramp-up schemes, and **Figure 3** illustrates the distributions of pin power and its apparent standard deviation of each case. The RMS value of the apparent standard deviation is calculated as follows:

$$\sigma_{A,RMS} = \sqrt{\sum_{i}^{N_{Act}} \left(\sigma_{A,i}^2 \times V_i \right) \Big/ V_{Act}} \qquad (1)$$

$\sigma_{A,i}$: Apparent standard deviation of the *i*-th node

$V_{Act} = \sum_{i}^{N_{Act}} V_i$: Active fuel volume

V_i : Volume of the *i*-th node

N_{Act} : The number of active fuel node

Table 3. Comparison of results from single run.

Case Name	k_{eff}	RMS / Max Power σ	
		Pin	Cell
STEP	1.00017 (0.8)	0.16% 0.47%	0.84 % 9.19 %
S-E(4)	1.00016 (0.7)	0.16% 0.41%	0.83 % 9.21 %
S-E(8)	1.00019 (0.6)	0.16% 0.42%	0.83% 9.26%
EXP	1.00016 (0.6)	0.16% 0.42%	0.83% 9.32%
STANDARD	1.00015 (1.1)	0.16% 0.42%	0.84% 9.63%

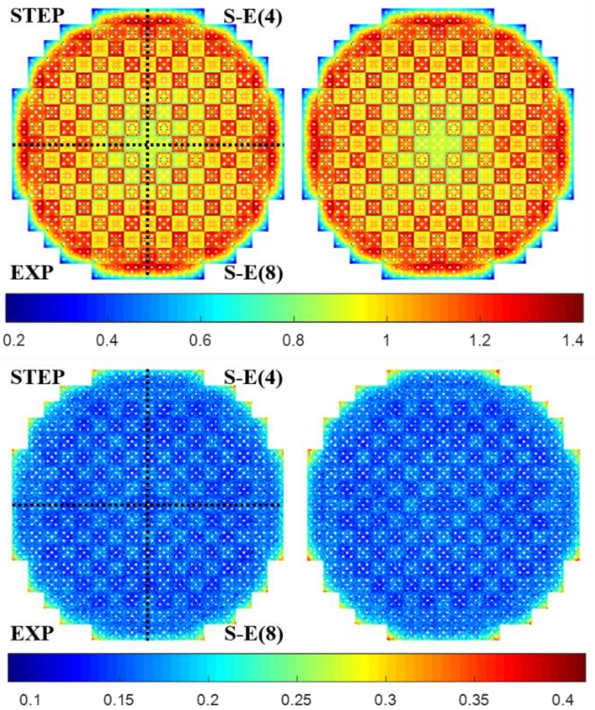

Figure 3. Pin power and apparent standard deviation (%) distributions.

All the ramp-up schemes show comparable results for the apparent standard deviations with the STANDARD case. As far as the single run results are concerned, S-E(4) should be the optimal choice whose computational cost reduction is the largest. But it is not the case in reality.

Throughout all the results, it can be observed that the statistical impact of the ramp-up schemes cannot be seen by merely investigating the single run results. Shannon entropy is a collective quantity and cannot capture the local rebalance of the source distributions, and apparent standard deviations are well-known to be biased by the inter-cycle correlation of the fission source distributions [8]. Thus, it is necessary to examine the real variances.

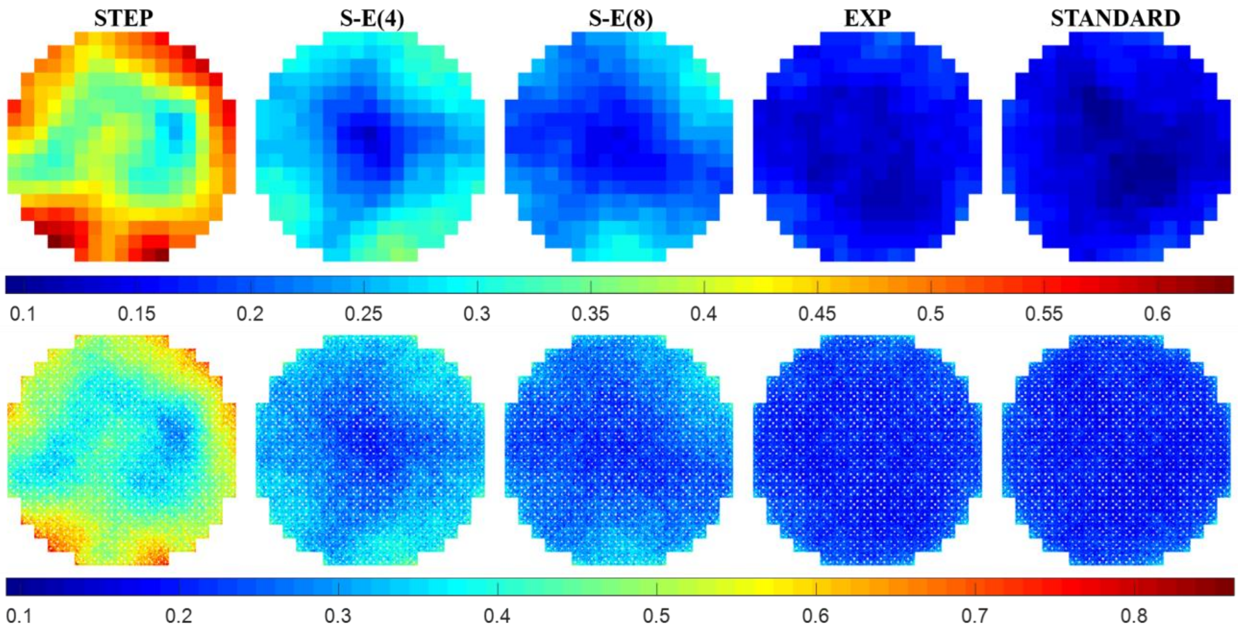

Figure 4. Assembly and pin power real standard deviation (%) distributions.

2.3. Real Variance Analysis

The real variances of the fission power were obtained from 20 independent runs for each case, whose results are presented in **Table 4**. The distributions of assembly and pin power real standard deviations are also illustrated in **Figure 4**. The calculation conditions are the same with those used in the single run analyses. The RMS value of the real standard deviation is calculated as follows:

$$\sigma_{\mathrm{R},RMS} = \sqrt{\sum_{i}^{N_{Act}} \left(\sigma_{\mathrm{R},i}^{2} \times V_i \right) \Big/ V_{Act}} \qquad (2)$$

where $\sigma_{R,i}$ is the real standard deviation of the *i*-th node, defined as:

$$\sigma_{R,i} = \sqrt{\frac{1}{N_S - 1} \sum_{j}^{N_S} \left(p_{ij} - P_i \right)^2} \qquad (3)$$

$P_i = \frac{1}{N_S} \sum_{j}^{N_S} p_{ij}$: Sample-average power of the *i*-th node

p_{ij} : Power of the *i*-th node and the *j*-th sample

N_S : The number of samples

The statistical impact of ramp-up to the active cycles, which was not observed in single run results, is revealed by the differences in the real standard deviations. In case of STEP, the RMS of real standard deviation of assembly and pin power appeared to be about 3.9 and 2.3 times larger than that of the STANDARD case, respectively. On the other hand, EXP showed comparable statistical results with the STANDARD case. The hybrid schemes showed intermediate behavior of STEP and EXP; more exponential steps resulted in less real standard deviations.

Table 4. Comparison of results from 20 independent runs.

Case Name	k_{eff} σ	RMS / Max Power σ	
		Assembly	Pin
STEP	1.13E-5	0.43% 0.63%	0.46% 0.86%
S-E(4)	6.57E-6	0.24% 0.35%	0.30% 0.61%
S-E(8)	7.99E-6	0.20% 0.30%	0.26% 0.57%
EXP	5.94E-6	0.12% 0.19%	0.20% 0.49%
STANDARD	5.62E-6	0.11% 0.17%	0.20% 0.47%

Comparison of results obtained from STEP and S-E(4) shows the importance of a proper choice of the ramp-up mode. As indicated in **Table 2**, S-E(4) has the smallest number of histories and thereby the largest reduction of computational cost, followed by STEP. However, S-E(4) has four steps of progressive population increase while STEP promptly creates all the neutrons. Such difference causes a substantial gap in the achieved uncertainty levels. That is, it is important to reserve cycles to 'disperse' the neutrons that are additionally produced by ramp-up, as they have highly correlated distributions due to localized fission neutron productions by increased weights.

3. Comprehensive Analysis Based on Figure of Merit

The combined effect of reduced computing time and increased uncertainty should be evaluated adequately to determine the optimal ramp-up scheme. Therefore, the Figure of Merit (FOM) was used to obtain a quantitative measure of the combined effect. The definition of FOM used in this study is as follows:

$$FOM = \frac{1}{\sigma_{RMS}^2 \times T} \quad (4)$$

σ_{RMS} : RMS of the real standard deviation of pin power
T : Computing time (min)

Table 5 compares the FOM of the ramp-up schemes. It can be noticed that the aspect of FOM is different from that of computing time. For example, STEP shows about 30% reduction in the total computing time compared to the STANDARD case. If only inactive cycle computing time is considered, the reduction ratio reaches over 80%. Despite its small computing time, however, the FOM of STEP is only 0.26 times of that of STANDARD due to the significantly larger uncertainty. In contrast, the FOM of EXP is 1.23 times of that of STANDARD even for its highest computing time among the ramp-up cases, as it retains a comparable uncertainty with STANDARD.

As the result, the optimal ramp-up scheme for this case turned out to be the full exponential scheme. All the other ramp-up schemes presented the FOM ratio of less than unity. Even though all the ramp-up schemes reduced the computing time substantially, the increased uncertainties as the side effect diminished their advantages.

Table 5. Comparison of performance with FOM.

Case	Time (Inactive)	σ_{RMS}^2	FOM	FOM Ratio
STEP	23m 57s (2m 22s)	2.15E-5	1940	0.26
S-E(4)	23m 53s (2m 20s)	8.70E-6	4813	0.65
S-E(8)	24m 34s (3m 22s)	6.59E-6	6176	0.83
EXP	26m 14s (4m 43s)	4.17E-6	9144	1.23
STANDARD	34m 32s (13m 1s)	3.89E-6	7452	1

4. Conclusion and Future Work

Use of ramp-up acceleration scheme paired with the CMFD acceleration under massive particle condition was investigated and an optimal ramp-up scheme was chosen based on a sensitivity study performed with the APR1400 full-3D initial core HFP problem. Use of massive number of particles necessitated an additional time-wise fission source convergence acceleration scheme other than the CMFD acceleration, for which the ramp-up scheme was introduced. Paring CMFD acceleration and ramp-up may lead to numerical instabilities since the CMFD iteration becomes unstable when there are insufficient amount of tallies. However, with PRAGMA's target population for typical power reactor calculations which reach hundreds of millions, still sufficient number of histories is ensured with ramp-up and the problem is readily resolved.

Under the CMFD acceleration which drags down the number of inactive cycles, the ramp-up scheme should reach the target population in limited number of cycles, which causes rather drastic population change. Therefore, amplification and propagation of statistical uncertainties to the active cycles were the major concerns. However, the results reveal that the ramp-up scheme still performs well with limited number of cycles if a proper ramp-up mode is employed. A full exponential ramp-up scheme which appeared to be the optimal for the presented case yielded comparable statistical results with the reference case without ramp-up while reducing 70% of the inactive cycle computing time.

However, this work did not consider many parameters that affect the performance of the ramp-up acceleration scheme. There are several factors including the number of inactive and active cycles, ramp-up factor, the number of histories per cycle, and etc. All the parameters were fixed and only the differences of the ramp-up modes were taken into account in the sensitivity study. Therefore, the full exponential ramp-up scheme that was optimal under the presented problem and conditions may not appear to be optimal when different problems and conditions are used. Thus, an extensive analysis on the ramp-up scheme paired with CMFD acceleration should be performed for a variety of problems and conditions.

ACKNOWLEDGMENTS

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REFERENCES

[1] N. Choi, K. M. Kim, H. G. Joo, "Initial Development of PRAGMA – A GPU-Based Continuous Energy Monte Carlo Code for Practical Applications" Transaction of the Korean Nuclear Society Autumn Meeting, Goyang, Korea, October 24-25 (2019).

[2] M. J. Lee, H. G. Joo, D. Lee, K. Smith, "Coarse Mesh Finite Difference Formulation for Accelerated Monte Carlo Eigenvalue Calculation," Annals of Nuclear Energy 65, pp. 101-113 (2014).

[3] R. C. Gast and N. R. Candelore, "Monte Carlo Eigenfunction Strategies and Uncertainties," Proceedings of the NEACRP Meeting of a Monte Carlo Study Group, ANL-75-2, Argonne, Illinois, July 1-3 (1974).

[4] X-5 Monte Carlo Team, "MCNP – A General Monte Carlo N-Particle Transport Code, Version 5, Volume I: Overview and Theory," Tech. Rep, LA-UR-03-1987, Los Alamos National Laboratory (2008).

[5] J. Dufek and K. Tuttelberg, "Monte Carlo Criticality Calculations Accelerated by a Growing Neutron Population," Annals of Nuclear Energy, 94, 16-21 (2016).

[6] A. Lund, P. Romano, A. Siegel, "Accelerating Source Convergence in Monte Carlo Criticality Calculations Using a Particle Ramp-up Technique," M&C 2017, Jeju, Korea, April 16-20 (2017).

[7] H. Hong and H. G. Joo, "Analysis of the APR1400 PWR Initial Core with the nTRACER Direct Whole Core Calculation Code and the McCARD Monte Carlo Code," Transactions of the Korean Nuclear Society Spring Meeting, Jeju, Korea, May 18-19 (2017).

[8] E. M. Gelbard and A. G. Gu, "Biases in Monte Carlo Eigenvalue Calculations," Nucl. Sci. Eng., 177, 1 (1994).