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Development Status of MCS Monte Carlo Dynamics Code for Reactor Transient Analysis

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1. Introduction

Driven by the growing demand for reactor transient analysis and the availability of advanced modern computing resources, several widely utilized Monte Carlo-based nuclear reactor analysis codes are undergoing enhancements to effectively address time-dependent challenges. Leveraging the accomplishments of the predictor-corrector quasi-static (PCQS) technique in the realm of reactor dynamics [1], codes like McBOX [2], RMC [3], and others have integrated this approach to precisely address time-dependent neutron transport problems, regardless of the time step size. Concurrently, a notable breakthrough in direct particle simulation, pioneered by Sjenitzer and Hoogenboom [4], has led to an alternative methodology termed time dependent Monte Carlo (TDMC). Although computationally intensive, this method has been successfully implemented in major codes such as TRIPOLI-4 [5], SERPENT [6], RMC [7], McCARD [8], and iMC [9], underlining its effectiveness.

Recently, the MCS Monte Carlo code developed by UNIST has also conducted reactor transient calculations using the TDMC methodology. A brief overview of the comparison between these results and the 3D MOC reactor transient results from STREAM3D is intended to be presented in this paper. Through the utilization of MCS, the well-known C5G7-TD problem [10] and brief VERA 3D reactor core transient scenario were addressed, and the results are thoroughly discussed with a focus on computational time.

2. Time-Dependent Monte Carlo (TDMC) Method

The TDMC scheme for time-dependent Monte Carlo reactor transient simulations has been comprehensively elucidated in Sjenitzer's previous study [4]. In this section, we enumerate several crucial features of the TDMC method that are imperative for achieving stable and dependable results. The core principle of TDMC involves the direct simulation of particles in the time domain, accounting for their flight time. The flight time of a particle is determined by dividing the sampled distance by the particle's velocity. Once the cumulative flight time surpasses the time-step boundary, the particle is retained for the subsequent time-step. To mitigate variance stemming from particle generation branching during simulation, TDMC employs the branchless technique, which adjusts particle weights rather than initiating a new branch at a fission event.

A pivotal facet of the TDMC approach is the concept of forced decay, which aims to reduce variance resulting from precursor uncertainty. In the forced decay strategy, each active precursor emits a neutron in every time step, in contrast to reality where a precursor only produces a neutron once. The weight of the neutron emitted from forced decay is modified to avert biased outcomes. Simultaneously, the precursor weight is also adapted post each time step. To regulate the population of particles to be simulated, the combing technique is implemented. This technique maintains the overall weight of the particle bank while resampling a limited quantity of particles based on their respective weights. The combing technique can be employed for both time sources and precursors, ensuring reasonable computational time irrespective of external reactivity insertions.

Fig 1 depicts the overall flowchart of the MCS TDMC application. In the results of this simulation, the variance at each time step was computed by dividing the history at that time step into batch size and calculating the batch mean and standard deviation. The variance of the results is presented as a 2-sigma interval.

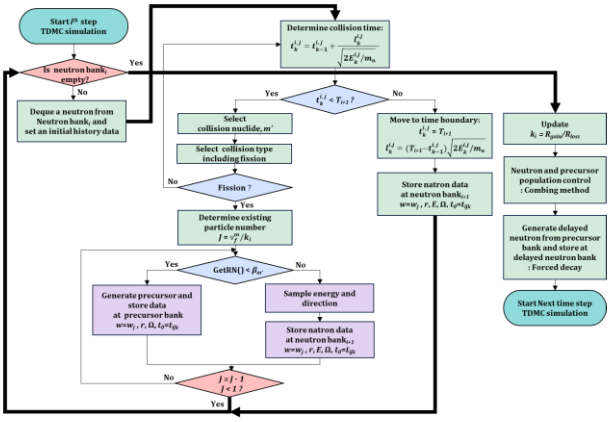


Fig. 1. Flow chart of the MCS TDMC simulation

3. Numerical Results

The MCS was employed to solve a two-dimensional C5G7-TD benchmark problem, with a subsequent comparison of the obtained results against those proposed in the benchmark specification document. Fig 2 illustrates that benchmark core geometry. The computational outcomes, compared with the reference solution as shown in Fig 3 and Fig 4.

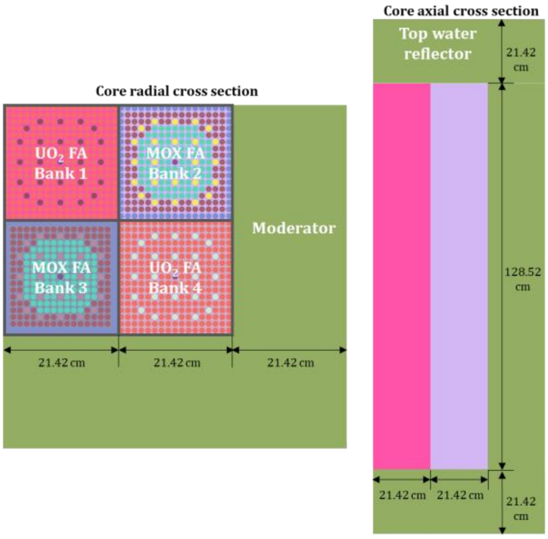


Fig. 2. C5G7-TD problem radial and axial geometry

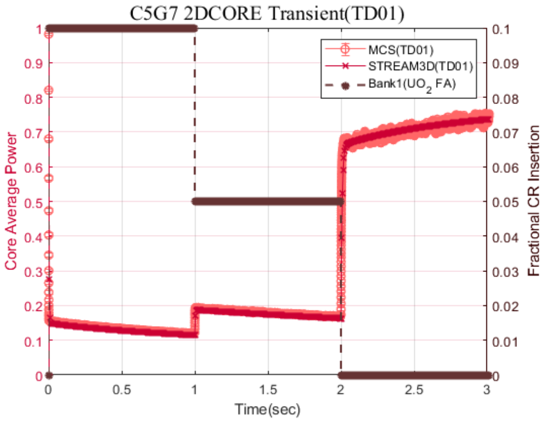


Fig. 3. C5G7-TD 2D core TD01 case results

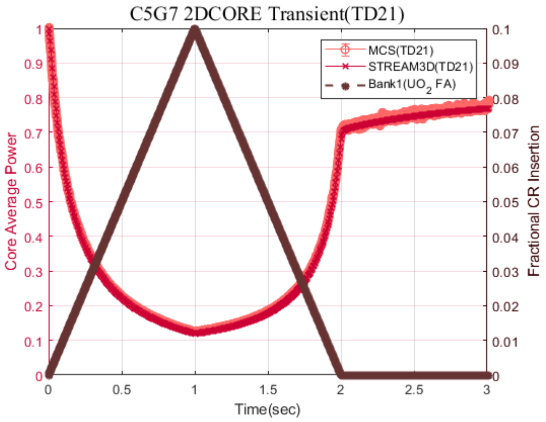


Fig. 4. C5G7-TD 2D core TD21 case results

The three-dimensional C5G7-TD problem was also effectively addressed using the MCS code, followed by a comprehensive comparison with the results computed by STREAM3D reference code. As evident from Fig 5 and 8, the time-dependent Monte Carlo simulations conducted with MCS exhibit a noteworthy level of concurrence with their respective reference solutions.

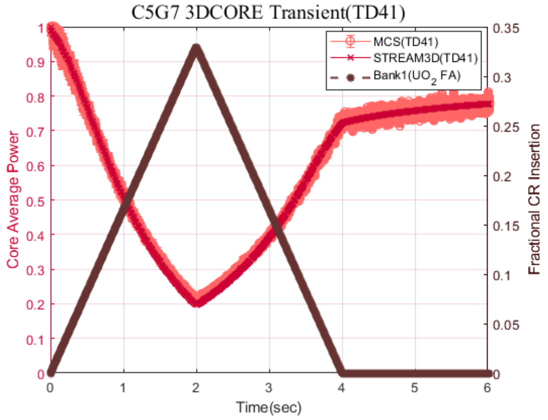


Fig. 5. C5G7-TD 3D core TD41 case results

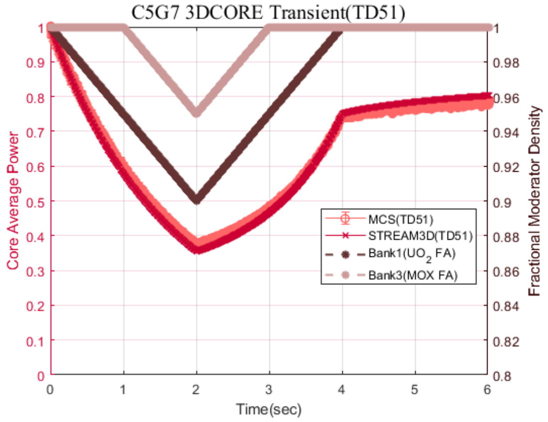
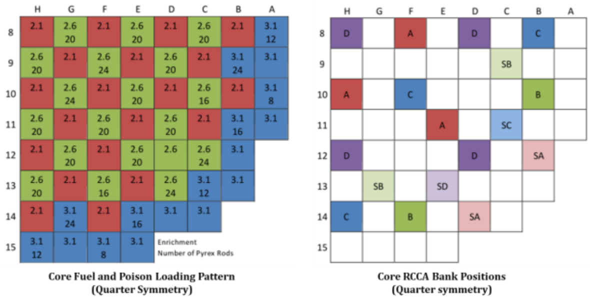


Fig. 6. C5G7-TD 3D core TD51 case results

An analysis was conducted on a three-dimensional VERA problem, and the geometry and results of the problem are presented in Fig 7 and Fig 8. These results were obtained by adopting a scenario involving the arbitrary withdrawal and insertion of control rods, and specific analytical calculations are planned for further investigation. Table 1 summarizes the approximate computing times for the 3D core calculations, categorized by different scenarios.



	H	G	F	E	D	C	B	A
8	2.1	2.6 20	2.1	2.6 20	2.1	2.6 20	2.1	3.1 12
9	2.6 20	2.1	2.6 24	2.1	2.6 20	2.1	3.1 24	3.1
10	2.1	2.6 24	2.1	2.6 20	2.1	2.6 16	2.1	3.1 8
11	2.6 20	2.1	2.6 20	2.1	2.6 20	2.1	3.1 16	3.1
12	2.1	2.6 20	2.1	2.6 20	2.6	2.6 24	3.1	
13	2.6 20	2.1	2.6 16	2.1	2.6 24	3.1 12	3.1	
14	2.1	3.1 24	2.1	3.1 16	3.1	3.1		
15	3.1 12	3.1	3.1 8	3.1	Enrichment Number of Pyrex Rods			

Core Fuel and Poison Loading Pattern
(Quarter Symmetry)

	H	G	F	E	D	C	B	A
8	D		A		D		C	
9						SB		
10	A		C				B	
11				A		SC		
12	D				D		SA	
13		SB		SD				
14	C		B		SA			
15								

Core RCCA Bank Positions
(Quarter symmetry)

Fig. 7. VERA benchmark problem core information

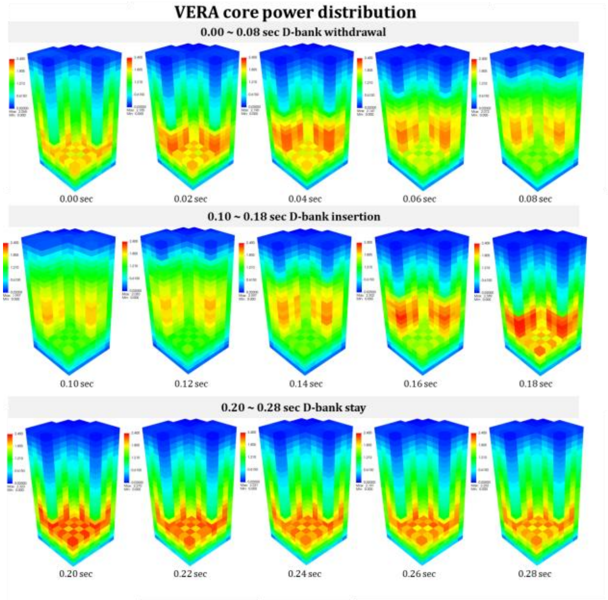


Fig. 8. VERA 3D core control rod bank withdrawal and insertion transient simulation results

Table I: MCS Reactor Transient Scenario Computing times

	C5G7 3D core	VERA 3D core
Time step size	0.1ms	0.1ms
Simulation scenario	1 sec	1 sec
Number of particles	10^7 particles	10^7 particles
Pin power tally relative error (%)	< 5 %	< 7%
Computing time with 100 cores	~ 3.5 days	~ 17 days

4. Conclusions and Future work

The primary aim of this study was to present the outcomes of time-dependent simulations conducted using MCS through the utilization of TDMC methodologies. The achieved results were compared against the reference solution that is the transient outcomes derived from the 3D MOC code STREAM3D. Remarkably, they demonstrated a high level of agreement within the bounds of statistical error. This study has affirmed the feasibility of performing calculations for both the C5G7-TD benchmark solution and the VERA core.

In forthcoming research, active efforts are being directed towards augmenting performance by incorporating multi-physics coupling and harnessing the capabilities of GPU code. Comprehensive analyses in this realm are scheduled for in-depth exploration.

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