Preliminary Accuracy and Performance Assessment of Depletion Analysis in the GPU-Optimized Monte Carlo Code GREAPMC Using MCS

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ABSTRACT

GREAPMC depletion and critical boron concentration (CBC) search are verified against MCS for a 3 × 3 PWR model up to 16.5 MWd/kgU. The maximum absolute CBC difference is 3.366 ppm, with close agreement in the peaking factor (F_q) and axial shape index (ASI). Radial and axial power RMS errors are at most 0.142% and 0.176% at BOC/MOC/EOC. Average particle throughput per GPU is approximately 112.95 and 322.60 times that of one MCS CPU process for 1M and 10M histories per cycle, respectively. Performance remains preliminary with the fixed transport-nuclide list and non-optimized depletion layer.

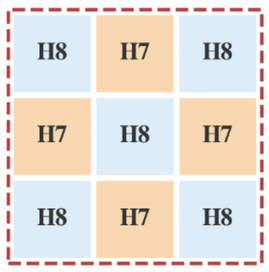
INTRODUCTION

- GREAPMC, CUDA C++ continuous-energy Monte Carlo code with history-based neutron tracking
- Depletion and internal CBC search with multi-GPU domain decomposition
- Accuracy and computational performance comparison of GPU-based GREAPMC and CPU-based MCS using the 3 × 3 PWR model

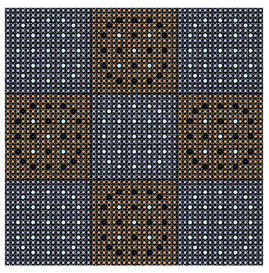
DESCRIPTION

- Modeling and Parameters

- Fixed transport array of 422 nuclides per GPU and a 1,441-nuclide depletion set
- Nine assembly-wise domains for the 3 × 3 PWR model, one assembly per GPU



(a) H7/H8 loading pattern



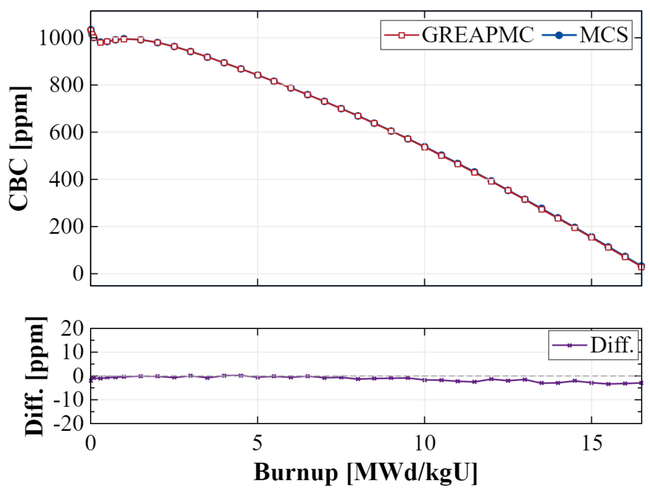
(b) 17 × 17 pin geometry

H8: 2.110 wt%, 24 GTs H7: 2.619 wt%, 20 Pyrex

Parameter	Accuracy comparison (10M)
Geometry	3 × 3 PWR, 17 × 17 fuel assemblies 365.76 cm (active fuel), 20 axial meshes
Nuclear data	ENDF/B-VII.1
Temperature	900 K (fuel/Pyrex), 600 K (moderator/structure)
Moderator density	0.743 g/cm³
Cycles / histories	100 inactive + 100 active / 10^7 per cycle

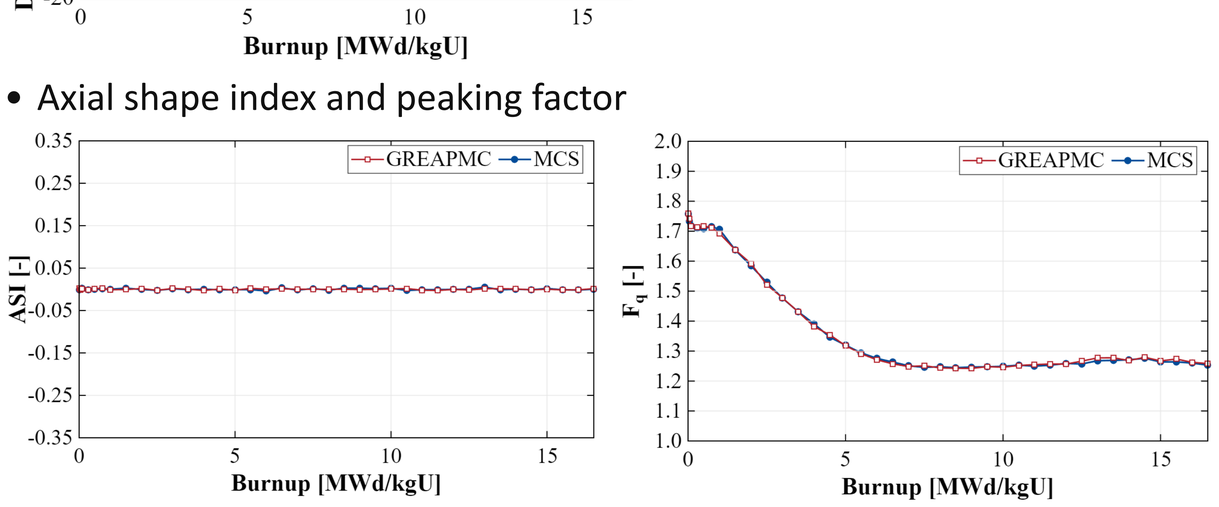
- Prescribed temperatures and SERPENT kappa data, no thermal-hydraulic feedback
- Reflective radial boundary conditions, no control rods

- Critical boron concentration



- Maximum absolute CBC difference, 3.366 ppm (mean 1.267 ppm)
- BOC, 1031.04 / 1033.10 ppm
- MOC, 668.45 / 669.77 ppm
- EOC, 29.33 / 32.25 ppm (GREAPMC / MCS)

- Axial shape index and peaking factor



- ASI, maximum absolute difference 0.004 at 11.0 MWd/kgU (mean 0.001)
- F_q, maximum absolute relative difference 0.775%

- Radial power distribution

BOC 0.00 MWd/kgU

1.083	0.918	1.083
0.02	0.02	0.02
1.082	0.918	1.082
0.02	0.01	0.02
0.10	0.01	0.08
0.918	0.998	0.918
0.01	0.01	0.01
0.917	0.998	0.918
0.02	0.01	0.01
0.02	0.01	-0.02
1.083	0.917	1.082
0.016	0.015	0.018
1.083	0.918	1.083
0.02	0.02	0.02
-0.03	-0.11	-0.08

Rel. Diff. [%]: RMS 0.06; Min -0.11; Max 0.10

GREAPMC / GREAPMC Rel. SD [%] / MCS / MCS Rel. SD [%] / Rel. Error [%]

MOC 8.00 MWd/kgU

0.996	1.006	0.996
0.01	0.01	0.02
0.996	1.004	0.997
0.01	0.01	0.02
0.01	0.21	-0.11
1.005	0.995	1.006
0.01	0.01	0.01
1.004	0.996	1.005
0.01	0.01	0.01
0.16	-0.05	0.05
0.995	1.005	0.995
0.01	0.01	0.02
0.996	1.004	0.997
0.01	0.02	0.02
-0.12	0.07	-0.23

Rel. Diff. [%]: RMS 0.13; Min -0.23; Max 0.21

GREAPMC / GREAPMC Rel. SD [%] / MCS / MCS Rel. SD [%] / Rel. Error [%]

EOC 16.50 MWd/kgU

0.974	1.030	0.973
0.01	0.01	0.01
0.975	1.029	0.975
0.02	0.02	0.02
-0.17	0.13	-0.16
1.030	0.988	1.029
0.01	0.01	0.01
1.028	0.988	1.028
0.01	0.01	0.01
0.21	-0.02	0.10
0.974	1.030	0.973
0.01	0.01	0.01
0.975	1.028	0.974
0.02	0.02	0.02
-0.09	0.13	-0.16

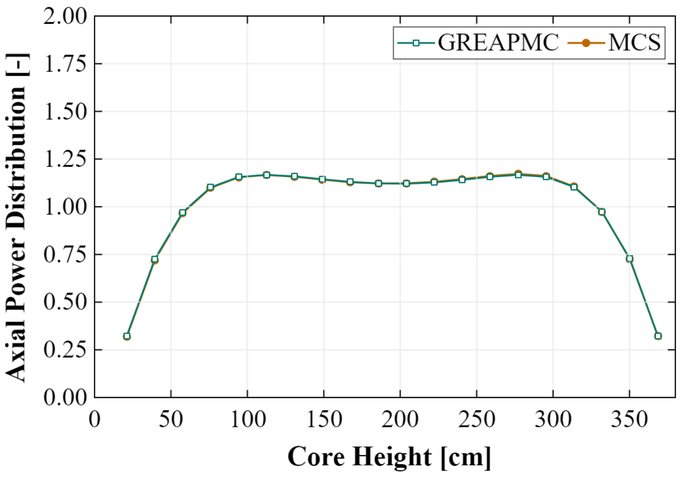
Rel. Diff. [%]: RMS 0.14; Min -0.17; Max 0.21

GREAPMC / GREAPMC Rel. SD [%] / MCS / MCS Rel. SD [%] / Rel. Error [%]

Error (%)	BOC	MOC	EOC
RMS	0.065	0.134	0.142
Max. abs.	0.113	0.231	0.215

- Absolute relative differences < 0.25% for all assemblies
- BOC, ≈1.08 in corner H8 and ≈0.92 in H7 assemblies
- MOC, nearly uniform power (0.995–1.006)
- EOC, reversed BOC distribution
- BOC / MOC / EOC, 0 / 8 / 16.5 MWd/kgU

- Axial power distribution at MOC



Error (%)	RMS	Max. abs.
BOC	0.175	0.895
MOC	0.176	1.227
EOC	0.112	0.889

- RMS errors ≤ 0.176%, maximum local difference 1.227%
- MOC axial mean normalized to 1.0
- Maximum normalized power (GREAPMC / MCS), BOC 1.4500 / 1.4493, EOC 1.1640 / 1.1644

- Computational performance

Histories per cycle	GREAPMC time (9 GPUs)	MCS time	MCS CPU processes	Speedup per GPU (vs. 1 CPU process)
1M	8.99 h	126.93 h	72	**112.95 faster**
10M	34.64 h	628.60 h	160	**322.60 faster**

- GREAPMC, 7 RTX A5000 + 2 RTX 3090 GPUs, CUDA 12.4
- MCS, Intel Xeon Gold 6242/6242R CPUs, one thread per MPI process
- Common conditions, same histories per cycle, cycle counts, burnup mesh, and CBC-search calculation
- Runtime including communication overhead from domain decomposition
- 10M resource use, 312 GPU-hours vs. 100,576 CPU-hours
- Neutron histories ×10, runtime ×3.85 and average particle throughput ×2.60
- Performance averaged over all 9-GPUs
- Preliminary performance, fixed transport-nuclide list and non-optimized depletion layer

CONCLUSION

GREAPMC closely predicts the reactivity and spatial power behavior calculated by MCS for the 3 × 3 PWR model. The maximum absolute CBC difference is 3.366 ppm. F_q and ASI agree closely with MCS, with radial and axial power RMS errors at most 0.142% and 0.176% at BOC/MOC/EOC. Average particle throughput per GPU is approximately 112.95 and 322.60 times that of one MCS CPU process for 1M and 10M histories per cycle, respectively. These results remain preliminary with the fixed transport-nuclide list and non-optimized depletion layer. Future work includes transport-nuclide list reduction, depletion-layer optimization, thermal-hydraulic feedback, and full-core reactor depletion verification.