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Javier Ortensi, Yaqi Wang, Hans R. Hammer, Frederick N. Gleicher, Sebastian Schunert, Mark D. DeHart, Richard C. Martineau
(Idaho National Laboratory)

Matthew Ellis and Kord Smith
(Massachusetts Institute of Technology)

Jaron P. Senecal
(Rensselaer Polytechnic Institute)

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Javier Ortensi*[1], Matthew Ellis[2], Yaqi Wang[1], Hans R. Hammer, Jaron P. Senecal[3]
Frederick N. Gleicher[1], Sebastian Schunert[1], Mark D. DeHart[1], Kord Smith[2], R. Martineau[1]

[1]*Idaho National Laboratory, P.O. Box 1625, Idaho Falls, ID 83415, javier.ortensi@inl.gov*
[2]Massachusetts Institute of Technology, Cambridge, MA 02139
[3]Rensselaer Polytechnic Institute, Troy, NY 12180, USA

INTRODUCTION

The validation of a reactor physics code system is an essential part of the code development process. It allows for the evaluation of the code's ability to predict and model the complex physical processes that take place in a nuclear reactor under various operational conditions. Idaho National Laboratory (INL) has been developing a set of reactor physics analysis tools within the MOOSE framework [1]. MAMMOTH [2] is the main reactor physics application, which integrates other MOOSE applications to solve complex multiphysics problems. Currently available under MAMMOTH are: 1) Rattlesnake [3] for solutions to the linearized Boltzman transport and radiative heat transfer equations, 2) BISON [4] for fuel performance analyses, 3) RELAP-7 [6] for low-resolution thermal-fluids, 4) PRONGHORN [7] for HTR thermal-fluids.

These tools have been developed with the necessary modeling flexibility to analyze a variety of experiments and reactor types, including the Advanced Test Reactor (ATR). Various standard reactor physics benchmarks have already been conducted with the code. Other studies are concurrently taking place with the primary goal of preparing Rattlesnake for ATR analysis. In addition, it is desirable to determine the capabilities of the code in predicting typical light water reactor (LWR) behavior.

In early 2013, the Computational Reactor Physics Group (CRPG) at the Massachusetts Institute of Technology (MIT) made the Benchmark for Evaluation and Validation of Reactor Simulations (BEAVRS) available to the public [3]. This benchmark is unlike other reactor physics benchmarks because it provides an unprecedented two cycles of detailed, measured PWR operational data. The dataset includes actual detector measurements, which would be used in typical hot zero power (HZP) physics testing and day-to-day core follow activities.

The scope of this work is limited to the calculation of the isothermal temperature coefficient (ITC) and the worth of control rod bank D at HZP conditions.

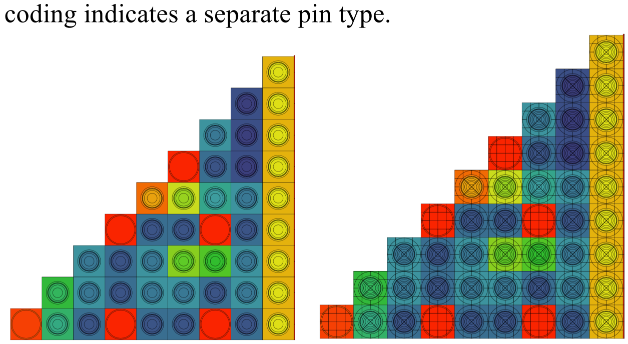
CORE MODELING APPROACH

The main objective of this work is to compare the HZP axially integrated detector measurements to the Rattlesnake predictions. To enable this comparison, the full core model uses a mesh with homogenized pin-cells. A traditional two-step process, cross section generation plus full core analysis, with a superhomogenization (SPH) equivalence procedure [7] allows the direct calculation of the ^{235}U fission rate at the detector locations.

Cross Section Preparation

The cross sections were prepared using the lattice physics code DRAGON5 [8], which is being developed at École Polytechnique Montréal. DRAGON5 includes several solution techniques available for a LWR lattice. The Method of Characteristics (MOC) solver was chosen because of its accuracy for assembly calculations. Pin-homogenized cross sections are produced in 8 energy groups. These cross sections are corrected with the transport-diffusion SPH equivalence so they can be used with the Rattlesnake diffusion operator.

Fuel pins with similar surroundings in the assembly were grouped to reduce computational expense and preserve some fidelity in the full core model. Fuel pins are categorized by their proximity to guide tubes, instrument tubes, burnable poisons, and the additional jacket of water on the perimeter of the assembly. There are a total of 15 pin-cell types defined. For each assembly, three geometries are created: a coarse geometry for the self-shielding calculation, a fine geometry for the flux solution, and a very coarse (pin-wise) geometry for the SPH procedure. Fig 1 includes an example of the self-shielding and the fine flux solution mesh, where the color-coding indicates a separate pin type.



(a) Self-Shielding Mesh (b) Flux Solution Mesh

Fig. 1. Lattice Discretization in DRAGON5.

In order to include the integral effect of the intermediate grid spacers the Zircaloy clad thickness in the fuel pins above the dashpot was modified in the preparation of cross sections. Our studies indicate that the inclusion of the grids with this appoach reduces the eigenvalue by 130 pcm for the HZP condition.

Mesh Generation

The BEAVRS analysis mesh was generated using the Python interface in CUBIT [9]. All radial and axial features important to neutron transport of the BEAVRS core were included in the CUBIT geometry, including the baffle and core barrel. The mesh contains mixed hex and wedge linear elements for a total of 8.5M elements in the full core model. Fig 2 shows a 1/4th core, baffle and barrel mesh detail.

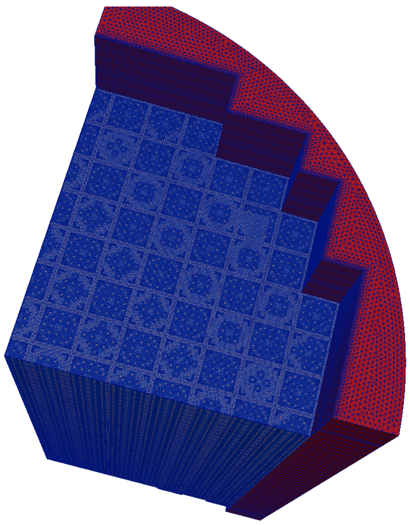


Fig. 2. Core Analysis Mesh for BEAVRS.

RESULTS

Sets of SERPTENT-2 (S2) [10] Monte Carlo reference calculations were generated to ascertain the level of accuracy of the DRAGON5 (D5) lattice physics results. Table 1 shows that the k_{inf} values for the MOC solver are within 30 pcm of the reference calculation, except for the control rod cases. At the moment, we have been unable to resolve the problem with the CR model. A group-wise reaction rate comparison for the assembly calculations was not conducted at this time.

Table 1. k_{inf} Assembly Results.

% enr.	BP Pins /CR	S2 MC	D5 MOC	Δk/k [pcm]
1.6	0	0.99335	0.99361	26.6
	CR	0.62040	0.61930	-177.2
2.4	0	1.13604	1.13623	16.6
	12	1.01271	1.01295	23.5
	16	0.97432	0.97456	24.7
	CR	0.74397	0.74268	-172.5
3.1	0	1.21814	1.21829	12.7
	6	1.16139	1.16164	21.4
	15	1.07710	1.07741	29.2
	16	1.06252	1.06270	17.2
	20	1.02690	1.02702	11.9

The results from the eigenvalue calculation at HZP conditions are shown in Table 2. The total solution time was 31 minutes on 480 CPU-cores (AMD Opteron 6136 at 2.4 GHz). No run optimization or scaling studies have been undertaken, which could significantly reduce the computation time. The results from OPENMC [11] and nTRACER [12] are also included for comparison. The Rattlesnake model predicts the HZP critical state well within the expected range of accuracy. Nevertheless, the results indicate that the cancellation of error produces an eigenvalue that is very close to critical and can mislead from the true accuracy of the results, therefore, power or detector distributions provide more information.

Table 2. Criticality calculation for the 1st cycle ARO HZP.

	k_{eff}
Rattlesnake	0.99994
OPENMC	0.99920 +/- 0.00004
nTRACER	0.99967

The comparison of the axially integrated detector signals from measurements and predictions is included in Fig. 3. This initial core has a significant tilt, which causes errors in distributions that are larger than anticipated. This effect has been discussed in a previous publication [13]. Table 3 shows a summary of the DRAGON5-Rattlesnake prediction discrepancies, with an RMS value of 4%, and a maximum of 9.8%. Since it is difficult to determine the fidelity of the simulation with the actual detector readings, a tilt corrected ^{235}U fission rate distribution at the detector locations was obtained from MIT. The Rattlesnake and nTRACER errors are included in Fig. 4 with an RMS difference of 2.08% and 2.43% and maxima of 5.98% and 6. 9%, respectively.

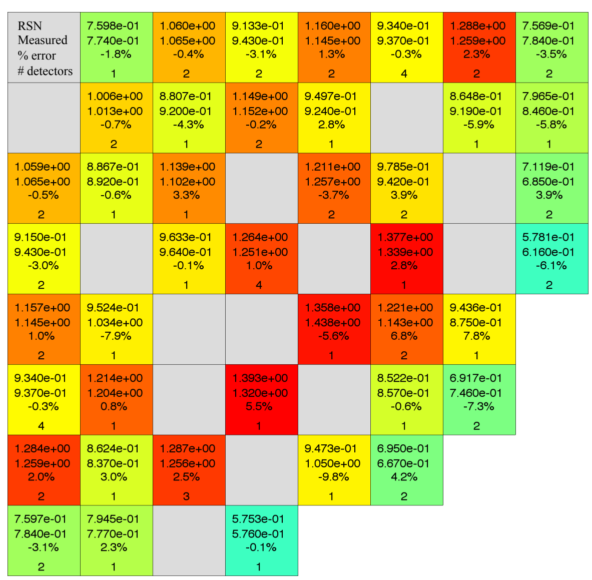


Fig. 3. Axially Integrated Detector Measurements.

-2.44%	-0.50%	-2.70%	1.01%	-0.15%	1.74%	-2.53%
-0.50%	-1.50%	0.50%	-2.42%	3.92%	-1.02%	-2.37%
	0.05%	-0.45%	-0.11%	-0.54%	3.62%	-2.13%
		1.21%		5.98%		-1.25%
			1.06%	2.15%	-1.26%	
				0.13%	-1.29%	

Rattlesnake
RMS = 2.08%
Max = 5.98%

-1.26%	0.21%	-1.33%	1.58%	0.71%	1.98%	0.77%
0.58%	-0.58%	1.11%	-0.99%	4.18%	0.52%	0.39%
	1.11%	-0.28%	1.13%	0.43%	4.27%	1.04%
		2.33%		6.90%		3.60%
			2.03%	3.15%	2.56%	
				3.16%	3.93%	

nTRACER
RMS = 2.43%
Max = 6.90%

Fig. 4. Percent differences in the ^{235}U fission rate distribution (lower right octant - tilt corrected).

The ITC discrepancy is 10.3% for Rattlesnake and was calculated with a ±5 ^{o}F perturbation from the HZP temperature of 560 ^{o}F. The prediction of the CR bank D worth is low by 100 pcm, which is expected since the lattice physics calculation is under predicting the eigenvalue for the controlled assembly.

Table 3. Criticality calculation for the 1st cycle ARO HZP.

	RMS error	Max. error	ITC [pcm/^{o}F]	Bank D worth [pcm]
Measured	-	-	-1.75	788
Rattlesnake	4.0%	9.8%	-1.93	688
OPENMC	5.4%	11.0%	-	771
nTRACER	4.3%	12.2%	-1.83	782

CONCLUSIONS AND FUTURE WORK

Results from this study demonstrate that the MOOSE based reactor physics tools, currently under development at INL, have the flexibility to model with high accuracy the HZP condition for a standard PWR. The DRAGON5-Rattlesnake full core pin-cell homogenized simulation produces eigenvalues and detector signals that are comparable to those generated with OpenMC and nTRACER. However, many improvements are necessary to achieve higher fidelity results.

Future work would focus on enhancing the cross sections with detailed group-wise reaction rate comparisons at the assembly level. This would allow the INL to pursue the full power and depletion analysis of the BEAVRS and focus on the multiphysics aspects of core analysis with the addition of the RELAP-7 and BISON applications.

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