Benchmark Calculations for BEAVRS and Watt Bar Unit 1 Using the SCALE-6.3.0/Polaris-PARCS v3.4.2 Code Package

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INTRODUCTION

The SCALE [1]/Polaris lattice physics code [2] was developed to prepare few-group homogenized cross sections for whole-core nodal diffusion calculations using, for example, GenPMAX [3] and PARCS [4]. SCALE-6.3.0/Polaris and PARCS v3.4.2 were recently developed, and the code package needs to be validated via benchmark calculations for operating pressurized water reactors (PWRs). Some SCALE/Polaris-PARCS calculations exist for PWRs to partly validate the code package with the AMPX [5] multigroup library [6]. However, the Polaris-PARCS code package has never been fully validated by obtaining uncertainties for key nuclear parameters. Therefore, the SCALE-6.3.0/Polaris-PARCS v3.4.2 code package with the ENDF/B-VII.1 AMPX 56-group library will be fully validated by evaluating uncertainties for reactivity, control rod worth, temperature coefficients, and pin and assembly peaking factors for PWRs.

The investigation presented here was part of the validation and performed benchmark calculations for the PWRs, including Watt Bar Unit 1 (WBN1) cycles 1–3 [7] and Benchmark for Evaluation And Validation of Reactor Simulations (BEAVRS) cycles 1–2 [8]. Figure 1 provides a flowchart of the Polaris-GenPMAXS-PARCS code package to simulate PWRs. The benchmark calculations were performed using the Polaris-PARCS procedure, and then the calculated results were compared with the measured data.

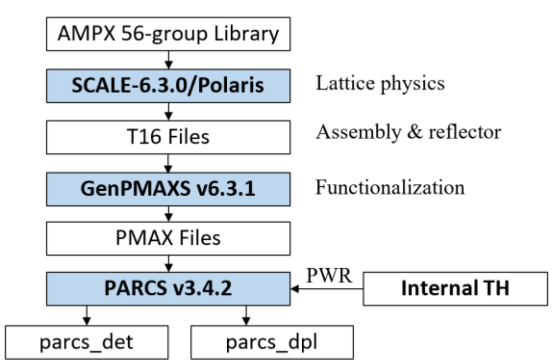

Fig. 1. Flowchart of the Polaris-PARCS procedure.

Because the benchmark calculations for WBN1 cycles 1–3 were performed using the whole-core multiphysics simulator Virtual Environment for Reactor Analysis (VERA) [10], the Polaris-PARCS results were also compared with the VERA results.

INVESTIGATIONS

Benchmark Problems

WBN1 is a Westinghouse Electric Company four-loop PWR operated by the Tennessee Valley Authority (TVA) that began operation at 3,411 MW_{th} power in 1996. The startup physics testing for WBN1 has provided valuable benchmarking data that TVA has made publicly available, contributing to the extensive validation basis developed for the Consortium for Advanced Simulation of Light Water Reactors (CASL) VERA core simulator. [7, 9]

TABLE I. Specifications of the WBN1 Core

Parameter	Design Data
Core power	3,411 MW_{th}
Operating pressure	2,250 psia (15.51 MPa)
Core flow rate	59.738 × 10^6 kg/h
Inlet temperature	565 K (291.85°C)
Number of fuel assemblies	193
Region 1 (cycle 1)	2.11 wt % ^{235}U
Region 2 (cycle 1)	2.619 wt % ^{235}U
Region 3 (cycle 1)	3.10 wt % ^{235}U
Region 4 (cycle 2)	3.709 wt % ^{235}U
Pin lattice configuration	17 × 17
Active fuel length	365.76 cm
Number of fuel rods	264
Number of grid spacers	8
Assembly pitch	21.50 cm
Pin pitch	1.260 cm
Fuel pellet radius	0.4096 cm
Cladding inner/outer radius	0.4180/0.4750 cm
Number of control banks	57
Control rod material (upper)	B_4C
Control rod material (lower)	AgInCd
Number of burnable poison rods	1,266
Burnable poison material	Pyrex, 12.5 wt % B_2O_3 IFBA and WABA

The reactor has 193 fuel assemblies of a Westinghouse 17 × 17 lattice design contained in a cylindrical core. Each assembly includes 264 fuel rods and 25 guide and instrument tubes. Table I provides the general specification of the WBN1 core, and detailed information is provided in Godfrey [7] and Horelik et al. [9].

Benchmark for Evaluation and Validation of Reactor Simulations (BEAVRS) [8] is a multicycle full-core PWR depletion benchmark based on two operational cycles of a commercial nuclear power plant that describes in detail fuel assemblies, burnable absorbers, in-core fission detectors, core loading patterns, and numerous in-vessel components. The benchmark also provides measured reactor data for hot zero power (HZP) physics tests, boron letdown curves, and 3D in-core flux maps from 58 instrumented assemblies. Table II provides the specifications of the BEAVRS core for cycles 1 and 2.

TABLE II. Specifications of the BEAVRS Core

Parameter	Design Data
Core power	3,411 MW_{th}
Operating pressure	2,250 psia (15.51 MPa)
Core flow rate	61.5 × 10^6 kg/h (5% bypass)
Inlet temperature	292.89°C
Number of fuel assemblies	193
Region 1 (cycle 1)	1.60 wt % ^{235}U
Region 2 (cycle 1)	2.40 wt % ^{235}U
Region 3 (cycle 1)	3.10 wt % ^{235}U
Region 4A (cycle 2)	3.20 wt % ^{235}U
Region 4B (cycle 2)	3.40 wt % ^{235}U
Total heavy metal mass (cycle 1)	81.8 Mt
Pin lattice configuration	17 × 17
Active fuel length	365.76 cm
Number of fuel rods	264
Number of grid spacers	8 (6 Zircaloy, 2 Inconel-718)
Assembly pitch	21.50364 cm
Pin pitch	1.25984 cm
Fuel pellet radius	0.39218 cm
Cladding inner/outer radius	0.40005/0.45720 cm
Number of control banks	57
Control rod material (upper)	B_4C
Control rod material (lower)	AgInCd
Number of burnable poison rods	1,266
Burnable poison material	Pyrex, 12.5 wt % B_2O_3

Benchmark Calculations

SCALE-6.3.0/Polaris with the ENDF/B-VII.1 AMPX 56-group library was used to generate 2-group assembly homogenized cross sections, power form factors, and axial and radial reflector cross sections. To consider all possible reactor states, various branch cases for boron concentrations, moderator, and fuel temperatures, moderator densities and control rod insertion were considered in the Polaris calculations. Then, GenPMAXS v6.3.1 was used to obtain functionalized cross section sets for each assembly type and reflector with the Polaris T16 files. The benchmark calculations were performed using PARCS v3.4.2 with the PMAX cross section sets for the WBN1 and BEAVRS HZP physics tests and hot full power (HFP) depletions. The PARCS output files with the extension of "parcs_det" and "parcs_dpl" provide detector responses and summary results. The Polaris-PARCS benchmark results were compared with the plant measured data.

Benchmark Results

Tables III and IV compare the control bank worth, critical boron concentrations, and isothermal temperature coefficients (ITCs) between the measured and calculated data in the HZP physics tests for WBN1 and BEAVRS. The calculated results were compared with only the measured data for cycle 1. There are very good agreements in the control bank worth, ITCs, and critical boron concentrations. When there is enough HZP measured data, uncertainties are estimated based on statistical analysis.

TABLE III. WBN1 Cycle 1 HZP Physics Test

Case	Control Bank Worth (pcm)			ITC (pcm/°F)		
	Meas.	Calc.	Diff.	Meas.	Calc.	Diff.
ARO*	–	–	–	-2.2	-3.39	-1.19
A	843	977	134	–	–	–
B	879	840	-39	–	–	–
C	951	1,031	80	–	–	–
D	1,342	1,450	108	–	–	–
SA	435	421	-14	–	–	–
SB	1,056	1,077	21	–	–	–
SC	480	458	-22	–	–	–
SD	480	458	-22	–	–	–
All	6,466	6,713	247	–	–	–

*All rods out

TABLE IV. BEAVRS Cycle 1 HZP Physics Test

Case	Critical Boron (ppm)		Control Bank Worth (pcm)			ITC (pcm/°F)		
	Meas.	Calc.	Meas.	Calc.	Diff.	Meas.	Calc.	Diff.
ARO	975	958	–	–	–	-1.75	-2.03	-0.28
D	902	896	788	794	4	-4.65	-3.49	1.16
C	810	795	1,203	1,276	73	-8.01	-8.27	-0.26
B	–	703	1,171	1,213	42	–	–	–
A	686	655	548	615	67	–	–	–
SE	–	613	461	5,266	65	–	–	–
SD	–	552	772	756	-16	–	–	–
SC	508	464	1,099	1,112	13	–	–	–

Figure 2 compares the HFP critical boron concentrations for WBN1, and Fig. 3 compares the HFP critical boron concentrations for BEAVRS. There are very good agreements between the calculated and measured critical boron concentrations within the maximum difference of 30 ppm. The Polaris-PARCS results slightly underestimate the critical boron concentrations compared with the measured ones.

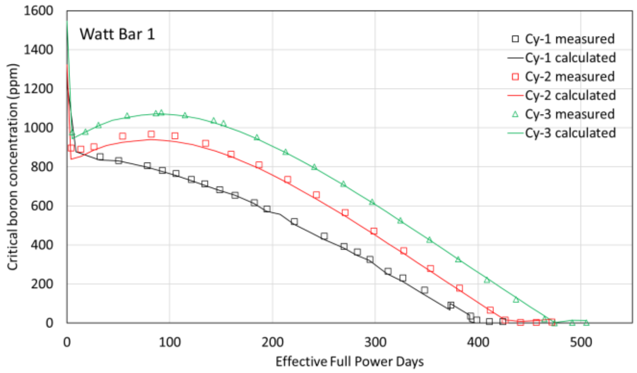

Fig. 2. WBN1 HFP critical boron concentrations.

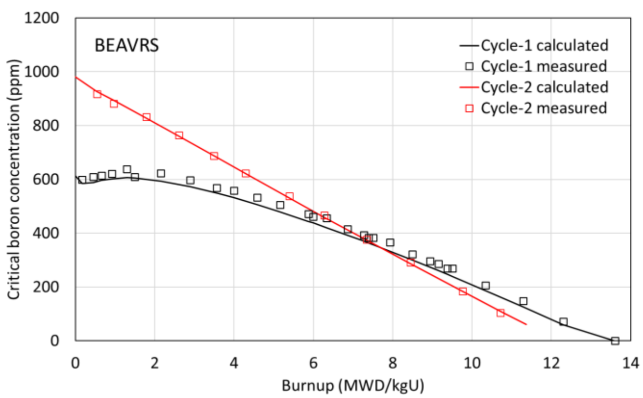

Fig. 3. BEAVRS HFP critical boron concentrations.

Figure 4 compares the in-core detector flux maps between the measured data and the calculated results for WBN1, and Fig. 5 compares the in-core detector flux maps between the measured data and the calculated results for BEAVRS. These figures include flux map comparisons for the 3D, axially integrated 2D radial, and radially integrated 1D axial distributions. The total 3D root mean square (RMS) errors are 4.55% for WBN1 and 4.87% for BEAVRS, the total radial 2D RMS errors are 1.66% for WBN1 and 1.51% for BEAVRS, and the total axial 1D RMS errors are 3.35% for WBN1 and 3.85% for BEAVRS. Table V compares the total 3D, 2D, and 1D flux map RMS errors for WBN1 between the VERA and the Polaris-PARCS results compared with the measured data. Although the 2D RMS errors of the Polaris-PARCS results are very comparable to the RMS errors of the VERA results, there are approximately 1.5% differences in the 1D and 3D RMS errors between the VERA and Polaris-PARCS results. This indicates that the axial reflector models for Polaris-PARCS must be improved. Figure 6 compares the 1D axial flux maps at two burnups for WBN1 cycle 1, and Fig. 7 compares the 1D axial flux maps at two burnups for BEAVRS cycle 1. The comparison indicates some axial power tilt, probably resulting from poor axial reflector cross sections or no consideration of control rod existence in the top reflector. Typically, it is much easier to resolve the axial reflector issue than the radial reflector issue.

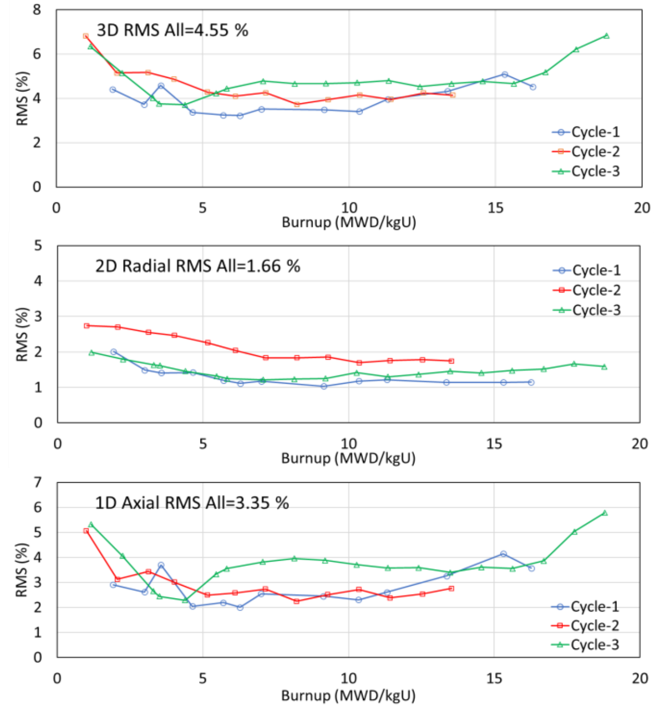

Fig. 4. Flux map comparison for WBN1.

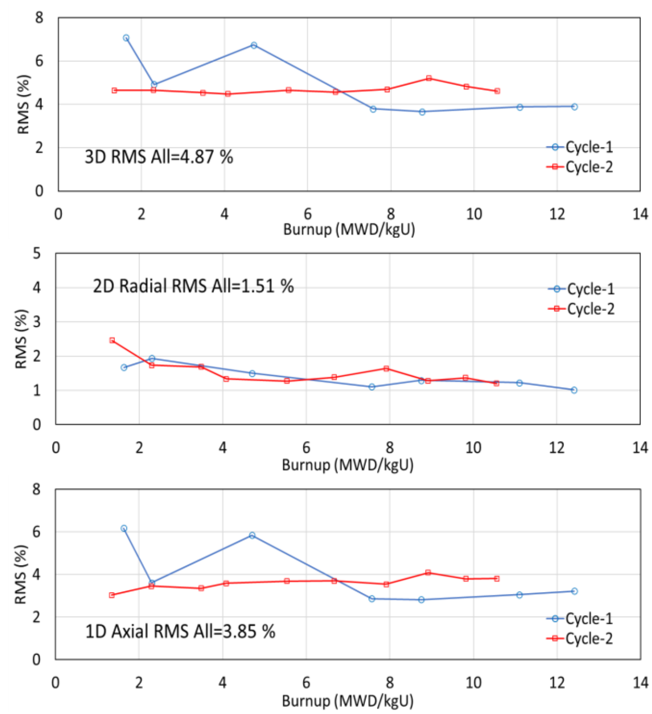

Fig. 5. Flux map comparison for BEAVRS.

TABLE V. WBN1 Flux Map (VERA vs. Polaris-PARCS).

Cycle	VERA RMS (%)			Polaris-PARCS RMS (%)		
	3D	2D	1D	3D	2D	1D
1	3.0	1.3	1.8	4.0	1.3	2.9
2	3.2	1.9	1.4	4.6	2.1	3.0
3	3.3	1.5	2.4	4.9	1.5	3.9

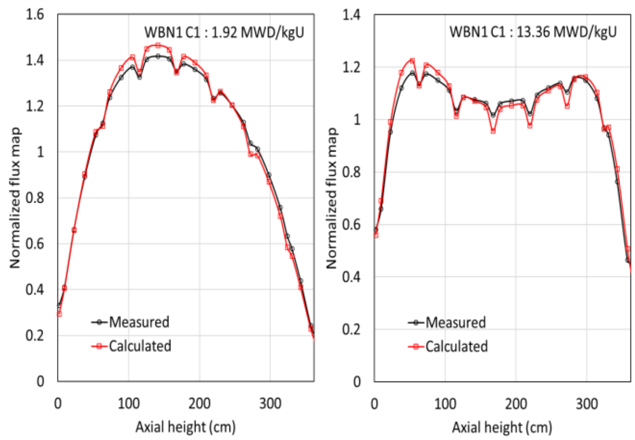

Fig. 6. Axial 1D flux map comparison for WBN cycle 1.

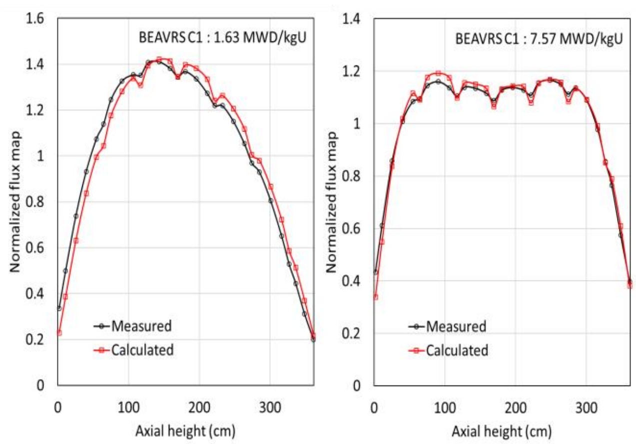

Fig. 7. Axial 1D flux map comparison for BEAVRS cycle 1.

CONCLUSION

The SCALE-6.3.0/Polaris-PARCS v3.4.2 benchmark calculations with the ENDF/B-VII.1 AMPX 56-group library were performed for WBN1 cycles 1–3 and BEAVRS cycles 1–2, and the benchmark results were compared with the measured data for control rod worth, ITC, critical boron concentrations, and flux maps. The benchmark results are very reasonable. However, the Polaris axial reflector models must be improved to achieve better agreement for the flux maps. More PWRs with more cycles must be added to complete the validation of the SCALE/Polaris-PARCS code package for PWR by estimating statistical uncertainties for key nuclear parameters through a comparison between measurements and simulations.

ACKNOWLEDGMENTS

This research was supported by the US Nuclear Regulatory Commission Office of Research.

REFERENCES

1. W. A. WIESELQUIST, R. A. LEFEBVRE, M. A. JESSEE, eds., *SCALE Code System*, ORNL/TM-2005/39, Version 6.2.4, Oak Ridge National Laboratory, Oak Ridge, TN (2020). https://www.ornl.gov/file/scale-62-manual/display.
2. M. A. JESSEE, W. A. WIESELQUIST, U. MERTYUREK, K. S. KIM, T. M. EVANS, S. P. HAMILTON, C. GENTRY, "Lattice Physics Calculations Using the Embedded Self-Shielding Method in Polaris, Part I: Methods and Implementation," *Ann. Nucl. Energ.*, **150**, 107830 (2021).
3. A. WARD, Y. XU, T. DOWNAR, "GenPMAXS – v6.3.1: Code for Generating the PARCS Cross Section Interface File PMAXS," University of Michigan (2020).
4. T. DOWNAR et al., "User Manual for the PARCS v3.0 U.S. NRC Core Neutronics Simulator," UM-NERS-09-0001, University of Michigan (2010).
5. D. WIARDA, M. E. DUNN, N. M. GREEN, M. L. WILLIAMS, C. CELIK, L. M. PETRIE, *AMPX-6: A Modular Code System for Processing ENDF/B*, ORNL/TM-2016/43 (2016).
6. M. A. JESSEE, A. M. WARD, A. T. GODFREY," Applications of VERA for Improvement in NRC Methods," CASL Virtual Meeting, ANS 2020 Winter meeting, Nov. 16–19 (2020).
7. A. T. GODFREY, "VERA Core Physics Benchmark Progression Problem Specifications," CASL-U-2012-0131-004 (2014).
8. P. DARNOWSKI, M. PAWLUCZYK, K. TIEN, "Simulations of the BEAVRS PWR with SCALE and PARCS," NUREG/IA-0529, International Agreement Report (2022).
9. N. HORELIK et al., "Benchmark for Evaluation and Validation of Reactor Simulations (BEAVRS)," *Proc. Int. Conf. Mathematics and Computational Methods Applied to Nuc. Sci. & Eng*., Sun Valley, Idaho (2013).
10. A. T. GODFREY et al., "VERA Benchmarking Results for Watts Bar Nuclear Plant Unit 1 Cycles 1–12," *Proc. PHYSOR 2016*, Sun Valley, Idaho (2016).