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Two-Step Uncertainty Analysis of Watts Bar Nuclear 1 Cycle 1 with SCALE/PARCS[1]

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Abstract — *The ability to quantify uncertainties in modeling and simulation of nuclear systems is of great importance. One source of uncertainty stems from the uncertainty in nuclear cross sectional data. A common approach to reactor core analysis is the two-step method in which homogenized few-group lattice cross sections are generated by lattice physics calculations and used in a full core simulator. Two common codes used in the two-step method are the SCALE code package and the PARCS (Purdue Advanced Reactor Core Simulator). It is important to understand how uncertainty in cross sectional data affects the core calculation results. Cross section uncertainties in SCALE are found in the covariance libraries. Using the Sampler stochastic uncertainty analysis super-sequence, covariance data are used to generate perturbation factors and calculate perturbed self-shielded cross sections for lattice and depletion calculations. These perturbed cross sections are used by the Purdue Advanced Reactor Core Simulator to perform full core calculations. Using a large number of perturbed cross sections, we can begin to quantify how the uncertainty in cross sectional data affects the core calculation end result. This paper will discuss the results of this uncertainty analysis methodology applied to the Virtual Environment for Reactor Applications benchmark progression problems.*

I. INTRODUCTION

Accurate modeling and simulation of nuclear systems requires the ability to quantify uncertainties found in the model. Uncertainties can arise from simplified models, boundary conditions, and nuclear data. A two-step approach to reactor core uncertainty analysis was performed using the SCALE/PARCS two-step method. The Virtual Environment for Reactor Applications (VERA) benchmark problems have been established by the Consortium of Advanced Simulation of Light Water Reactors and were chosen for this study [1].

A new Sampler stochastic uncertainty analysis super-sequence was used to study the impact of nuclear cross section uncertainty on core calculations. Polaris is a new lattice physics module included in the SCALE 6.2.1 code package that provides light water reactor (LWR) modeling capabilities. The Sampler/Polaris super-sequence was used to stochastically sample cross sectional data at the assembly level and calculate perturbed homogenized few-group assembly cross sections. These perturbed cross sections were used in the US Nuclear Regulatory Commission (NRC) core simulator, PARCS, for core analysis [2]. This paper will provide descriptions of the benchmark problems modeled and will present the results of the uncertainty analysis obtained from the SCALE/PARCS two-step method.

II. UNCERTAINTY ANALYSIS METHODOLOGY

Polaris is a new LWR lattice physics module in the SCALE 6.2.1 code package. Polaris was designed to be more user friendly and run faster than TRITON, the previous SCALE lattice physics control module. Polaris utilizes the embedded self-shielding method to calculate self-shielded few-group cross sections and a 2-D method of characteristics neutron transport solver [3]. Polaris can also perform depletion calculations using the SCALE/ORIGEN depletion and decay solver.

The Sampler super-sequence was developed for the SCALE code system [4]. Sampler uses the XSUSA code to generate perturbation factors by sampling uncertainty data in the SCALE covariance library. Using these perturbation factors, the Sampler super-sequence is capable of automating perturbed self-shielded cross section calculations for lattice physics and depletion calculations [5]. Sampler allows the user to obtain the overall response uncertainty caused by nuclear cross section data uncertainties. XSUSA assumes few-group cross sectional data are multivariate normal distributions. Currently, these distributions are sampled in a predetermined sequence to generate the perturbation factors. After XSUSA generates the random perturbation factors, the SCALE calculations are performed by the Sampler super-sequence.

Single assembly problems were modeled with Polaris using a 56 group library to produce homogenized few-group assembly cross sections. These cross sections were then post-processed by the GenPMAXS code [6] into cross section files

that could be read by PARCS. PARCS is a versatile reactor core simulator and is used to perform the steady-state and depletion benchmark calculations. Once all of the calculations have been performed by PARCS, statistics for the parameters of interest can be calculated.

For steady-state benchmark problems, 200 stochastically sampled sets of few-group cross sections were generated for each assembly type. This number was chosen based on a previous study that showed how the Sampler mean core k_{eff} value converged to an average value as the number of samples was increased [7]. Core calculations were performed for each perturbed cross section set to generate 200 solutions. The mean and standard deviation of core k_{eff} values, core power distributions and control rod bank worths were calculated. For the depletion benchmark problem, 100 stochastically sampled sets of few-group cross sections were generated. This number was chosen to reduce the computational time required to generate the cross section sets. The mean and standard deviation of the critical boron concentrations, peak assembly power, and axial offset throughout cycle 1 were calculated.

III. VERA BENCHMARK PROGRESSION PROBLEMS

The zero power physics tests and cycle 1 depletion benchmarks were modeled at a high level of granularity. These benchmarks are beneficial because they model the Watts Bar Nuclear 1 (WBN1) core in great detail and contain measured plant data. A detailed description of the VERA benchmark progression problems can be found in [1].

1. Zero Power Physics Tests

This benchmark problem models a full core of Westinghouse 17 × 17 fuel assemblies loaded in the initial WBN1 loading pattern at beginning of life and hot zero power (Fig. 1).

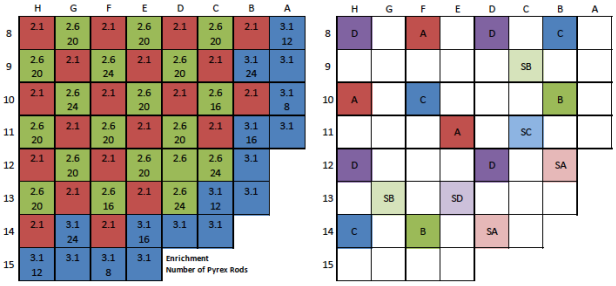

Fig. 1. The WBN1 initial loading pattern (right) and control rod bank configuration (left).

The goal of this test is to successfully perform calculations associated with fuel cycle startup. The core consists of three enrichment zones of 2.11 wt%, 2.610 wt%, and 3.10 wt% enriched assemblies. Some assemblies also contain burnable poison Pyrex control rods. Control rod banks utilize hybrid B_4C (boron carbide) rod cluster control assemblies with AIC (silver-indium-cadmium) rod tips. Axial and radial reflectors are modeled explicitly from the top and bottom assembly core plates and the core baffle/barrel. The core neutron pad is also modeled and included in the radial reflector model.

All material temperatures are modeled at 565 K, and the coolant density is modeled at 0.743 g/cm^3. Two sets of calculations modeling the initial core criticality and control rod bank worths are performed. The initial critical core has bank D at 167 steps inserted with a boron concentration of 1,285 ppm. Control rod bank worths are calculated at a boron concentration of 1,170 ppm by individually inserting each bank, calculating k_{eff}, and comparing it to the all rods out core.

2. Cycle 1 Depletion

This benchmark problem models the first 18-month operating cycle of the WBN1 plant. The goal of this problem is to successfully calculate the critical boron concentration throughout the operating cycle. The core rated power is modeled at 3,411 MW, and the coolant mass flow rate is modeled at 131.7 Mlbs/h. A simplified operating history is modeled in PARCS based on the benchmark description. Critical boron concentrations are calculated at each depletion step and compared to measured data from the operating cycle 1 core.

IV. RESULTS AND ANALYSIS

The zero power physics tests and cycle 1 depletion benchmarks were modeled using SCALE 6.2.1 and PARCS. Two types of Polaris calculations are presented: a standalone (SA) Polaris lattice calculation and a Sampler/Polaris super-sequence calculation. Both types of Polaris calculations generated homogenized few-group assembly cross sections used by PARCS. Calculated results were compared to various Monte Carlo–based benchmark solutions (KENO-VI [8] and Shift [9]), a full core method of characteristics solution (MPACT [10]), and measured plant data.

1. Zero Power Physics Tests

A set of 200 stochastically sampled few-group cross sections was generated for each assembly type using the Sampler/Polaris super-sequence and used by PARCS to model the zero power physics tests. Statistical analysis was performed on the PARCS results to determine the mean and standard deviations of multiple core parameters. Table I shows the Polaris SA and Sampler mean core k_{eff} values of for the initial critical core compared to the reference KENO-VI result [1]. The Polaris SA and Sampler mean k_{eff} values deviate from the KENO-VI result by about 83 pcm and 32 pcm, respectively. The 51 pcm difference between the Polaris SA and Sampler mean k_{eff} is the result of minor nonlinear variations in k_{eff} from cross section perturbations.

Description	k_{eff}	Δk pcm
Polaris SA	0.999065	−83
Sampler mean	0.999581	−32
KENO	0.999899	
	±0.00001	

TABLE I. WBN1 critical core k_{eff} values.

The standard deviation of the Sampler core k_{eff} value was found to be 565 pcm. This value is similar to the core k_{eff} standard deviation values found in a similar uncertainty analysis study performed by Zhou [7].

The Sampler running mean k_{eff} value is plotted against the number of samples in Fig. 2. The running mean k_{eff} value varied rapidly for a low number of samples and began to approach the mean value when the number of samples was sufficiently large. After about 150 samples, the change in the running mean k_{eff} was on the order of 10 pcm. After about 200 samples, the variation in Sampler mean k_{eff} had decreased further.

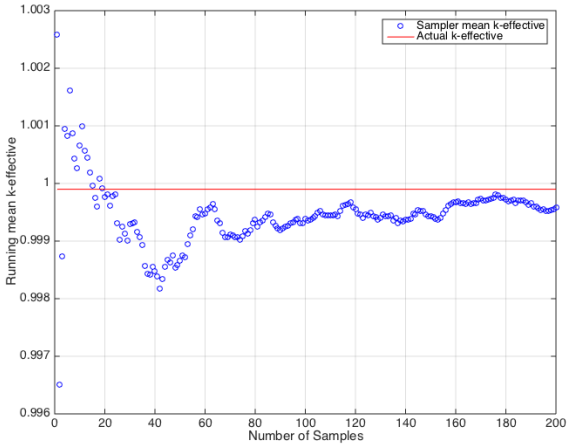

Fig. 2. Sampler running mean k_{eff} versus number of samples.

The small, slow changes in the running k_{eff} value indicate the running mean is beginning to converge to a mean value. For the purpose of this study, this slow change was determined to be acceptable to use as an "approximately converged" solution. To show a proper convergence, it is suggested at least an additional 100 samples be taken.

The core radial power profiles for the Polaris SA and Sampler mean calculations are shown in Fig. 3. The SA and mean solutions exhibited a similar root mean square (RMS) relative error value of 1.18% and 1.20% respectively. The relative standard deviations of the Sampler core radial power distribution are shown in Fig. 4. The RMS of the standard deviations was 2.06%. Once again, this value is similar to values found in the study performed by Zhou [7].

0.9487 0.78% 1.25%					
0.9193 -0.83% -0.36%	0.9973 1.37% 1.80%				
1.0181 1.30% 1.68%	0.9083 -1.66% -1.27%	1.0648 1.16% 1.46%			
0.9850 -1.22% -0.92%	1.0819 0.99% 1.24%	1.0412 -1.21% -1.00%	1.1615 0.94% 1.04%		
1.0647 -0.01% 0.14%	1.0471 -1.55% -1.40%	1.1746 0.71% 0.77%	1.0850 -1.23% -1.21%	1.2368 0.92% 0.82%	
1.0480 -1.94% -1.91%	1.1619 0.28% 0.28%	1.1520 -1.22% -1.27%	1.1508 0.73% 0.62%	0.8969 -0.98% -1.11%	0.9126 1.41% 1.18%
1.0841 0.20% 0.07%	1.0652 -2.13% -2.25%	1.1039 0.32% 0.13%	1.0496 -0.36% -0.58%	0.9452 2.03% 1.76%	0.6296 2.11% 1.82%
0.7931 -0.28% -0.49%	0.9071 1.08% 0.83%	0.8046 0.41% 0.15%	0.6590 1.27% 1.01%		

KENO Assembly Power
Polaris SA relative error
Sampler Mean relative error

Fig. 3. Core relative radial power distribution comparison.

0.9606 3.69%					
0.9160 3.65%	1.0153 3.42%				
1.0352 3.10%	0.8968 3.10%	1.0803 2.45%			
0.9759 2.43%	1.0954 2.16%	1.0308 1.79%	1.1736 1.02%		
1.0662 1.37%	1.0325 1.29%	1.1837 0.76%	1.0719 0.29%	1.2470 0.69%	
1.0280 0.35%	1.1651 0.12%	1.1374 0.28%	1.1580 0.80%	0.8869 1.20%	0.9234 2.12%
1.0849 0.98%	1.0412 1.06%	1.1053 1.46%	1.0436 1.84%	0.9619 2.38%	0.6411 2.70%
0.7892 1.84%	0.9146 2.17%	0.8058 2.29%	0.6656 2.46%		

Sampler Mean Assembly Power
Sampler Assembly Standard Deviation

Fig. 4. Sampler mean assembly power and relative standard deviation resulting from nuclear data uncertainty.

The core axial power profiles for the Polaris SA and Sampler mean calculations with PARCS are shown in 5. Included in the figure are the Sampler mean axial powers and standard deviations for a few axial positions. The Polaris SA and Sampler mean axial power profiles were very similar in shape to the reference KENO-VI power shape. The dips in the KENO-VI axial power are a result of the presence of spacer grids. These dips in power were not present in the SCALE/PARCS solutions because the spacer grids were not modeled. In general, the core axial power shape was much less sensitive to nuclear data uncertainties than the core radial power shape, with statistical uncertainties around 0.2%. Although not shown in the figure, the KENO-VI axial powers displayed statistical uncertainties between 0.0001%–0.006%.

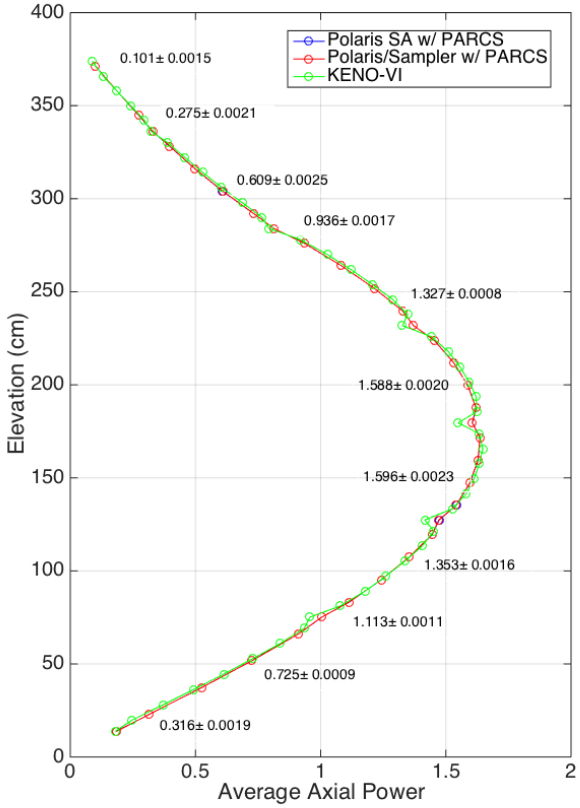

Fig. 5. Core relative axial power profile comparison.

The control rod bank worth calculations were performed by calculating core k_{eff} values for cases in which a single control rod bank was inserted into the core and by comparing them to the all rods out k_{eff} value. Table II below shows the Sampler mean bank worths of each control rod bank compared to measured plant data. Relative errors for the SCALE/PARCS bank worths generally ranged betweena about 3%–8%. These errors are comparable to those seen in similar studies performed with MPACT, KENO-VI, and Shift. Bank A and SA were two standout cases with large relative errors of 7.9% and 6.5% respectively. Bank A also contained the bank worth with the highest uncertainty with a standard deviation of 44 pcm while banks SC and SD contained the lowest uncertainty with standard deviations of 4 pcm each. In general, banks with higher number of control rods and banks with rodded assemblies located in closer proximity to each other in the core contained higher uncertainty.

Bank	Measured	Sampler Mean	Relative Error	Sampler Std.
A	843	911	8.0%	4.7%
B	879	870	−1.0%	2.5%
C	951	982	3.2%	2.6%
D	1,342	1,407	4.8%	2.0%
SA	435	463	6.3%	3.3%
SB	1,056	1,058	0.1%	0.8%
SC	480	464	−3.4%	0.9%
SD	480	464	−3.4%	0.9%

TABLE II. Comparison of control rod bank worths.

2. Cycle 1 Depletion

A set of 100 stochastically sampled few-group cross section histories were generated for the depletion benchmark using the Sampler/Polaris super-sequence. These cross section histories were used in a simplified depletion model created in PARCS to simulate the cycle 1 depletion history. Critical boron concentrations were calculated for cycle 1 and compared to plant measured data (Fig. 6). The calculated critical boron concentrations showed good agreement with the plant measured data and were found to be within about 20–40 ppm of measured boron throughout the cycle with a maximum difference being around 36 ppm at 392.3 effective full power days. The critical boron concentrations displayed an RMS standard deviation of 49.6 ppm with the highest uncertainty at the beginning of the cycle (59.7 ppm) and the lowest uncertainty at the end of cycle (29.1 ppm).

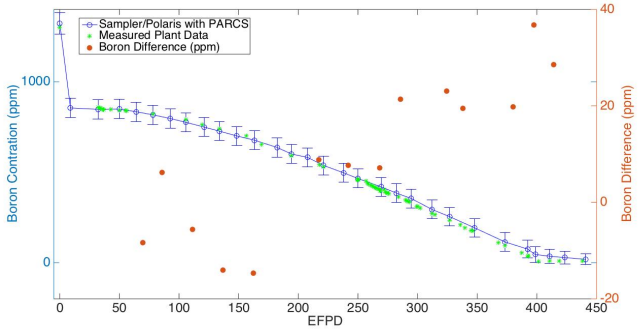

Fig. 6. Cycle 1 critical boron concentration.

The SCALE/PARCS peak assembly power and axial offset through cycle 1 were compared to an MPACT cycle 1 calculation [11] since no plant data was readily available (Fig. 7). The SCALE/PARCS peak assembly power shows good agreement with the MPACT solution with an RMS error of 0.4%. SCALE/PARCS did not capture the dip in power as well as the MPACT calculation because of a partial core shutdown around 375 effective full power days and because only one time step was used to model the partial shutdown in the PARCS depletion model. To more accurately capture the effects of the partial shutdown, a “dummy” time step should be used to

perform another state point calculation during the shutdown period. The SCALE/PARCS peak assembly powers displayed an RMS standard deviation of 0.6%. Uncertainties in the peak assembly power were higher in the middle of cycle and lower near the end of cycle.

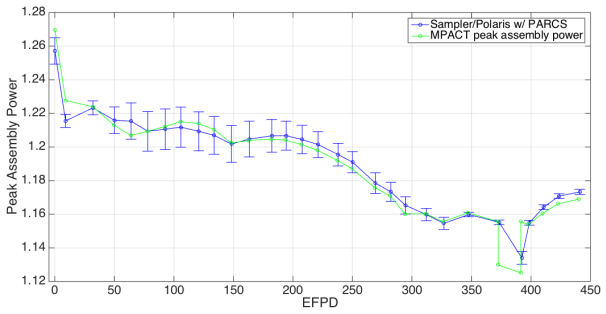

Fig. 7. Peak assembly power through cycle 1.

V. CONCLUSION

An uncertainty analysis study of the VERA benchmark problems was performed using the SCALE/PARCS two-step method. Perturbation factors generated by the XSUSA code were used to produce sets of perturbed homogenized few-group assembly cross sections using the Sampler supersequence. These sets of perturbed cross sections were then used in the SCALE/PARCS two-step method calculations. Sampler mean k_{eff}, radial, and axial power shapes of the initial critical core showed good agreement with the reference solution. The core Sampler k_{eff} had a standard deviation of 565 pcm. The core radial power shape was much more sensitive to nuclear cross section uncertainties than the axial power shape, showing an RMS uncertainty of 2.06% compared with a very small uncertainty for the axial power shape. Sampler mean control rod bank worths also showed good agreement with the reference solution, with bank A containing the highest uncertainty and banks SC and SD containing the lowest uncertainty. The SCALE/PARCS two-step method was also capable of correctly predicting the critical boron concentration throughout cycle within about 40 ppm with an RMS uncertainty of 49.6 ppm. The peak assembly power was also correctly calculated throughout cycle 1 with an RMS error of 0.4% and an RMS standard deviation of 0.6%.

VI. ACKNOWLEDGMENTS

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