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Neutronic Calculations of the AP1000 Reactor Core with the PRAGMA/SPHINCS Code System

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1. Introduction

As technology advances and passive safety requirements are implemented together with reduced refueling frequency, problems arise with a definite lack of homogeneity inside of a reactor core. Such a heterogeneous core poses a significant challenge to conventional core analysis methods used in older nuclear codes.

The most common approach in the past was to use the two-step calculation method. However, the presence of burnable absorbers and more direct control rod strategies make the spatial gradients within the core more extreme and highly localized. When analyzing such a core the limitations of nodal methods become more prevalent. Furthermore, lattice calculations based on deterministic transport methods require resonance and multigroup approximations which have a negative effect on simulation accuracy.

To address these core characteristics, other methods had to be used. Pin-wise neutron diffusion methods with pin-wise constants show considerably improved accuracy in predicting reactivity and pin power distributions. These methods enable a high-fidelity representation of the reactor core through pin-level neutron flux resolution, which allows for precise predictions of reactor's response to various operational conditions. To take advantage of these methods, Power Analysis using GPU-based Monte Carlo Algorithm (PRAGMA) [1] was developed by Seoul National University. To further enhance computational capabilities, an additional code called SNU Pin-Homogenized Innovative Neutronics Core Simulator (SPHINCS) [2] was developed to work with PRAGMA. SPHINCS utilizes Super Homogenization (SPH) to reduce the errors in reactor core calculations and to lower computational intensity. Together they create a code system made for simulating modern reactor cores.

The goal of this paper is to verify the accuracy of the PRAGMA/SPHINCS (P/S) code system by using a sufficiently complex nuclear reactor. For this purpose, the Westinghouse AP1000 was chosen. It is a Pressurized Water Reactor (PWR) classified as generation III+ design. It is a very complex core that exhibits high heterogeneity making it a suitable benchmark to showcase the capabilities of the PRAGMA/SPHINCS code system.

2. Methodology

The geometric and material specifications of the AP1000 reactor core were primarily obtained from the official Design Control Document (DCD) [3]. Where information required for the core model was not provided in the DCD, open literature was used as a supplementary source [4]. The DCD was used to define the fuel rod, fuel assembly, and reflector dimensions, as well as the fuel enrichment and B_{10} density, while additional details of the core geometry and material data were adopted from Darnowski et al. [4].

The AP1000 advanced PWR operates at a nominal thermal power of 3400 MWt and contains 157 fuel assemblies with three different enrichment regions of ^{235}U : 2.35 w/o (53 assemblies), 3.40 w/o (52 assemblies), and 4.45 w/o (52 assemblies) as seen in Fig. 1.

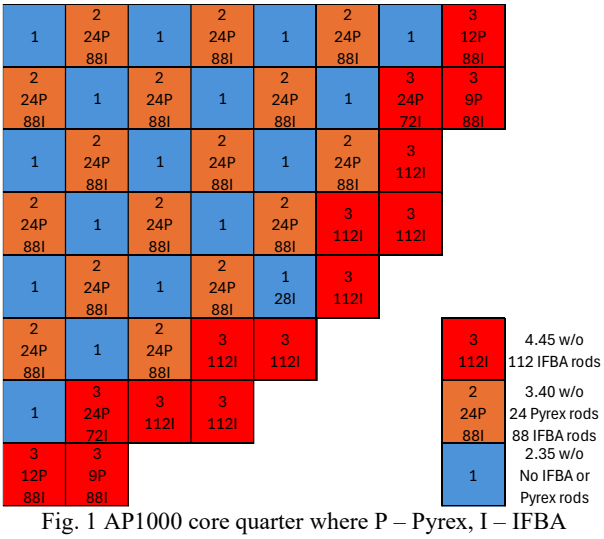


Fig. 1 AP1000 core quarter where P – Pyrex, I – IFBA

A Westinghouse style assembly is a 17 x 17 matrix as can be seen in Fig. 2. A fuel rod has the geometry as presented in Fig. 3. Among the fuel rods there are 24 guide tubes and one instrument tube in each assembly, their geometry is identical and is presented in Fig. 4 [3]. At the beginning of cycle (BOC) the core has two types

of burnable absorbers: Integral Fuel Burnable Absorbers (IFBA) rods which are normal fuel rods with an additional coating of an absorber with B_{10} content of 0.772 mg/cm, and Pyrex rods which occupy guide tubes in specific assemblies with B_{10} content of 6.24 mg/cm [3]. The geometry of the IFBA and Pyrex rods can be seen in Fig. 5 and Fig. 6 respectively. The active core region is 426.72 cm tall. Fuel rods are at a pitch of 1.26 cm. The top and bottom 20.32 cm sections of the fuel rod contain regions of reduced enrichment. In fuel rods with no IFBA the reduced enrichment is 1.58 w/o whereas in rods with IFBA the enrichment is 3.2 w/o.

There are multiple types of assemblies. While the most common is the regular one seen in Fig. 2, there are also five configurations of IFBA assemblies as seen in Fig. 7.

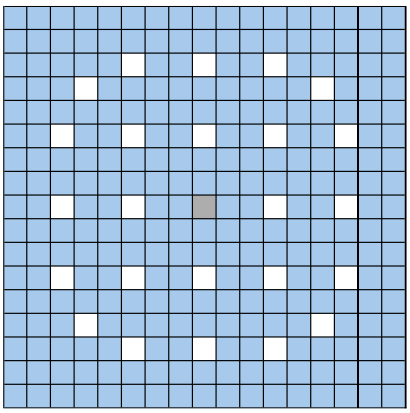
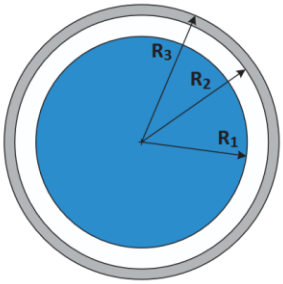
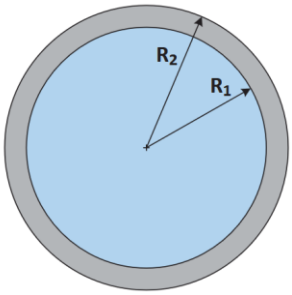


Fig. 2 Fuel assembly cross section



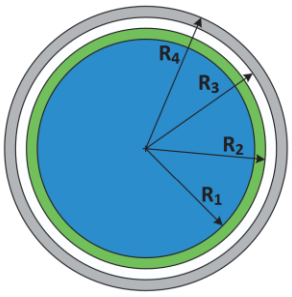
Symbol	Material	Radius [cm]
R_1	UO_2	0.409575
R_2	Helium	0.417830
R_3	ZIRLO	0.474980

Fig. 3 Fuel rod cross section [4]



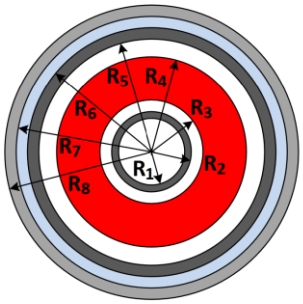
Symbol	Material	Radius [cm]
R_1	Water	0.56134
R_2	ZIRLO	0.61214

Fig. 4 Guide tube cross section [4]



Symbol	Material	Radius [cm]
R_1	UO_2	0.409595
R_2	ZrB_2	0.412155
R_3	Helium	0.417830
R_4	ZIRLO	0.474980

Fig. 5 IFBA rod cross section [4]



Symbol	Material	Radius [cm]
R_1	Air	0.213995
R_2	SS-304	0.230505
R_3	Air	0.241300
R_4	B_2O_3-SiO_2	0.426720
R_5	Air	0.436880
R_6	SS-304	0.483870
R_7	Water	0.561340
R_8	ZIRLO	0.612140

Fig. 6 Pyrex rod cross section [4]

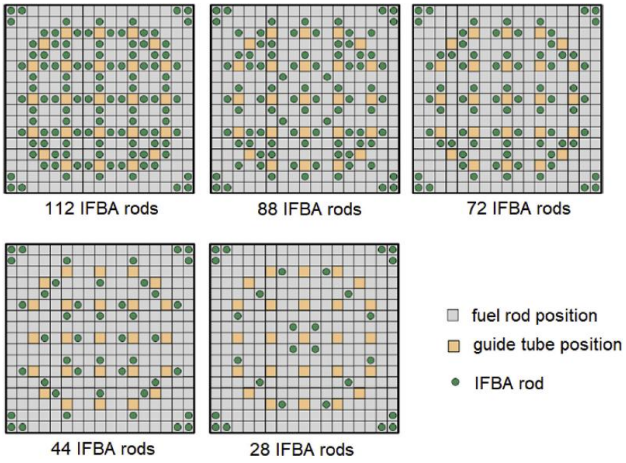


Fig. 7 Configurations of the IFBA burnable absorber rods in the AP1000 fuel assemblies [5]

The calculation began by recreating the detailed geometry of the AP1000 in PRAGMA. Simulations were carried out on quarter core with central symmetry. The number of simulated particles per calculation cycle was 50000000. The total amount of cycles was 70 with the first 20 being inactive. PRAGMA uses the ENDF/B-VII.1 nuclear data library for its calculations. The next step was to create 2D, single assembly calculations for the purpose of providing pin-wise cross-section data used in SPHINCS. Pin-wise cross-section data carried over four energy groups. Afterwards, cross-section data for axial and radial reflectors was acquired from the full core geometry. Once the cross-section data was prepared, a SPHINCS input file was made following the AP1000 specifications together with the created cross-section data. The axial mesh for the P/S calculations was divided into 30 nodes, with particular

attention given to aligning the node boundaries with changes in enrichment.

To assess the capabilities of the P/S code system, three different BOC configurations, as specified in the DCD [3], were calculated: Cold Zero Power (CZP), Hot Zero Power (HZP), and HZP 2. Their details can be seen in Table I. It is important to note that in all considered calculations control rods are fully withdrawn. The HZP 2 configuration differs only by a higher boron concentration from HZP and is used for comparison against reference results. Both HZP configurations do not account for thermohydraulic feedback. To further verify the accuracy of P/S relative to PRAGMA, two additional core configurations, one with only axial reflectors and the other with only radial reflectors, were calculated with a vacuum boundary condition.

Table I: Core configuration data

Configuration	Temperature [K]		Boron concentration [ppm]	Xenon	Pressure [bar]
	Fuel	Moderator			
CZP	293.15	293.15	0	None	1.01325
HZP	564.82	564.82	1382	None	155.13
HZP 2	564.82	564.82	1502	None	155.13

3. Results

The main result of the calculation is the k_{eff}. Another result acquired through calculation is the pin-power distribution that can be seen on Fig. 8 and Fig. 9 for the CZP and HZP configuration respectively.

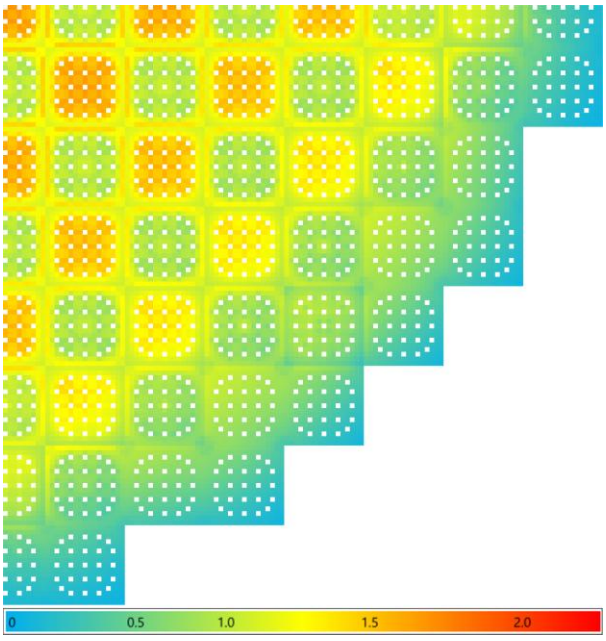


Fig. 8 Pin-power distribution in the 3D AP1000 core calculated by P/S code system for the CZP configuration

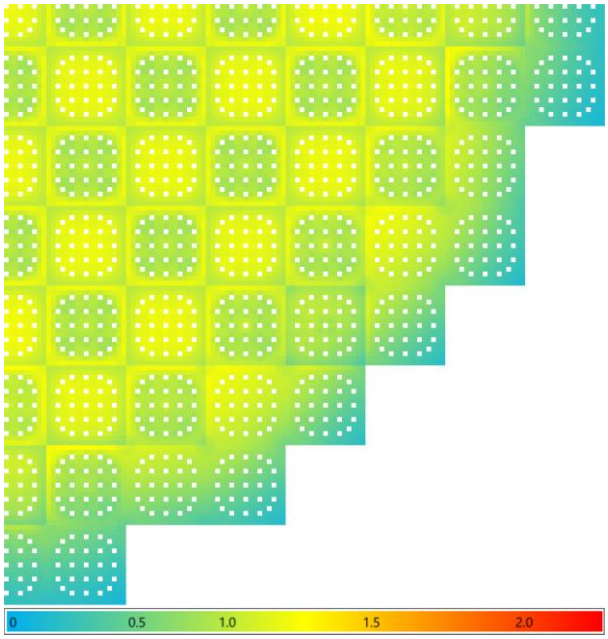


Fig. 9 Pin-power distribution in the 3D AP1000 core calculated by P/S code system for the HZP configuration

It can be seen in Table II that both PRAGMA alone and P/S together give very close results for the CZP and HZP configurations. The Δρ of each configuration to reference result was calculated using Eq. (1).

$$\Delta\rho = \left(\frac{1}{k_{ref}} - \frac{1}{k_{calc}}\right) \times 10^5 \quad (1)$$

The pin-power distribution for the CZP configuration shows high power concentration in the middle of the core as can be seen in Fig. 8. Fig. 9 shows very uniform power distribution with the HZP configuration with a slight decrease at the edges of the core. Table III presents a comparison of the Mean Absolute Error (MAE), Root Mean Square Error (RMSE), and the Maximum Absolute Error (MaxAE) for the normalized 2D radial quarter core pin-power distributions of the two configurations. The error values for the HZP configuration are very low, whereas those for the CZP configuration are higher due to higher moderator density sharpening flux depressions around neutron absorbers degrading SPH performance. The ρ values for the PRAGMA pin power results are larger than the error metrics.

Table IV presents a comparison of the results obtained for configurations with only axial reflectors and only radial reflectors using PRAGMA and P/S. For the axial-reflector configurations, the Δρ values for both the CZP and HZP configurations are statistically insignificant. The radial-reflector configurations exhibit higher Δρ values, but these remain within the acceptable range. As shown in Table V, the Serpent results [5] exhibit somewhat larger deviations from the DCD results [3] compared with the PRAGMA and P/S results for the CZP configuration. On Table VI it can be seen that the boron worth of both PRAGMA and P/S is in agreement with the information presented in the DCD [3].

Table II: K_{eff} comparison for AP1000 core calculations

Configuration	DCD	PRAGMA	PRAGMA ρ (PCM)	Serpent	Serpent ρ (PCM)	P/S	Δρ DCD-PRAGMA (PCM)	Δρ DCD-P/S (PCM)	Δρ DCD-Serpent [PCM]
CZP	1.205	1.20559	6.7	1.20201	2.8	1.20423	40.8	-52.9	-206.4
HZP 2	0.99	0.99030	11.5	0.99188	4.1	0.99146	30.9	148.2	191.5

Table III: Comparison of normalized pin-power fractional error metrics for PRAGMA and P/S

CZP				HZP			
PRAGMA Pin-power ρ	MAE	RMSE	MaxAE	PRAGMA Pin-power ρ	MAE	RMSE	MaxAE
0.32541	0.04044	0.06988	0.22024	0.18684	0.01092	0.02976	0.09937

Table IV: K_{eff} comparison of reflector configurations

Configuration	PRAGMA	PRAGMA ρ (PCM)	P/S	Δρ PRAGMA-P/S (PCM)
CZP axial reflector	1.20185	8.8	1.20144	-28.3
HZP axial reflector	0.99501	13.1	0.99519	18.3
CZP radial reflector	1.20563	7.0	1.20426	-94.4
HZP radial reflector	1.00086	11.1	1.00137	50.1

Table V: K_{eff} comparison between published data and present calculations. Based on this paper's results and information from [3] and [5]

Configuration	DCD	PRAGMA	PRAGMA ρ (PCM)	Serpent	Serpent ρ (PCM)	P/S	Δρ DCD-PRAGMA (PCM)	Δρ DCD-Serpent [PCM]	Δρ DCD-P/S (PCM)
CZP	1.205	1.20559	6.7	1.20201	2.8	1.20423	40.8	-206.4	-52.9
HZP 2	0.99	0.99030	11.5	0.99188	4.1	0.99146	30.9	191.5	148.2

Table VI: Boron worth comparison between this paper's results and the DCD [3]

Configuration	DCD	PRAGMA	PRAGMA ρ (PCM)	P/S	DCD boron worth (PCM/ppm)	PRAGMA boron worth (PCM/ppm)	P/Sboron worth (PCM/ppm)
HZP	1	1.00050	11.2	1.00135	8.42	8.57	8.31
HZP 2	0.99	0.99030	11.5	0.99146			

4. Conclusion

The primary objective of this paper was to compare the calculation results for the AP1000 core achieved through the P/S system with the focus on the CZP and HZP configurations with the DCD data. For the two configurations the results are satisfactory and demonstrate the capability of the P/S code system.

In comparison with the results presented in the referenced Serpent calculations [5], the PRAGMA and P/S results demonstrate closer agreement with the AP1000 DCD results [3]. It should be noted that the referenced Serpent calculations were performed using a different nuclear data library, specifically ENDF/B-VII.0, which may contribute to the observed differences between the results.

Furthermore, it can be noted that the PRAGMA calculations were carried out on a single Nvidia RTX 4080 GPU and took roughly 40 minutes. The P/S calculations require prior PRAGMA calculations that last 30 minutes per assembly type and one hour and 10 minutes for both the axial and radial reflectors. With total preparation time taking seven hours and 50 minutes to complete. However, after the preparations each P/S calculation takes at most 15 seconds on a single AMD Ryzen Threadripper PRO 7985WX 64-core CPU. Since the preparation calculations are only needed to be done once this allows for a major time reduction while calculating out many different core configurations.

The next stage of this work will involve extending the analysis to configurations with control rods and thermohydraulic feedback.

Acknowledgement

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