REACTOR PHYSICS & COMPUTATIONAL ANALYSIS LABORATORY

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

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PRESENTATION OUTLINE

01 **Objective & Code System**

02 **Two-Step Procedure**
Cross-section generation and core solution

03 **AP1000 BOC Model**
Loading pattern, enrichments and absorbers

04 **Calculation Conditions**
Monte Carlo settings and SPHINCS model

05 **Results**
k-eff, boron worth, pin and assembly power

06 **Conclusions & Future Work**

PAPER GOAL

Verification of the accuracy of the PRAGMA/SPHINCS code system

The Code System

PRAGMA
Power Analysis using GPU-based Monte Carlo Algorithm
Developed by SNU

SPHINCS
SPH-based Pin-wise Homogenized Innovative Nuclear reactor Core Solver
Developed by RPL at KINGS

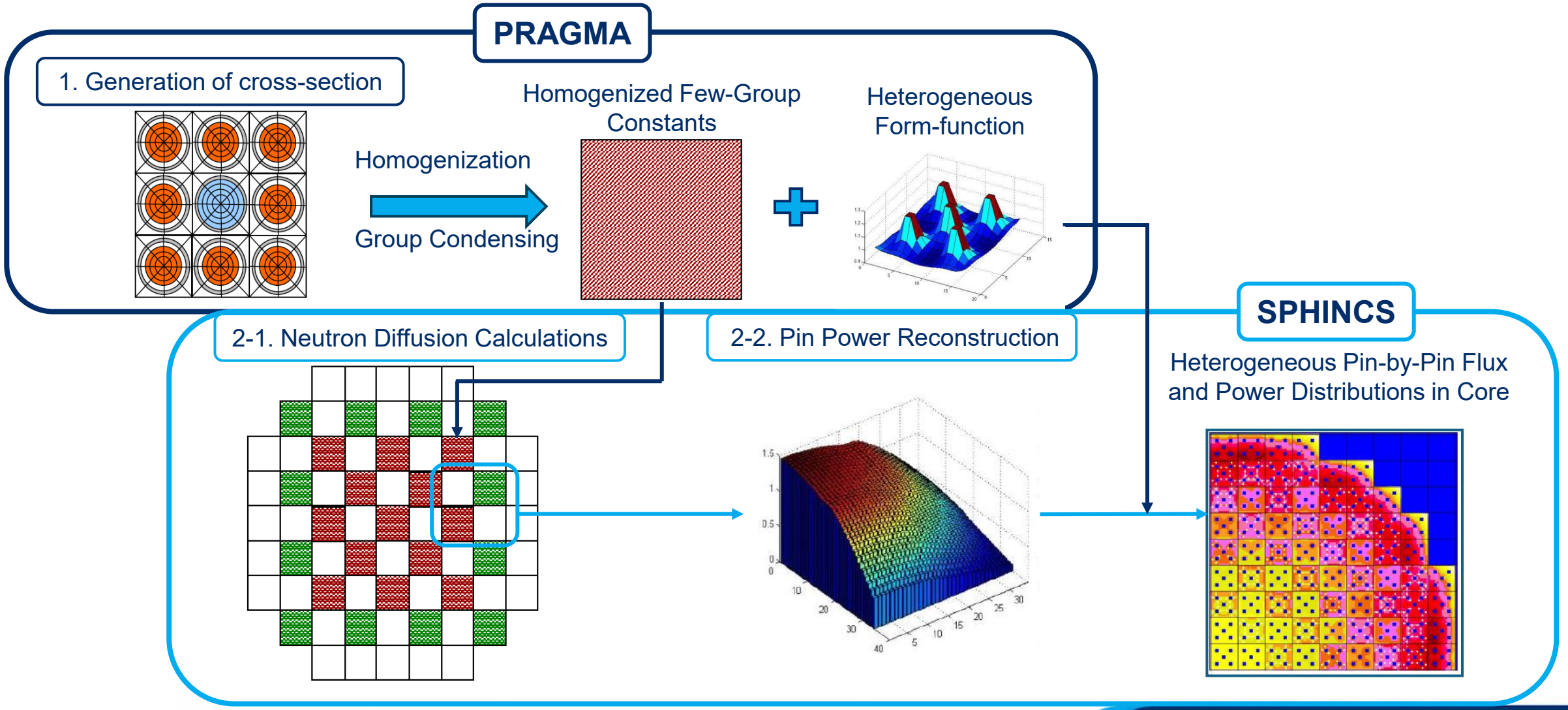
Two-Step Calculation

The Benchmark Reactor

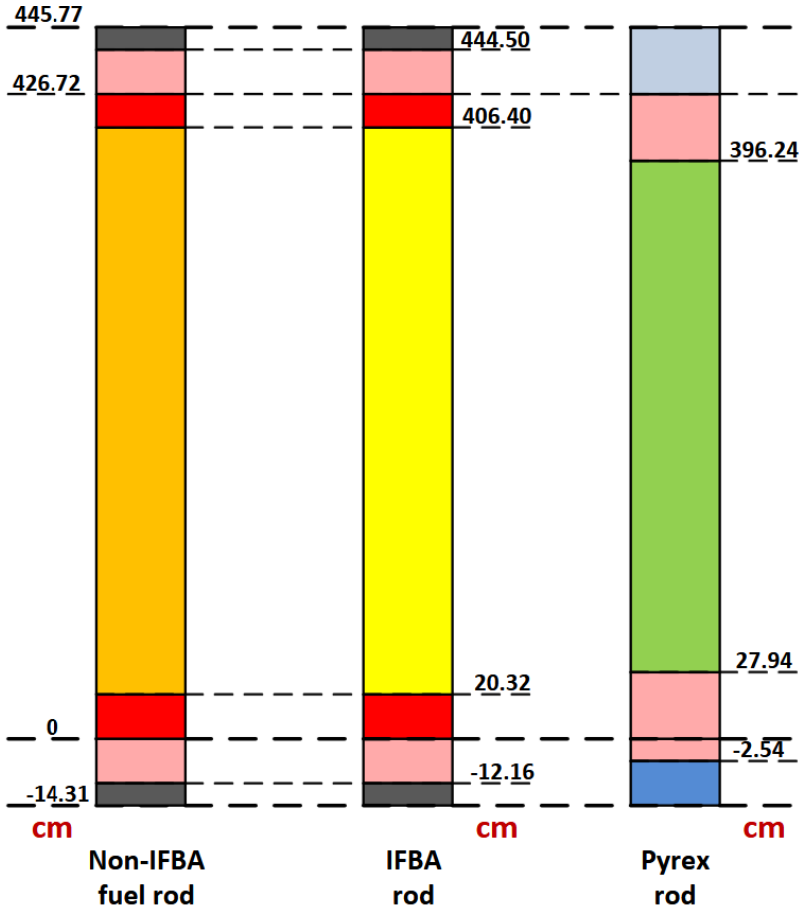
The AP1000 Reactor
Gen III+ PWR

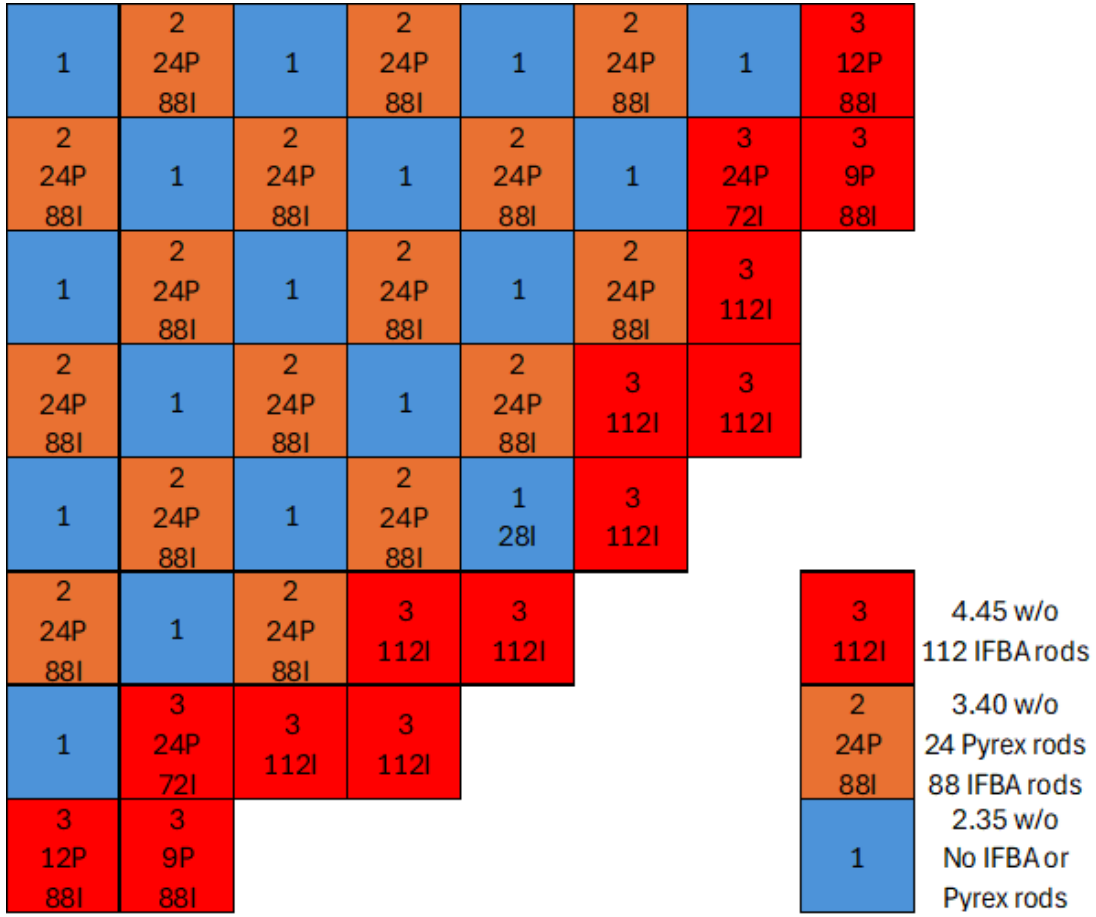
- Designed with passive safety and simplified plant architecture in mind
- 3415 MWth
- 1110 Mwe

TWO-STEP PRAGMA/SPHINCS CALCULATION PROCEDURE



AP1000 BOC CORE DETAILS

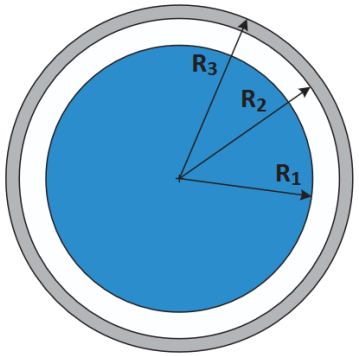




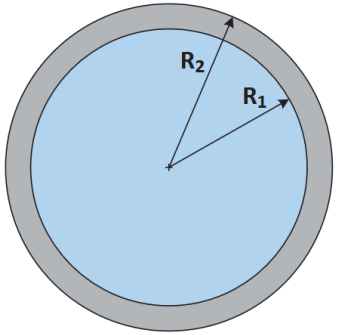
AP1000 BOC

- 157 17x17 fuel assemblies
- 9 different configurations
- 3 enrichment levels
- IFBA and Pyrex rods

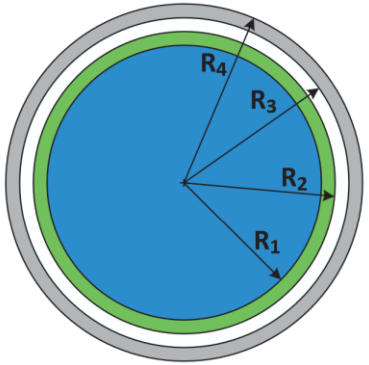
AP1000 BOC CORE DETAILS



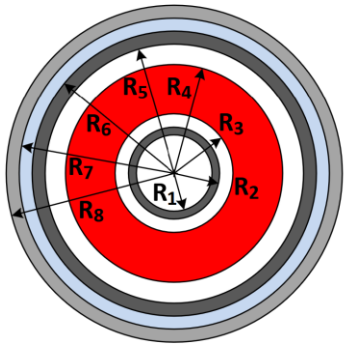
Symbol	Material	Radius [cm]
R_1	UO_2	0.409575
R_2	Helium	0.417830
R_3	ZIRLO	0.474980



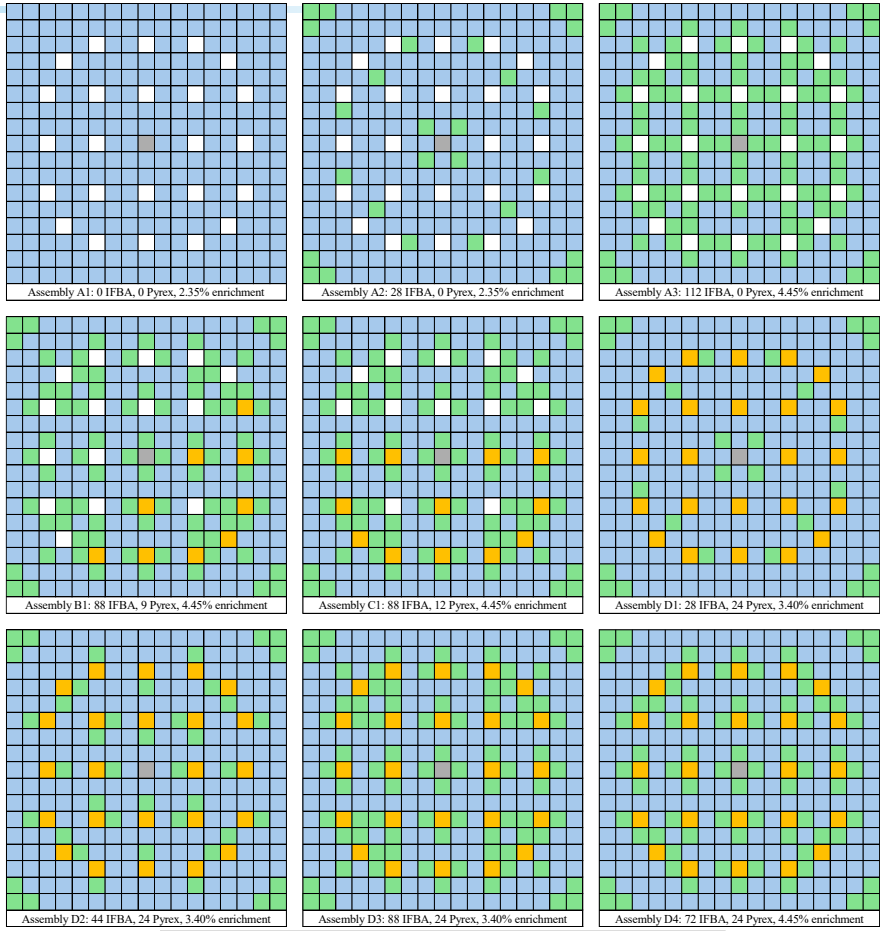
Symbol	Material	Radius [cm]
R_1	Water	0.56134
R_2	ZIRLO	0.61214



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



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



	Fuel rods
	Empty guide tubes
	Empty instrumentation tubes
	IFBA rods
	Pyrex rods

AP1000 BOC

- 157 17x17 fuel assemblies
- 9 different configurations
- 3 enrichment levels
- IFBA and Pyrex rods

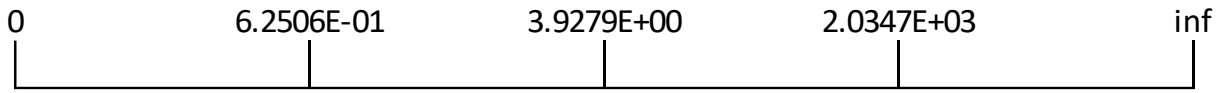
CALCULATION CONDITIONS

PRAGMA

- 50 000 000 Neutrons per cycle
- 20 Inactive + 50 active cycles
- **2.5 bilion** active histories
- ENDF/B-VII.1 Nuclear Data Library
- Whole core calculation time of **~50** minutes

SPHINCS

- Axial mesh with 30 nodes in the active core region
- 4 Energy groups:



- **~15** Seconds for a 3D core calculation
- One time cross section data preparation (**~8 hours**):
  30 minutes per assembly type x 9
  70 minutes for axial and radial reflector each

Once cross-section data exists, each core solve is ~200x faster than whole-core PRAGMA calculation

K_{eff} COMPARISON

Configuration data

Configuration	Temperature [K]		Boron concentration [ppm]	Xenon	Pressure [bar]	DCD K_eff
	Fuel	Moderator				
CZP	293.15	293.15	0	None	1.01325	1.205
HZP	564.82	564.82	1382	None	155.13	1.000
HZP 2	564.82	564.82	1502	None	155.13	0.990

This papers results

PRAGMA

Configuration	K_eff	ρ (PCM)	Δρ DCD [PCM]
CZP	1.205600	6.9	41.3
HZP	1.001657	10.1	165.4
HZP2	0.991526	11.5	155.5

PRAGMA/SPHINCS

Configuration	K_eff	Δρ DCD [PCM]
CZP	1.205776	53.4
HZP	1.002911	290.3
HZP2	0.992973	302.4

Reference results

Darnowski et al.

Configuration	K_eff	ρ (PCM)	Δρ DCD [PCM]
CZP	1.205360	17.0	25.0
HZP	1.000930	24.0	93.0
HZP2	0.990610	26.0	62.0

Stefani et al.

Configuration	K_eff	ρ (PCM)	Δρ DCD [PCM]
CZP	1.202010	2.8	-206.4
HZP2	0.991880	4.1	191.5

Observations

- All PRAGMA/SPHINCS results are within **150 pcm** of PRAGMA results
- CZP is closer (**12.1 pcm**), where both HZP cases are overpredicted (**124.9** and **146.9 pcm**)
- The results show comparable accuracy levels to the DCD with referenced Stefani et al. while Darnowski et al. shows higher model accuracy
- CZP shows increased accuracy to the DCD (**53.4 pcm**)

BORON WORTH COMPARISON

Boron worth analysis

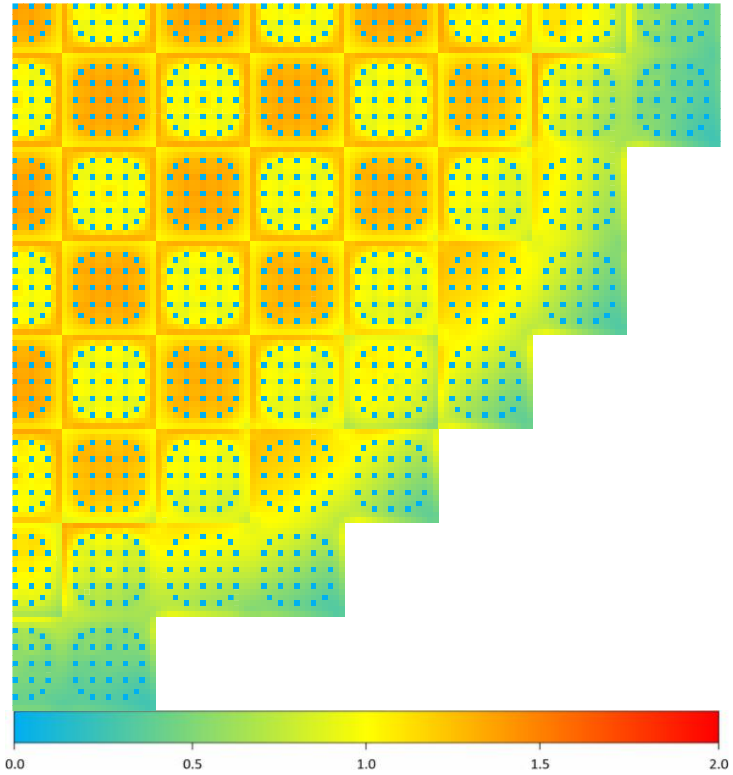
Configuration	HZP	HZP 2
Boron concentration [ppm]	1382	1502
DCD k_eff	1	0.99
PRAGMA k_eff	1.00166	0.99153
PRAGMA ρ (PCM)	10.1	11.5
PRAGMA/SPHINCS k_eff	1.00291	0.99297
DCD boron worth (PCM/ppm)	8.42	
PRAGMA boron worth (PCM/ppm)	8.50	
Difference DCD-PRAGMA [%]	0.99%	
PRAGMA/SPHINCS boron worth (PCM/ppm)	8.32	
Difference DCD-PRAGMA/SPHINCS [%]	-1.21%	

Observations

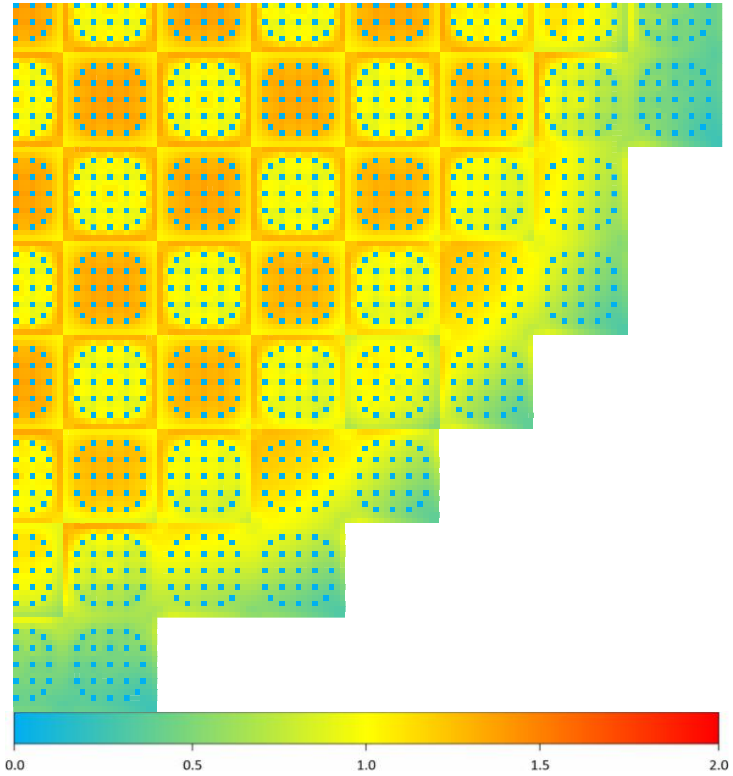
- Worth derived from Δρ between HZP (**1382 ppm**) and HZP2 (**1502 ppm**)
- Boron worth: DCD **8.42**
  PRAGMA **8.50**
  PRAGMA/SPHINCS **8.32**
- Relative difference between the DCD and both codes is within **1.5%**
  (PRAGMA **0.99%**
  PRAGMA/SPHINCS **-1.21%**

PIN-POWER COMPARISON HFP QUARTER CORE

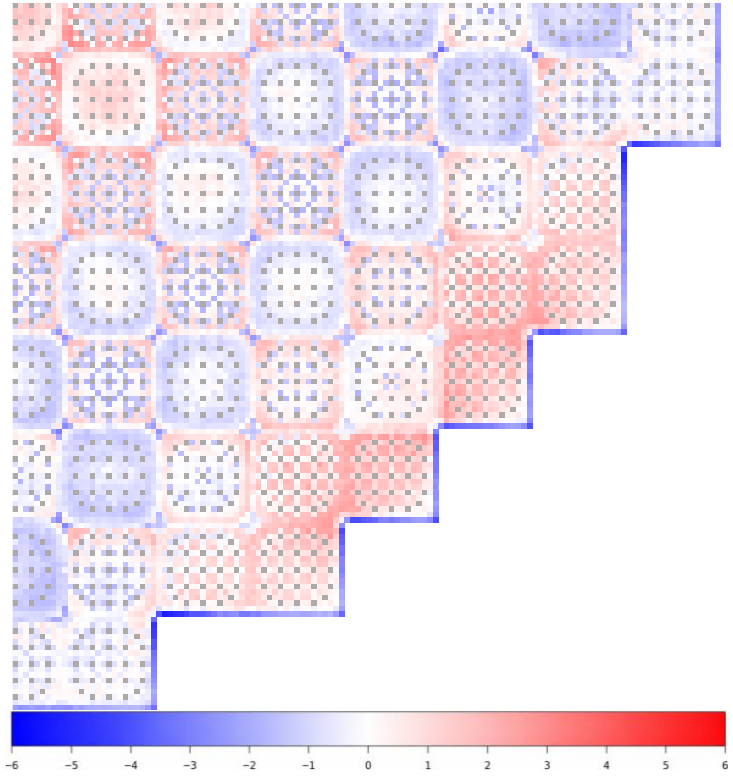
PRAGMA



PRAGMA/SPHINCS



Absolute difference



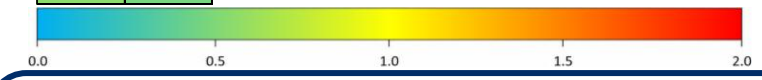
- Absolute difference is: (PRAGMA/SPINCS - PRAGMA) x 100
- Pins at the edges of the core show decreased power

- RMSE is **0.784** while MAX is **5.328**
- With the outer edge excluded MAX is **3.47**
- PRAGMA/SPHINCS shows higher pin power at the edge of the core

ASSEMBLY WISE POWER COMPARISON FOR HFP

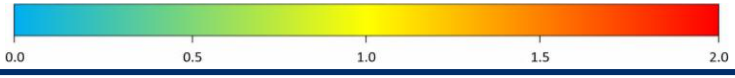
PRAGMA

1.245	1.109	1.241	1.102	1.237	1.112	0.937	0.549
1.109	1.243	1.104	1.233	1.084	1.154	0.880	0.470
1.242	1.104	1.231	1.085	1.198	0.992	0.857	
1.102	1.232	1.086	1.192	1.016	1.073	0.643	
1.237	1.085	1.198	1.017	0.897	0.749		
1.113	1.154	0.993	1.076	0.749			
0.938	0.881	0.858	0.644				
0.550	0.471						



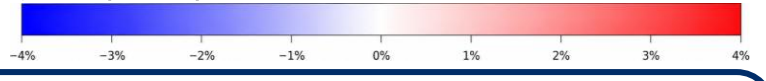
PRAGMA/SPHINCS

1.252	1.117	1.243	1.103	1.229	1.111	0.927	0.546
1.117	1.247	1.108	1.228	1.082	1.146	0.880	0.466
1.243	1.108	1.229	1.085	1.193	0.994	0.859	
1.103	1.228	1.085	1.188	1.020	1.084	0.648	
1.229	1.082	1.193	1.020	0.898	0.755		
1.111	1.146	0.994	1.084	0.755			
0.927	0.880	0.859	0.648				
0.546	0.466						



Absolute difference

0.73%	0.83%	0.18%	0.07%	-0.81%	-0.15%	-0.95%	-0.31%
0.84%	0.40%	0.42%	-0.46%	-0.23%	-0.82%	-0.04%	-0.44%
0.12%	0.41%	-0.25%	-0.01%	-0.49%	0.20%	0.22%	
0.08%	-0.43%	-0.06%	-0.37%	0.37%	1.06%	0.53%	
-0.85%	-0.28%	-0.53%	0.28%	0.09%	0.65%		
-0.21%	-0.83%	0.07%	0.83%	0.61%			
-1.05%	-0.14%	0.08%	0.39%				
-0.37%	-0.46%						



- There is a small (**~0.50%**) decrese in power in the middle ring of the core
- In the center of the core and at the edges there is an increase in power (**~0.80%**)
- The RMSE is **0.44** and MAX **1.06**

CONCLUSIONS

K_{eff}

- PRAGMA/SPHINCS shows accurate results even when calculating complex heterogeneous cores

Boron Worth

- PRAGMA/SPHINCS within **-1.21%** of the DCD
- PRAGMA within **0.99%**

Pin-Power Distribution

- PRAGMA/SPHINCS showcases very accurate pin-power and assembly power distribution when compared to PRAGMA

Computational Efficiency

- Constants need to be generated **only once**, and can be reused for many repeated calculations (**~15 s** each)
- **~200x** faster than equivalent calculation using PRAGMA

Future Work

Next steps:

- Depletion calculation
- Control rod modeling
- Thermal-hydraulic feedback coupling
- Reflection diffusion Coefficient Correction

REFERENCES

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- [2] J. Yoon, H.C. Lee, H.G. Joo, H.S. Kim, High performance 3D pin-by-pin neutron diffusion calculation based on 2D/1D decoupling method for accurate pin power estimation, Nuclear Engineering and Technology 53 (11) (2021) 3543–3562, https://doi.org/10.1016/j.net.2021.05.028.
- [3] Westinghouse, 2011. AP1000 Design Control Document Rev. 19. Chapter 4 – Section 4.3 – Reactor, Nuclear Design.
- [4] P. Darnowski, P. Ignaczak, P. Obrębski, M. Stępień, and G. Niewiński, Simulations of the AP1000-based reactor core with Serpent computer code, Archive of Mechanical Engineering, Vol. LXV, No. 3, 295-325, 2018.
- [5] G. L. Stefani, J. M. L. Moreira, J. R. Maiorino, and P. C. R. Rossi, Detailed neutronic calculations of the AP1000 reactor core with the Serpent code, Progress in Nuclear Energy, Vol. 116, pp. 95-107, 2019

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Thank You

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Questions and Answers