Validation of SERPENT2/SUBCHANFLOW using Beginning-of-Transient Experimental Data from Rostov-2 VVER-1000 Core at 36.37 EFPD

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Outline

Introduction

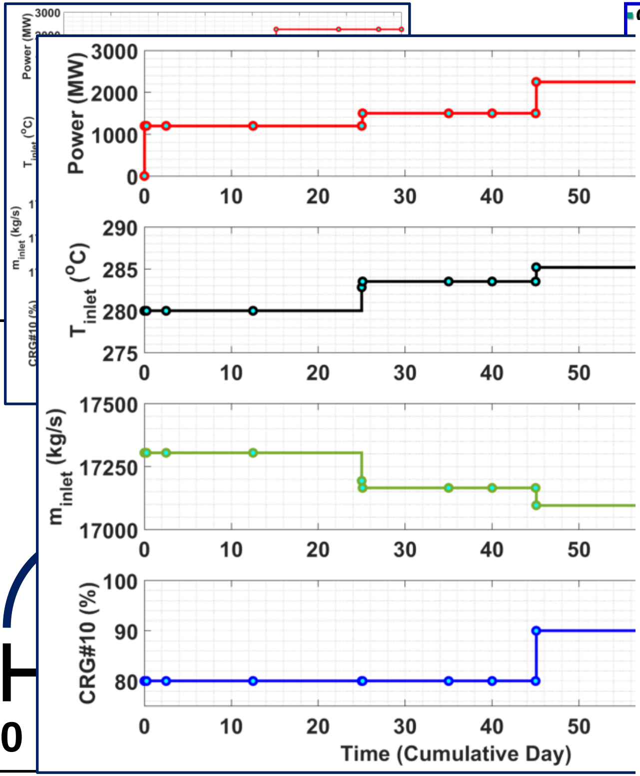
- Pin and subchannel level depletion simulations using **SERPENT2/SUBCHANFLOW***
  - **Update of inputs**
    - Employed the definition of “cumulative total days” in benchmark** for burnup steps
  - A comprehensive code-to-code comparisons and evaluations of the results

- Core Characterization at the beginning-of-transient
  - Utilization of burnup-dependent core composition
  - **Validation** includes both neutronic and thermal-hydraulic comparisons with measured data
    - Assess model accuracy and predictive capability

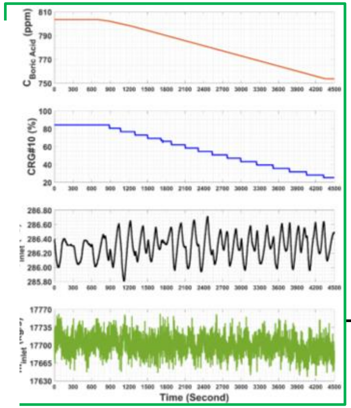
* Diego Ernesto Ferraro. 2021. Monte Carlo-based multi-physics analysis for transients in Light Water Reactors. PhD thesis, Karlsruhe Institute of Technologie (KIT), Karlsruhe, GERMANY

*** M. Avramova, K. Ivanov, P. Rouxelin, Y. Kutllu, K. Velkov, S. Nikonov, P. Gordienko, B. Shumskiy and O. Kavun, "Benchmark on reactivity compensation of boron dilution by stepwise insertion of control rod cluster into the VVER-1000 core, Specifications and Support Data, Version 2.0," OECD/NEA. NEA/EGMPEBV/DOC(2024), 2024.*

Rostov-2 VVER-1000 Core:
Reactivity Compensation Experiment



- **Core at 36.37 EFPD (31.5.2010)**
  - Average Core Burnup level at ~1.45 MWd/kg_U
  - Critical control rod position: 10 CR group banks located in 61 FAs
    - CR Groups 1-9: ARO
    - CR Group 10: 84.43% ARO (15.17 %ARI)
  - Boric acid concentration: 4.6 g/kg (803.5 ppm)
- **TH-Parameters at Transient start**
  - Power: 2097.6 MW (69.92% of nominal Power)
  - Core inlet temperature: 559.15 K
  - Primary system pressure: 15.7 MPa
  - Loops mass flow rate (100%): 18262.78 kg/s
    - Core mass flow rate (97%) : 17714.89 kg/s
    - Bypass mass flow rate (3 %) : 547.89 kg/s



Boron dilution and stepwise CR insertion transient test

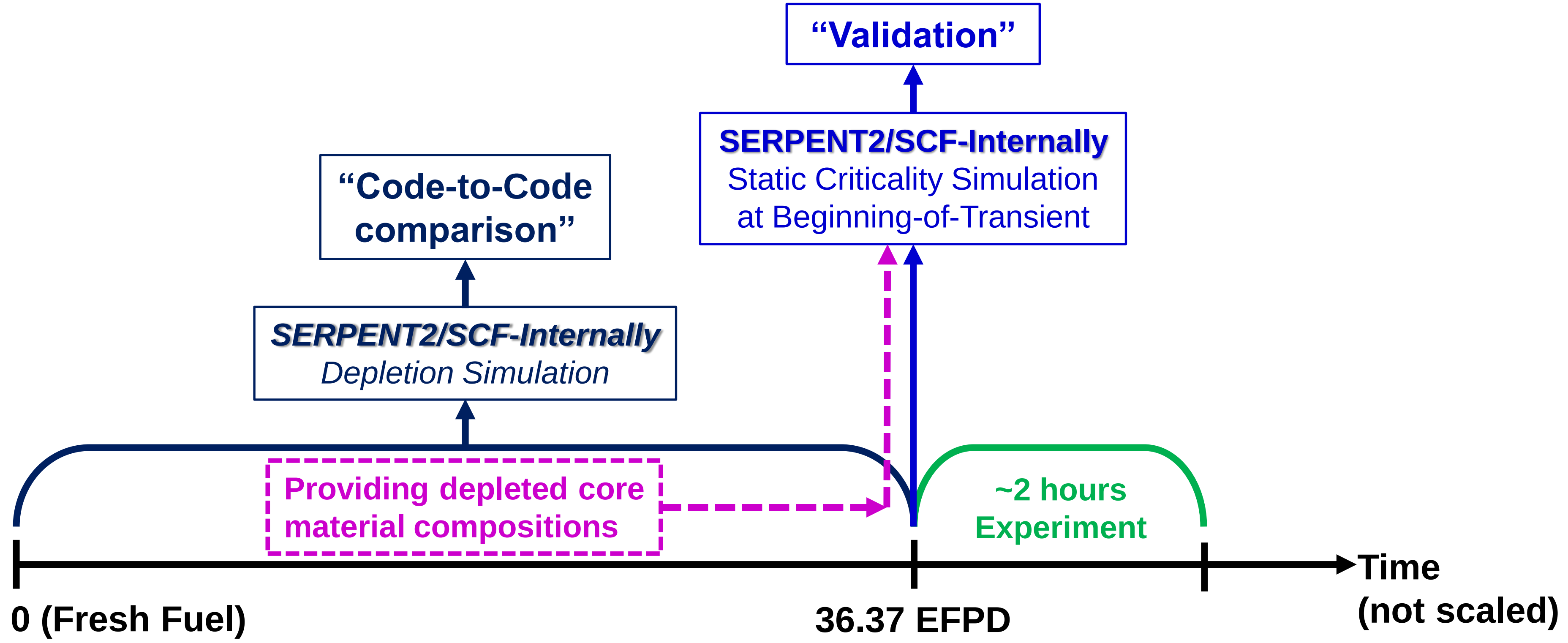
0

Time (not scaled)

Reactor operation history

Analysis Approach and Modelling

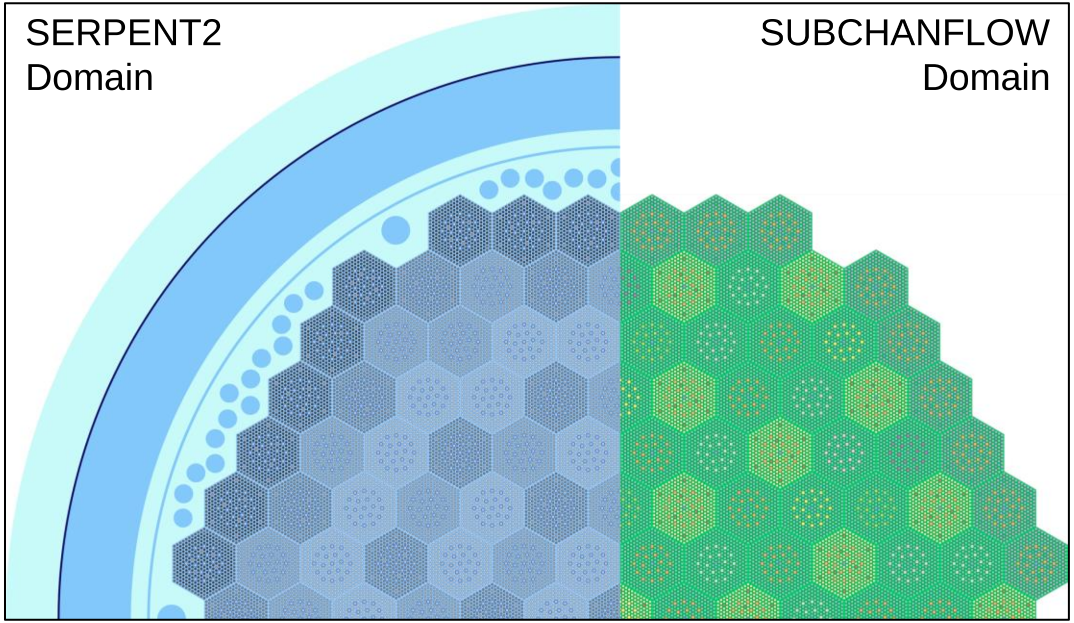
Analysis Approach



Reactor operation history

Core Models

- 53953 independent fuel cells definitions
- 'Explicit' modelling
- Xenon is poisoning
- 15 axial depletion division
- 762,840 depletion zones

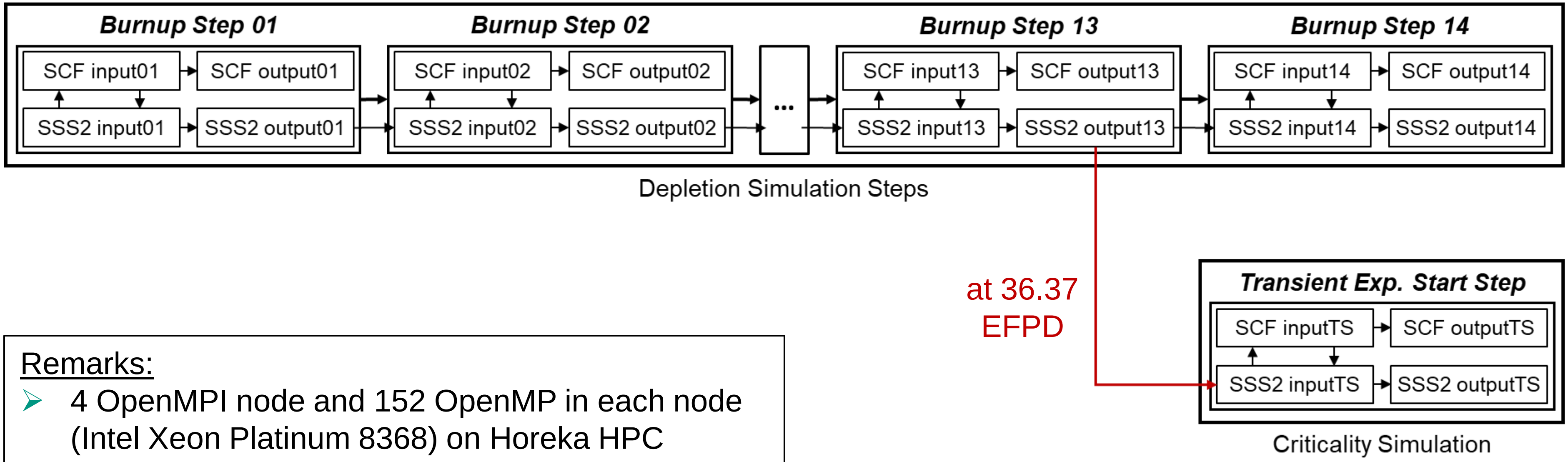


Radial View of SERPENT2 and SUBCHANFLOW core models

- 53953 subchannels and fuel rods
- Radially: 10+2 nodes for fuel and clad
- VVER-specific thermo-physical properties

- Axially 30 interface nodes to exchange feedback

Solution Methodology

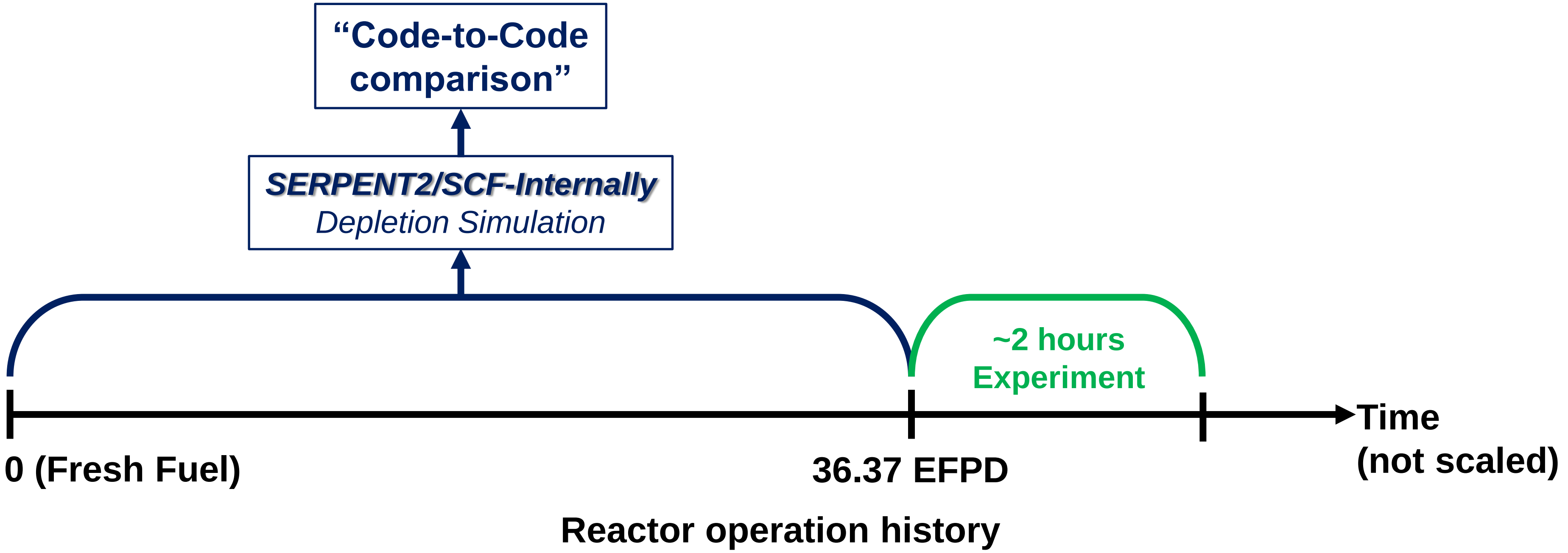


Remarks:

- 4 OpenMPI node and 152 OpenMP in each node (Intel Xeon Platinum 8368) on Horeka HPC
- Total memory ~0.75 TB
  - with domain decomposition method
- Total sim. time for depletion **~408 hours**.

Discussion of Results

Analysis Approach

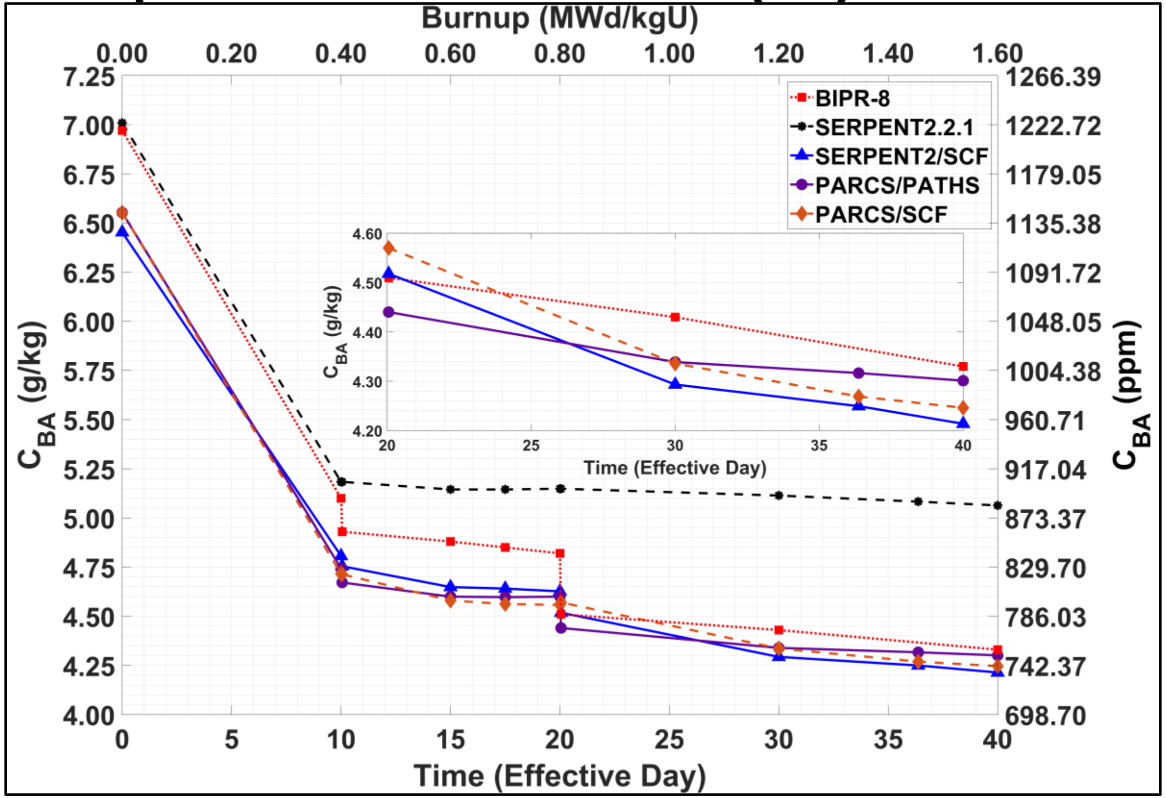


Code-to-Code Comparison: Global Results (1/2)

Comparison of the Depletion Results

Time Steps			Benchmark		High-Fidelity	3D Nodal Level	
Step	Effective Full Power Days	Cumulative Total Days	BIPR-8 The Calculated Total Core Burnup (MW_d/kg_U)	SERPENT2.2.1 Burnup Estimates (MW_d/kg_U)	*SERPENT2/SCF Burnup Prediction (MW_d/kg_U)*	PARCS/PATHS Burnup Prediction (MW_d/kg_U)	PARCS/SCF Burnup Prediction (MW_d/kg_U)
1	0.0	0.0	*n/a*	0.0	0.0	0.0	0.0
2	0.010	0.025	*n/a*	*n/a*	9.97E-07	0.0	0.0
3	0.100	0.250	*n/a*	3.99E-03	3.59E-03	4.0E-03	0.0
4	1.000	2.500	*n/a*	3.99E-02	3.95E-01	3.9E-01	3.9E-01
5	5.000	12.50	*n/a*	0.199	0.199	0.199	0.199
6	10.00	25.00	0.40	0.399	0.398	0.398	0.398
7	10.05	25.10	0.40	0.401	0.400	0.400	0.400
8	15.00	35.00	0.60	0.598	0.597	0.597	0.597
9	17.50	40.00	0.70	0.698	0.697	0.697	0.697
10	20.00	45.00	0.80	0.797	0.797	0.797	0.797
11	20.05	45.07	0.80	0.799	0.798	0.798	0.798
12	30.00	58.34	1.20	1.196	1.195	1.195	1.195
13	36.37	66.83	*n/a*	1.450	1.449	1.449	1.449
14	40.00	71.67	1.60	1.595	1.594	1.594	1.594

Code-to-Code Comparison: Global Results (2/2)



Change of Critical Boron Concentration

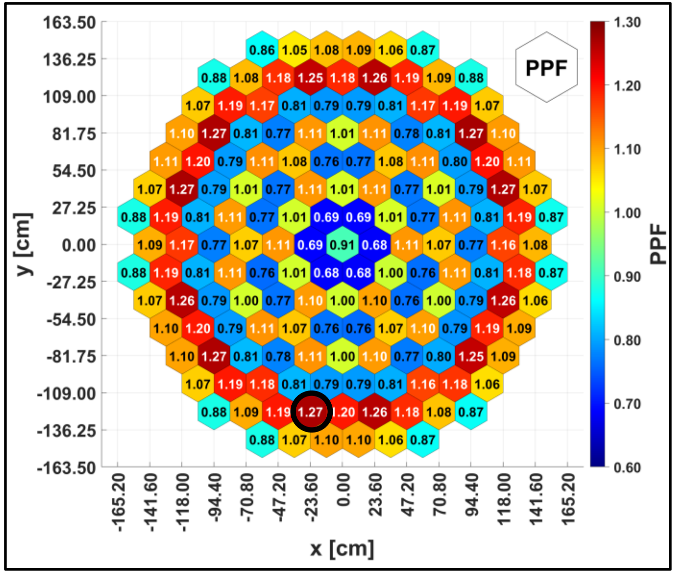
Code-to-Code Comparison: Neutronic Results (1/2)

Comparison of FA Level Power Peaking Factors

T_{eff}, eff. day	BIPR-8 K_q / NK	SSS2/SCF K_q / NK	PARCS/PATHS K_q / NK	PARCS/SCF K_q / NK
0.00	-	-	-	-
10.00	*1.27* / 010	1.27 / 010	1.29 / 010	1.28 / 010
10.05	*1.26* / 154	1.27 / 154	1.27 / 154	1.28 / 154
15.00	*1.25* / 137	1.25 / 137	1.27 / 137	1.26 / 137
17.50	*1.25* / 154	1.24 / 154	1.26 / 154	1.27 / 154
20.00	*1.24* / 027	1.23 / 027	1.26 / 027	1.27 / 027
20.05	*1.21* / 137	1.18 / 137	1.23 / 137	1.25 / 137
30.00	*1.20* / 114	1.15 / 114	1.21 / 114	1.20 / 114
40.00	*1.21* / 110	1.24 / 110	1.18 / 110	1.19 / 110

Where,

K_q: Value of the relative power of the FA, Rel. units.
NK: FA number

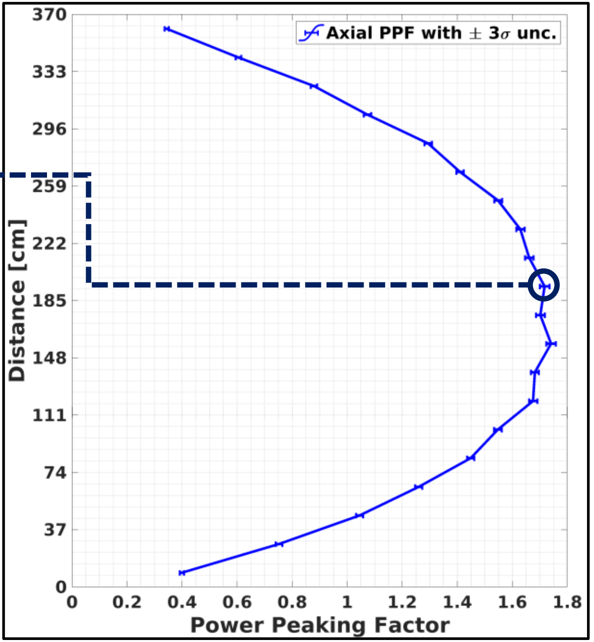


Radial View of FA Level PPFs predicted by SSS2/SCF at 10 EFPD

Code-to-Code Comparison: Neutronic Results (2/2)

Comparison of FA Axial Level PPFs

T_{eff}, eff. day	BIPR-8 K_v / NK-NZ	SSS2/SCF K_v / NK-NZ	PARCS/PATHS K_v / NK-NZ (20 Nodes)	PARCS/SCF K_v / NK-NZ (20 Nodes)
0.00	-	-	-	-
10.00	*1.74* / 010-13	*1.73* / 010-11	1.52 / 010-12	1.52 / 010-12
10.05	*1.72* / 129-12	*1.71* / 129-10	1.08 / 129-11	1.08 / 129-11
15.00	*1.71* / 114-12	*1.69* / 114-10	1.26 / 114-11	1.25 / 114-11
17.50	*1.70* / 010-12	*1.67* / 010-10	1.56 / 010-11	1.57 / 010-11
20.00	*1.69* / 154-12	*1.65* / 154-10	1.57 / 154-11	1.57 / 154-11
20.05	*1.63* / 012-12	*1.56* / 012-10	1.43 / 012-11	1.47 / 012-11
30.00	*1.60* / 010-12	*1.57* / 010-10	1.59 / 010-11	1.61 / 010-11
40.00	*1.59* / 080-13	*1.63* / 080-11	1.35 / 080-12	1.33 / 080-12



FA010 Axial PPF Distribution at 10 EFPD

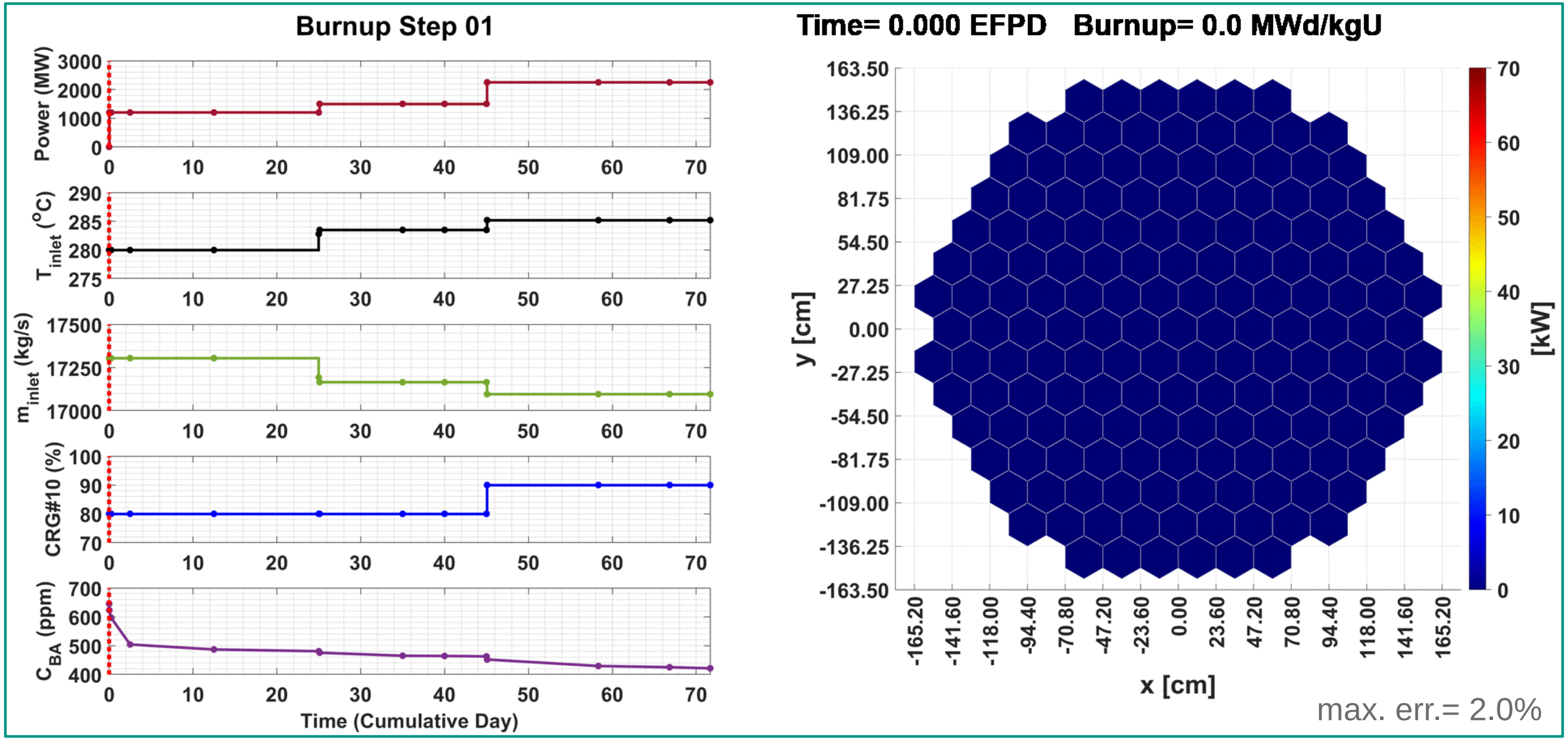
Where,

K_v: Maximum value of the PPF in the core volume, Rel. units.

NK: FA number

NZ: FA axial level (+2 refl. level for SERPENT2, +1 refl. level for PARCS)

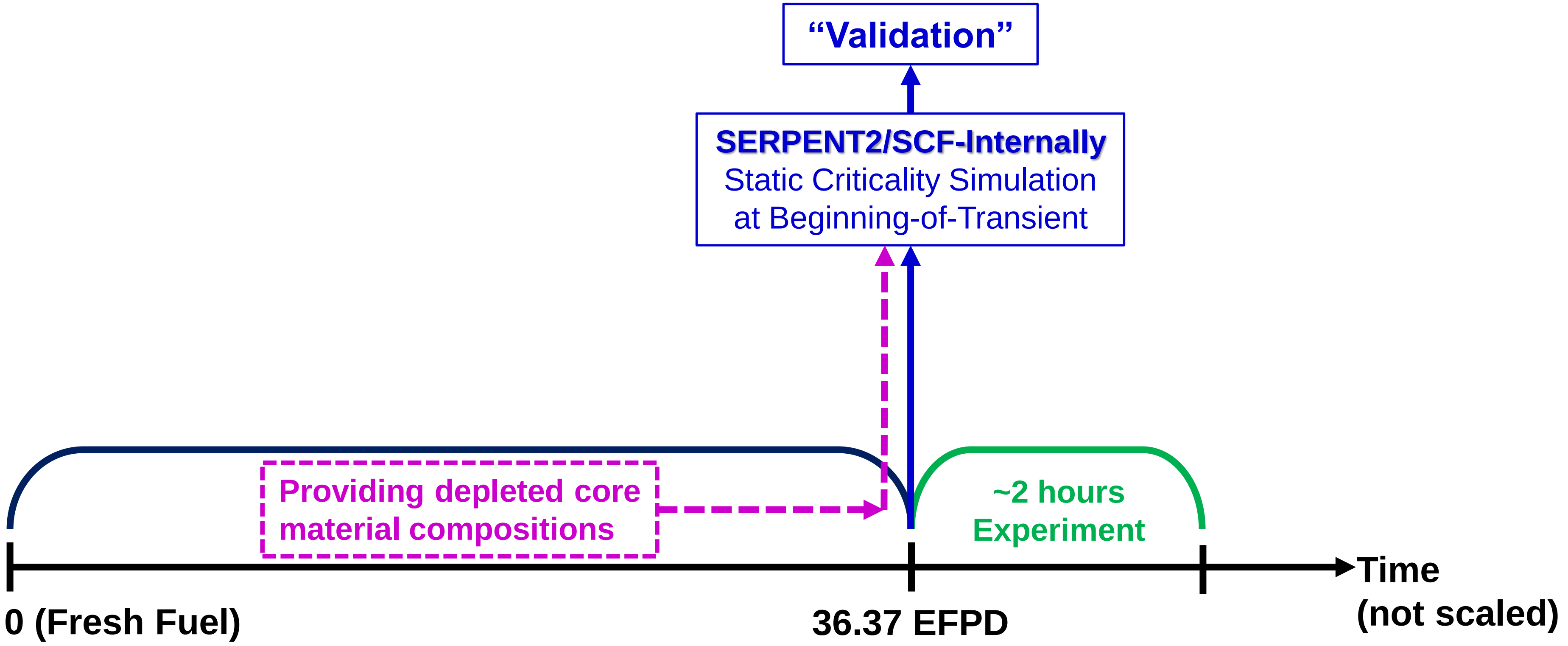
Pin Power Mapping during Depletion Time



Estimation of the change in radial pin level power distributions in the Rostov-2 VVER-1000 core during depletion time by SERPENT2/SUBCHANFLOW

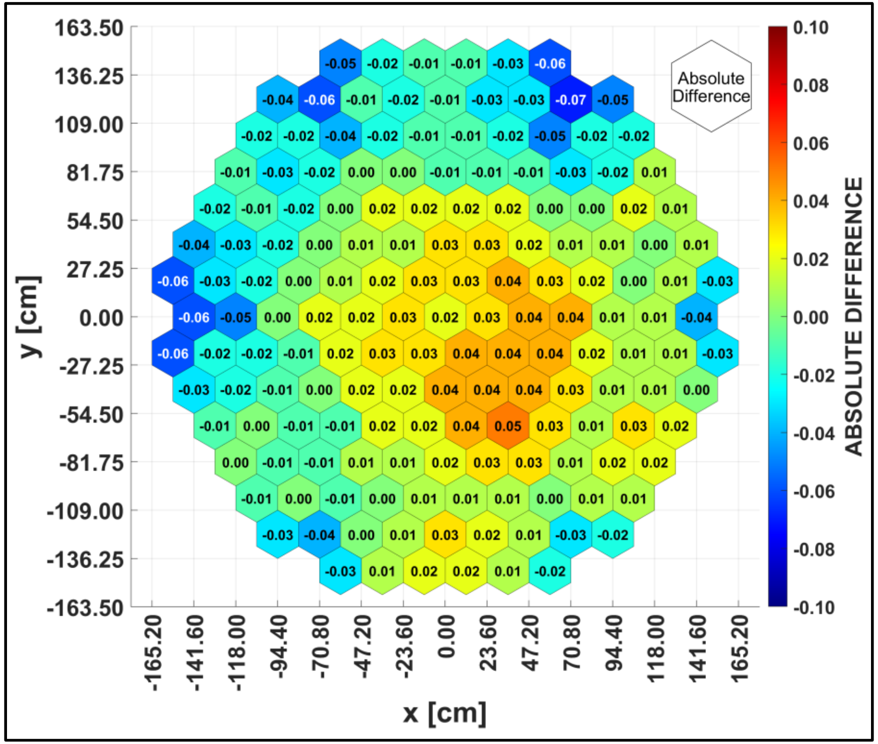
Validation of SERPENT2/SUBCHANFLOW

Analysis Approach



Reactor operation history

FA-Level Neutronic Assessment

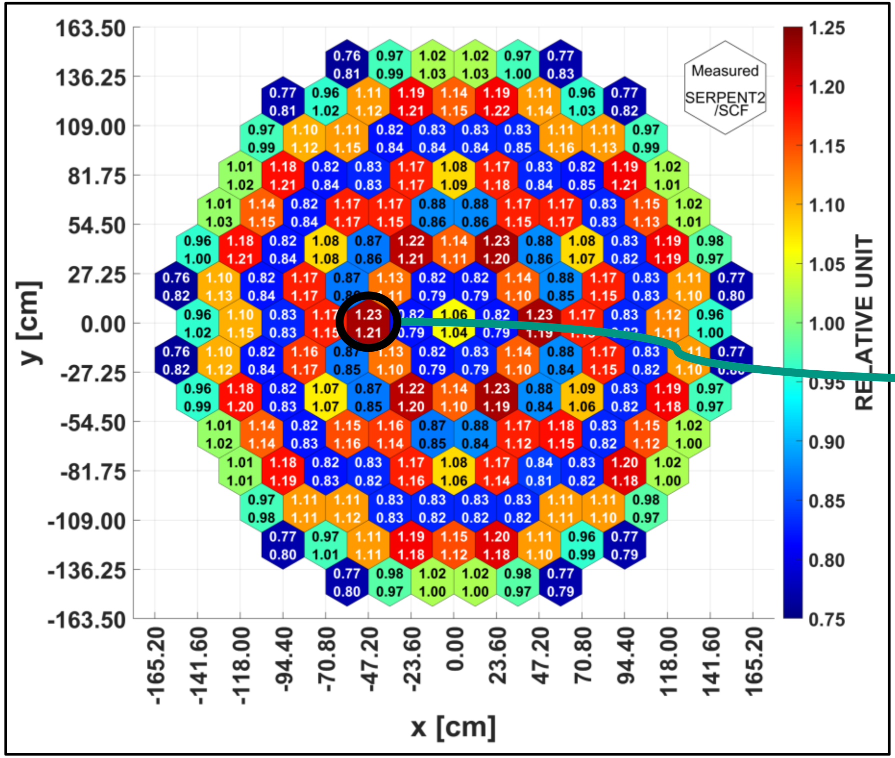


(*difference= measured-calculated*)

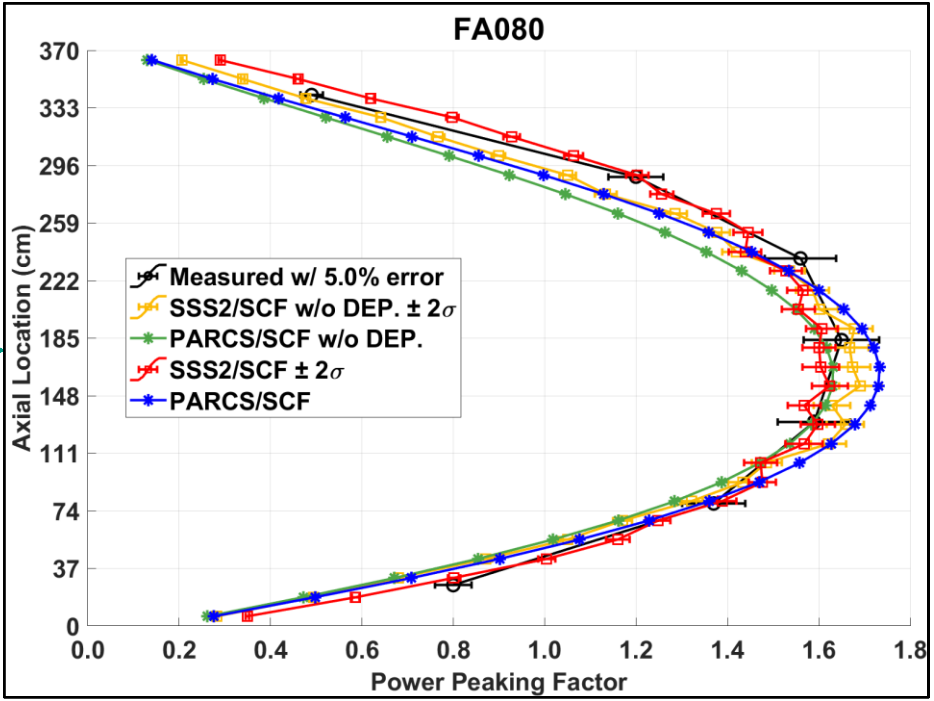
Max. difference ~7%

FA level PPFs variation between measured data and SERPENT2/SCF
at the beginning-of-transient experiment at 36.37 EFPD

FA-Level Neutronic Assessment
Axial Power Profile Evaluation (1/3)

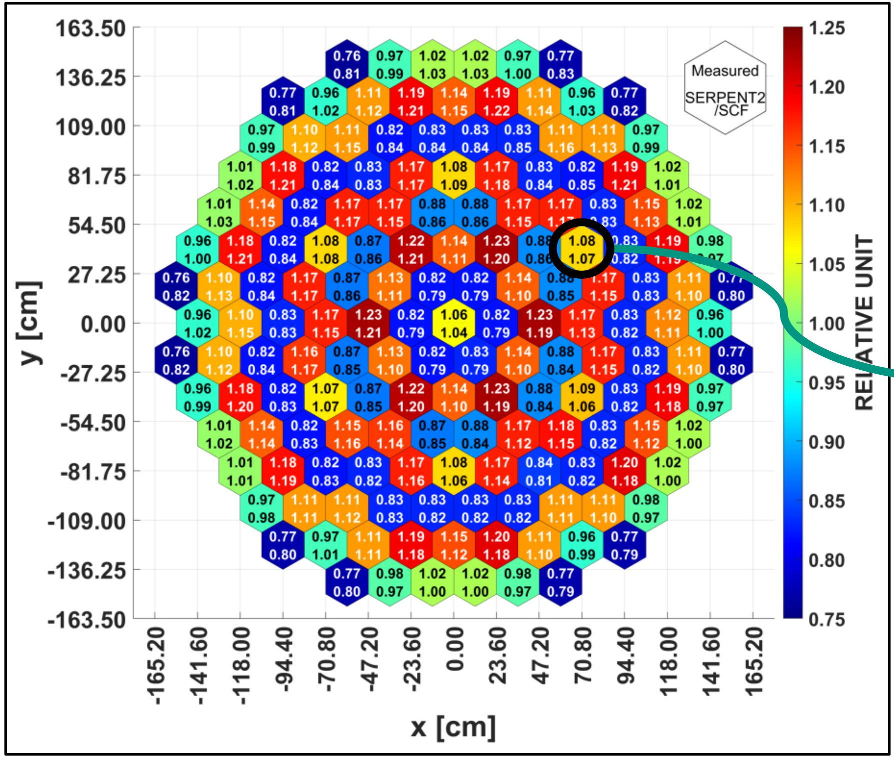


FA-Level Power Peaking Factors

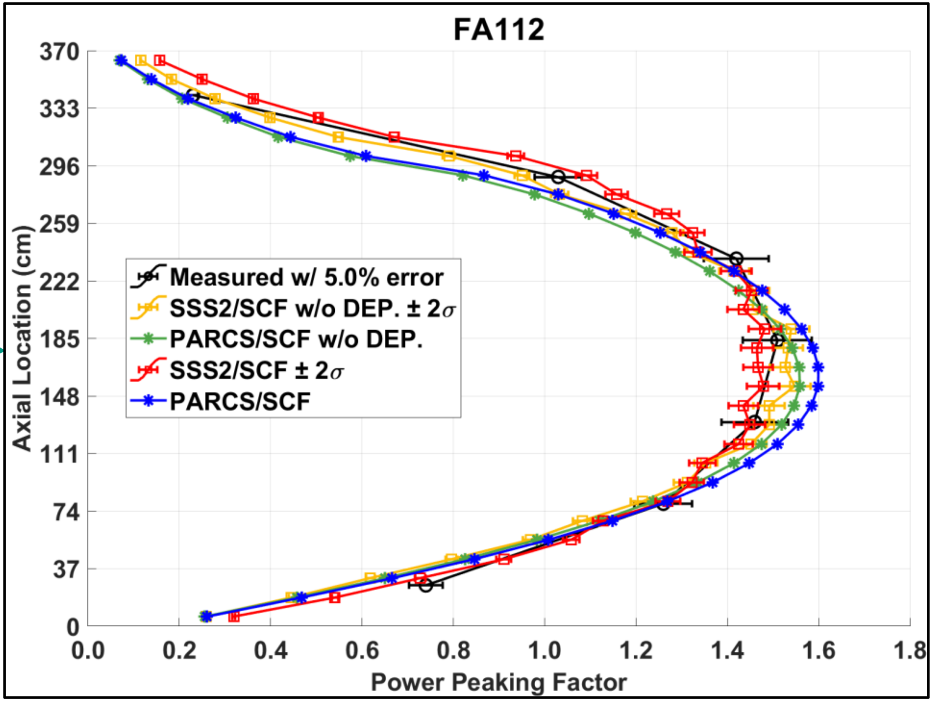


FA080 (highest power FA) axial PPFs

FA-Level Neutronic Assessment
Axial Power Profile Evaluation (1/3)

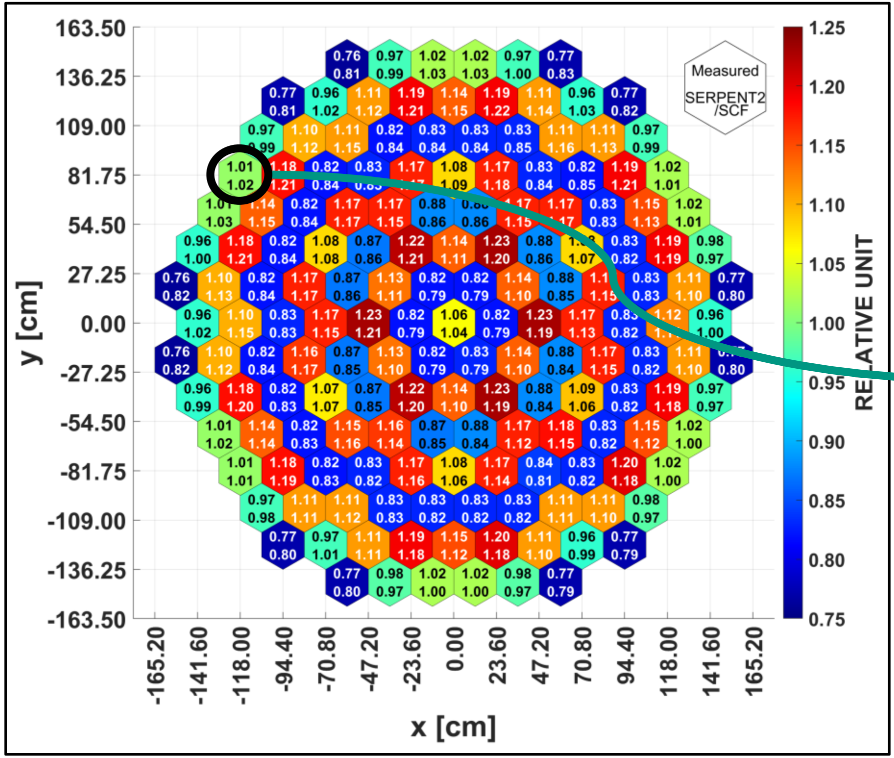


FA-Level Power Peaking Factors

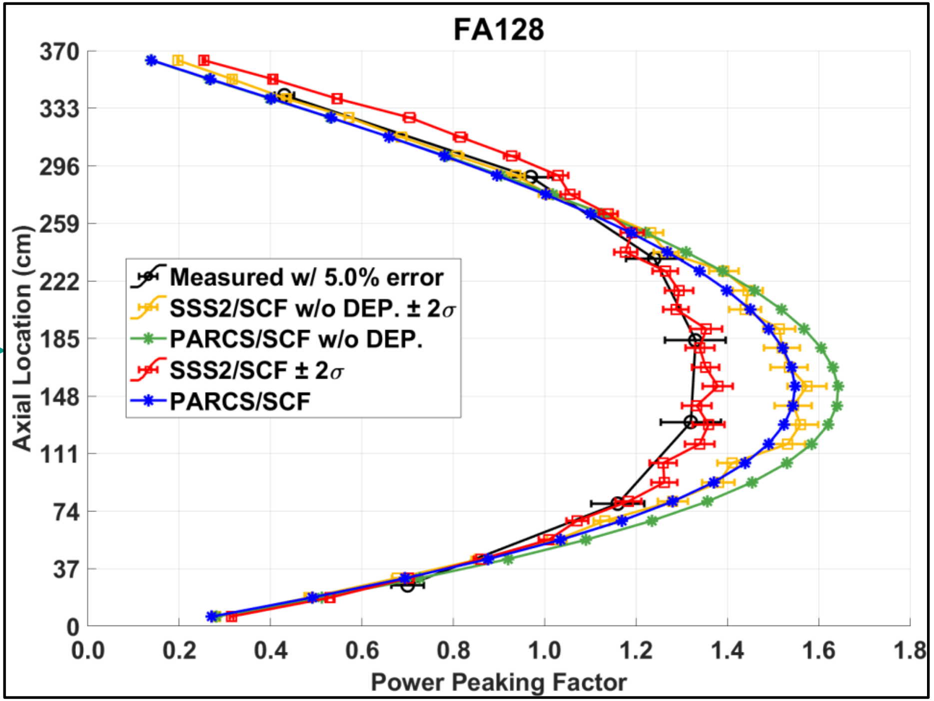


FA112 (CR partly inserted FA) axial PPFs

FA-Level Neutronic Assessment
Axial Power Profile Evaluation (1/3)

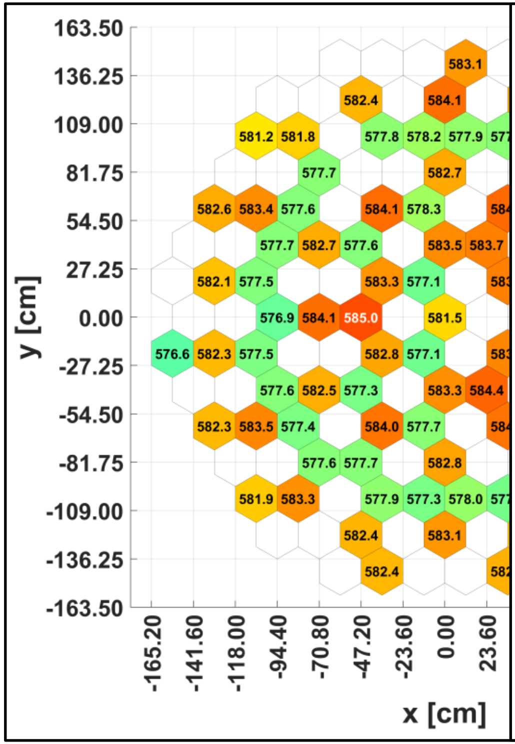


FA-Level Power Peaking Factors

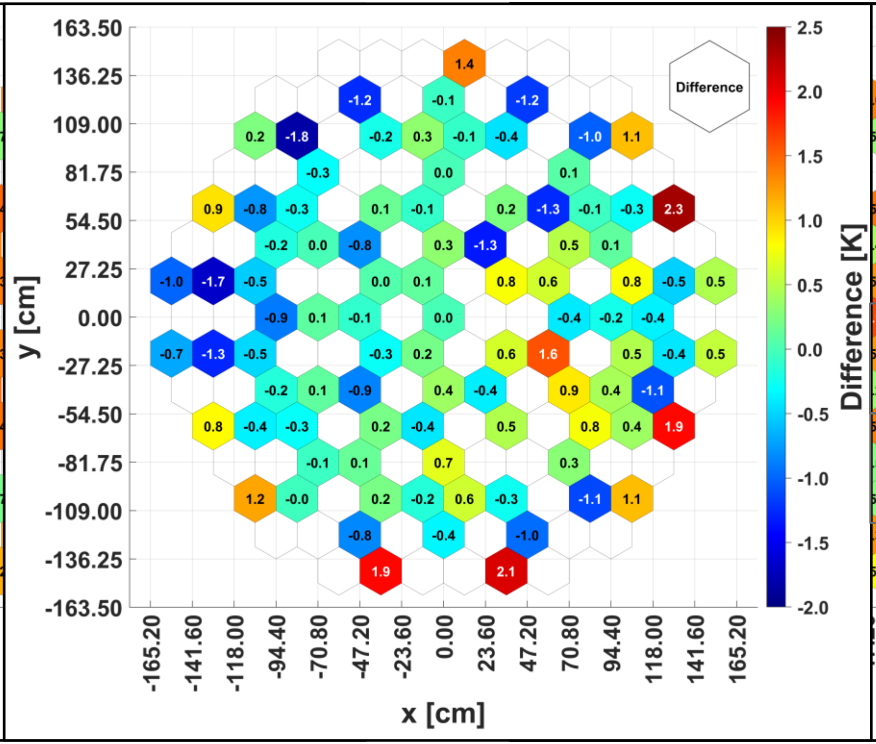


FA128 (including highest power pin) axial PPFs

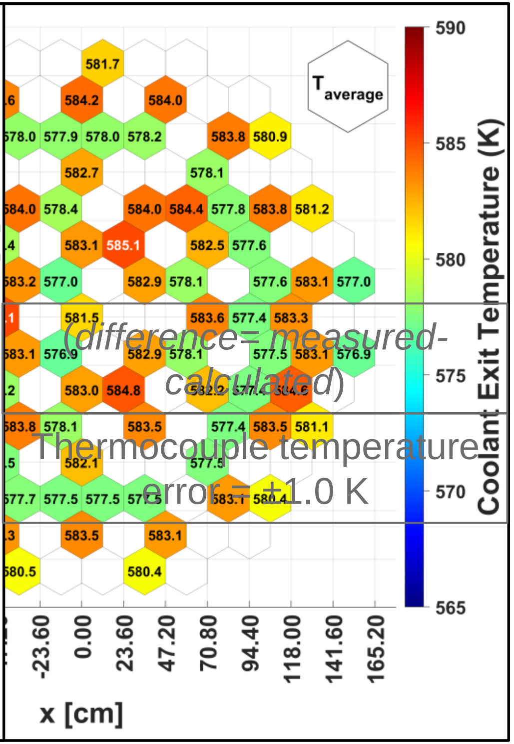
Thermal-Hydraulic Assessment Based on Measured Outlet Temperature



Measured coolant temperature at the FA outlet at the beggining-of-transient experiment

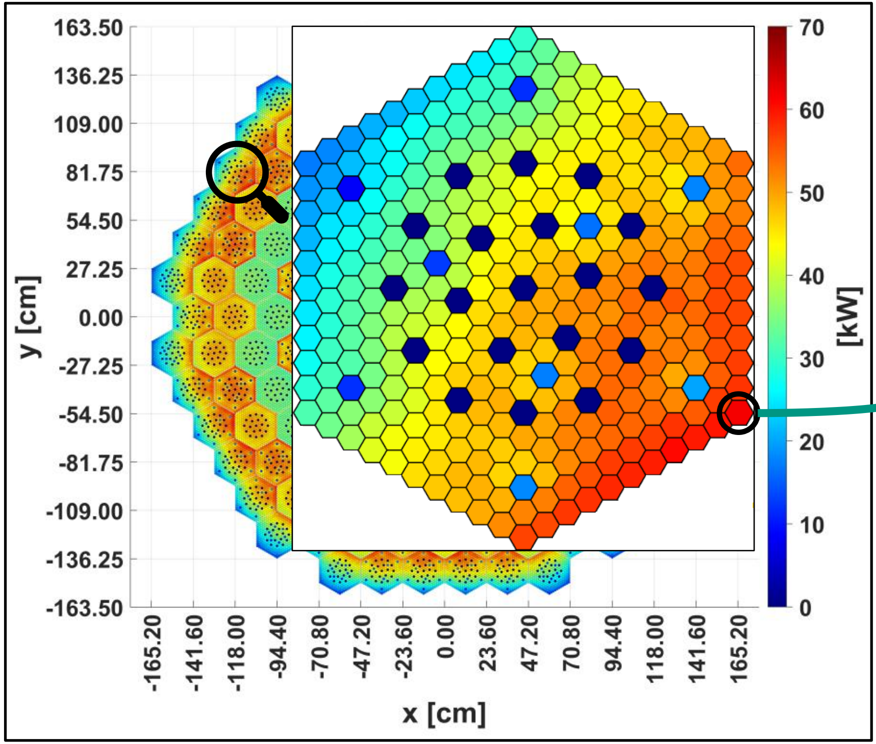


Difference Between measured and calculated FA-level coolant exit temperature in the core

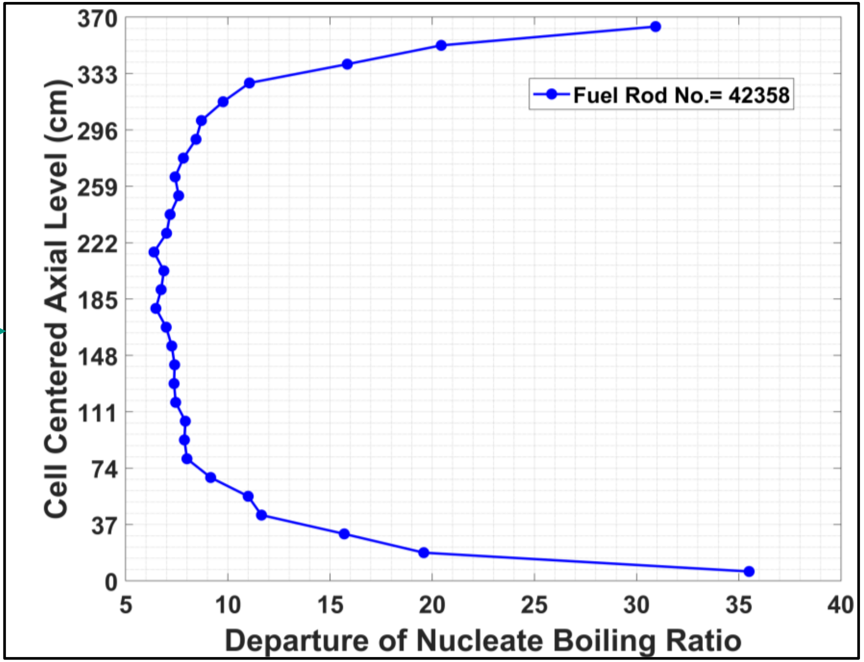


Calculated FA-level average coolant exit temperature distribution in the core by SSS2/SCF

Prediction of Local Parameter with Safety Criteria



SERPENT2/SCF Pin-level power distribution in the core with the location of the pin with the highest power



DNBR prediction for the fuel rod 42358 which generates highest power in the core

Summary & Conclusion

- High-fidelity core analysis was conducted using the coupled SERPENT2/SUBCHANFLOW for the Rostov-2 VVER-1000 core.
  - The study features the first-of-its-kind full-core simulation at the pin and subchannel level for a depleted VVER-1000 core.
  - The core state at 36.37 EFPD was characterized using burnup-dependent isotopic composition derived from internal depletion simulations.

- A good level of agreement was observed between the measured data and the predictions obtained from SSS2/SCF.

- Safety-relevant parameters, such as pin-level power and DNBR, were assessed and found to remain within acceptable margins.

- Results demonstrate the suitability of SERPENT2/SUBCHANFLOW coupling for core characterization and safety-oriented analyses in VVER-type reactors.

Thank you for your attention!

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