KIT Contribution to Phase I: High-Fidelity Pin-by-Pin Burnup Analysis of the VVER-1000 Core Using SERPENT2/SUBCHANFLOW

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Outline

- Objectives
- Tools
- Benchmark on reactivity compensation of boron dilution by stepwise insertion of control rod cluster into the VVER-1000 core
- Static Simulation of the Rostov-2 VVER-1000 Core
  - Neutronic pin-by-pin model for SERPENT2
  - Thermal hydraulic subchannel level model for SUBCHANFLOW
- Validation of SERPENT2/SUBCHANFLOW Depletion Capability Using Rostov-2 VVER-1000 Core Data
  - Burnup History for the Depletion Simulation
  - SERPENT2/SUBCHANFLOW Critical Boron Concentration Simulation
  - Discussion of Results
  - Results for the Transient Experiment Starting Time at 36.37 days
- Conclusion and Outlook

Objectives

- Provide a reference solution for Rostov-2 Benchmark* Phase I with high-fidelity pin-by-pin and subchannel level using SERPENT2/SUBCHANFLOW**
  - Development of the detailed model for the begin-of-cycle (BOC) Rostov-2 VVER-1000 **fresh-core**.

- Validation of depletion capability of SERPENT2/SUBCHANFLOW using data of Rostov-2 Benchmark

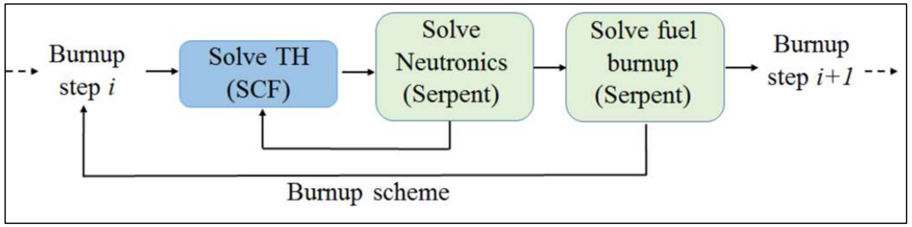
- Provide a detailed information about state of the depleted core at the beginning of transient case.

* M. Avramova, K. Ivanov, 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 1.6," OECD/NEA. NEA/EGMPEBV/DOC(2021), Paris, 2021.
** 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

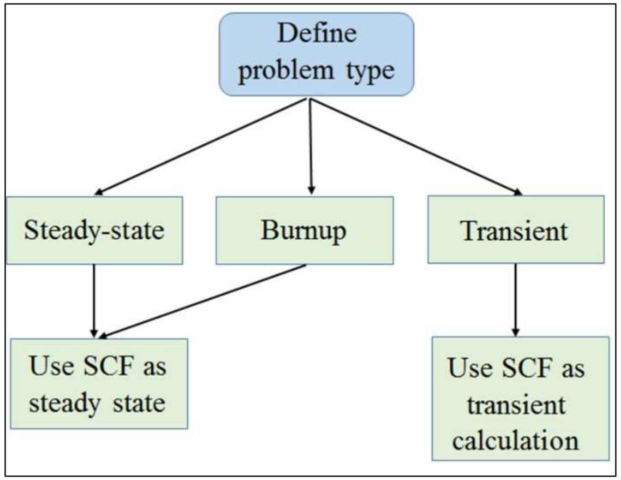
Tools

The internal master-slave SERPENT2/SUBCHANFLOW coupling

- Main aspects:
  - SERPENT2 Version 2.1.32 and SUBCHANFLOW Version 3.7.1.
  - Codes are integrated in a single tool.
  - Interchange of fields internally by memory.
  - Coupled flow control managed by master code SERPENT2.
  - SERPENT2 applies burnup schemes.
  - SCF calculates steady state.



Burnup calculations flow

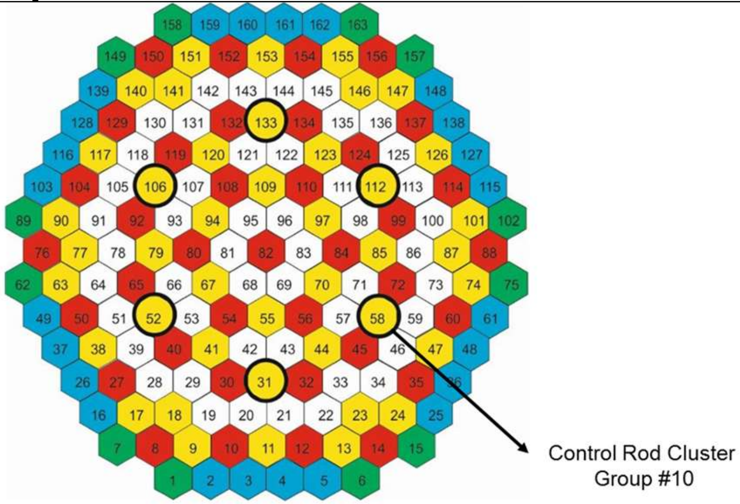


Options in the developed master-slave coupling

- **ENDF/B-VII** neutron libraries were utilized for SERPENT2 simulations.

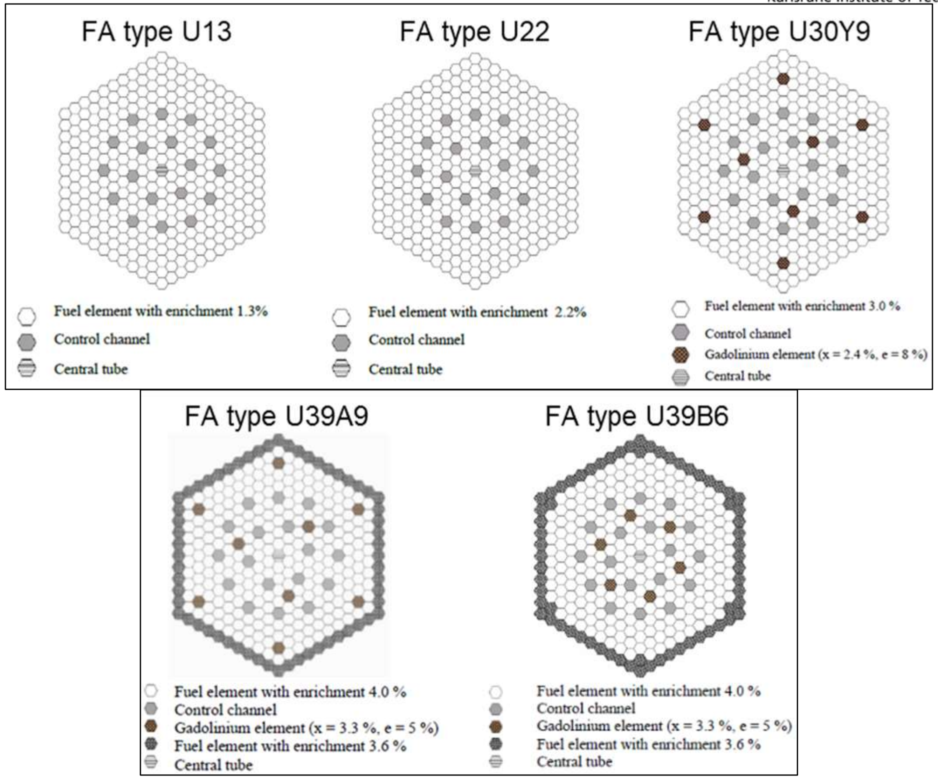
Benchmark on reactivity compensation of boron dilution by stepwise insertion of control rod cluster into the VVER-1000 core

Description of Rostov-2 VVER-1000 Core



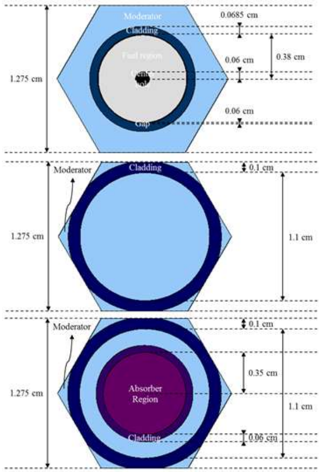
- FA type U39A9 with Uranium-235 3.89% average enrichment (243 fuel rods with 4.0% enrichment, 60 fuel rods with 3.6% enrichment, 9 fuel rods with Gd with 3.3% enrichment, content of Gd2O3 – 5%)
- FA type U30Y9 with Uranium-235 2.98% average enrichment (303 fuel rods with 3.0% enrichment, 9 fuel rods with Gd with 2.4% enrichment, content of Gd2O3 – 8% by weight)
- FA type U39B6 with Uranium-235 3.9 % average enrichment (240 fuel rods with 4.0% enrichment, 66 fuel rods with 3.6 % enrichment, 6 fuel rods with Gd with 3.3% enrichment, content of Gd2O3 – 5%)
- FA type U22 with Uranium-235 2.2% enrichment
- FA type U13 with Uranium-235 1.3% enrichment

Fuel-loading map of the reactor core of Rostov Unit 2, Cycle 1

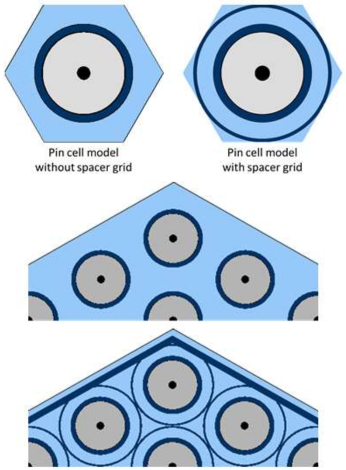


Radial arrangement of elements in the fuel assemblies

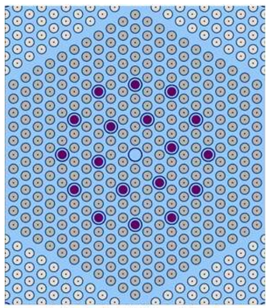
Static Simulation of the Rostov-2 VVER-1000 Core
Neutronic pin-by-pin model for SERPENT2



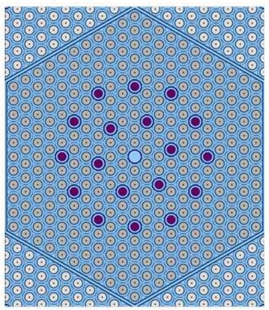
Pin cell models



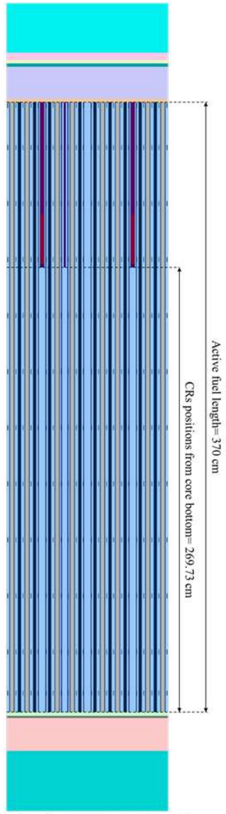
Spacer Grid views



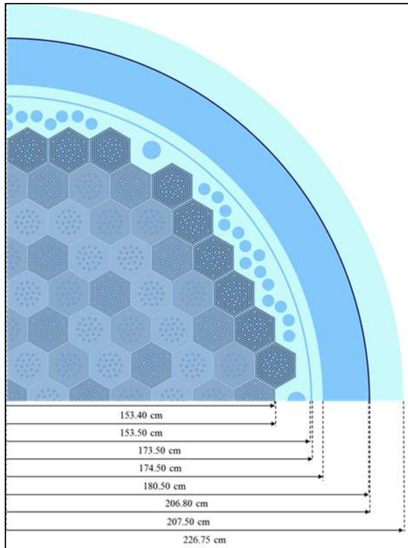
Radial view of partly CR inserted FA model without spacer grid



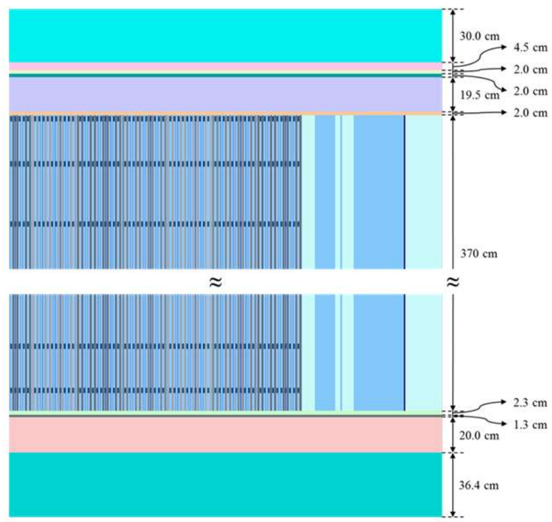
Radial view of partly CR inserted FA model with spacer grid



Axial view of partly CR inserted FA model with spacer grid



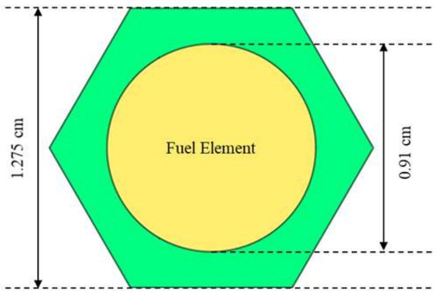
SERPENT2 XY cut figure of ¼ the core with radial reflectors dimensions



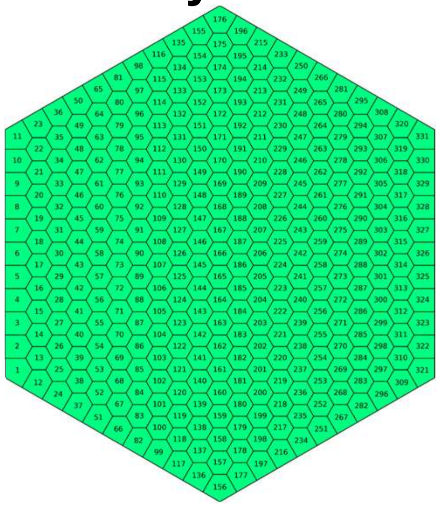
SERPENT2 XZ cut figure of ½ the core with axial reflectors dimensions

- **53953** independent fuel cells definitions.
- Axial 12 spacer grids models.
- Axial 3 CR zones (Dy_2O_3-TiO_2, B_4C, 42CrNM alloy)

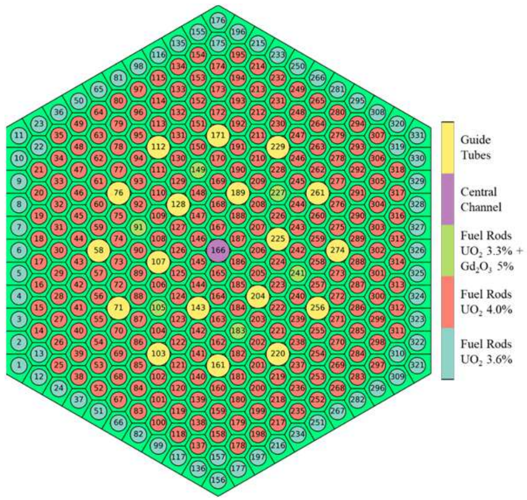
Static Simulation of the Rostov-2 VVER Core
Subchannel level thermal hydraulic model for SUBCHANFLOW



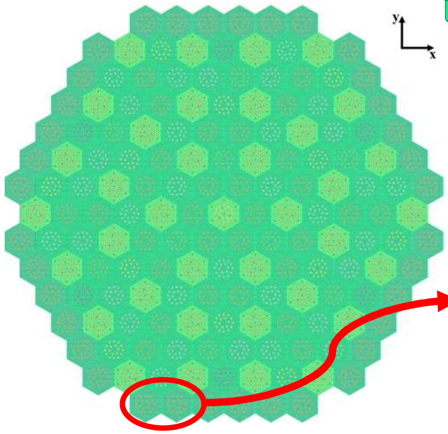
SCF **rod centered** model

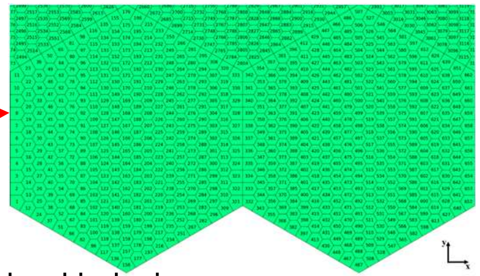


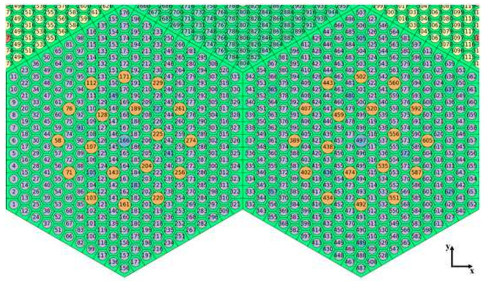
SCF FA model - channel indexing



SCF FA model - rod indexing







SCF Core model - channel and rod indexing

- **Python based preprocessor** was used to generate **rod and channel layout and connectivity relations** and “ifc” files for code feedback exchange.

- 30 axial nodes***53953 sub-channels**= 1,618,590 channels
- 30 axial nodes***53953 rods**= 1,618,590 divided rods

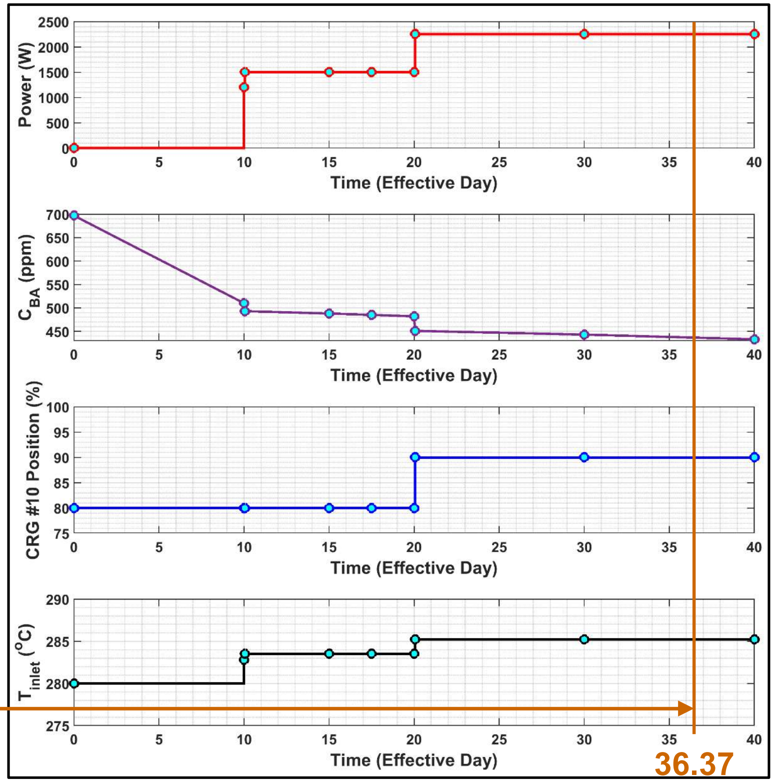
Validation of SERPENT2/SUBCHANFLOW Depletion Capability Using Rostov-2 VVER-1000 Core Data

Burnup History for the Depletion Simulation

- Data of the total core burnup simulation calculation, performed by BIPR-8, is presented in the table. (Table was adopted from benchmark document v1.6)

Depletion steps	T_{eff}, eff. day	T_{in}, ºC	CR10, %	P, MW_t	C_{BA}, g/kg
1	0.00	280.00	80.00	*3*	6.97
2	10.00	282.80	80.00	1200.00	5.10
3	10.05	283.50	80.00	1500.00	4.93
4	15.00	283.50	80.00	1500.00	4.88
5	17.50	283.50	80.00	1500.00	4.85
6	20.00	283.50	80.00	1500.00	4.82
7	20.05	285.20	90.00	2250.00	4.51
8	30.00	285.20	90.00	2250.00	4.43
-	40.00	285.20	90.00	2250.00	4.33

Boron dilution transient experiment starting time is at 36.37 days.



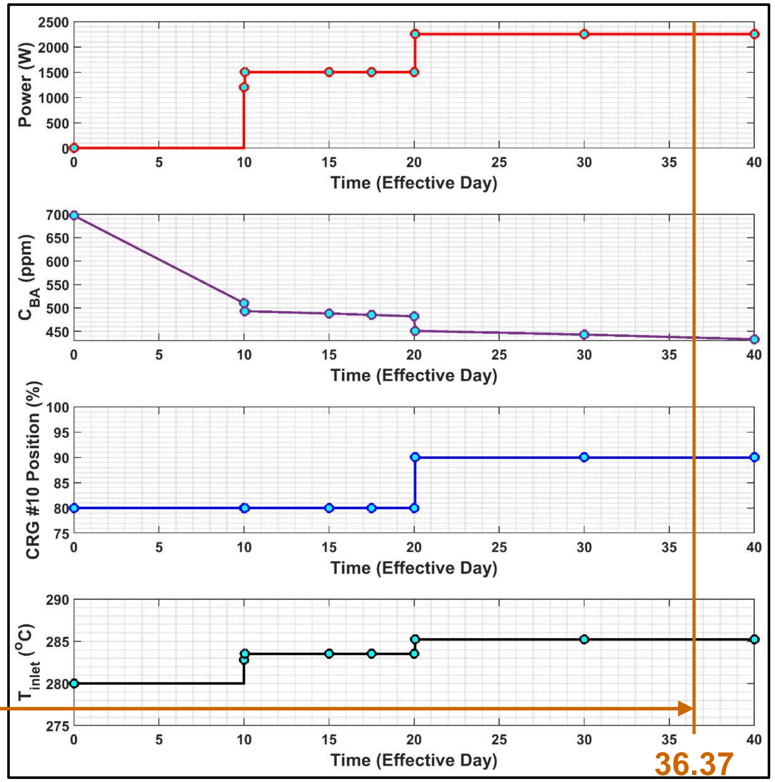
Operation History for The First Cycle

Validation of SERPENT2/SUBCHANFLOW Depletion Capability Using Rostov-2 VVER-1000 Core Data

Burnup History for the Depletion Simulation

- 9 time steps (0, 10 10.05, 15, 17.5, 20, 20.05, 30, *36.37*, 40) during 40 effective days
  - Benchmark code (BIPR8) results for the comparisons
  - *Intermediate step for the transient experiment start time at 36.37 days*
- Control Rod position: CR group 1-9 are out and only CR group 10 position (from core bottom) is changing.
- Total circuits mass flow rate for nominal conditions (100% total flow)=84000 m^3/h
  - Core mass flow rate (97% of the total mass circuit flow)= 81480 m^3/h
- Equilibrium Xenon

Boron dilution transient experiment starting time is at 36.37 days.



Operation History for The First Cycle

Validation of SERPENT2/SUBCHANFLOW Depletion Capability Using Rostov-2 VVER-1000 Core Data

SERPENT2/SUBCHANFLOW Critical Boron Concentration Simulation

- **SERPENT2**
  - Active cycle and inactive cycle: 500 and 200, respectively and Particle number: 1,000,000
  - 100 additional inactive cycle to run for the convergence of the iteration
  - tft temperature card and ifc files card options for the multi-physics calculations and interface
  - 30 interface nodes to exchange feedback with SCF
  - div card for sub dividing 15 axial depletion zones of the active core
  - rfw and rfr write and read cards for the change simulation parameters for each burnup step continue the simulations
  - Without DD (domain decomposition) mode

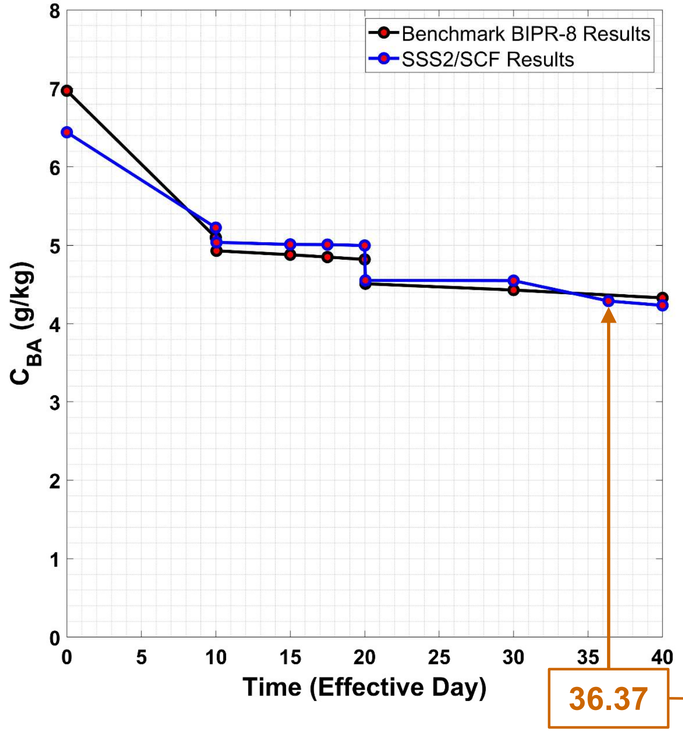
- **SUBCHANFLOW**
  - VVER-specific thermophysical properties in SCF was used.
  - Axially 30 nodes, radially 10 nodes for fuel and 2 nodes for clad
  - Doppler temperature predicted as in benchmark formulation.

- **Simulation Architecture**
  - 8 OpenMPI node and 152 OpenMP in each node task for the coupled simulation on HoreKa HPC Large queue (KIT/SCC).
  - Conv. criteria: rho= 30 pcm
    Coolant Dens.= 0.001 g/cm3,
    Fuel Temperature= 10 K,
    Coolant Temperature= 2.5 K

Validation of SERPENT2/SUBCHANFLOW Depletion Capability Using Rostov-2 VVER-1000 Core Data

Discussion of Results (1/5)

- Comparison between benchmark BIPR-8 code (deterministic) and SSS2/SCF critical boric acid conc. results



Change of Critical Boron Concentration

- Maximum C_{BA} difference is about 0.5 g/kg at the BOC.
- Burnup values at 40 days:

Simulation Codes	Burnup (MW_d/kgU)
SSS2/SCF	0.797
BIPR-8	1.60

- Critical C_{BA} at 36.37 days is equal to **4.29 g/kg.**

Boron dilution transient experiment starting time is at 36.37 days.

Validation of SERPENT2/SUBCHANFLOW Depletion Capability Using Rostov-2 VVER-1000 Core Data
Discussion of Results (2/5)

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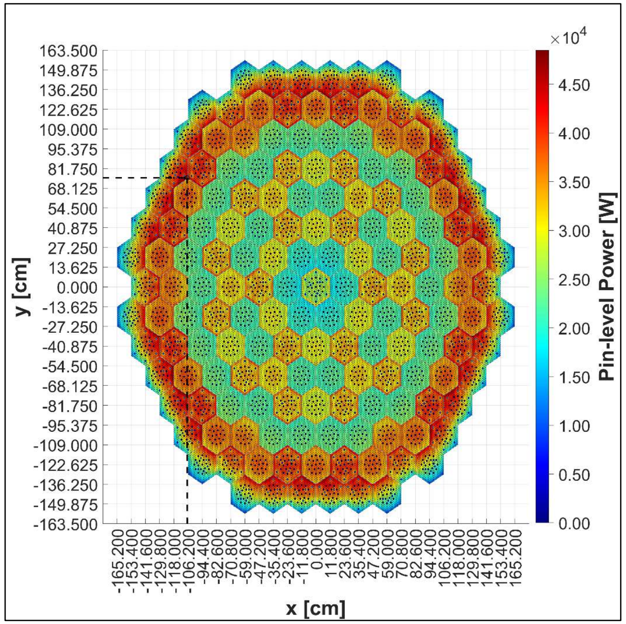
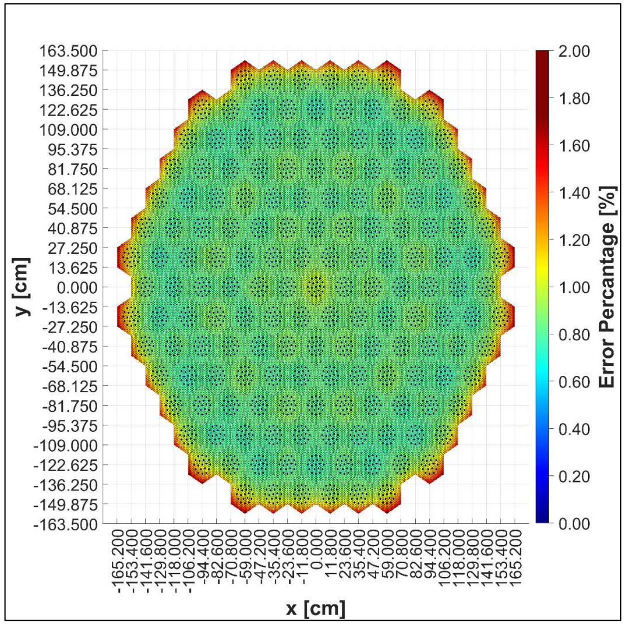
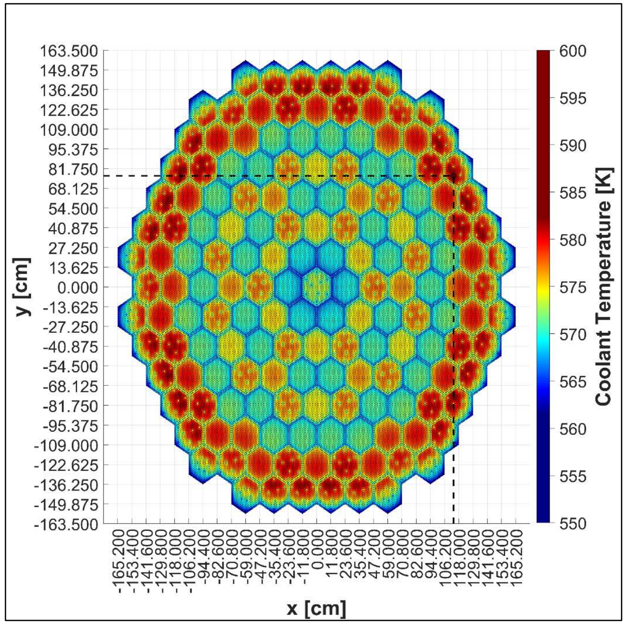
- <u>Depletion step 7:</u> P=2250 MW Effective day=20.05 $\mathbf{C_{BA}}$**=4.55 g/kg** CRG10=90% withdrawn



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



Pin power statistical error distribution in the core



Sub-channel level coolant exit temperature distribution in the core and the sub-channel location which has the hottest coolant exit temperature

Validation of SERPENT2/SUBCHANFLOW Depletion Capability Using Rostov-2 VVER-1000 Core Data

Discussion of Results (3/5)

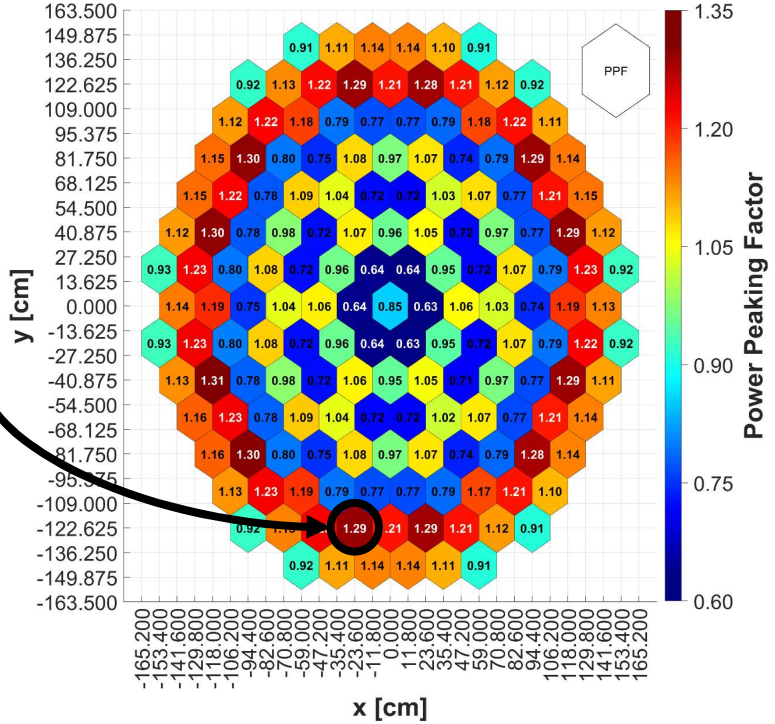
- Comparison between benchmark BIPR-8 code (deterministic) and SSS2/SCF results

T_{eff}, eff. day	BIPR-8 Kq / NK	SSS2/SCF Kq / NK
0.00	-	-
10.00	1.27 / 010	1.29 / 010
10.05	1.26 / 154	1.27 / 154
15.00	1.25 / 137	1.28 / 137
17.50	1.25 / 154	1.27 / 154
20.00	1.24 / 027	1.28 / 027
20.05	1.21 / 137	1.24 / 137
30.00	1.20 / 114	1.24 / 114
40.00	1.21 / 110	1.17 / 110

Where,

Kq: Value of the relative power of the FA

NK: FA number



Radial view of FA level power peaking factor

- Maximum difference is up to ~3%.

Validation of SERPENT2/SUBCHANFLOW Depletion Capability Using Rostov-2 VVER-1000 Core Data

Discussion of Results (4/5)

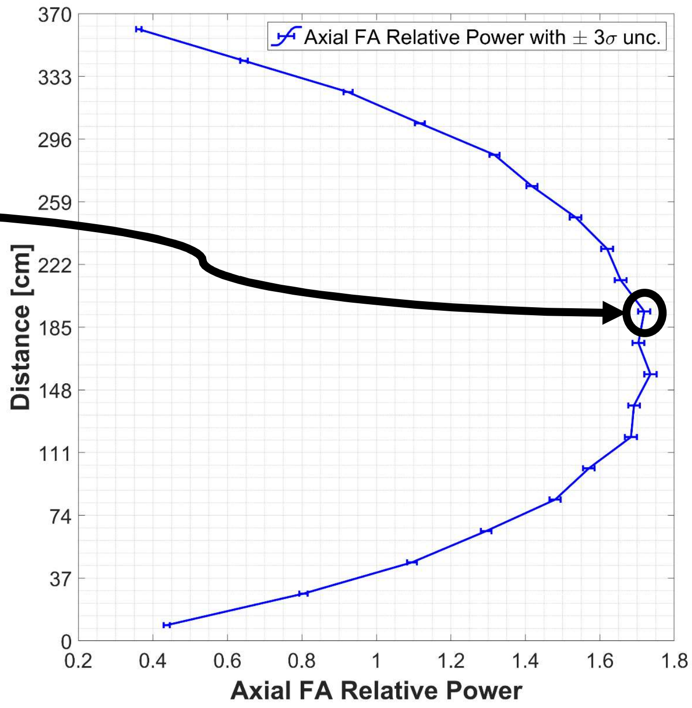
- Comparison between benchmark BIPR-8 code (deterministic) and SSS2/SCF results

T_{eff}, eff. day	**BIPR-8 Kv / NK-NZ**	**SSS2/SCF Kv / NK-NZ**
0.00	-	-
10.00	1.74 / 010-13	1.72 / 010-11
10.05	1.72 / 129-12	1.66 / 129-10
15.00	1.71 / 114-12	1.67 / 114-10
17.50	1.70 / 010-12	1.67 / 010-10
20.00	1.69 / 154-12	1.64 / 154-10
20.05	1.63 / 012-12	1.58 / 012-10
30.00	1.60 / 010-12	1.55 / 010-10
40.00	1.59 / 080-13	1.44 / 080-11

Where,

Kv: Max. value of the PPF in the core volume
NK: FA number
NZ: FA axial level (+2 reflector level)

- Maximum difference is up to ~9%.



FA axial relative power distribution

Validation of SERPENT2/SUBCHANFLOW Depletion Capability Using Rostov-2 VVER-1000 Core Data

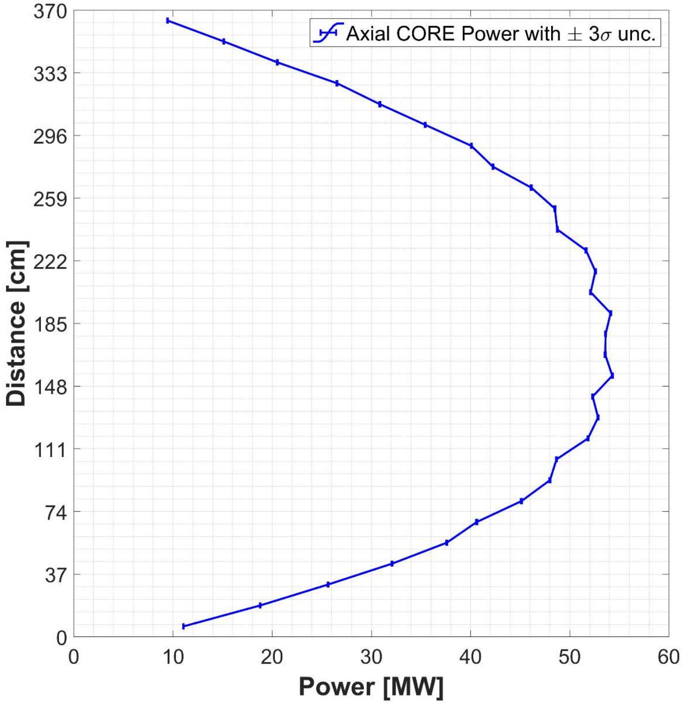
Discussion of Results (5/5)

- Comparison between benchmark BIPR-8 code (deterministic) and SSS2/SCF results

T_{eff}, eff. day	BIPR-8 Axial Offset	SSS2/SCF Axial Offset
0.00	-	-
10.00	-8.30	-7.83
10.05	-9.29	-8.21
15.00	-9.25	-9.04
17.50	-9.17	-8.64
20.00	-9.09	-8.80
20.05	-8.33	-6.33
30.00	-7.91	-6.01
40.00	-7.35	-6.45

Where,

$$\text{Axial Offset} = \frac{P^{TOP} - P^{BOTTOM}}{P^{TOP} + P^{BOTTOM}} \times 100$$

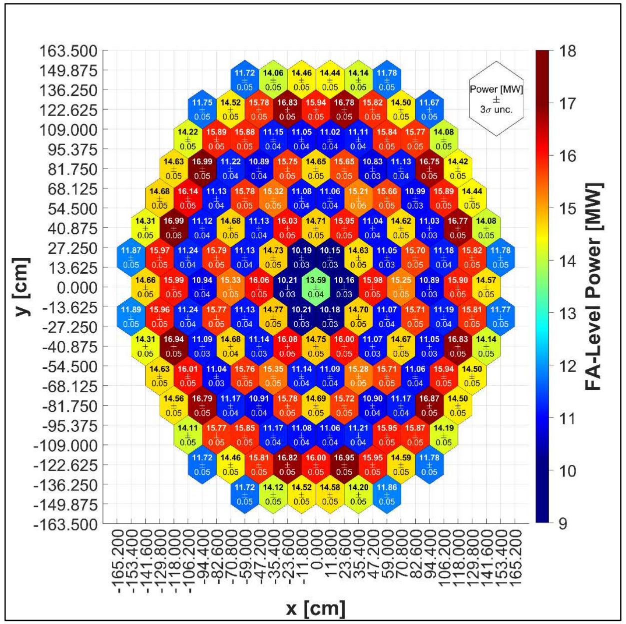


Core average axial power distribution

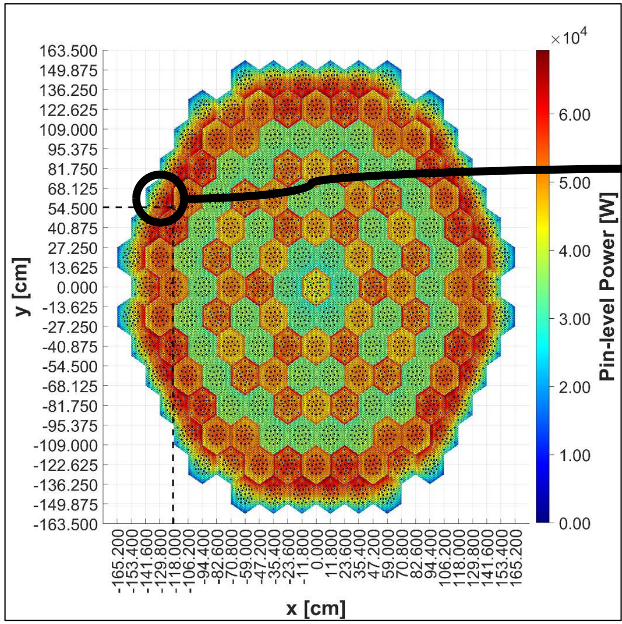
Validation of SERPENT2/SUBCHANFLOW Depletion Capability Using Rostov-2 VVER-1000 Core Data

Results for the Transient Experiment Starting Time at 36.37 days (1/3)

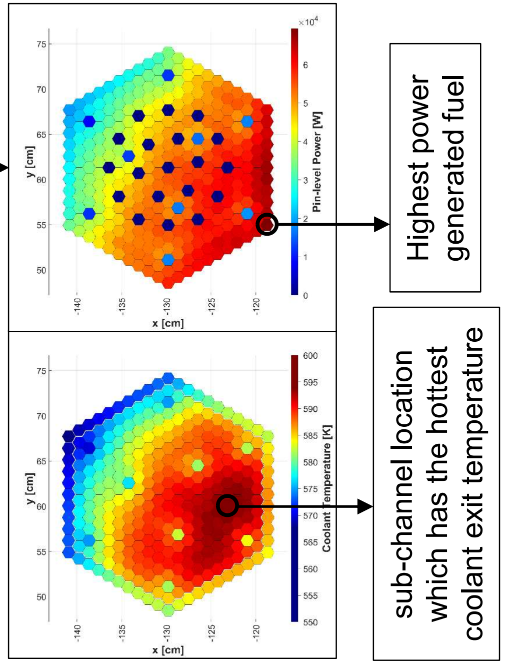
- Intermediate Depletion step: P=2250 MW Effective day= 36.37 days $\mathbf{C_{BA}}$**=4.29 g/kg** CRG10=90% withdrawn



FA-level power distribution in the core



Pin-level power distribution in the core with the location of the fuel with the highest power (similar statistical error distribution trend with previous graph up to 2%)

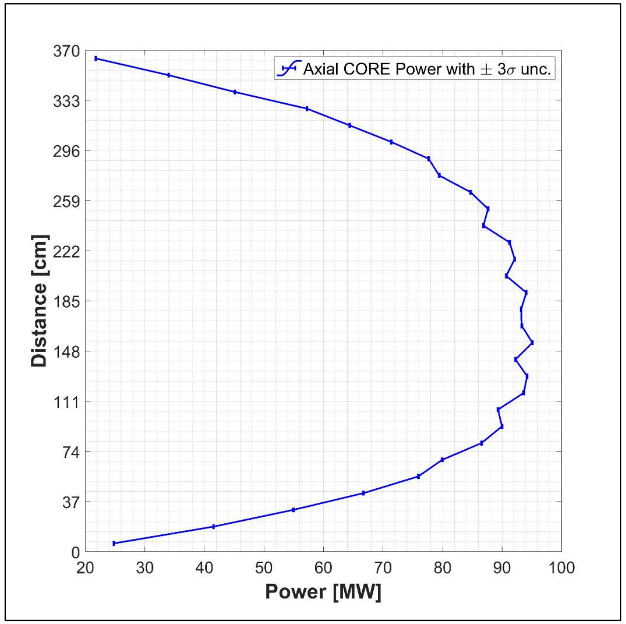


Pin-level power and Sub-channel level coolant exit temperature distribution in the FA No. 116

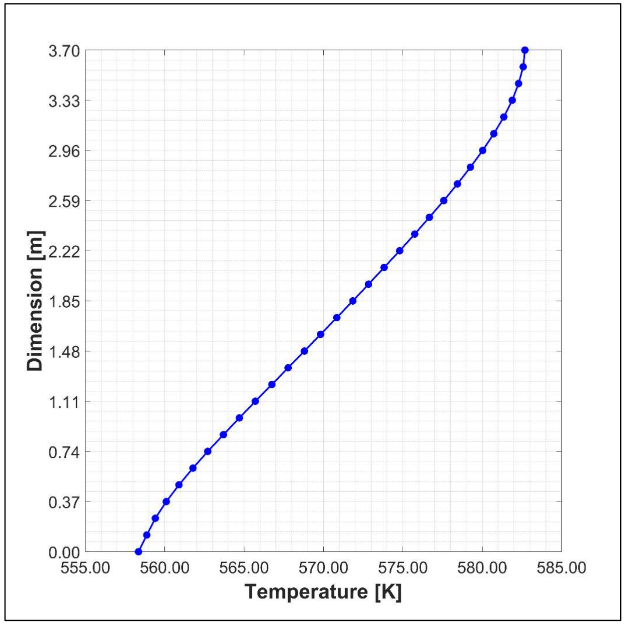
Validation of SERPENT2/SUBCHANFLOW Depletion Capability Using Rostov-2 VVER-1000 Core Data

Results for the Transient Experiment Starting Time at 36.37 days (2/3)

- Intermediate Depletion step: Thermal-Hydraulic results

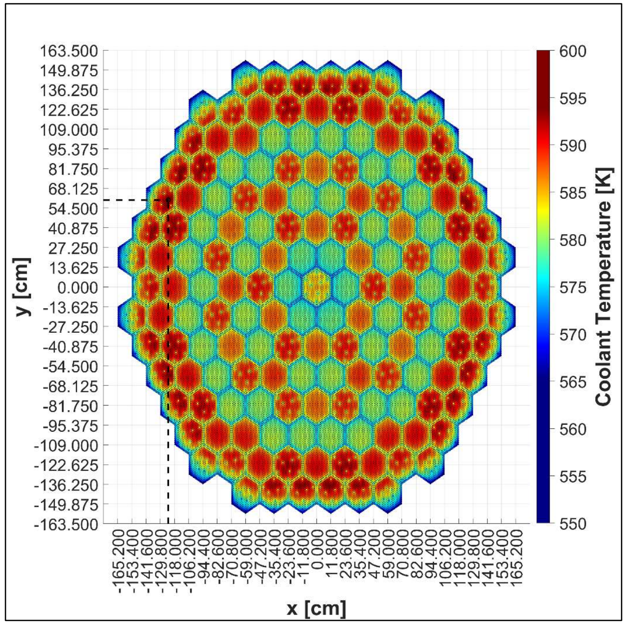


Core average axial power distribution



Core average axial coolant temperature distribution

- ~30 K heat-up in the core

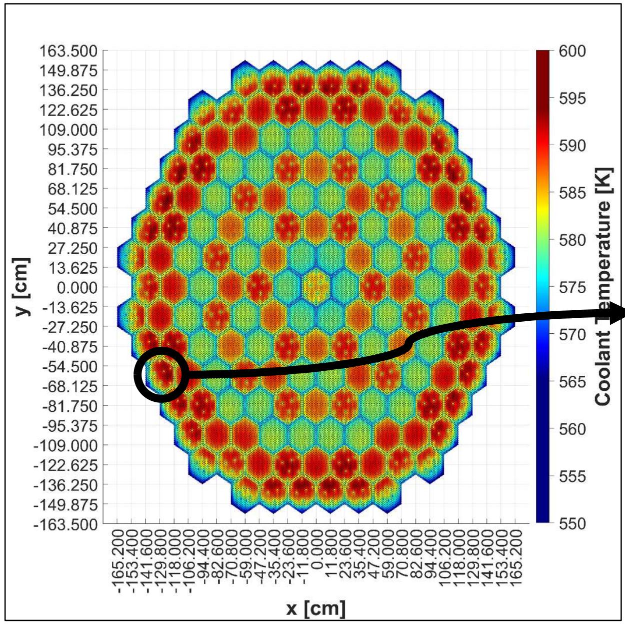


Sub-channel level coolant exit temperature distribution in the core and the sub-channel location which has the hottest coolant exit temperature

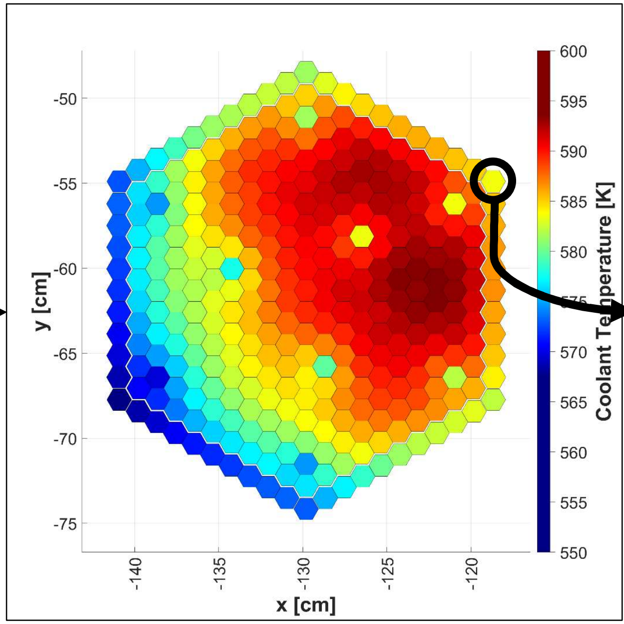
Validation of SERPENT2/SUBCHANFLOW Depletion Capability Using Rostov-2 VVER-1000 Core Data

Results for the Transient Experiment Starting Time at 36.37 days (3/3)

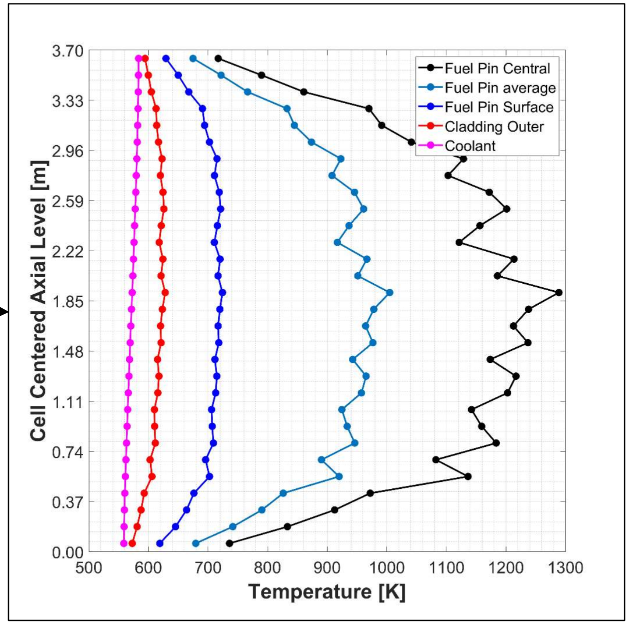
- Intermediate Depletion step: Thermal-Hydraulic results



Sub-channel level coolant exit temperature distribution in the core



Sub-channel level coolant exit temperature distribution in the FA No. 37 which has the hottest fuel rod center temperature



Pin 12247 axial temperature distribution (the hottest fuel rod center temperature in the core)

Conclusion and Outlook

- Master-slave SSS2/SCF coupling works **fine** and **stable** for the depletion simulations.
  - Totally **762,840 depletion zones** and **~2.7 TB** Memory.
  - **~250 hours simulation time (~10 days)** for all BU steps to get a converged solutions.
  - **~275,000 CPU-hours** were consumed during simulations.
  - SSS2/SCF Burnup value is equal to **0.797 MWd/kgU** while BIPR-8 total core burnup value is equal to **1.60 MWd/kgU** at 40 days.
    - Burnup values at 36.37 days
      - SSS2/SCF (simulated with data obtained from benchmark table): **0.689** MWd/kgU
      - PARCS/PATHS (simulated with measured data obtained from KI presentation): **0.683** MWd/kgU
- *Finally, this work aligns with the emerging multi-physics coupling trends in nuclear engineering*
  - *provides more precise predictions of pin and subchannel level safety parameters within reactor cores*
  - *addresses the specific challenges and requirements faced in adopting advanced computational methods.*

- PARCS 3D core models were developed and are being improved for nodal bases depletion and transient simulation analysis.

Thank you for your attention!