CASMO5/SIMULATE5 vs. Serpent2 3D 2x2 Mini-Core CBH Benchmark Problem

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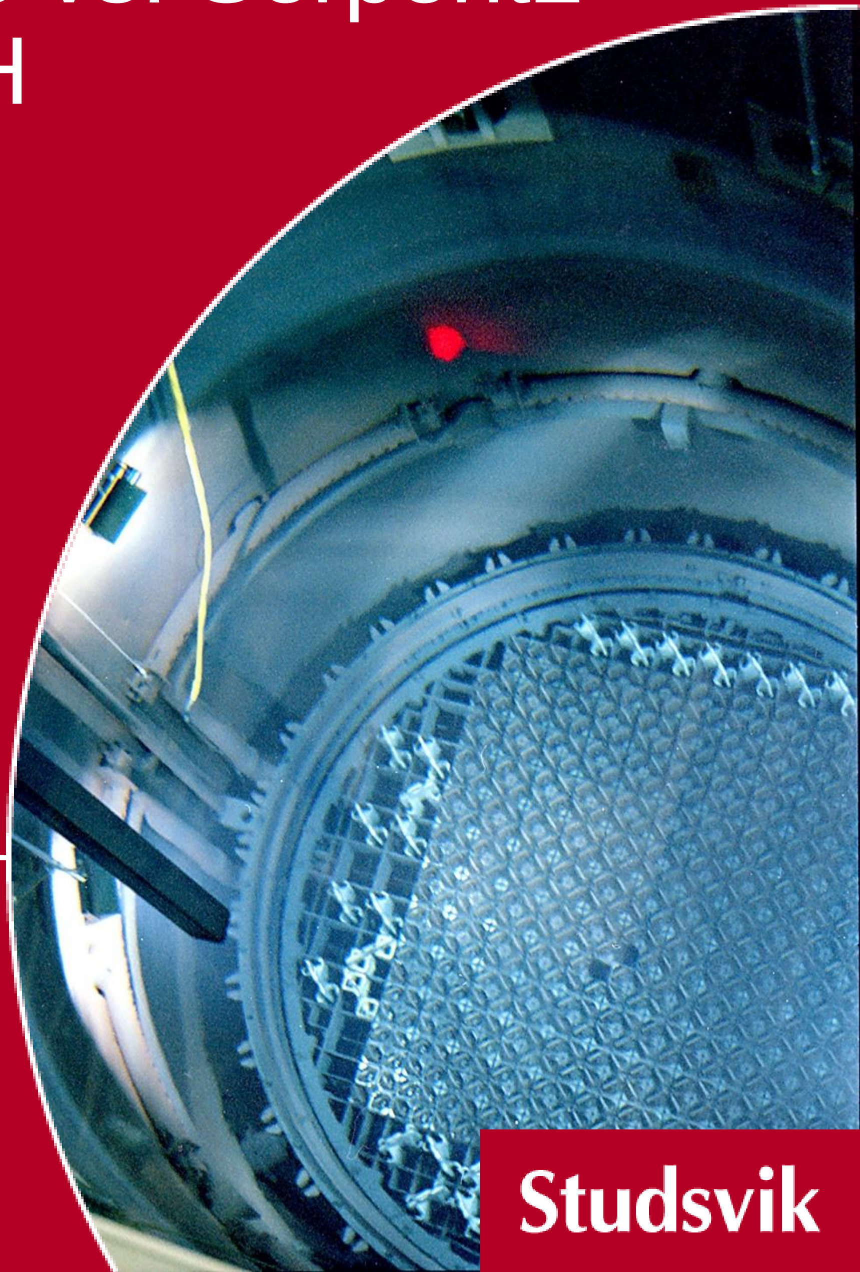

Serpent User Group Meeting 2022

29th August – 1st September, TUM in Garching, Germany

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Presentation Layout

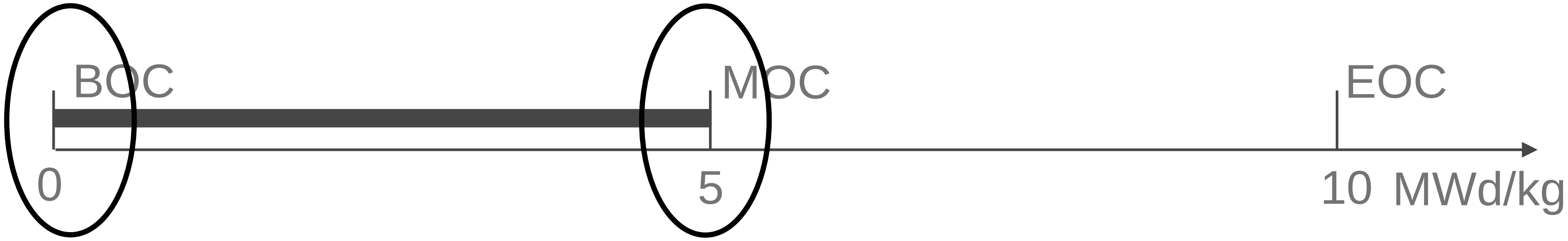
- Background
- Benchmark Configuration
- Serpent2 3D Reference Calculations
- CASMO5/SIMULATE5 Calculations
- 3D Simulation Results – Eigenvalues
- 3D Simulation Results – Nodal Power Distributions
- 3D Simulation Results – Pin Power Distributions
- Summary of Main Observations
- Conclusions and Future Work

Background

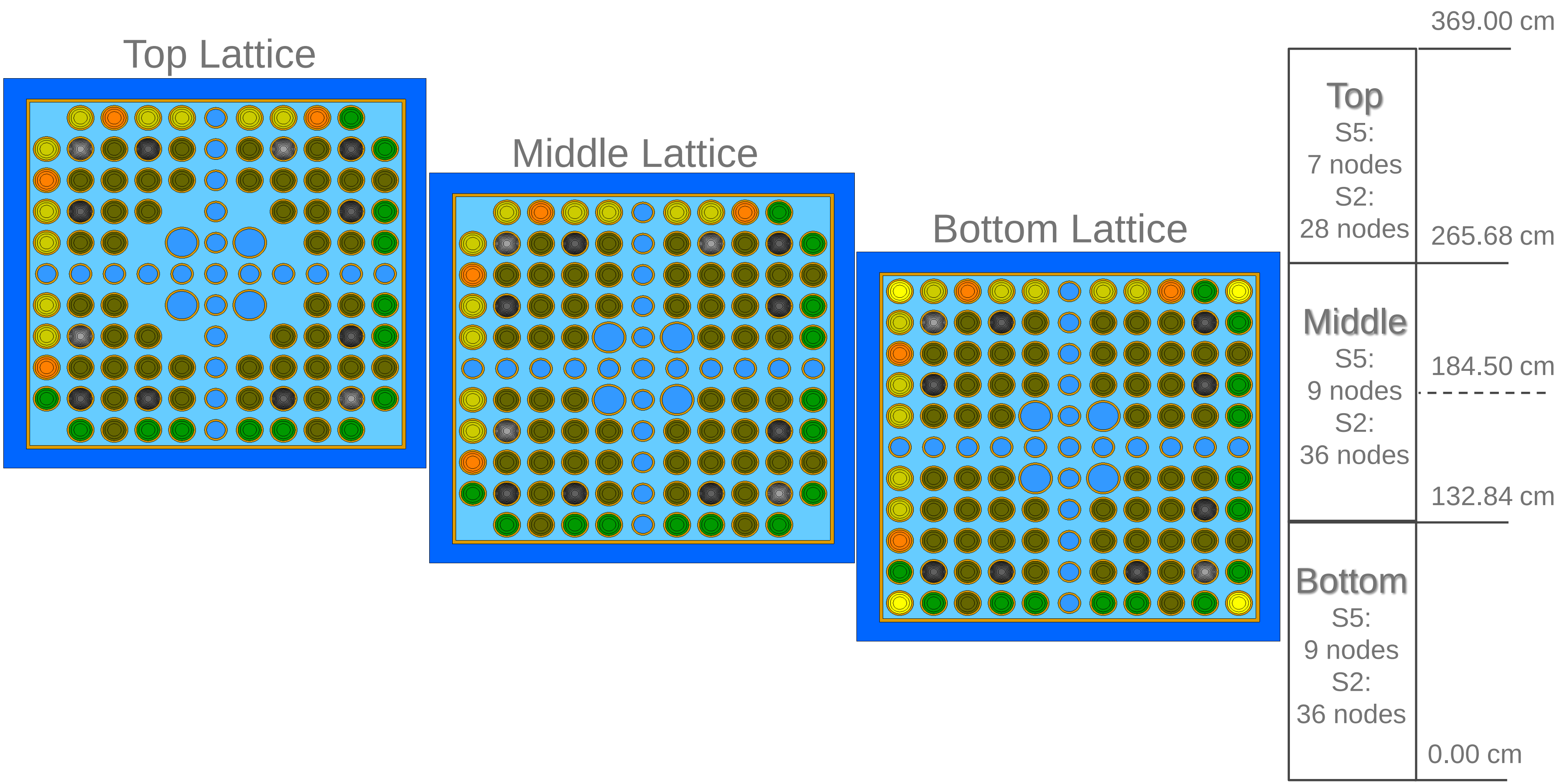
- Control Blade History (CBH) constitutes one of the most challenging core operational conditions to handle in an industrial level nodal core simulator
  - Difficult to anticipate the CR movements upfront during XS generation when a two-step methodology is adopted
- Most benchmarks addressing CBH are performed in 2D
- In this work a full 3D 2x2 mini-core benchmark has been devised to address CBH
  - Objective is to assess the ability of any core simulator to capture the CBH effect in a core configuration that tries to resemble typical conditions and operations of a real BWR

Benchmark Configuration

- 3D 2x2 BWR mini-core loaded with 10x10 PLFR fuel
  - Regular fuel pitch to facilitate comparisons of pin powers
  - Typical nuclear design corresponding to 12-month cycles
    - Bottom lattice: 4.15 w/o U-235, 8x6.00 & 2x3.00 w/o Gd_2O_3
    - Middle lattice: 4.19 w/o U-235, 8x6.00 & 4x3.00 w/o Gd_2O_3
    - Top lattice: 4.15 w/o U-235, 8x6.00 & 4x3.00 w/o Gd_2O_3
- Simulated burnup range of 0-10 MWd/kg
  - 0-5 MWd/kg: CR inserted 50 % into the core
  - 5-10 MWd/kg: CR fully withdrawn from the core

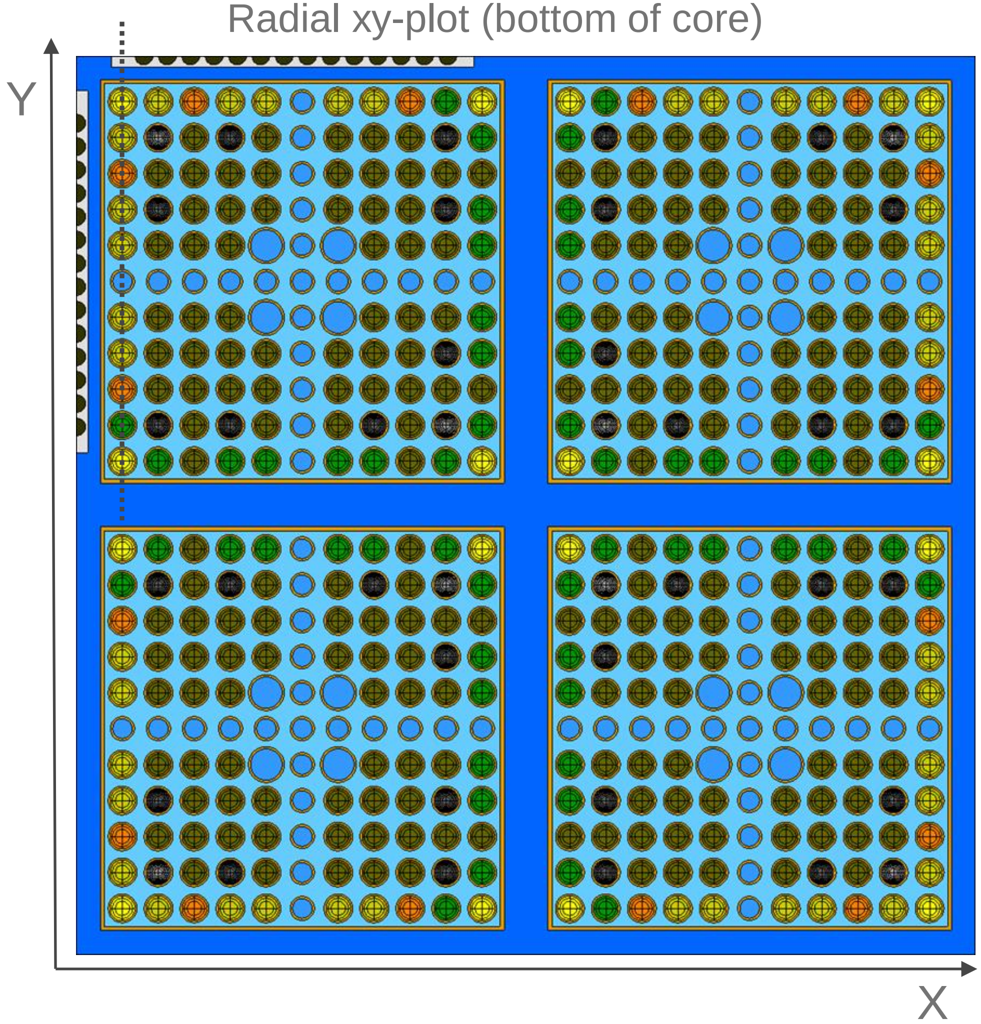


Benchmark Configuration

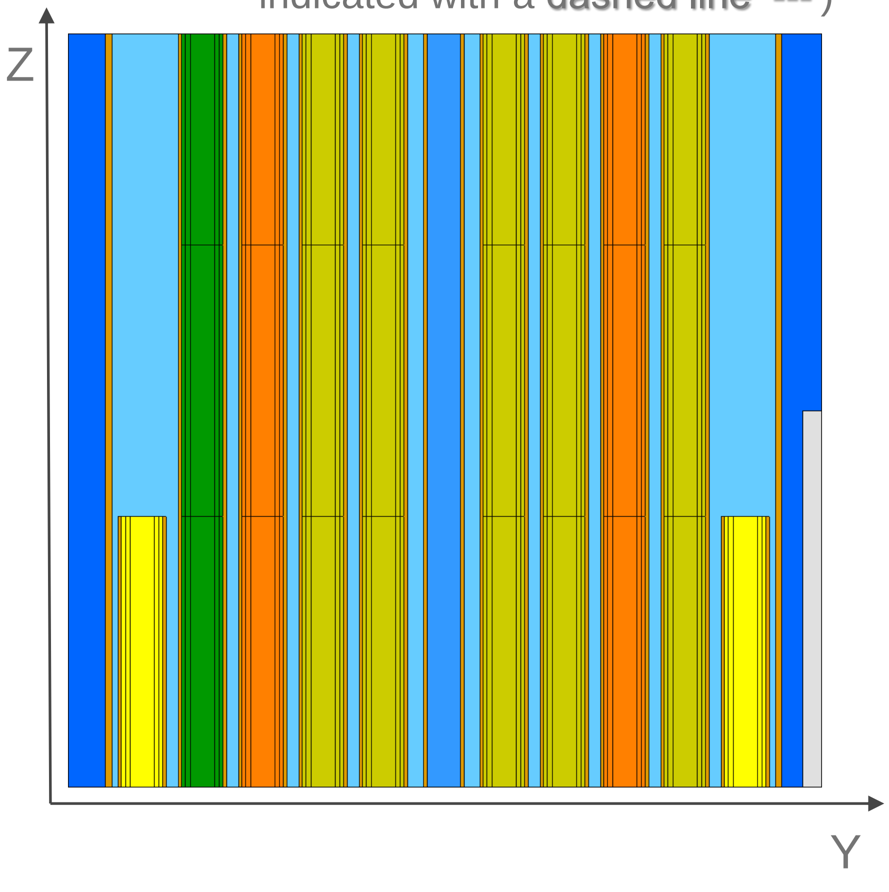


Benchmark Configuration

Radial xy-plot (bottom of core)



Axial yz-plot (outer pin row of the rodded bundle indicated with a **dashed line** '---')



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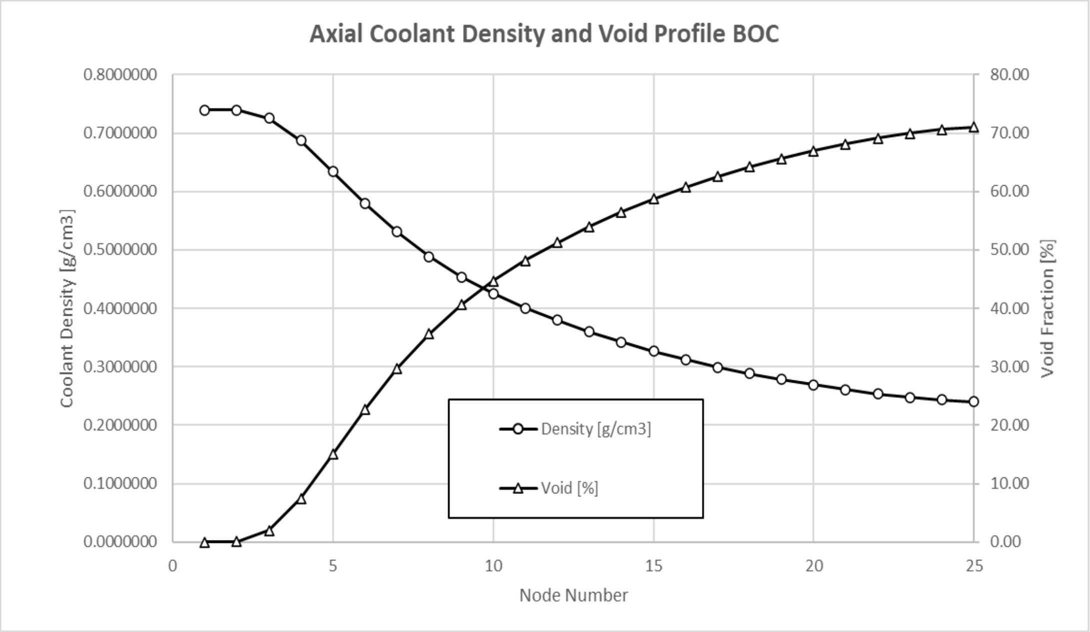
Benchmark Configuration

- State parameters kept fixed at typical nominal values
  - Predefined axial coolant density profile
  - T_m = 559 K
  - T_f = 900 K
  - Equilibrium xenon conditions
- Core loaded with fresh fuel assemblies
- Boundary conditions
  - Radially reflective
  - Axially vacuum
  - No reflectors



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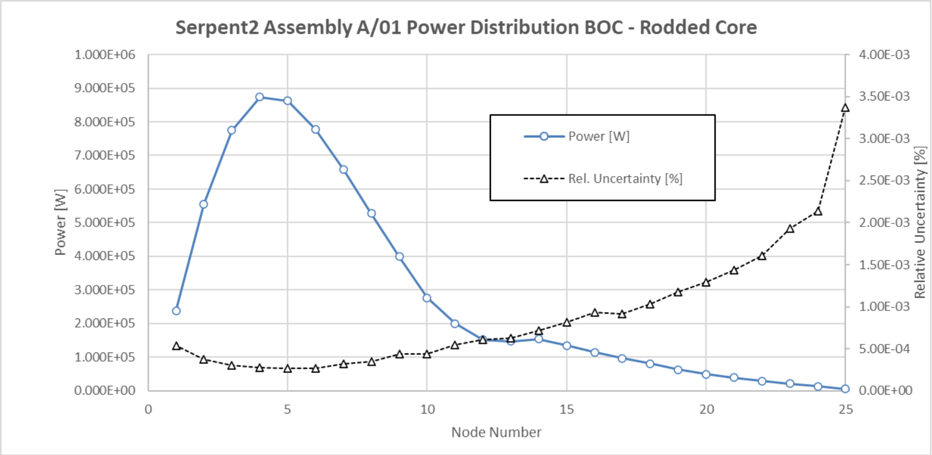
Serpent2 3D Reference Calculations

- Important Serpent2 models and options
  - Nominal 3D 2x2 core power set to 40 MW
  - Fixed core coolant density profile and temperatures
  - 4 million neutrons/cycle x 200 active cycles
    - At zero burnup 300 inactive cycles
    - At subsequent burnups 100 inactive cycles using the fission source of the previous transport calculation (`set fsp 1 100`)
    - Statistical uncertainties
      ≈ 4-5 pcm in eigenvalues
      ≤ 0.5 % (relative) in power (W)



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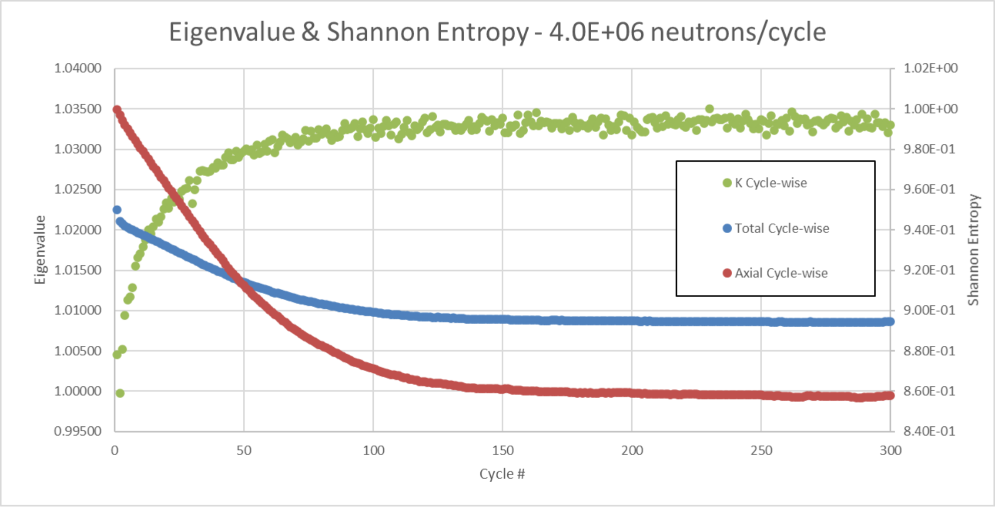
Serpent2 3D Reference Calculations

- Important Serpent2 models and options (cont.)
  - Fission source convergence and eigenvalue stability



Fission source convergence judged to be achieved after around 300 inactive cycles

Eigenvalue Bias: 500 inactive cycles

# Cycles w/ 1.0E+06 neutrons	Eigenvalue	Uncertainty	Difference [pcm]
2000	1.07866	0.00003	N/A
1000	1.07868	0.00004	2
500	1.07859	0.00005	-7
250	1.07856	0.00007	-10
125	1.07871	0.00009	5

# Neutrons/cycle w/ 500 cycles	Eigenvalue	Uncertainty	Difference [pcm]
1000000	1.07859	0.00005	N/A
500000	1.07799	0.00007	-60
100000	1.06898	0.00017	-961
50000	1.05912	0.00023	-1947
10000	1.04987	0.00051	-2872
5000	1.05274	0.00073	-2585
1000	1.06215	0.00164	-1644

Based on the analysis of a 3D single-channel, and scaling up from 1 channel to 4 channels, the choice of using 4 million neutrons/cycle was deemed acceptable to obtain a stable eigenvalue

Serpent2 3D Reference Calculations

- Important Serpent2 models and options (cont.)
  - DBRC activated $\Rightarrow$ up-scatter effects in resonance treatment
    - Increase of resonance absorption and decrease of reactivity
  - Unresolved resonance probability table sampling
  - Depletion with Predictor/Corrector and CRAM (matrix exponential)
    - Depletion step size 0.250 MWd/kg
  - Depletion mesh
    - Axially 100 nodes with size 3.69 cm
    - Radially: Fuel pins without BA – 3 radial rings & 4 sectors
Fuel pins with BA – 10 radial rings & 4 sectors
  - Equilibrium xenon conditions
    - Xenon treated as a burnable isotope even at equilibrium conditions
    - Burnup mesh crucial even for a power calculation without depletion

CASMO5/SIMULATE5 Calculations

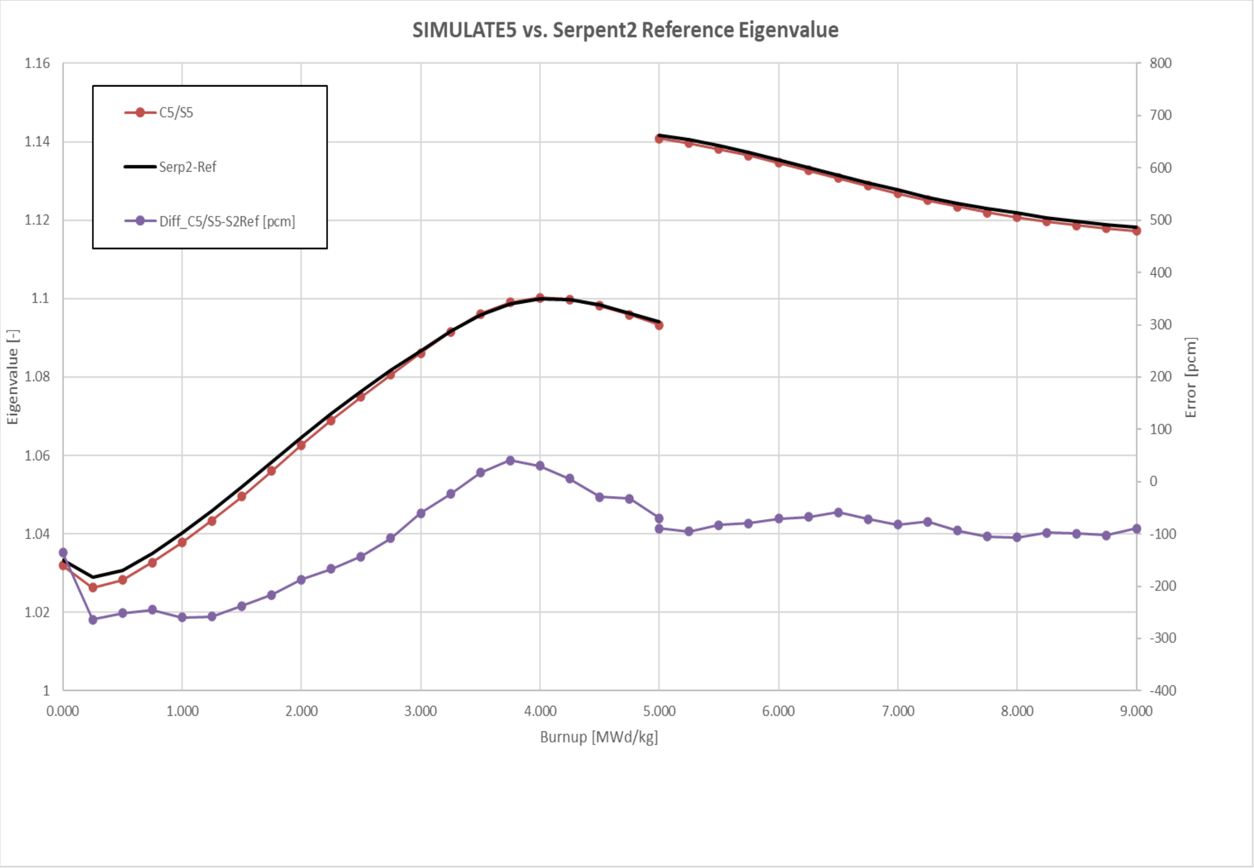
- Standard CASMO5 options applied in lattice physics
  - No thermal expansion
  - Hot case matrix and rodded depletion (CBH) for all void conditions
  - Nodal XS data in 4 energy groups
  - Sub-mesh XS data using DFs with exponential flux representation
- Standard SIMULATE5 options applied in core calculations
  - Radial sub-mesh XS rehomogenization model activated for both the nodal solution and pin power reconstruction
  - Radial sub-mesh depletion and isotope tracking activated
  - Xenon spectrum effects accounted for
  - Pin power reconstruction utilizing radial sub-mesh fluxes

3D Simulation Results – Eigenvalues

Core Eigenvalues CRin50 BOC:		
S2 Reference (+/- 4 pcm)	1.03325	Diff. [pcm]
CASMO5-SIMULATE5	1.03189	-136

Core Eigenvalues CRin50 MOC:		
S2 Reference (+/- 4.2 pcm)	1.09399	Diff. [pcm]
CASMO5-SIMULATE5	1.09329	-70

Core Eigenvalues CRout MOC:		
S2 Reference (+/- 4.3 pcm)	1.14170	Diff. [pcm]
CASMO5-SIMULATE5	1.14080	-90



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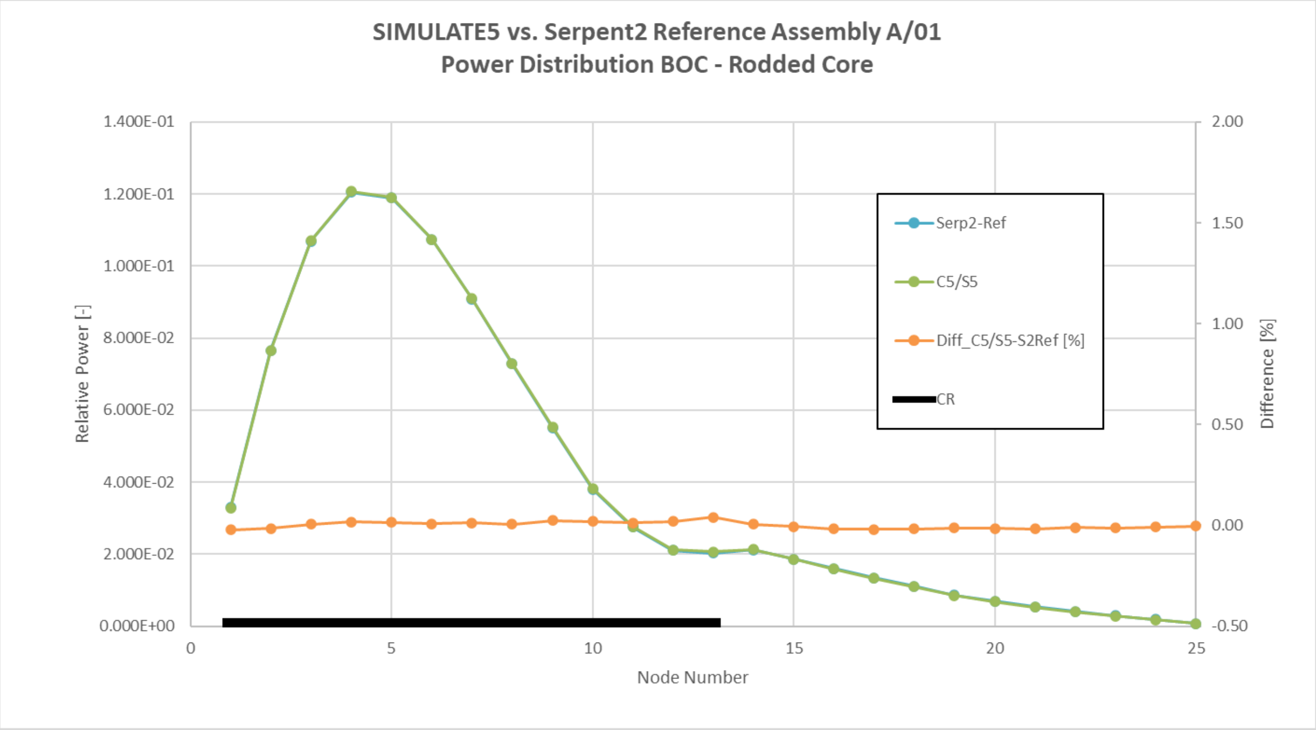
3D Simulation Results – Nodal Power Distributions **Rodded BOC** Core

Assembly Power Distribution CRin50 BOC:

	S2 Ref.			C5/S5-S2 [%]	
CR	1	2	**CR**	1	2
A	0.724		A	-0.27	
B	1.067	1.142	B	0.15	-0.03
Total:		1.000E+00	Total:		0.00



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3D Simulation Results – Nodal Power Distributions **Rodded MOC** Core

Assembly Power Distribution CRin50 MOC:

S2 Ref.

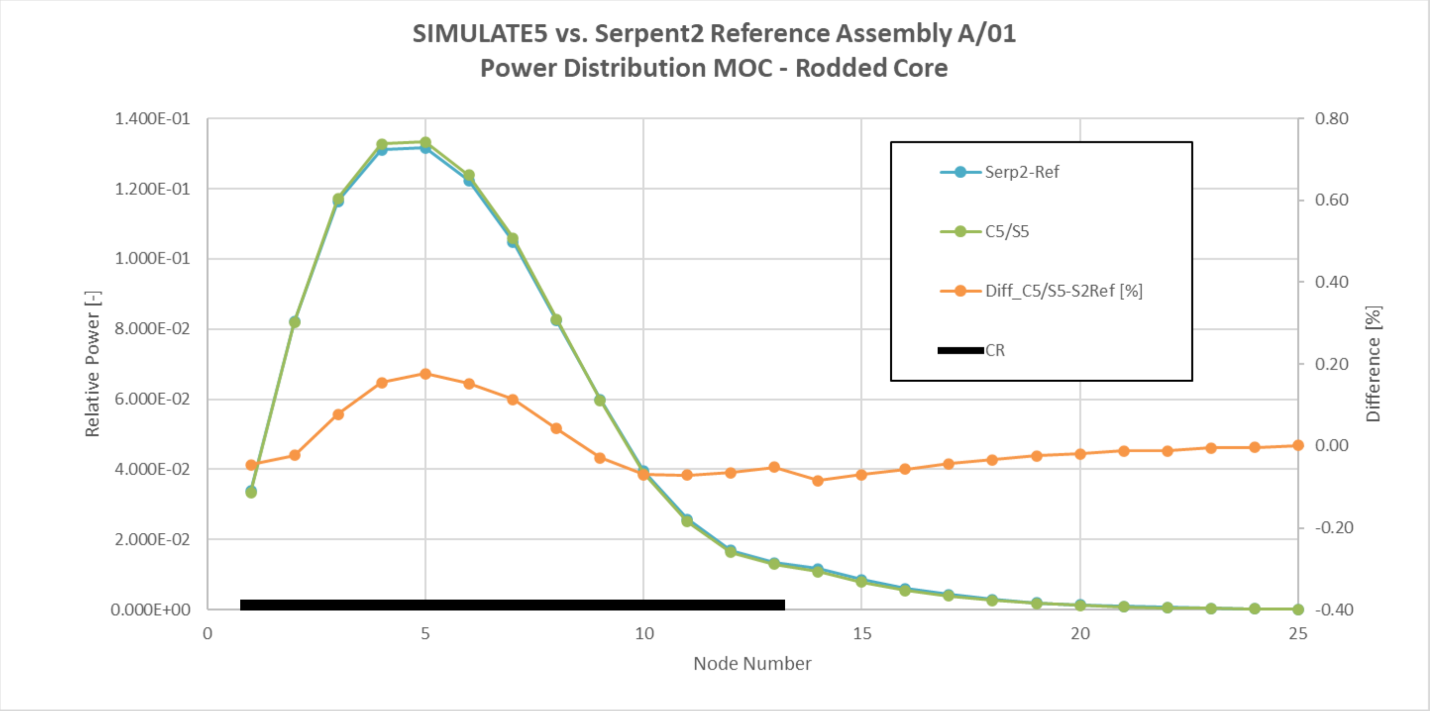
CR	1	2
A	0.715	
B	1.072	1.142

Total: 1.000E+00

C5/S5-S2 [%]

CR	1	2
A	-0.71	
B	0.24	0.21

Total: 0.00



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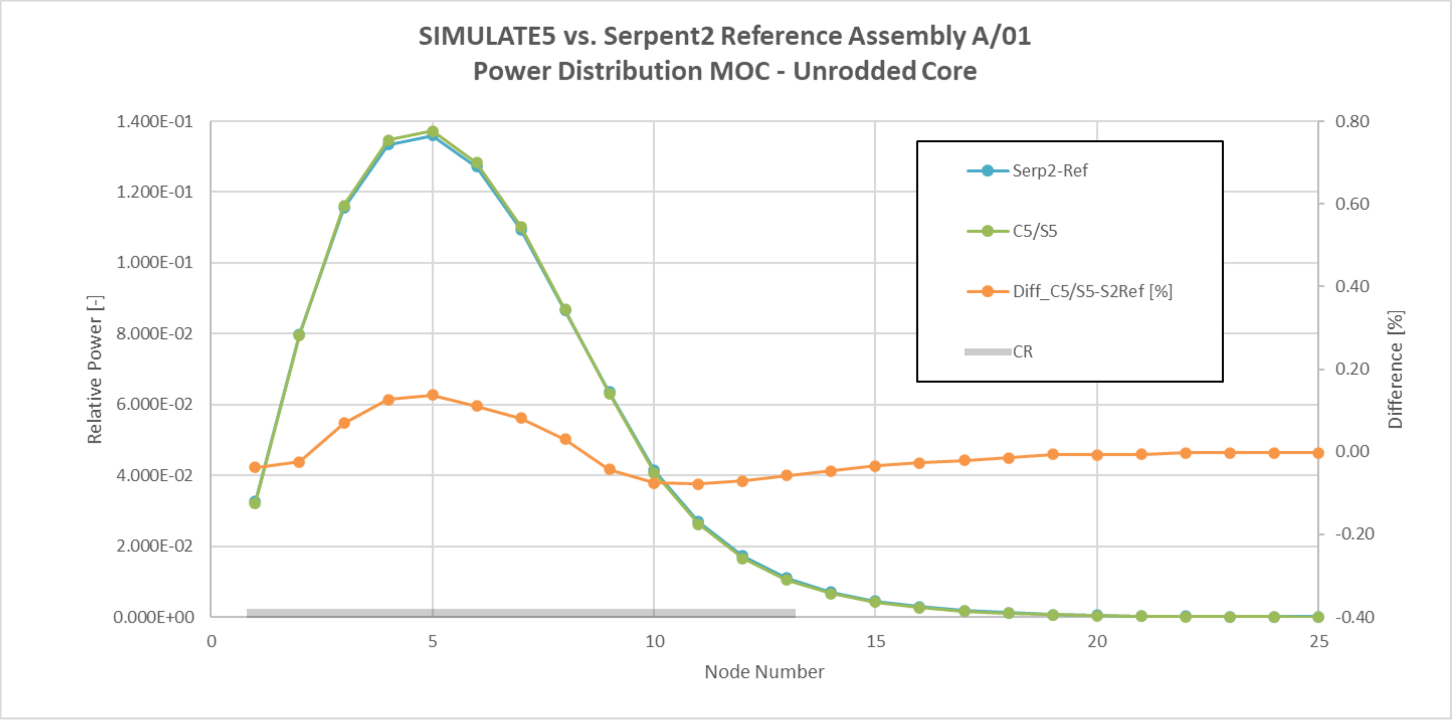
3D Simulation Results – Nodal Power Distributions **Unrodded MOC** Core

Assembly Power Distribution CRout MOC:

	S2 Ref.			**C5/S5-S2 [%]**	
CR	1	2	**CR**	1	2
A	0.996		A	-0.39	
B	1.004	0.998	B	0.06	0.23
Total:	1.000E+00		Total:	-0.01	



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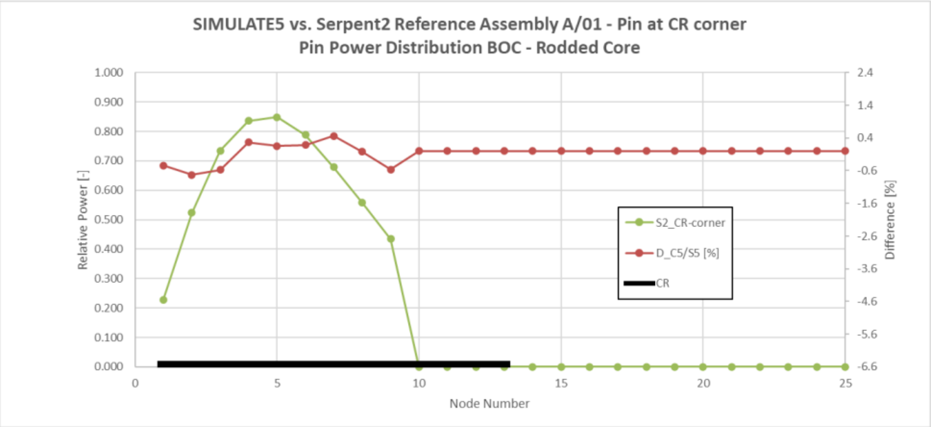
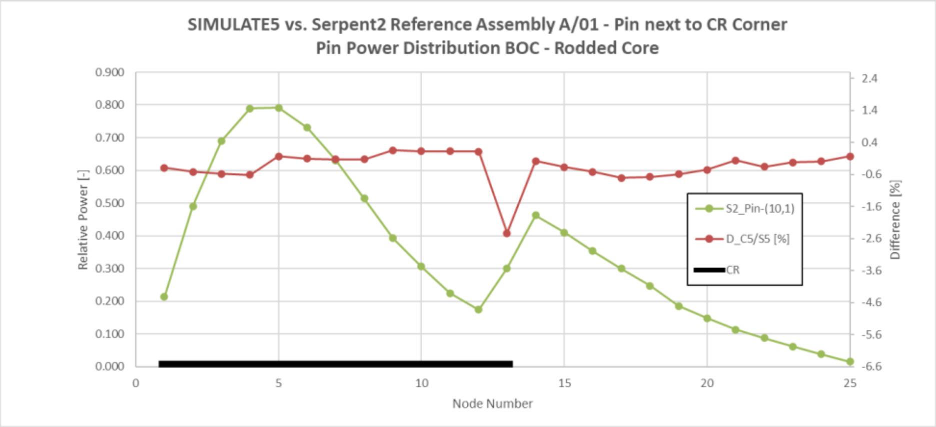
3D Simulation Results – Pin Power Distributions **Rodded BOC Core**





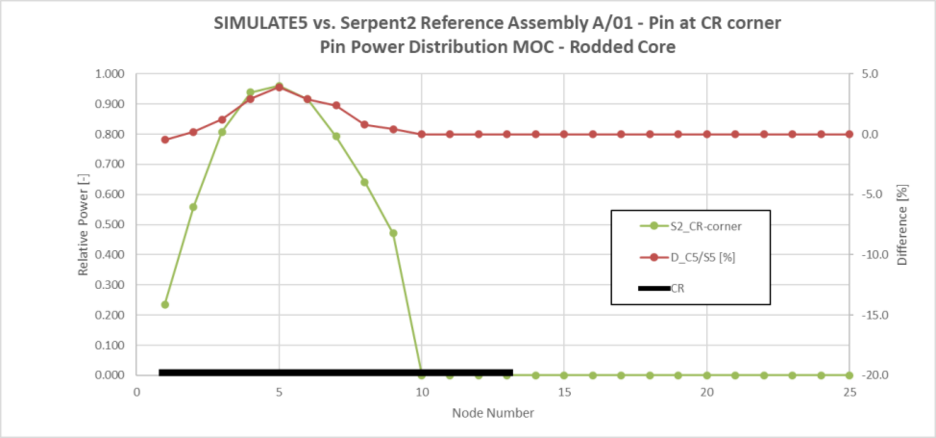
C5/S5 Pin Power Errors [%] – Node 5

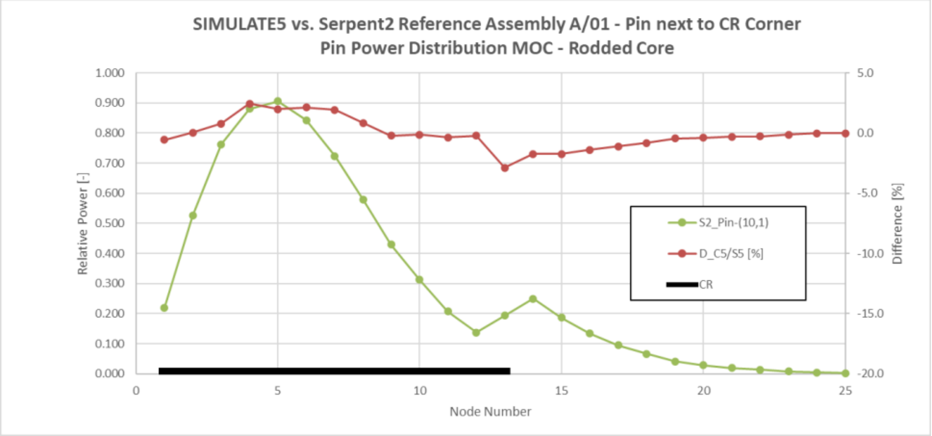
0.1										
0.0	-2.0									
-0.7	-0.2	-0.9								
-1.6	-2.2	-1.7	-2.9							
-0.8	-1.0	-2.2	-5.5	0						
0	0	0	0	0	0					
0.0	0.9	-0.9	-3.1	0	0	0				
0.1	1.3	0.3	-0.1	-3.1	0	0.5	5.5			
-2.0	0.6	-0.6	5.0	0.7	0	1.0	1.6	2.2		
-4.5	-1.4	-1.5	-1.7	0.4	0	0.4	-1.5	1.4	-1.7	
-6.4	-3.8	2.9	-2.3	-0.9	0	0.8	3.6	-0.9	0.2	0.0

C5/S5 Pin Power Errors [%] – Node 13

0.0										
-2.4	-0.6									
-2.9	-2.4	-2.1								
-0.6	-0.2	-1.3	1.2							
-0.6	-0.8	-1.4	1.1	0						
0	0	0	0	0	0					
-0.7	-0.8	-1.1	1.5	0	0	0				
-0.3	-0.1	-0.9	1.4	1.0	0	1.6	2.0			
1.4	1.0	0.8	1.5	1.5	0	1.7	1.3	1.9		
0.7	0.4	1.5	0.4	2.3	0	2.4	0.6	2.3	0.8	
0.0	0.8	2.0	1.7	2.3	0	3.0	2.6	3.2	2.7	0.0

3D Simulation Results – Pin Power Distributions **Rodded MOC Core**





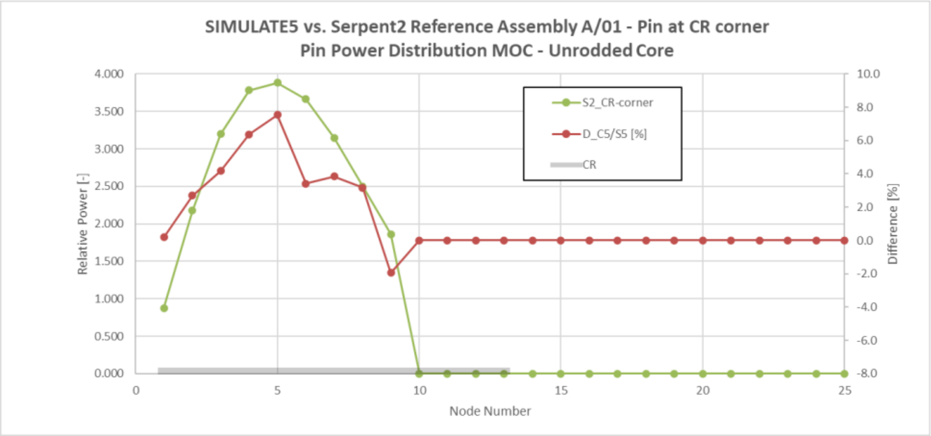
C5/S5 Pin Power Errors [%] – Node 5

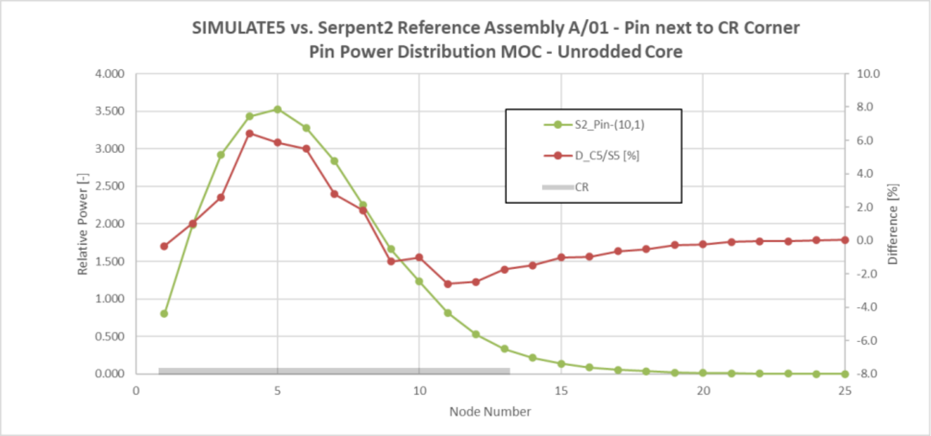
3.9										
2.0	3.2									
0.7	-0.4	-1.6								
0.2	-2.3	-1.6	-2.1							
0.2	-1.3	-2.3	-3.5	0						
0	0	0	0	0	0					
1.6	0.7	1.1	-2.3	0	0	0				
1.4	-0.6	-0.7	-0.6	0.5	0	2.3	3.7			
-2.6	-2.9	-4.1	0.2	-0.2	0	0.5	-1.2	2.6		
-3.2	-4.4	-2.2	-7.0	0.8	0	2.6	-4.6	3.4	2.7	
2.5	2.7	5.2	2.5	4.4	0	7.3	7.6	6.2	8.3	9.9

C5/S5 Pin Power Errors [%] – Node 13

0.0										
-2.9	-1.2									
-3.0	-2.4	-2.6								
-1.3	-0.5	-2.0	-0.7							
-1.5	-2.0	-2.6	-1.0	0						
0	0	0	0	0	0					
-1.4	-2.4	-2.6	-1.3	0	0	0				
-1.5	-0.8	-2.1	-0.8	-0.9	0	-0.8	-0.7			
-0.7	-0.9	-1.4	-0.4	-0.4	0	-0.8	-0.7	-0.5		
-1.1	-0.5	-1.1	-0.2	-0.2	0	-0.3	-0.2	-0.1	-0.4	
0.0	-1.2	-1.1	-0.3	-0.4	0	-0.3	-0.5	-0.8	-0.3	0.0

3D Simulation Results – Pin Power Distributions **Unrodded MOC Core**





C5/S5 Pin Power Errors [%] – Node 5

7.5										
5.9	12.0									
4.6	0.7	-2.2								
5.6	-4.6	1.3	1.9							
6.3	1.8	1.2	2.7	0						
0	0	0	0	0	0					
6.3	2.8	0.4	0.4	0	0	0				
5.3	0.4	-1.9	2.0	2.4	0	1.6	1.7			
-2.8	-1.9	-3.8	-0.7	0.2	0	1.1	-0.3	3.4		
-0.8	-4.6	-2.6	-8.0	1.6	0	3.4	-4.4	2.9	2.1	
9.3	4.2	3.7	6.3	5.5	0	5.0	5.5	8.5	8.5	10.1

C5/S5 Pin Power Errors [%] – Node 13

0.0										
-1.7	-0.7									
-1.9	-1.5	-1.2								
-1.4	-0.6	-1.4	-1.9							
-1.5	-1.4	-1.9	-2.0	0						
0	0	0	0	0	0					
-1.2	-1.6	-1.6	-1.8	0	0	0				
-1.4	-0.8	-1.1	-1.3	-2.1	0	-1.9	-1.5			
-1.9	-1.7	-1.7	-1.3	-1.9	0	-2.0	-1.5	-1.5		
-1.9	-0.8	-1.7	-0.6	-1.9	0	-1.7	-0.7	-1.4	-1.0	
0.0	-1.8	-2.1	-1.7	-1.7	0	-1.5	-1.2	-2.3	-1.9	0.0

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Summary of Main Observations

- Eigenvalues
  - Very stable SIMULATE5 predictions with the error ≤ ±250 pcm over the whole burnup range independent of CR movement
- Nodal Powers
  - Very accurate axial power predictions with the error ≤ ±0.2 % over the whole burnup range independent of CR movement
  - The error in radial power predictions remains below 1 % over the whole burnup range independent of CR movement
  - Excellent accuracy in the nodal powers obtained at the burnup point of CR withdrawal with the error ≤ ±0.4 %

Summary of Main Observations

- Pin Powers
  - At fresh rodded BOC conditions the pin power errors remain in general below a few percent
  - At rodded MOC conditions the pin powers in the vicinity of the CR are overpredicted by a few percent
  - At unrodded MOC conditions (most challenging CBH condition)
    - The pins next to the withdrawn CR blade overpredicted by 5-8 %
      - Acceptable results since the pin powers are expected to be underpredicted by 15-20 % if the CBH is not accounted for at all
    - Larger errors are obtained close to the detector towards core bottom
      - Suspected to be caused by axial leakage effects not fully accounted for in a two-step nodal core analysis methodology in combination with the presence of BA and the sensitivity of its depletion to the prevailing flux spectrum

Conclusions and Future Work

- Excellent results regarding the eigenvalue and nodal power predictions
- Acceptable pin power predictions obtained still having room for some improvements especially in the vicinity of the detector
  - Conservative predictions are obtained for the most limiting pins
- Rather unrealistic axial power shapes were induced that suggests for modifications in the benchmark specification
  - Addition of axial bottom and top reflectors to the core model
  - Modified void profile to push more power towards the top of the core (currently close to zero the whole burnup range)
  - Serpent2 reference calculations ongoing

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