

Business from technology

# **BEAVRS benchmark calculations with Serpent-ARES code sequence**

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## Outline

- Goal of the study
- The ARES nodal diffusion code
- BEAVRS Benchmark
- Results

The complete work is reported in:

J. Leppänen, R. Mattila and M. Pusa. “*Validation of the Serpent-ARES Code Sequence using the MIT BEAVRS Benchmark – Initial Core at HZP Conditions.*” Submitted to Ann. Nucl. Energy.

## Goals of the study

- This study is related to a larger project involving Serpent as the group constant generator for Finnish fuel cycle and transient simulator codes (ARES, HEXBU-3D, TRAB-3D, HEXTRAN)
- Specific goals:
  - Test and demonstrate the Serpent-ARES coupling in a realistic LWR geometry
  - Evaluate the methods used in Serpent for group constant generation
  - Point out any methodological shortcomings
  - Determine the level of accuracy obtained using nodal diffusion codes in comparison to a reference 3D Monte Carlo solution
  - Evaluate the impact of approximations on homogenization
  - Obtain better understanding on deterministic methods in core analysis
- This presentation covers the first part of the study (HZP initial core calculations), the next stage involves fuel cycle simulations with thermal hydraulics and burnup

## The ARES Code (1/2)

- ARES<sup>a</sup> is a fuel cycle simulator code developed at the Finnish Radiation and Nuclear Safety Authority (STUK) since 2000 for independent safety analyses of Finnish NPP's
- Stationary fuel cycle simulations for PWR and BWR cores with rectangular fuel geometry:
  - Evaluation of safety margins
  - Burnup calculations for transient simulations
  - Reference calculations for commercial codes (SIMULATE)
- Originally designed to use group constant data generated using CASMO
- One of the inspirations for starting Monte Carlo code development at VTT in 2004

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<sup>a</sup>AFEN REactor Simulator

## The ARES Code (2/2)

- Physics:
  - Two-group nodal diffusion method
  - Based on three-dimensional analytical function expansion nodal model (AFEN)<sup>a</sup>
  - Nodal flux solution in eigenmode representation, using 18 analytical form functions per flux mode
  - Coupling between nodes using 8 radial ADF's per group (boundary and edge)
- Improved diagonal coupling between nodes: better accuracy near assembly edges, solution more sensitive to ADF's
- The calculations in this study were limited to HZP initial core → no burnup, thermal hydraulics or interpolation between state points

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<sup>a</sup>R. Mattila. "*Three-dimensional analytic function expansion nodal model.*" YE-PD-9/2002, VTT Technical Research Centre of Finland, 2002.

## Test case (1/5)

- The MIT BEAVRS benchmark<sup>a</sup> was established in 2012 as a test case for high-fidelity core analysis methods (primarily 3D Monte Carlo)
- Detailed description of a commercial 1000 MWe PWR initial core:
  - Standard  $17 \times 17$  PWR fuel, three assembly types (1.6, 2.4 and 3.2 w/o U-235)
  - Burnable absorber in 5 configurations: 6, 12, 15, 16 and 20 pins (configurations with 6 and 15 pins asymmetrically positioned)
  - Control rod clusters in 4 control and 5 shutdown banks
  - Operation history for first two cycles
- Experimental results: control rod bank worths, power distributions, boron letdown curve

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<sup>a</sup>N. Horelik and B.Herman. “*Benchmark for evaluation and validation of reactor simulations.*” MIT Computational Reactor Physics Group (2012).

## Test case (2/5)

- Serpent models: 3D model for reference results, 2D assembly-level models for homogenization (single-assembly and colorset configurations)
- ADF's and pin-power peaking factors calculated separately using a Matlab script (see Maria's presentation)
- No major approximations in geometry: spacer grids homogenized with assembly, gas-filled instrumentation tubes omitted
- ARES model:
  - 9 unique assembly types
  - 3 reflector node types
  - 21 axial nodes (19 active + 2 reflector)

*The 3D Monte Carlo calculation was carried out using the same code and cross section data that was used for homogenization → the best imaginable reference solution for the 3D nodal diffusion calculation*

## Test case (3/5)

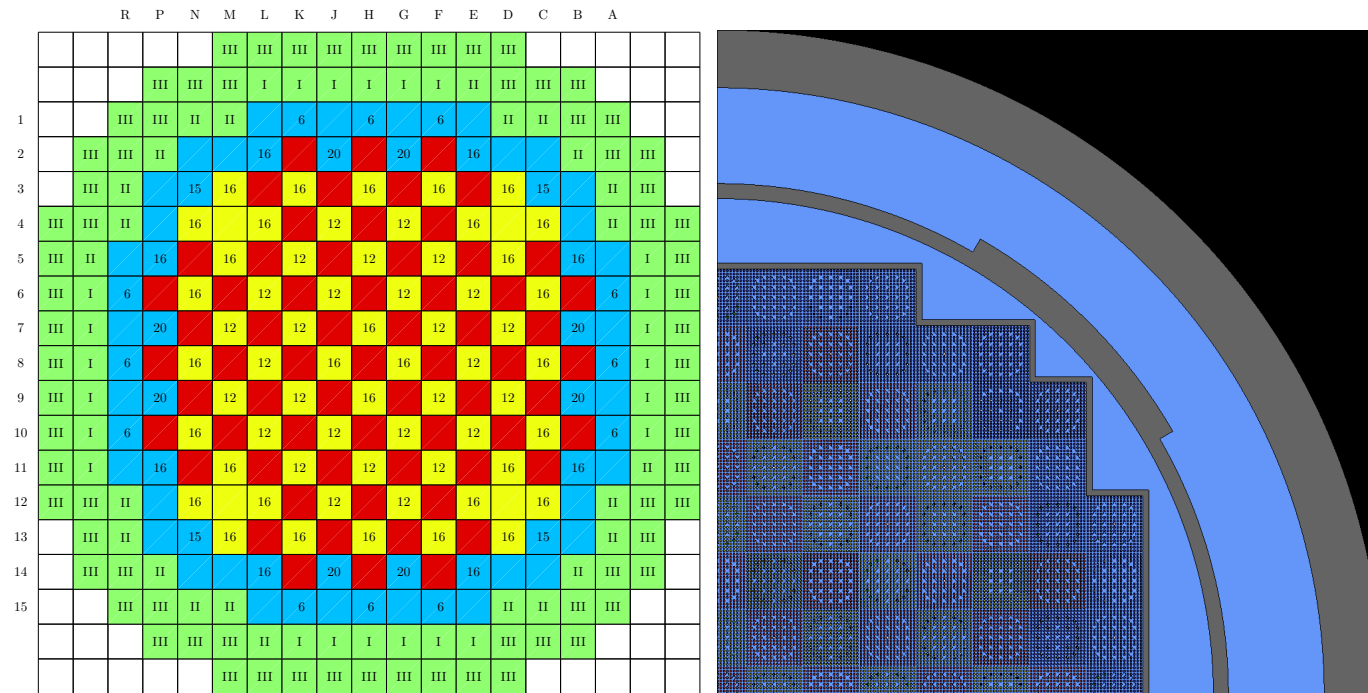


Figure 1: Left: Core layout with fuel enrichment (red = 1.6, yellow = 2.4 and blue = 3.2 w/o U-235), number of burnable absorber pins and reflector type, Right: Geometry plot of the Serpent 3D model at core mid-plane.



## Test case (4/5)

- The calculations were repeated with different approximations for homogenization, by starting from simple and gradually refining the model:
  1. All assemblies homogenized in single-assembly calculations without B1 leakage correction
  2. All assemblies homogenized in single-assembly calculations with B1 leakage correction
  3. Like Config 2., but assemblies with 3.1 w/o enriched fuel and zero and six burnable absorber pins homogenized in colorset with 0.5 assembly widths of surroundings
  4. All assemblies homogenized in colorset with 0.5 assembly widths of surroundings
  5. Like Config 3., but assemblies with 3.1 w/o fuel homogenized in colorset with 1.5 assembly widths of surroundings
  6. All assemblies homogenized in colorset with 2.5 assembly widths of surroundings

## Test case (5/5)

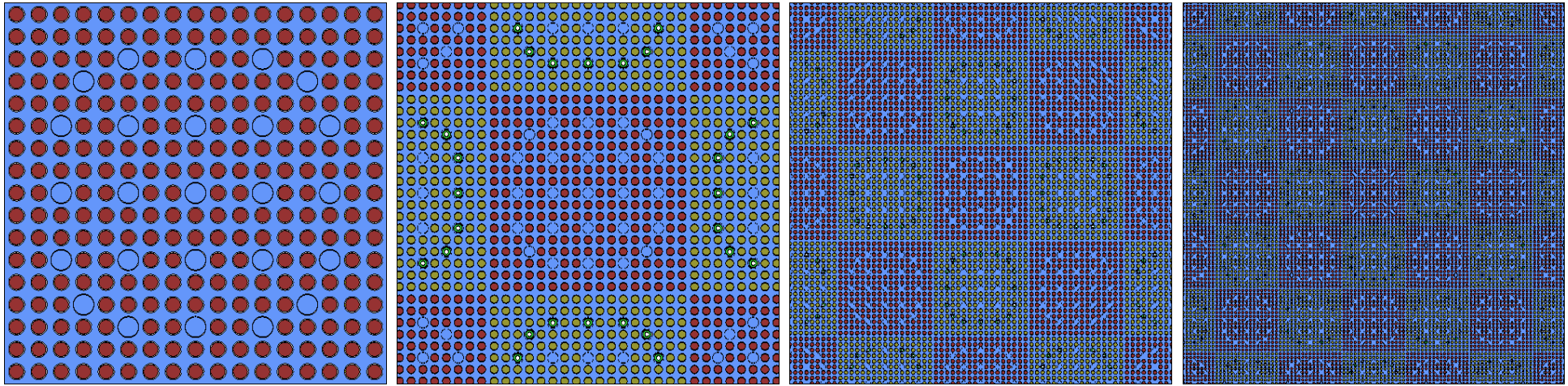


Figure 2: Single assembly and colorset configurations

## Results (1/6)

Table 1: Summary of results: Effective multiplication factor calculated by ARES, maximum negative and positive differences in assembly power between ARES and Serpent 3D, and error fractions and mean absolute errors in ARES pin-power distribution.

Config.	$k_{\text{eff}}$	Differences	Error fractions			Mean
			< 1%	< 2%	< 3%	
1	0.99922	[-7.7 , 12.0]	13.5	29.0	44.8	4.1
2	0.99953	[-8.4 , 10.9]	16.8	31.5	43.8	4.0
3	0.99831	[-2.8 , 2.8]	42.6	78.7	94.8	1.3
4	0.99994	[-3.8 , 8.7]	27.9	58.8	80.8	1.9
5	0.99949	[-1.6 , 1.4]	71.7	98.1	99.7	0.7
6	0.99995	[-1.6 , 0.6]	82.4	97.7	99.7	0.1

## Results (2/6)

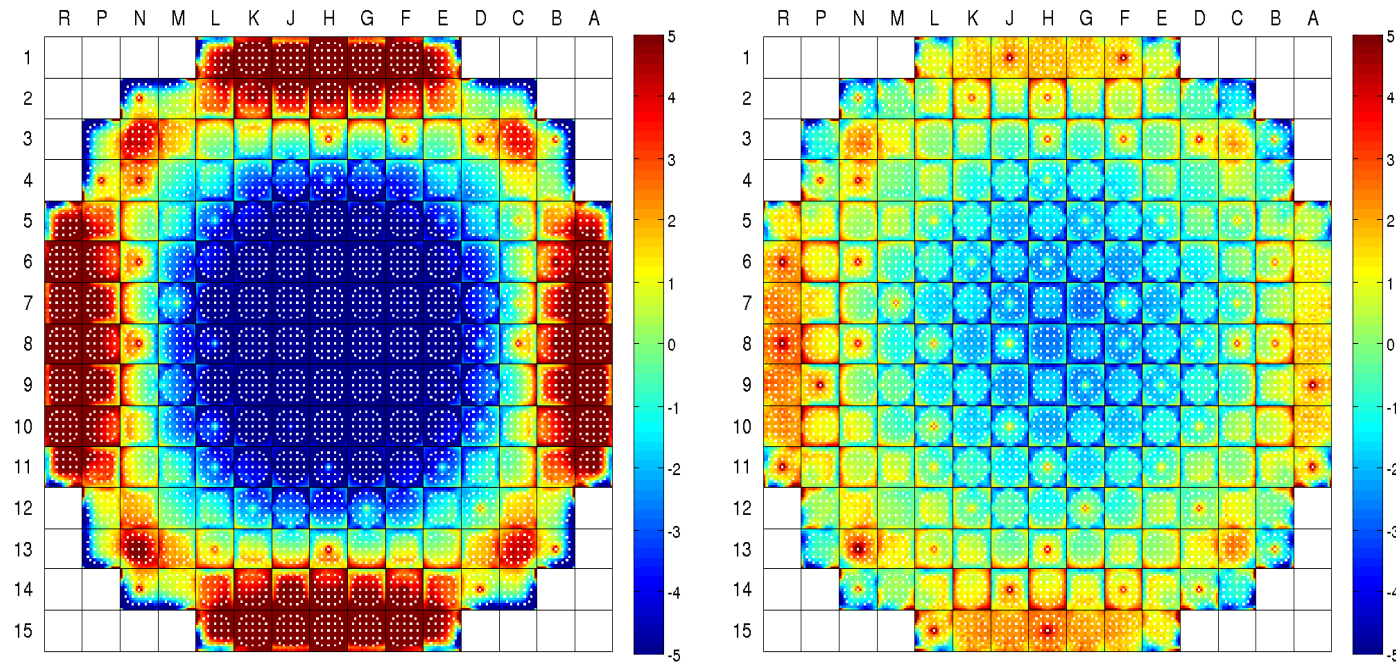


Figure 3: Left: Config 2 – All assemblies homogenized in single-assembly calculations. Right: Config 3 – Assemblies with 6 BA pins homogenized with surroundings.

## Results (3/6)

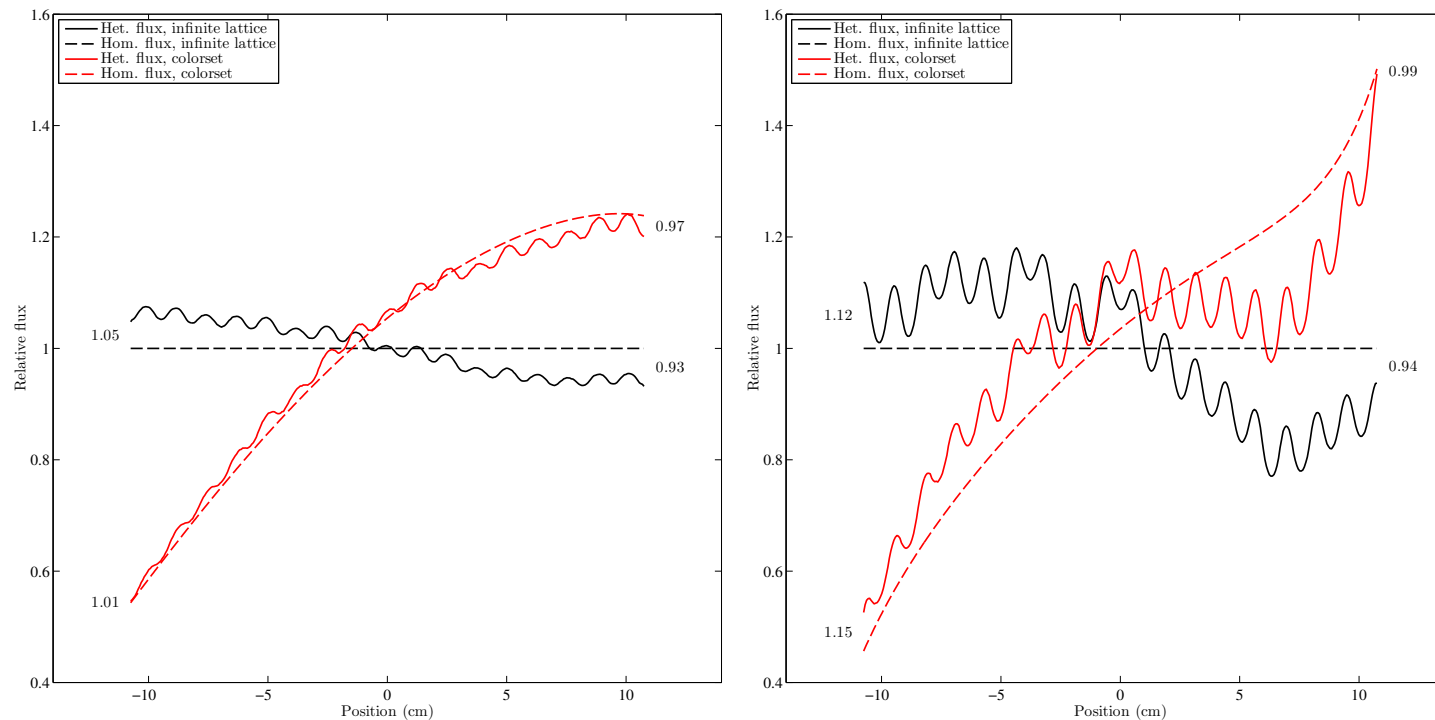


Figure 4: Impact of surroundings in homogeneous and heterogeneous flux in assemblies with 6 BA pins. Left: fast group. Right: thermal group.



## Results (4/6)

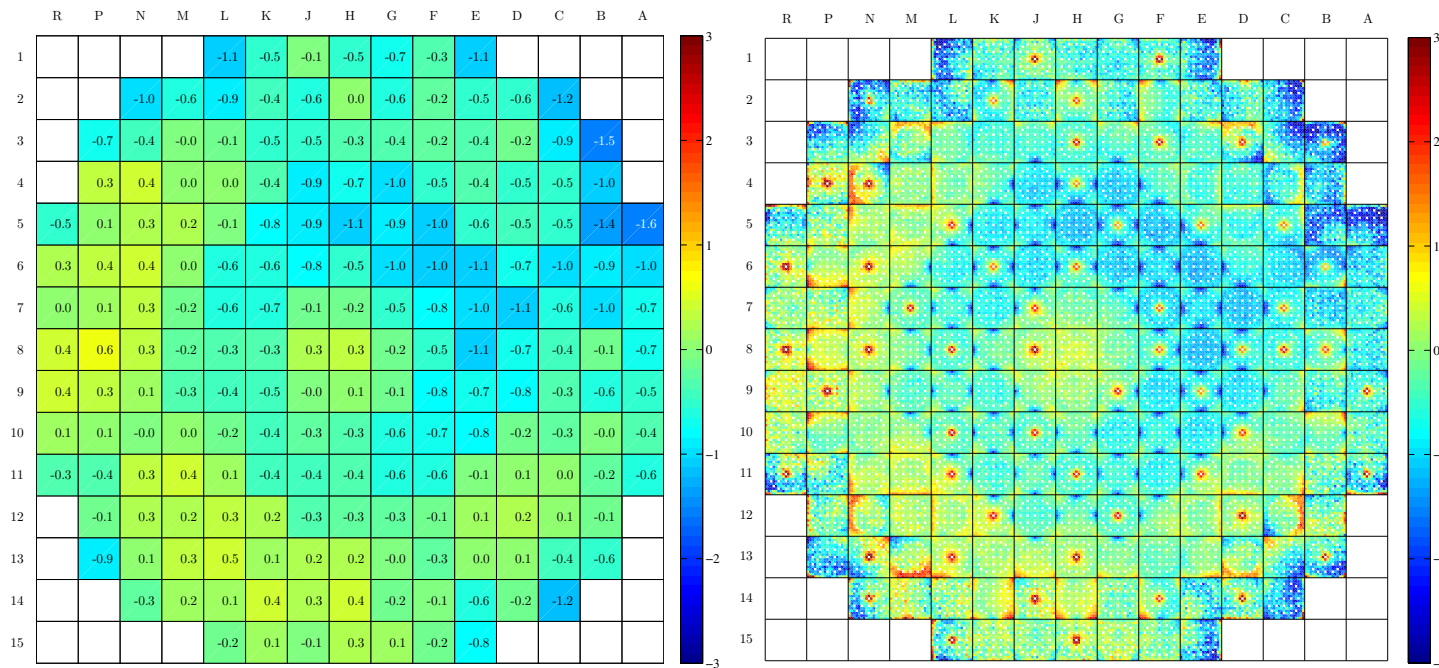


Figure 5: Config 6 – All assemblies homogenized in colorset with 2.5 assembly widths of surroundings (best results). Left: relative differences in assembly power at core mid-plane. Right: relative differences in pin power at core mid-plane.

## Results (5/6)

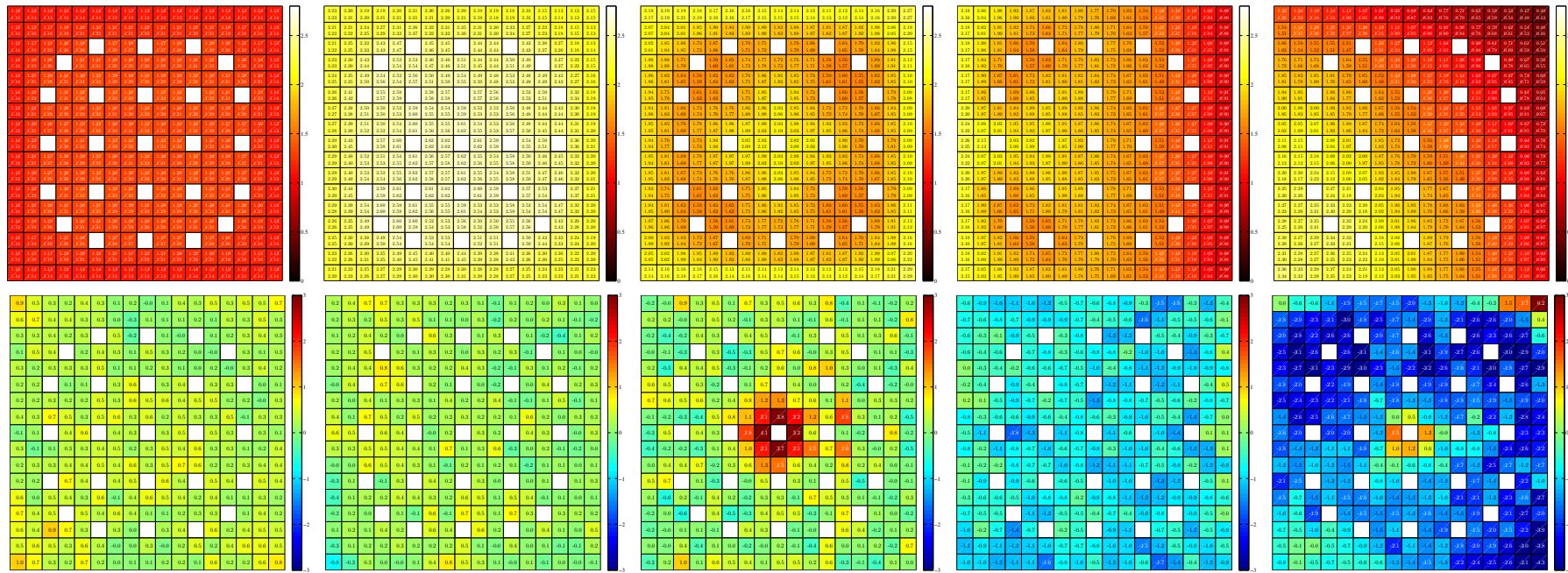


Figure 6: Pin-level results in selected assembly positions (left to right: A8, M12, P9, A8 and B3). Top row: power distributions, Bottom row: relative differences to Serpent 3D calculation (in percent).

## Results (6/6)

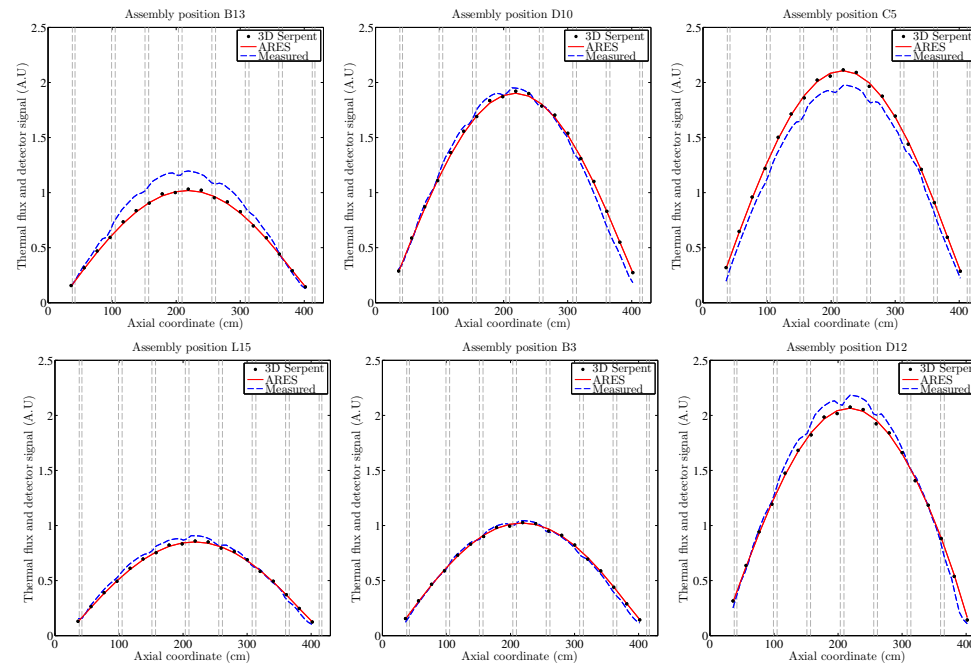


Figure 7: Node-averaged thermal flux distributions at selected assembly positions from 3D Serpent and ARES calculations, together with experimental fission chamber measurements in the central instrumentation tube.



## Summary and conclusions

- Lessons learned:
  - Serpent (v. 2.1.16) is capable of producing all group constants needed for simulating the HZP initial core of a PWR using a nodal diffusion code
  - The neutronics model in ARES is capable of producing very accurate results at pin-level, compared to the reference 3D Monte Carlo solution
  - The ARES flux solution is sensitive to ADF's, and the best results are obtained when a sufficiently large region of surroundings is included with the homogenized assembly
- What's next:
  - HFP and fuel cycle simulations requires additional data and interpolation between state points → methods yet to be completed
  - Automated ADF calculation and burnup sequence with branch and coefficient calculations
  - Time constants for transient simulations
  - Group constant generation for HEXBU-3D, TRAB-3D and HEXTRAN codes

**Thank you for your attention!**