High-fidelity multiphysics calculations for VVER reactors in the McSAFE project

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McSAFE EU H2020 project

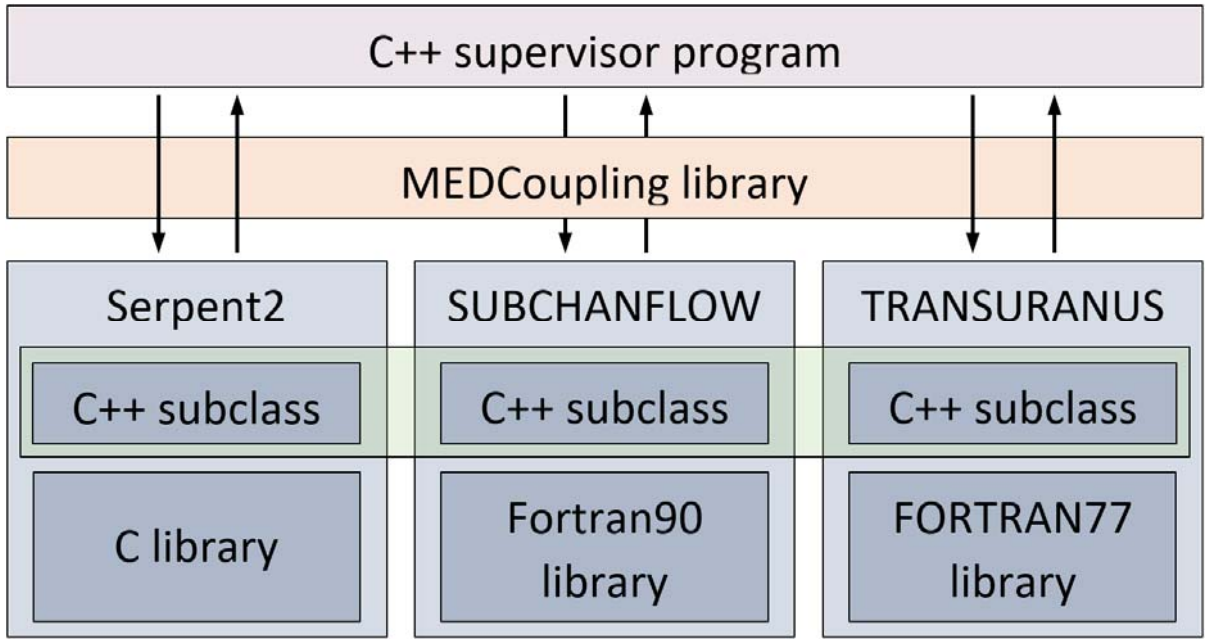
- Objectives:
  - Improve the prediction of local safety parameters through high-fidelity.
  - Develop multiphysics tools based on Monte Carlo particle transport, subchannel thermalhydraulics and fuel-performance analysis.
  - Solve steady-state, depletion and transient problems.
  - Optimize the codes for massive problems such as full-core burnup.
  - Validate with PWR and VVER plant data.
- Participants:
  - KIT (SUBCHANFLOW).
  - JRC, HZDR (TRANSURANUS).
  - VTT (Serpent2).
  - CEA (Tripoli), DNC (MCNP), AMEC (MONK), NRI, KTH.
  - EKK, CEZ, EdF.
- Continuation of the NURESAFE and HPMC projects.

Serpent2-SCF-TU

- Codes:
  - Serpent2: continuous-energy Monte Carlo particle transport.
  - SUBCHANFLOW: MATRA- (COBRA-) based subchannel code.
  - TRANSURANUS: fuel-performance analysis.
- Objectives:
  - Perform fully coupled pin-by-pin depletion calculations.
  - Optimize the system for High Performance Computing (HPC).
  - Develop a suitable modelling approach (pin-by-pin, hot channel) for full-core.
  - Validate with PWR and VVER experimental data from the industry partners.
- Coupling approach:
  - Pin-level feedback, fully coupled calculation scheme.
  - TRANSURANUS replaces the rod solver of SUBCHANFLOW.
  - Object-oriented design.
  - Mesh-based (geometry agnostic) field exchange.
  - Pre- and post-processing capabilities for PWR and VVER reactors.

Object-oriented coupling

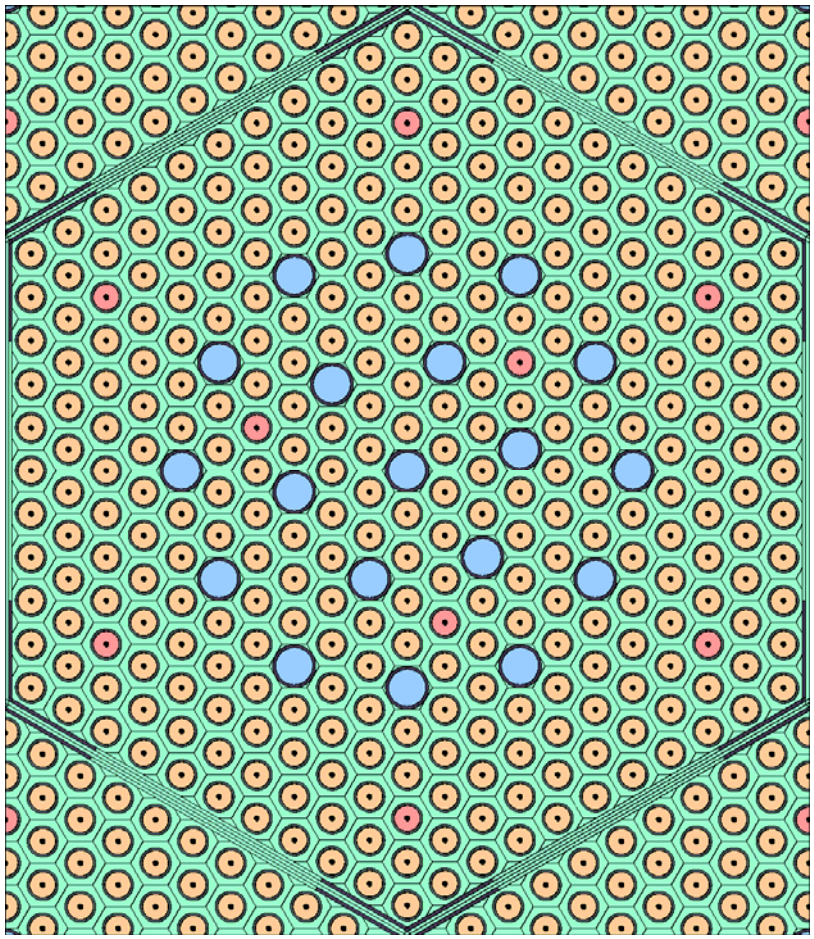
- Object-oriented design:

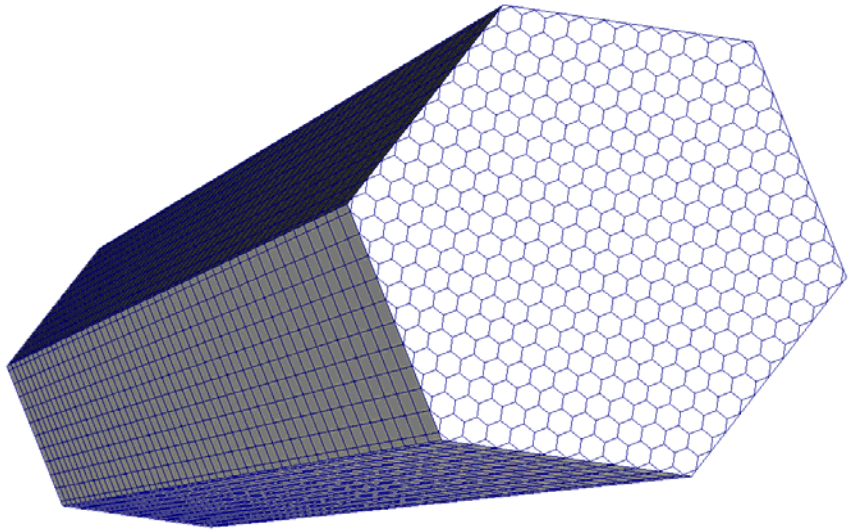


- Advantages:
  - The codes are kept completely separate and maintainability is enhanced.
  - Suitable model for collaborative development projects.
  - The coupling through the supervisor is flexible and somehow generic.

Mesh-based feedback

- Serpent2:



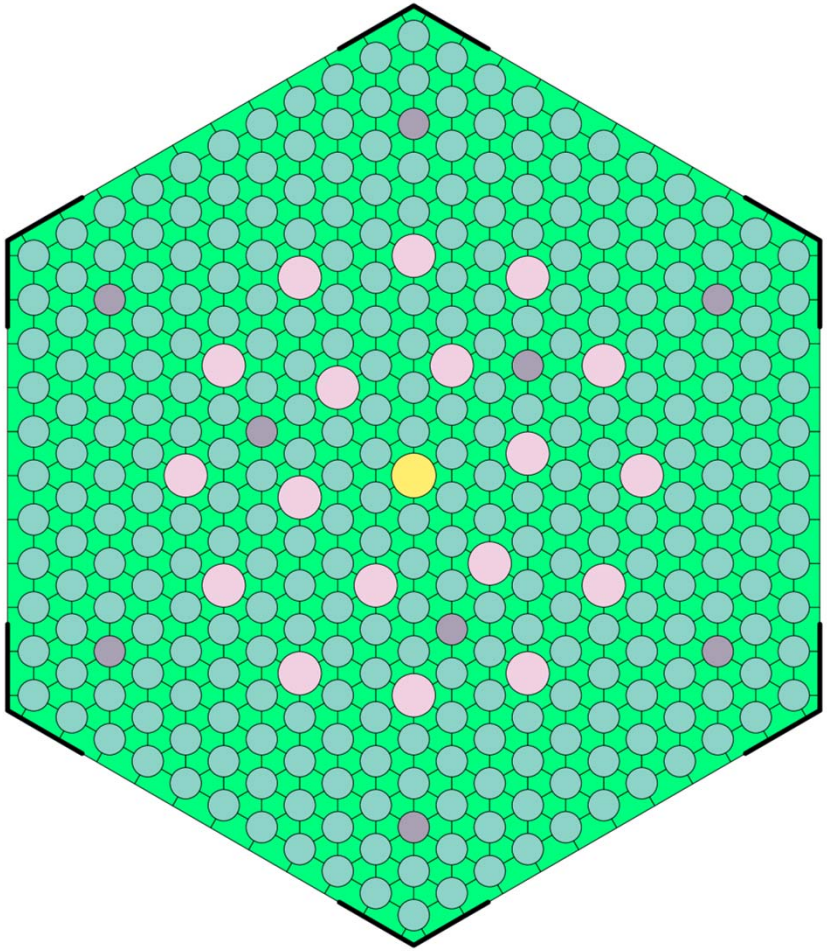


Multiphysics interfaces:

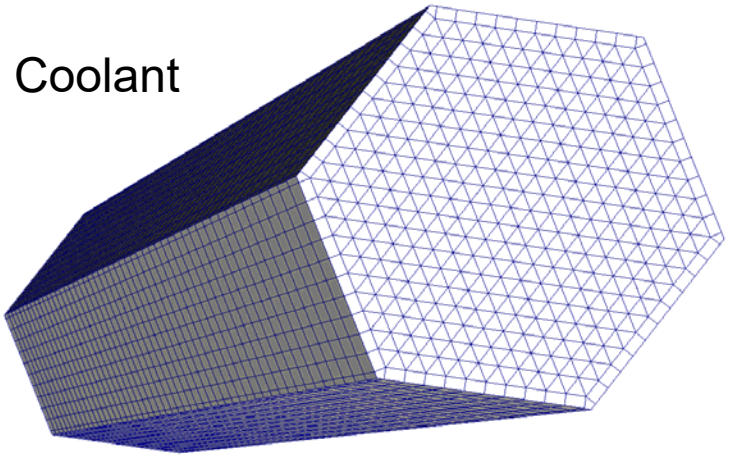
- Superimposed meshes.
- Not linked directly to the tracking geometry.
- Define temperatures and densities and tally power.

Mesh-based feedback

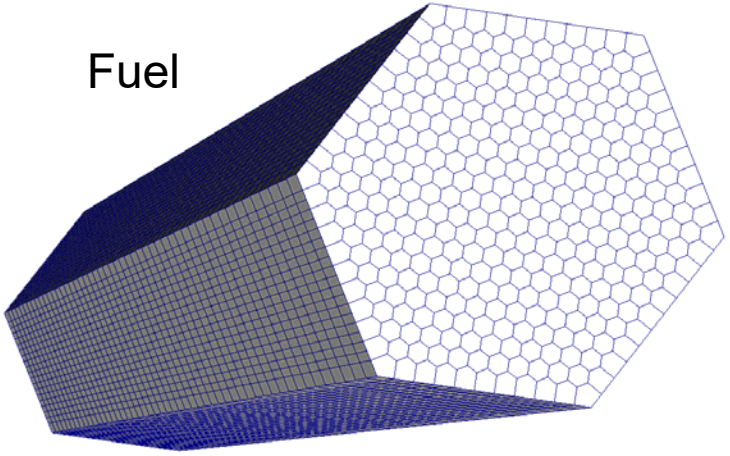
- SUBCHANFLOW:



Coolant

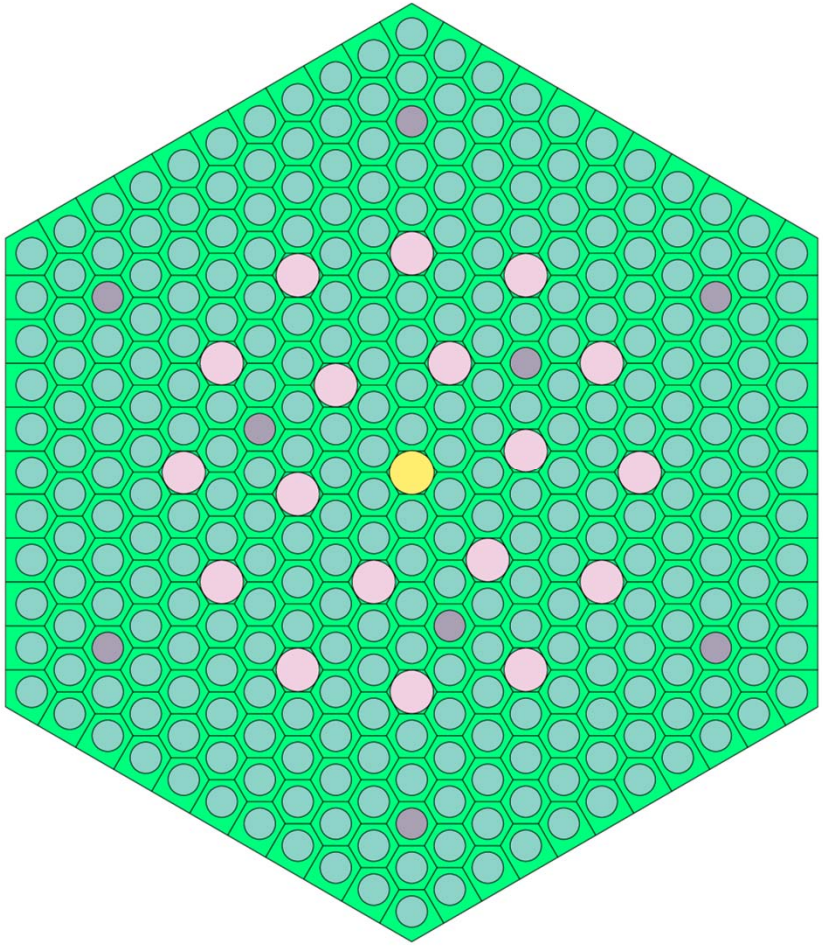


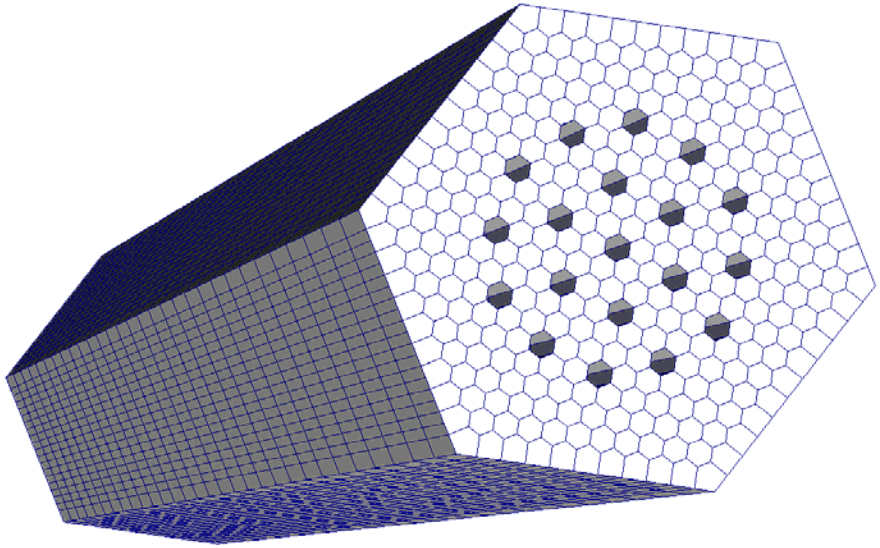
Fuel



Mesh-based feedback

- TRANSURANUS:

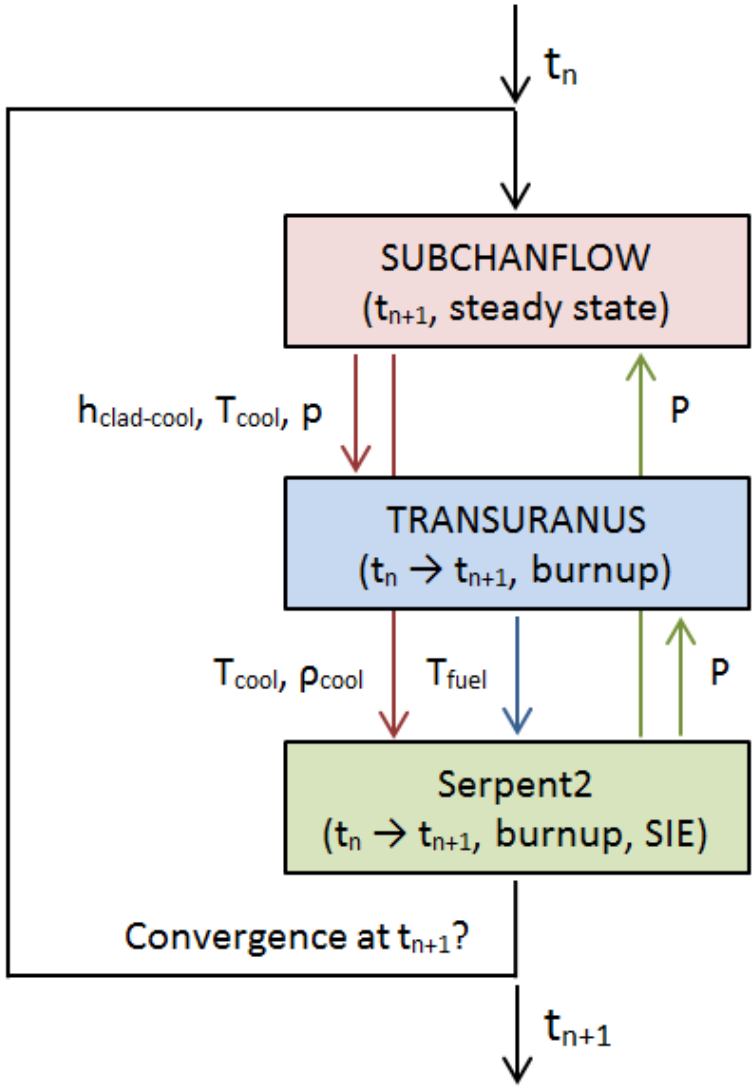




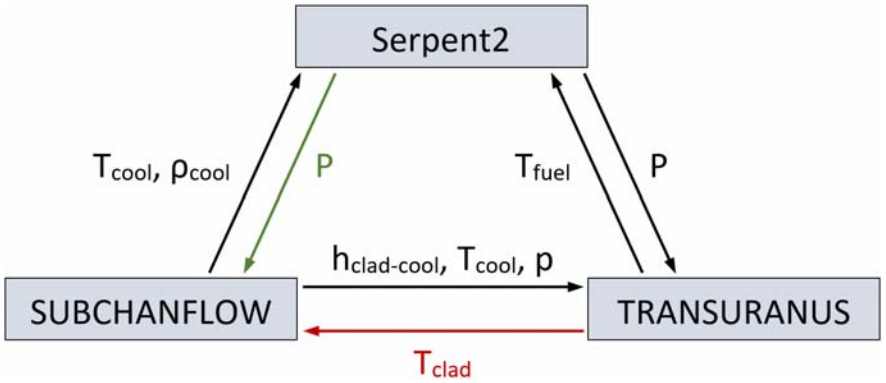
Multiphysics mesh:

- Used to gather results and set input variables.
- Contains only the fuel rods.

Calculation scheme

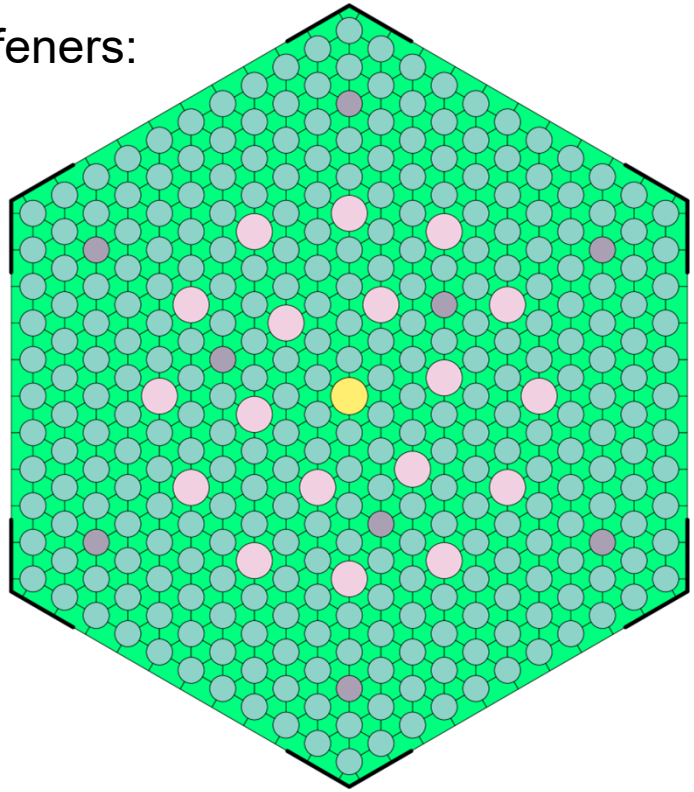


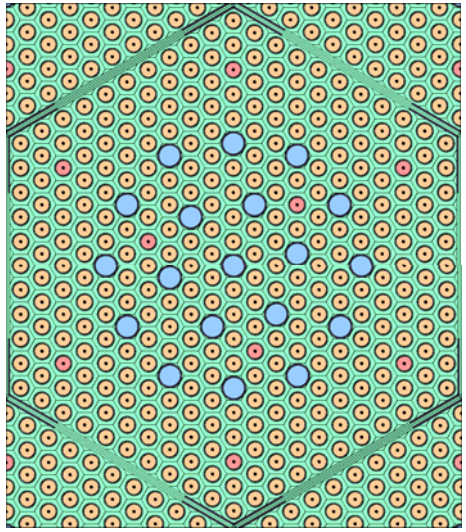
- Semi-implicit depletion scheme.
- Solution of the Bateman equations both in TU and Serpent2.
- The only Serpent2 data used in TU is the power distribution.
- The TU neutronic model is still used.
- SCF does not model the rods.

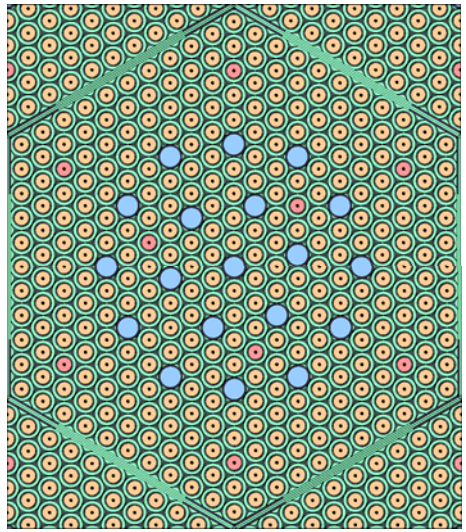


Core structural components

- Serpent2:
  - Constructive Solid Geometry (CSG).
  - Explicit modelling of all relevant structures.
- SUBCHANFLOW:
  - Explicit modelling of stiffeners:
    - Wetted perimeters.
    - Subchannel gaps.
  - Spacer grids:
    - Local pressure loss coefficients.
    - Typical values used.
- TRANSURANUS:
  - Standard fuel performance models.

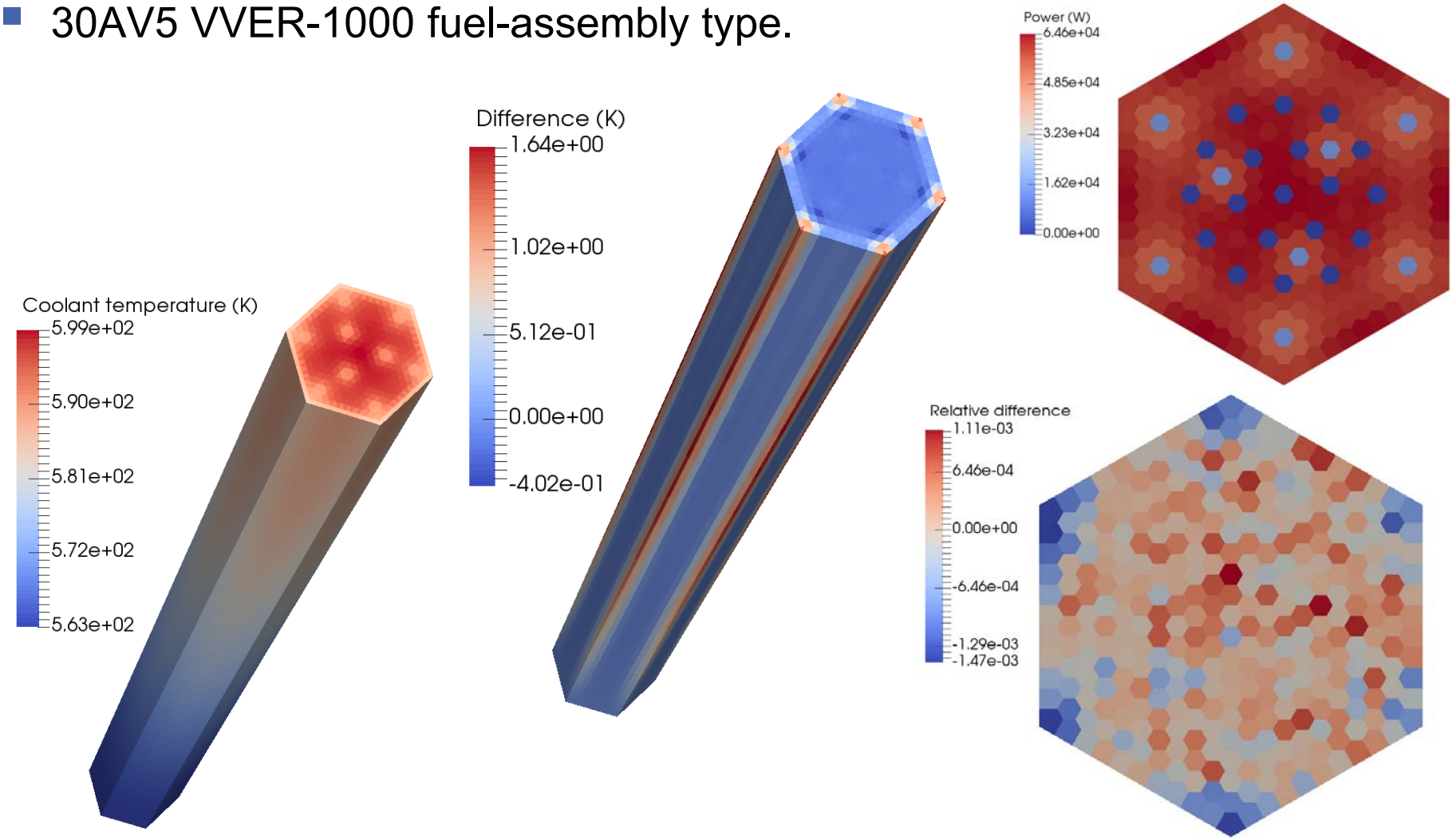






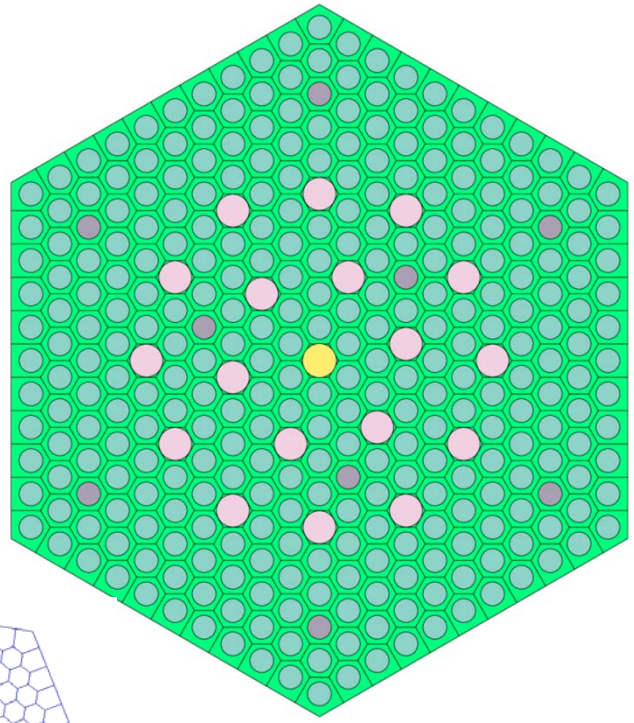
Results: stiffeners

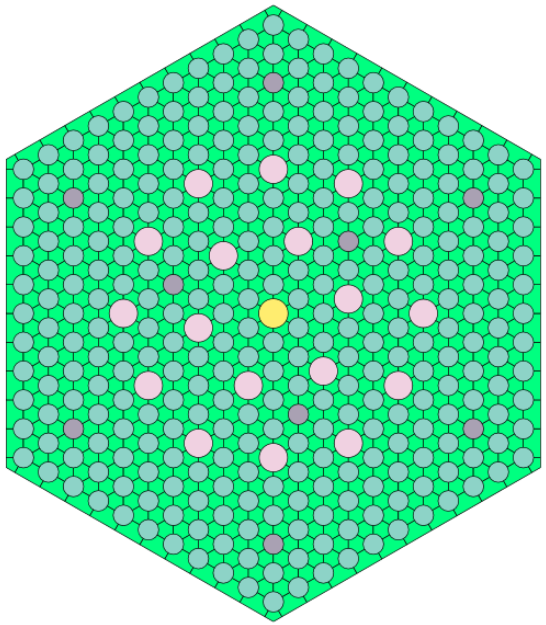
- 30AV5 VVER-1000 fuel-assembly type.

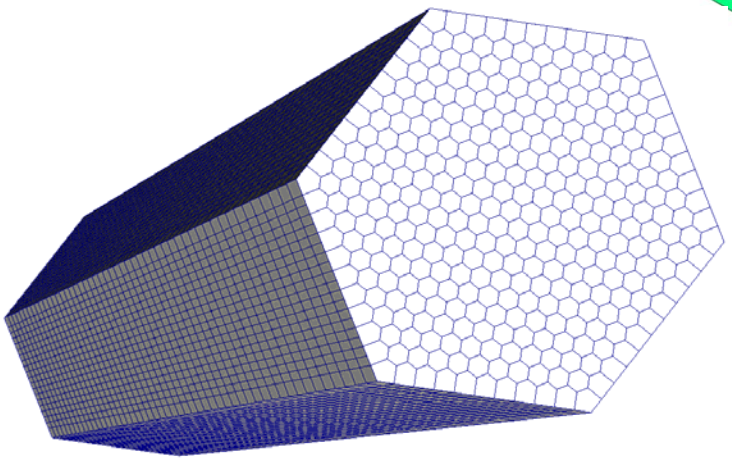


Subchannel models

- Coolant-centered subchannels:
  - Widely used and physically sound.
  - Complex interpolation needed.
- Fuel-centered subchannels:
  - Parameters harder to define.
  - More convenient for multiphysics.

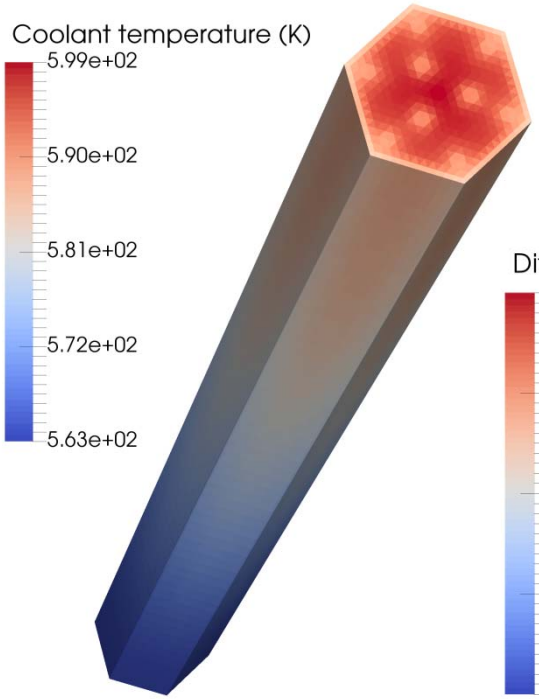


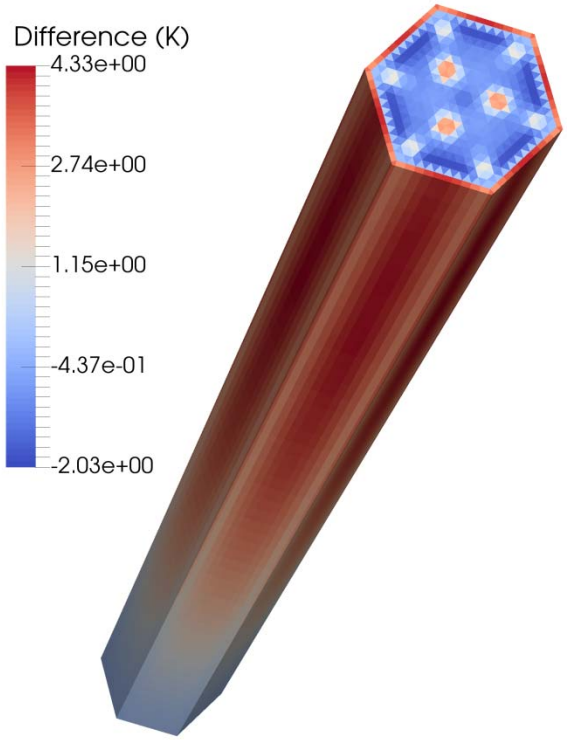


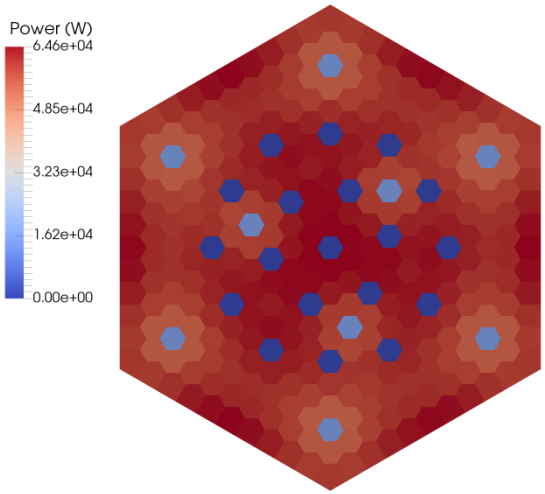


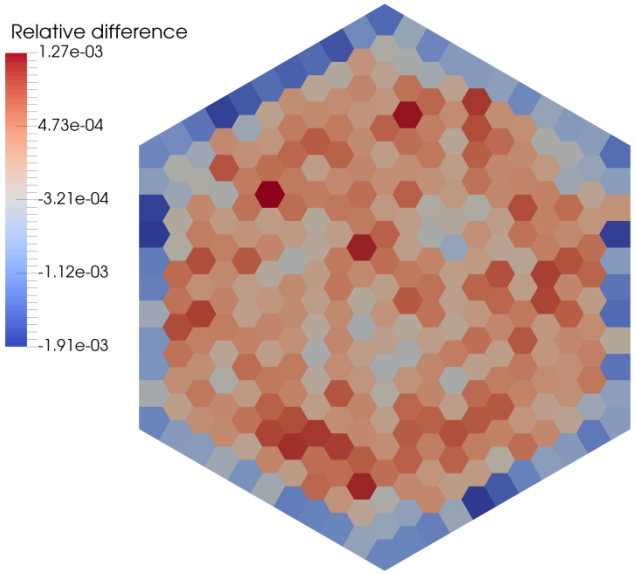
Results: subchannel models

- 30AV5 VVER-1000 fuel-assembly type.



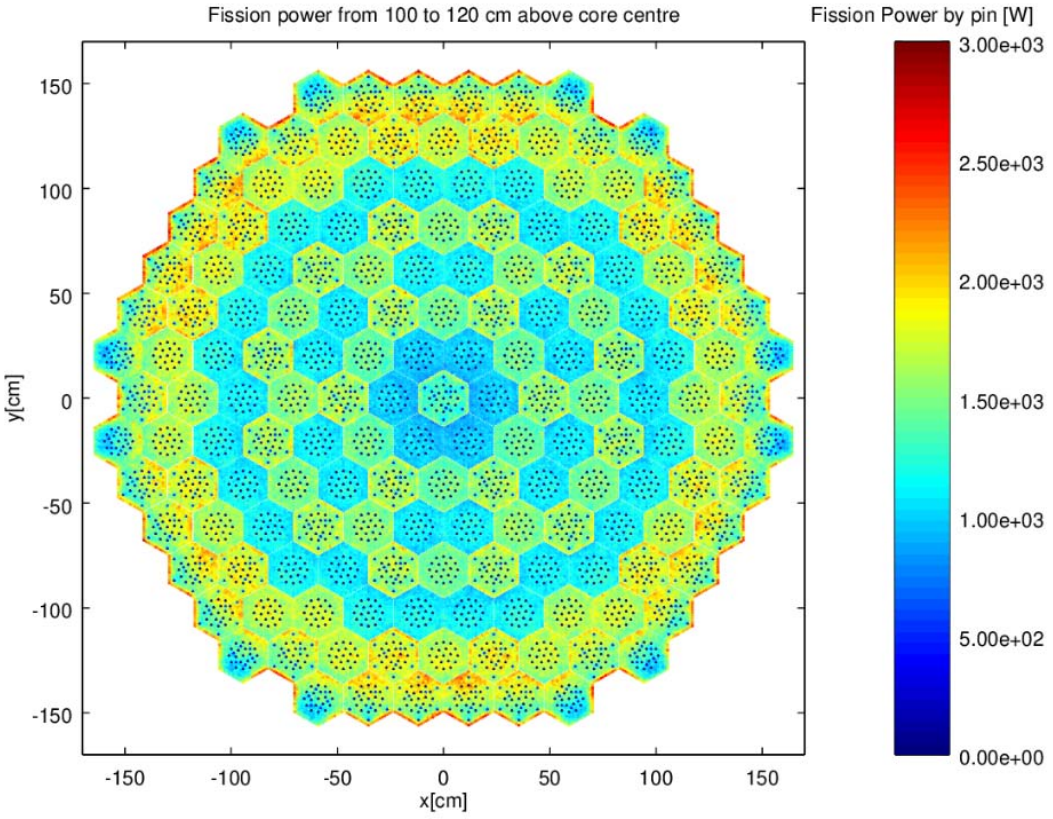






Results: steady-state full-core

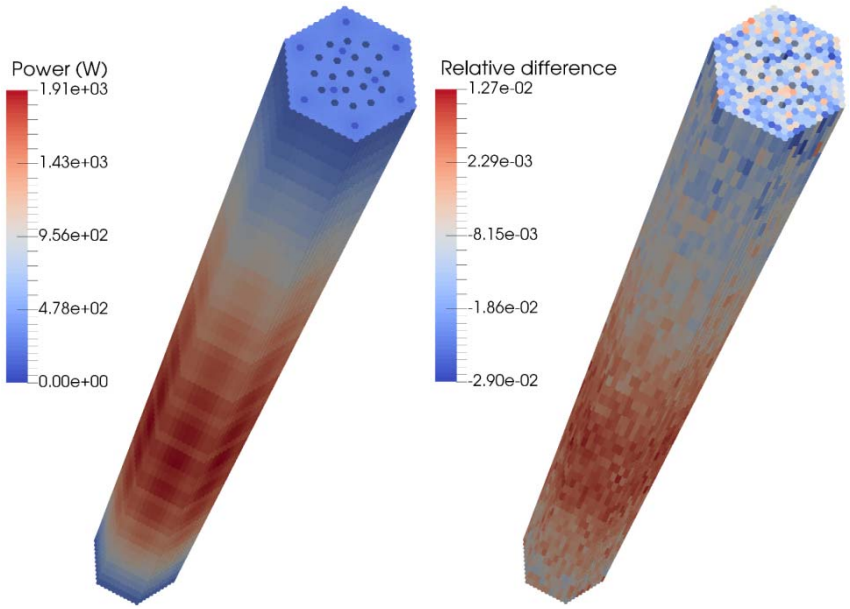
- Full-core VVER-1000 benchmark [1].
- Modelling approach:
  - Pin-by-pin coupling.
  - Nodal-level Xe.
  - Run in the FH2 cluster.
- Criticallity calculation:
  - K_{eff} = 1.00149 ± 8e-5.
  - ~150 pcm deviation.
- Further steps:
  - Pin-by-pin comparisons.
  - Depletion.

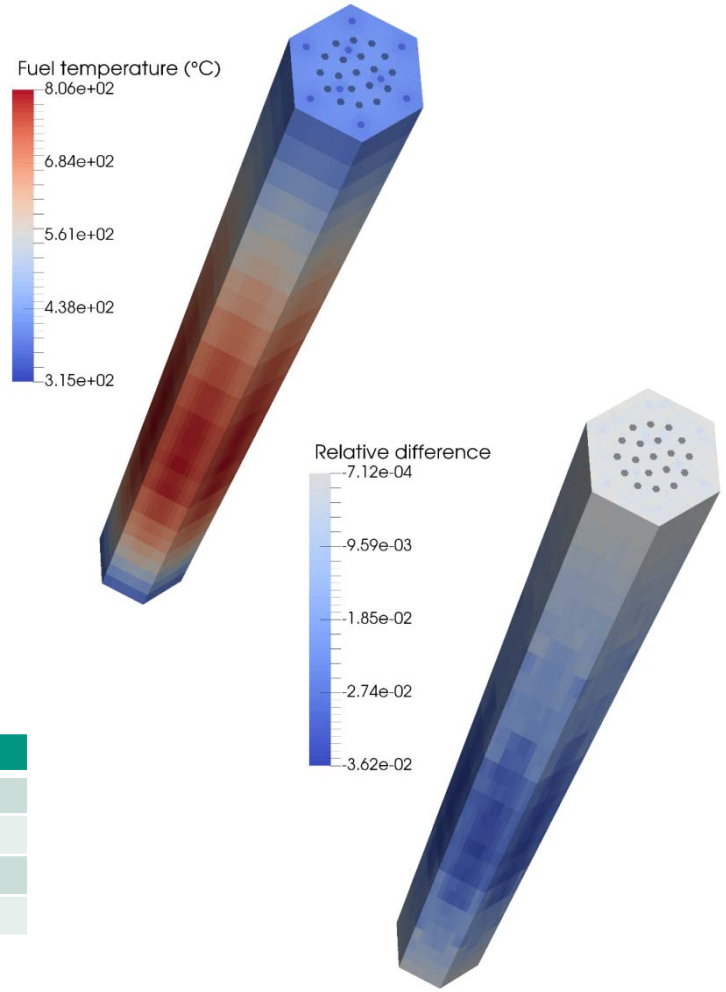


[1] Loetsch, T. et al "Corrections and additions to the proposal of a benchmark for core burnup calculations for a WWER-1000 reactor" Proceedings of the twentieth symposium of atomic energy research, (p. 790). Hungary: Kiadja and KFKI Atomenergia Kutatointezet (2010).

Results: steady-state (TU)

- 30AV5 VVER-1000 fuel-assembly type.



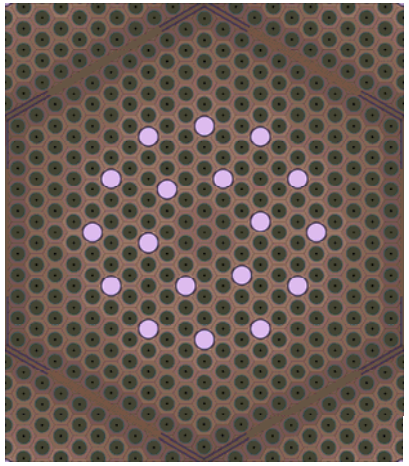


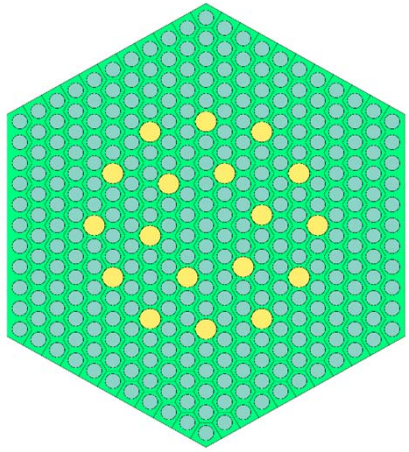
Difference: Serpent-SCF-TU – Serpent-SCF

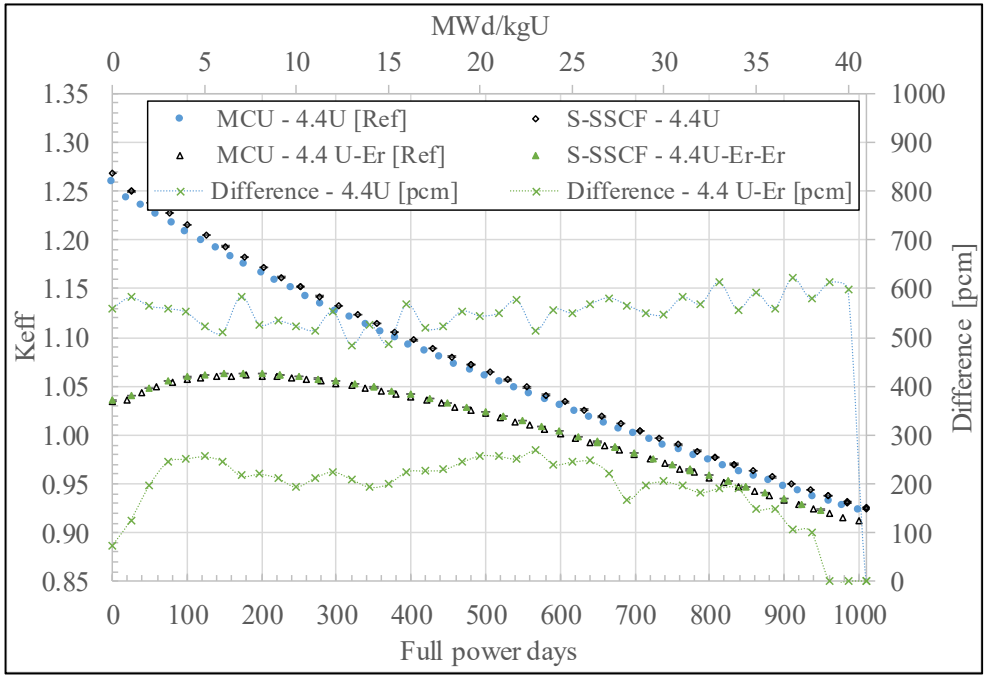
Field	Maximum difference	Average difference
Power (W)	22.12 (2.90%)	4.61 (0. 46%)
Coolant density (kg/m³)	0.43 (0.06%)	0.09 (0.01%)
Coolant temperature (°C)	0.17 (0.03%)	0.04 (0.01%)
Fuel temperature (°C)	28.86 (3.62%)	11.75 (1.73%)

Results: depletion

- VVER-1000 FA benchmark [1].



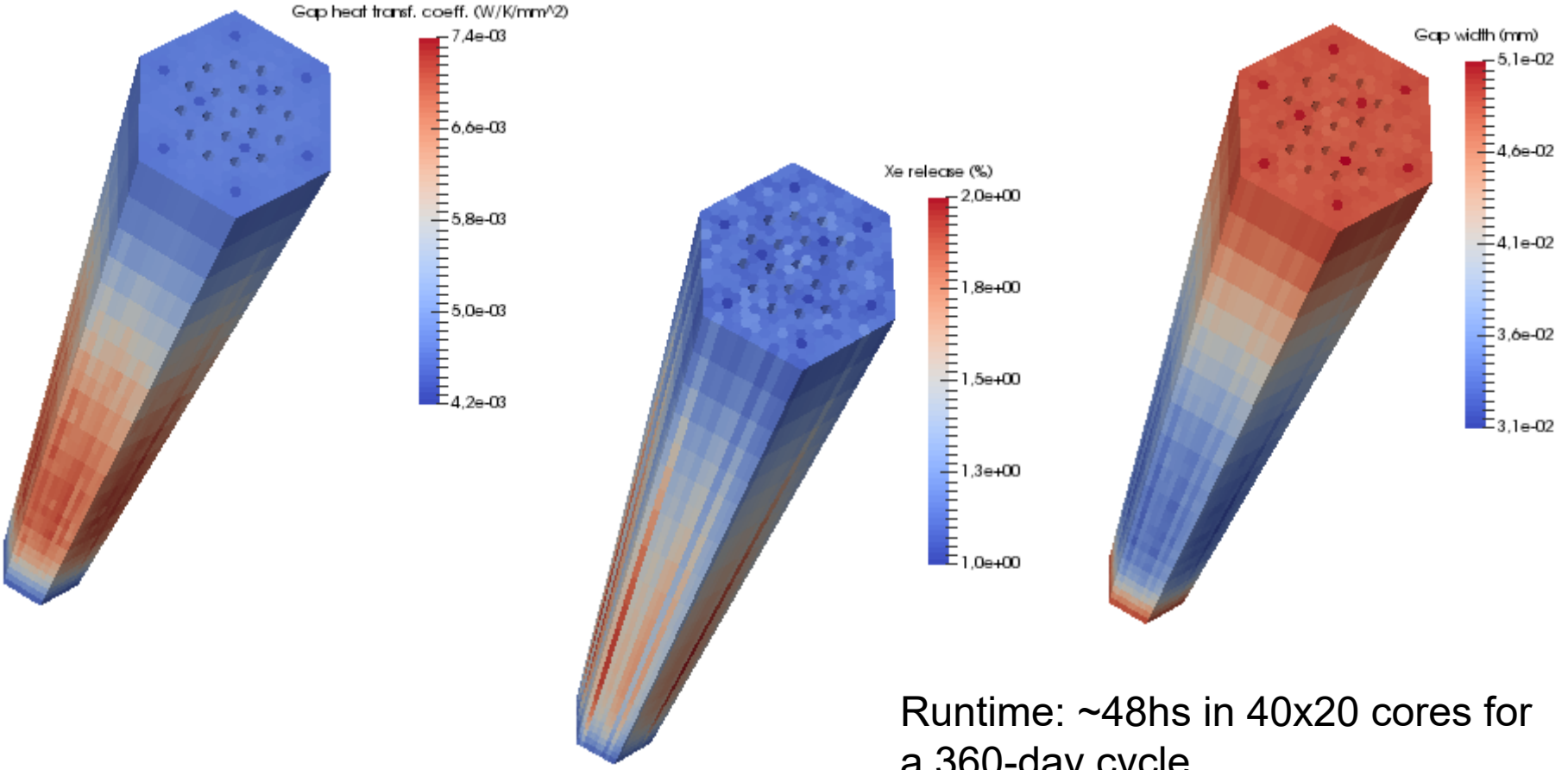




[1] Bikeev, Artem et al. "MCU Code Precision Calculation of a Full-Scale VVER-1000 Model Considering Feedbacks" Proceedings of M&C 2017.

Results: depletion (TU)

- 30AV5 VVER-1000 fuel-assembly type (t = 60 days).



Runtime: ~48hs in 40x20 cores for a 360-day cycle.

Open issues

- Neutronic feedback to TRANSURANUS:
  - Currently only the linear heat rate is used, the simples posible feedback.
  - Using power and flux radial profiles not feasible, at least not with the current modelling approach, i. e. having all pins in TRANSURANUS.
  - Other average parameters? Isotope compositions?
- Doppler feedback to Serpent2:
  - Currently volume averaging or empirical formulas are used.
  - Analysis of radial fuel temperature profiles in the near future.
- Modelling approach:
  - With the current approach we'd simulate ~60,000 TU rods for full-core cases!
  - Hot-channel methodology? Average pin for each fuel-assembly?
- Memory bottleneck for Serpent2 depletion:
  - A full core takes about 2TB for pin-by-pin depletion.
  - Domain decomposition in progress.

Conclusions

- Current status:
  - Three code coupling with pin-level feedback implemented.
  - Verification with single-fuel-assembly PWR and VVER steady-state cases.
  - Analysis of single-fuel-assembly depletion cases underway.
  - Optimization towards full-core capabilities in progress.
- Open issues:
  - Analysis of the TRANSURANUS side of the depletion scheme, including adding more neutronic feedbacks from Serpent2.
  - Analysis of the Doppler feedback to Serpent2.
  - Optimization of the modelling in TRANSURANUS (and the other codes).

Questions? Comments?