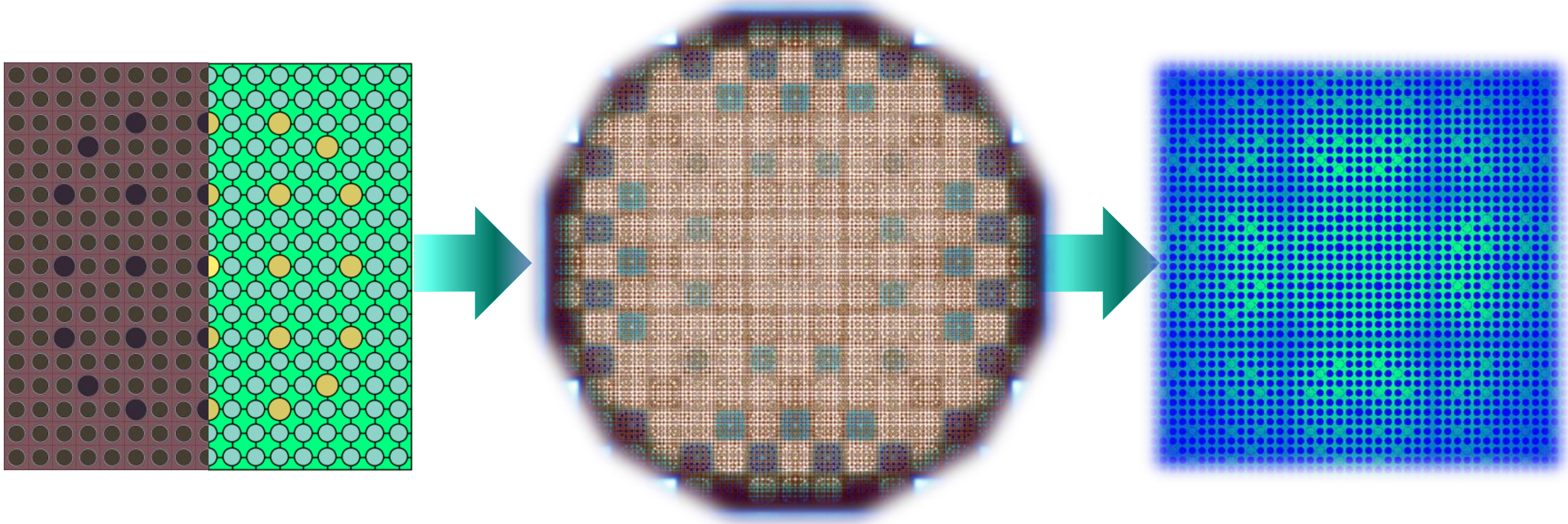
Karlsruhe Institute of Technology

Serpent multi-physics analysis for transients in Light Water Reactors

Diego Ferraro
Karlsruhe Institute for Technology (KIT)

Serpent User Meeting Group 2020 – 27th – 30th October, Garching, Germany

INSTITUTE for NEUTRON PHYSICS and REACTOR TECHNOLOGY (INR)



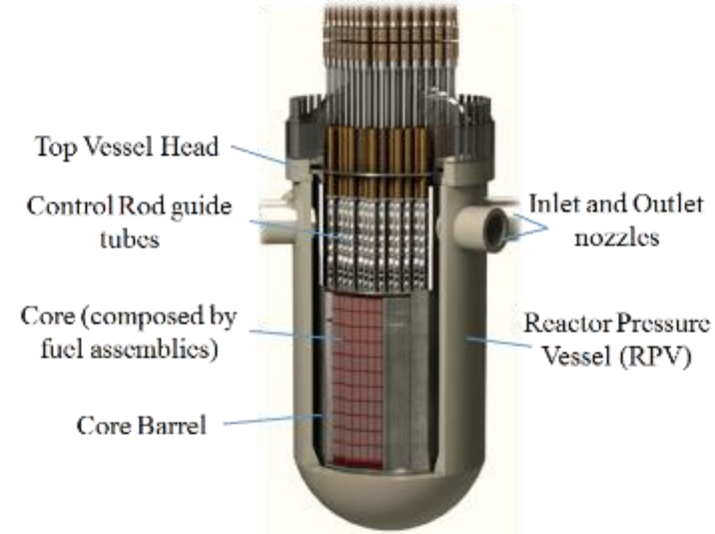
Outline

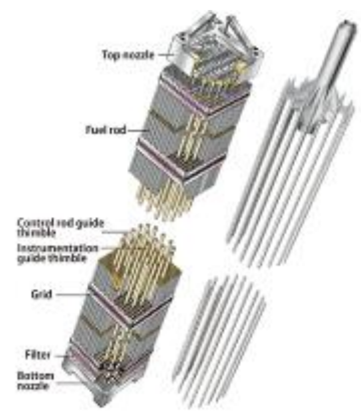
1. Introduction
2. The MC-based approach for coupled transients
3. Developed Serpent + SCF (master-slave) coupling
4. Verification and validation examples:
   - ✓ Full-core Steady-state
   - ✓ Comparison with experimental results from SPERT-IIIE
   - ✓ Full scope PWR RIA-kind case
5. Conclusions

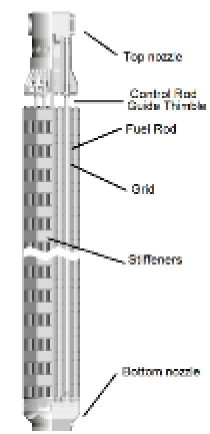
1.1 Introduction

The state of the art for reactor core calculations

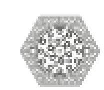
- The reactor core is a complex (multidisciplinary) problem.
- From the wide span of designs, only LWR are here discussed.
- Diverse time scopes are usually considered (i.e steady-state, burnup, ***transients***).
- The two-step (***cell-core***) approach remains as the industry-standard.
- This approach has inherent limitations.
- During recent years a worldwide trend to develop high-fidelity approaches is observed.
- Objective: lower number of approximations, direct calculation of relevant parameters.





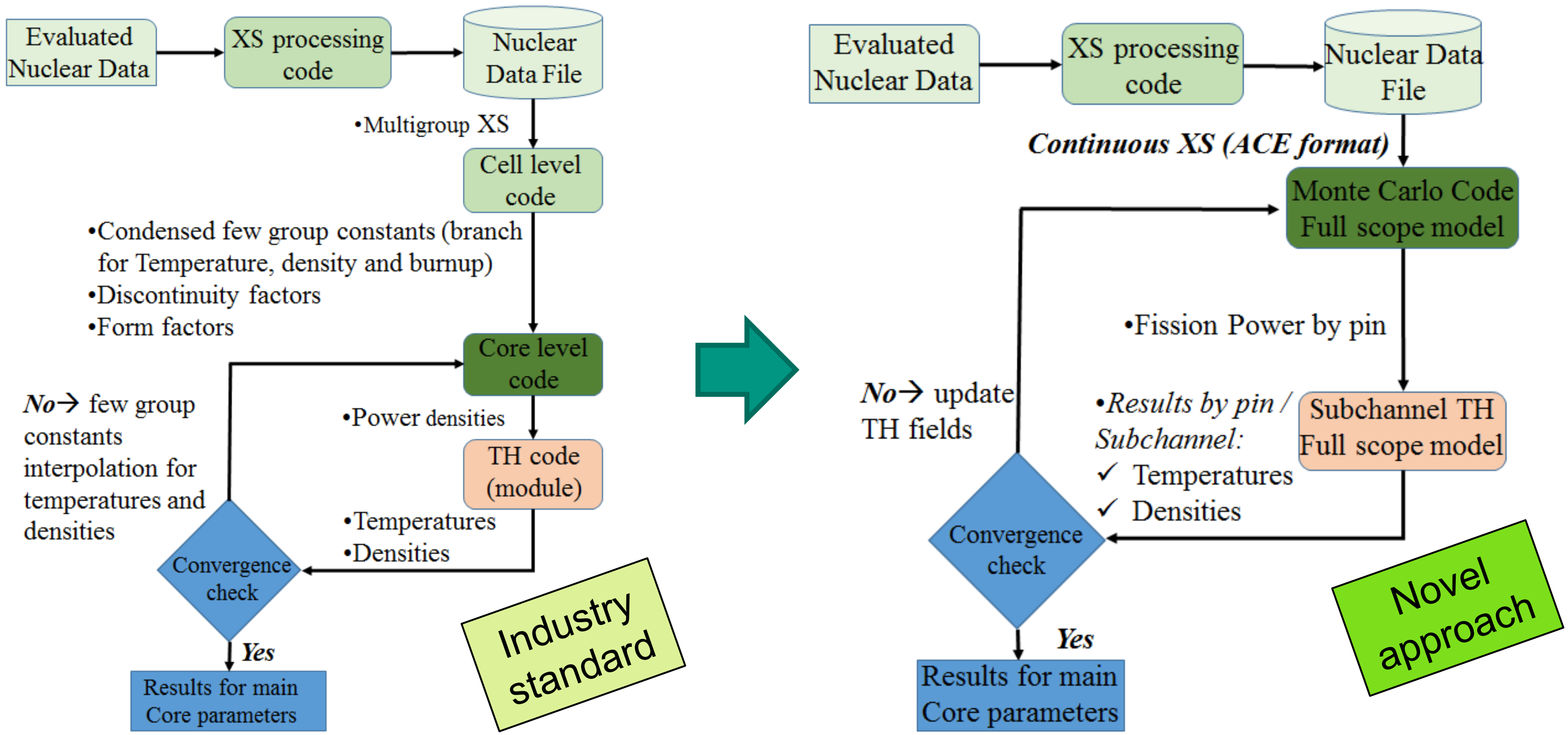


➡ ***Can we use MC-based neutronic codes plus subchannel TH to develop coupled transient calculations?***



The high-fidelity proposal

- Replace the two-step approach by a direct pin-by-pin (MC-based) coupled calculation.



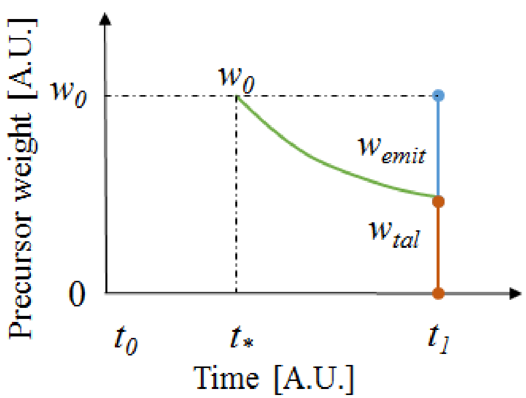
Potential advantages : Avoid the cell-core approach & reconstruction methods, direct safety-related calculations, fully alternative path.

Potential drawbacks : *Complexity, inherent limitations, calculation times.*

2.1 The MC-based approach
Serpent + SCF

- ***MC-based Neutronics: Serpent 2***

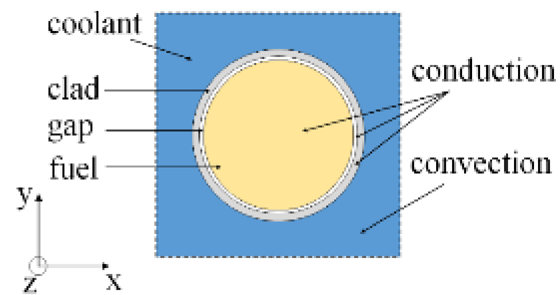
1. Take advantage of multiphysics capabilities (IFC).
2. Serpent transient calculations within reactors:
   - ✓ Fixed source approach
   - ✓ Known energy and distance of live neutrons → time is known
   - ✓ Precursors are also modelled as waiting in interaction sites



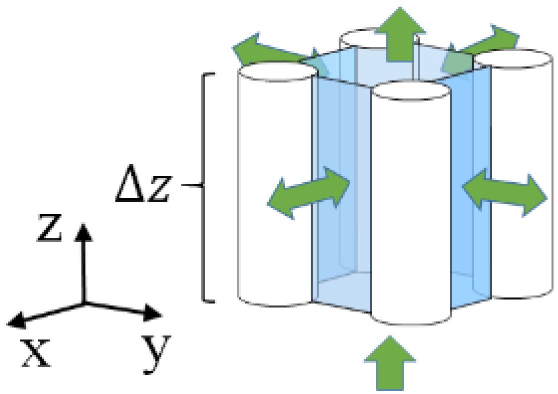
http://serpent.vtt.fi/mediawiki/index.php/Transient_simulations

- ***Subchannel TH: SUBCHANFLOW***

✓ Solve conduction + convection at pin level (for a vapor + liquid mix)



✓ For coolant: balance of mass, energy and lateral plus lateral momentum

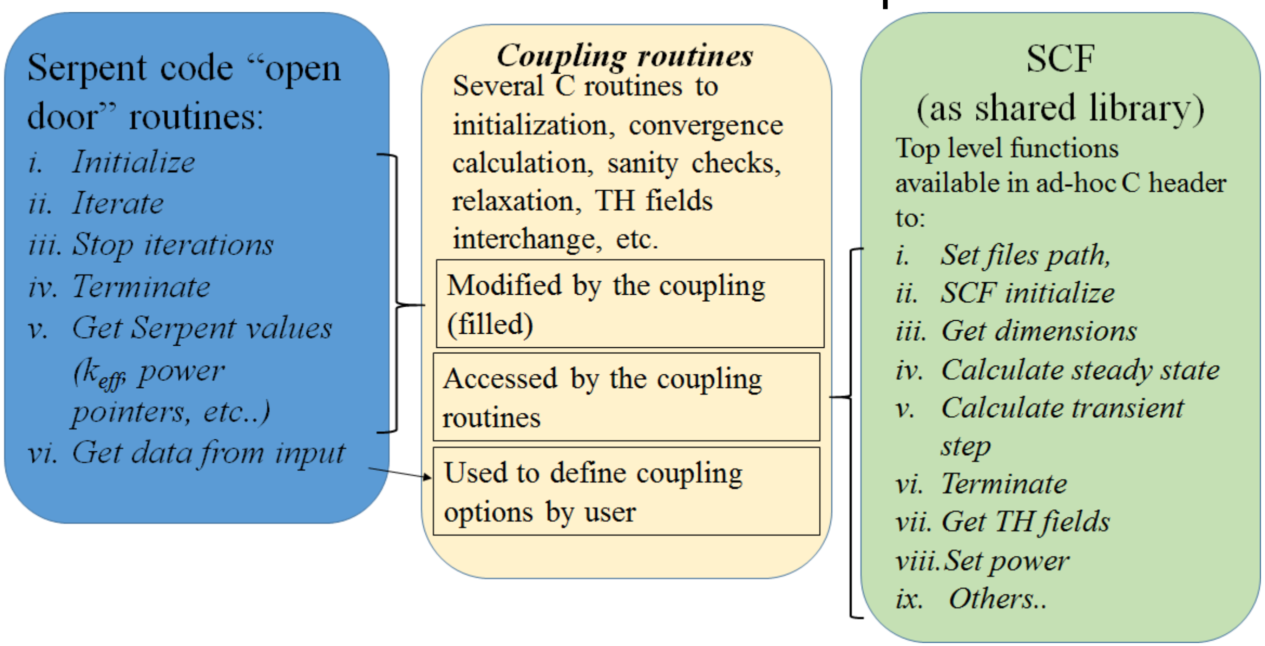


✓ Steady state + transients

3.1 Developed tool

Basics of the internally coupled S-SCF tool

- How can we develop a coupled tool? What should we avoid?
- Master-slave (internal) approach is selected using a “new-philosophy” → maintainability + user friendly
- ***Serpent-SCF*** developed from scratch to tackle both ***steady-state, burnup and transient*** calculations
- Proven to be suitable for realistic coupled transient calculations [1].



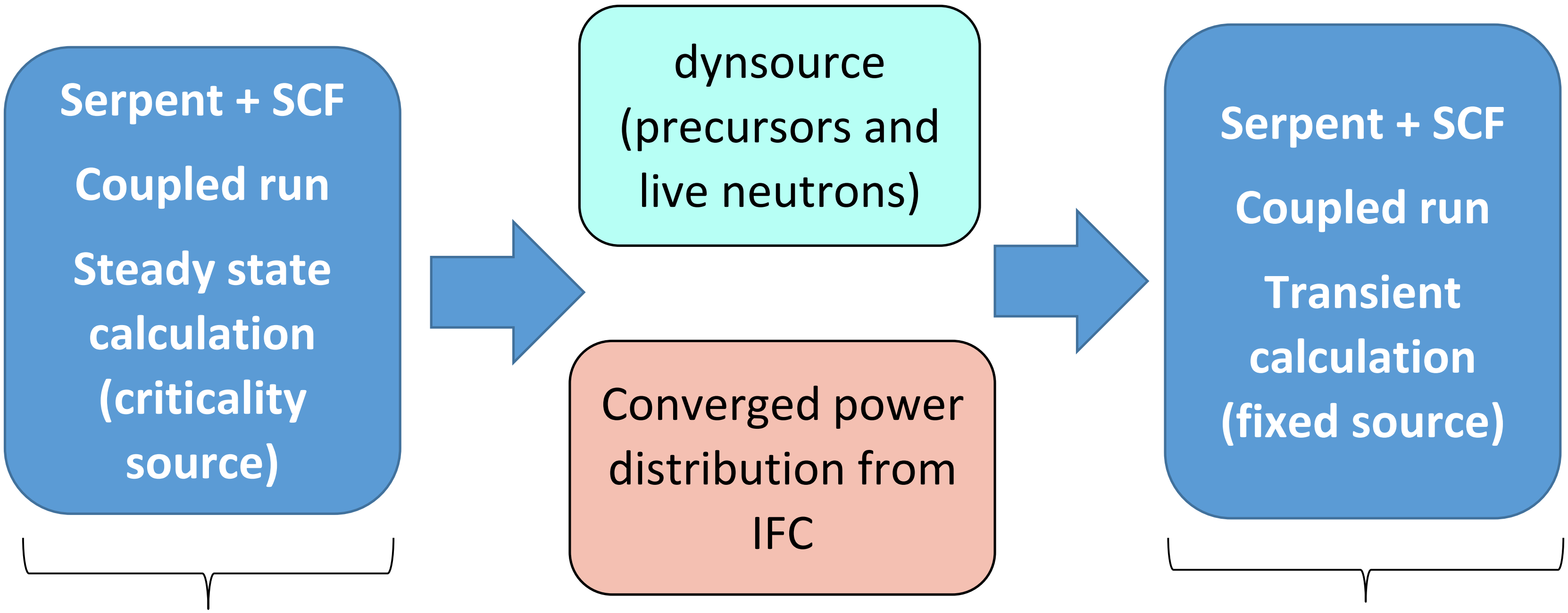
- ✓ Codes are kept well separated. Ad-hoc coupled routines.
- ✓ Use top level routines in Serpent and SCF (as library).
- ✓ Combined in a single executable.

[1] D. Ferraro et al. “Serpent/SUBCHANFLOW pin-by-pin coupled transient calculations for a PWR minicore” Annals of Nuclear Energy, 137:107090, 2020.

3.2 Developed tool

Coupled transients modelling in Serpent-SCF

- The two-steps approach for the transient coupled case:



First run: initial condition of the transient (critical)

Second run: transient

[1] D. Ferraro et al. “Serpent/SUBCHANFLOW pin-by-pin coupled transient calculations for a PWR minicore” Annals of Nuclear Energy, 137:107090, 2020.

4. Verification & Validation

Validation of the Serpent/SCF approach for transients

- Validation of the tool represents a key issue.
- The approach followed was: Testing → Verification → Validation.
- Both steady-state, burnup and transient calculations should be assessed.
- ***Summary of capabilities*** are to be discussed.
- Scope: RIA-kind (Reactivity insertion accident) → f.e. Rod Ejection.
- Several publications available, for diverse LWR geometries using pin-by-pin coupling.

Steady-state for full-core PWR cases

Validation for RIA-kind scenarios (experimental data)

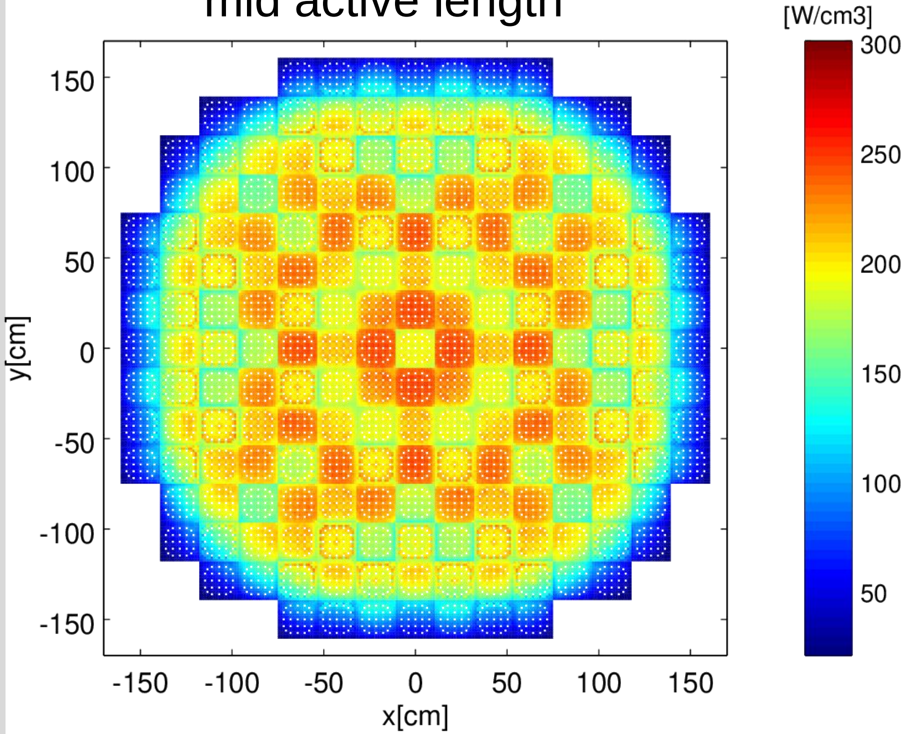
Verification for RIA-kind scenarios (full scope PWR)

4.1 Verification & Validation

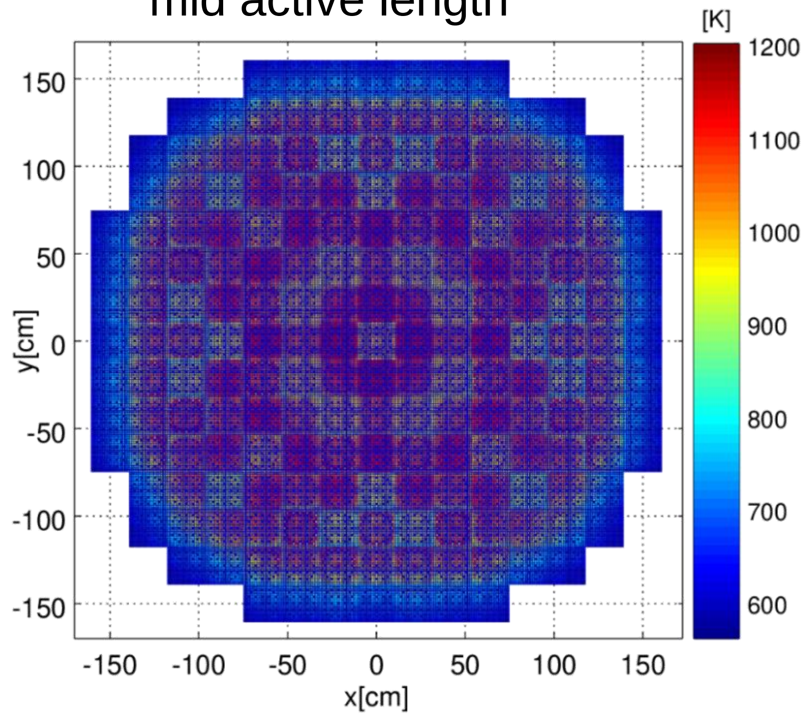
Steady-state for LWR cases (1)

- ***PWR numerical MOX/UO2 benchmark at HFP (Hot Full Power) [2] - Pin by pin coupled analysis in square geometry for steady-state:***

Pin-wise power distribution at mid active length



Temperature distribution at mid active length



✓ Consistent behavior + Differences with reported results <30 ppm Boron.

✓ Pin-power distribution differences <2%.

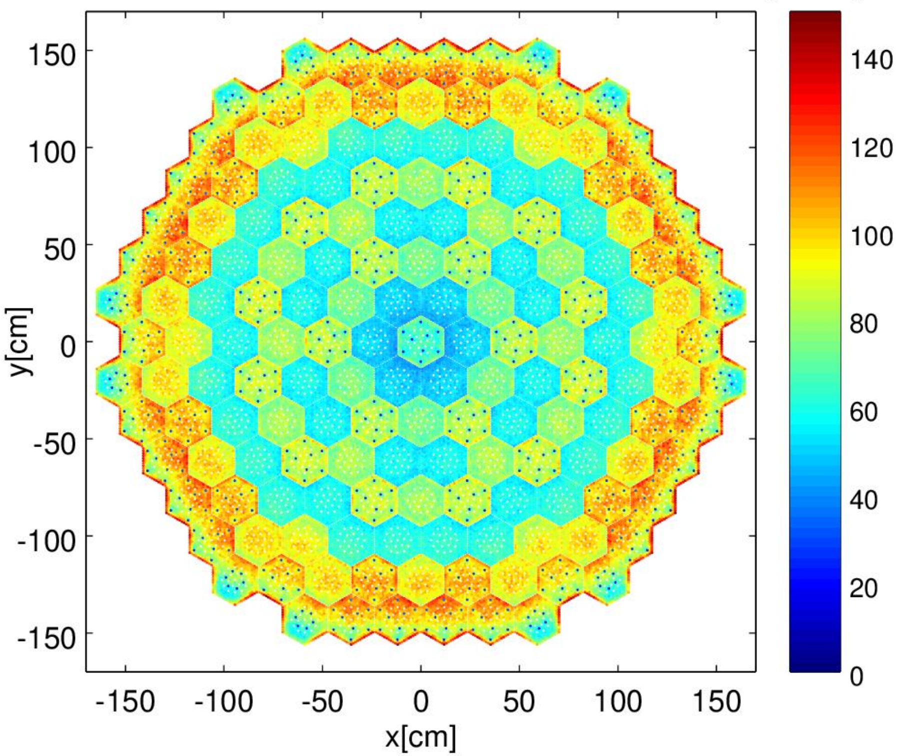
[2] D. Ferraro et al. “OECD/NRC PWR MOX/UO2 core transient benchmark pin-by-pin solutions using Serpent/SUBCHANFLOW” –Annals of Nuclear Energy 147:107745,2020.

4.1 Verification & Validation

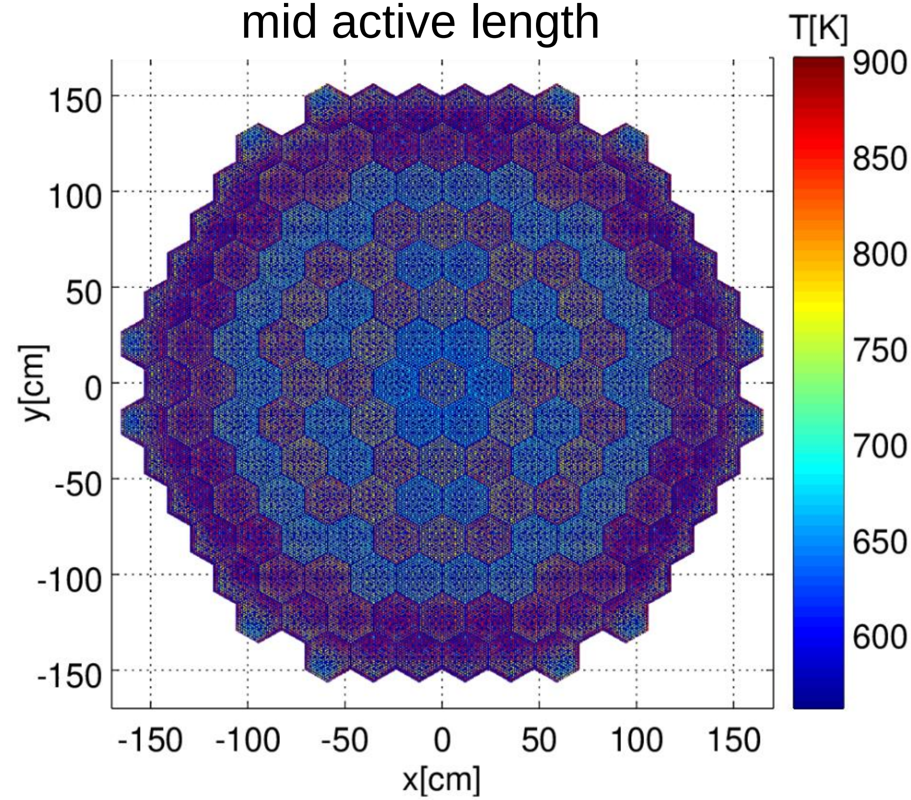
Steady-state for LWR cases (2)

- ***VVER experimental benchmark (Hot Full Power) - Pin by pin coupled analysis in hexagonal geometry for steady-state [3]:***

Pin-wise power distribution at mid active length



Temperature distribution at mid active length

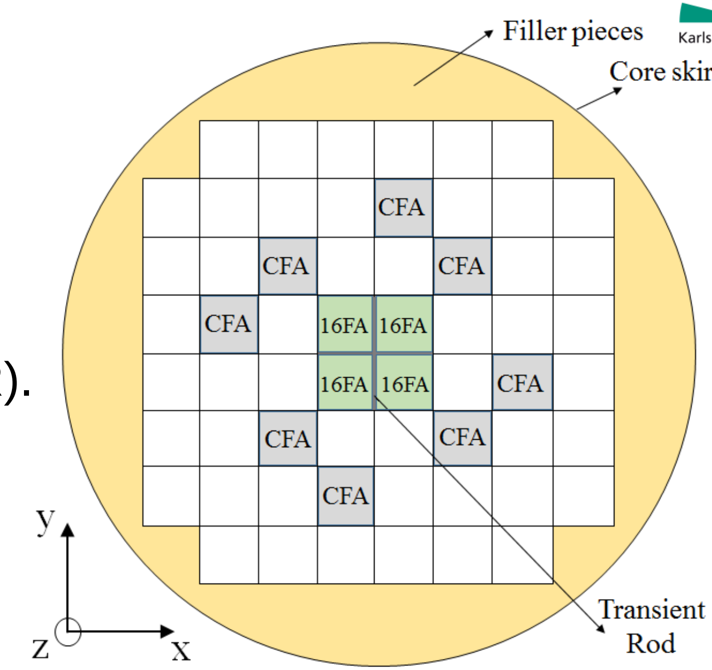


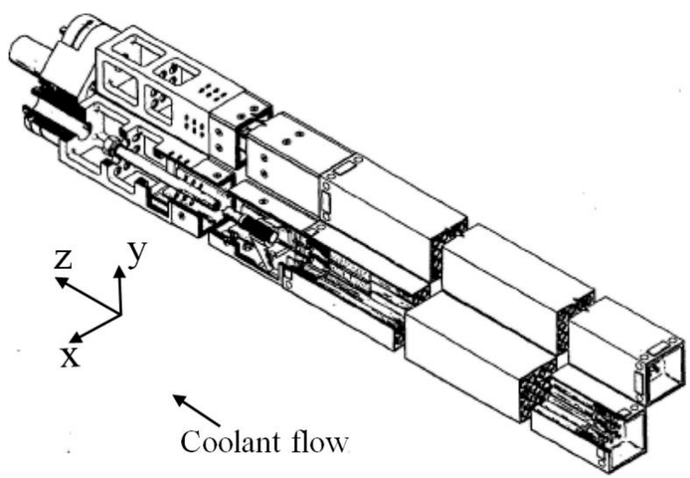
✓ Consistent behavior + Diff. with reported results (critical): 300 pcm at 1500 MWth.

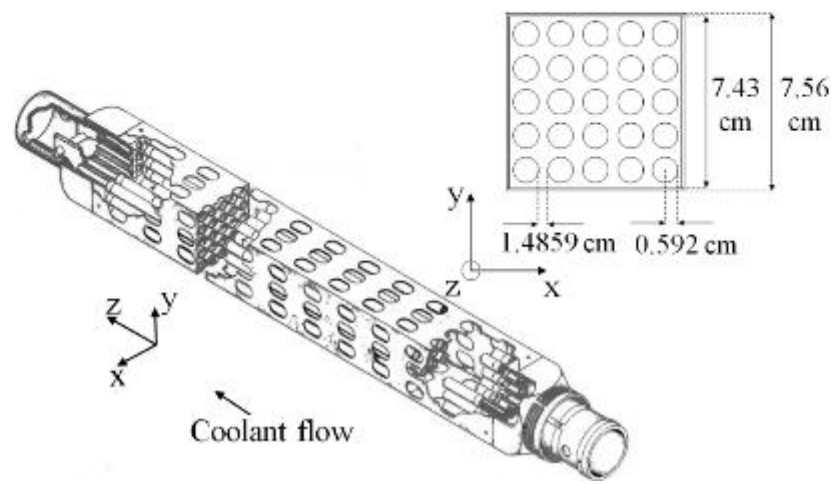
[3] Diego Ferraro et al " Serpent / SUBCHANFLOW coupled calculations for a VVER core at hot full power. In PHYSOR2020

4.2 Validation for transients
The SPERT-IIIE experiments

- USA 1950s-1960s safety program.
- Devoted to RIA transients investigation (several configurations and reactors).
- Fuel Rodded type, SS cladding. Square lattice array, 3 types of FA : standard, central and Control (fuel follower with CR).
- Operation at pressure and temperature similar to PWR.
- Transient experiments done through withdrawal of central CR.





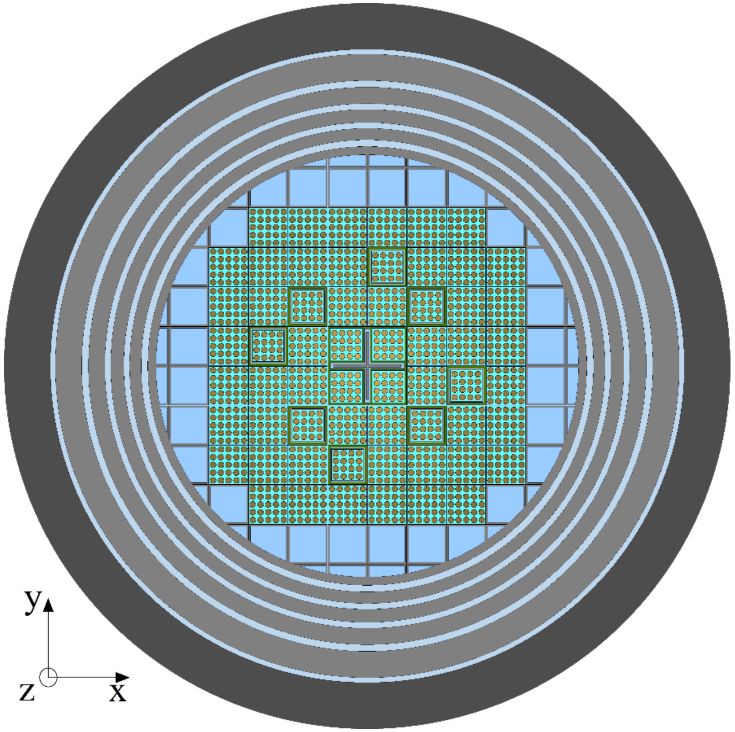


4.2 Validation for transients

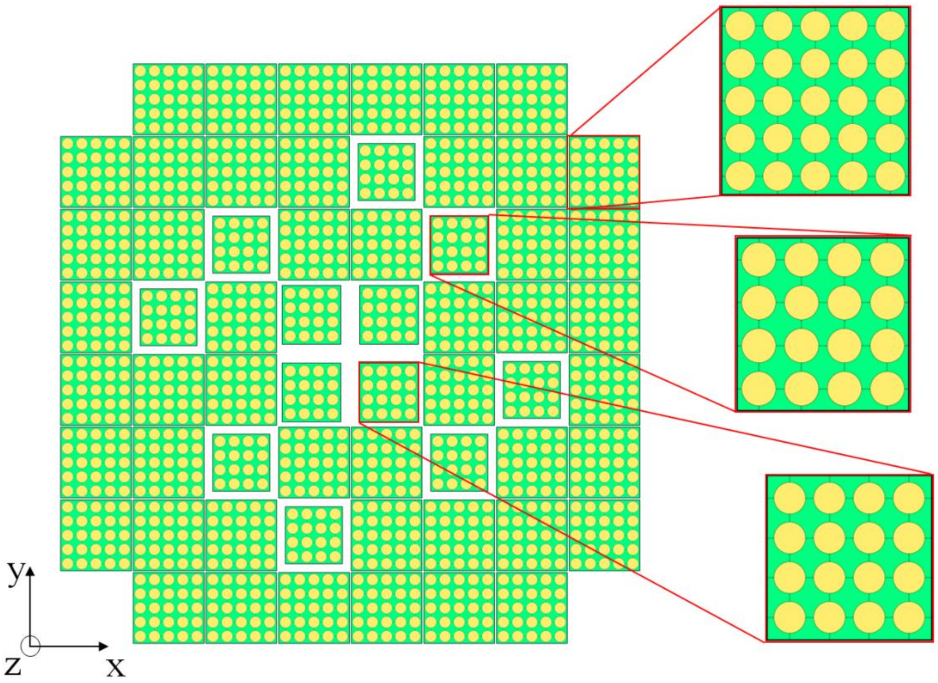
SPERT-IIIE modelling approach

- Pin-by-pin models developed and validated for cold and HFP states [4]
- Steady-state and transient calculations
- Several modeling decisions
- Two transients were selected: T-84 and T-85

Serpent model



SCF model



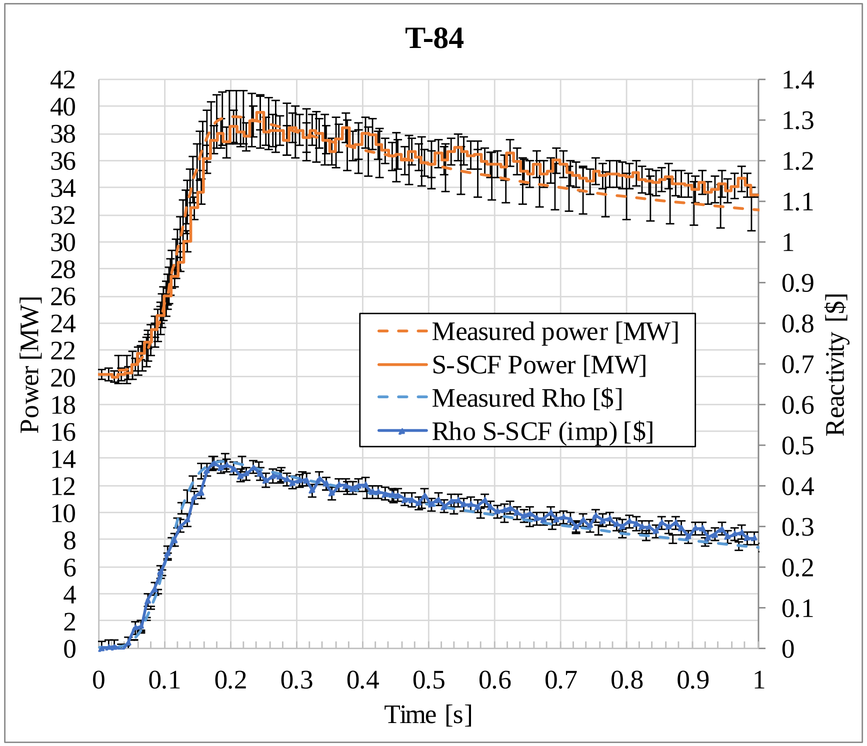
[4] D. Ferraro et al. " Serpent/SUBCHANFLOW pin-by-pin coupled transient calculations for SPERT-IIIE hot full power test " – Annals of Nuclear Energy - Volume 142 (2020).

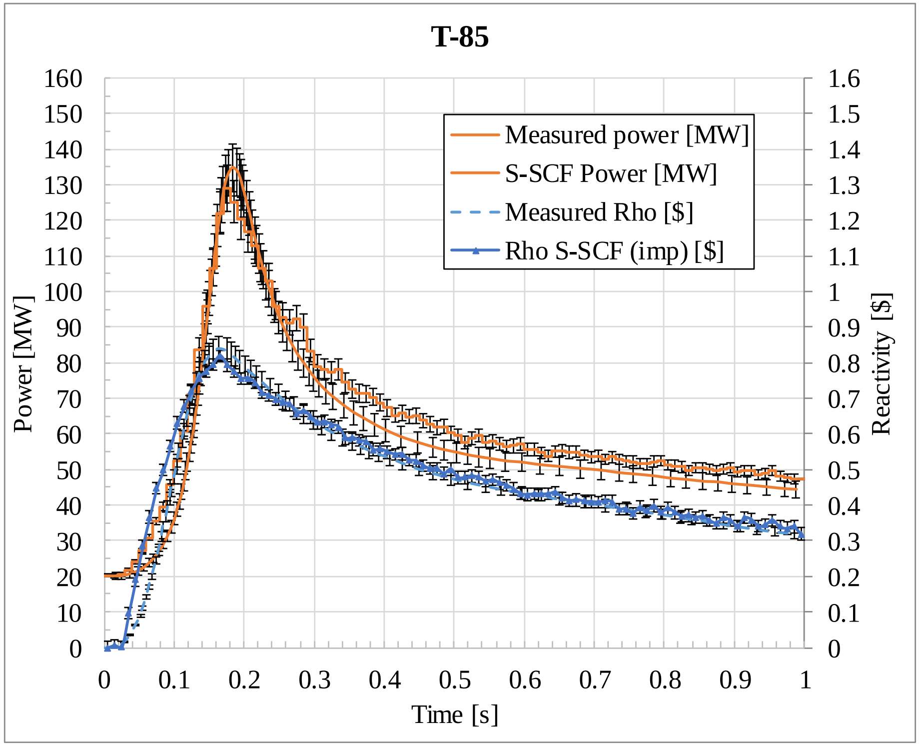
4.2 Validation for transients

SPERT-IIIE: Global results for T-84 and T-85

- Results for coupled transient Serpent-SCF (global):

ID	Modeled			
	CR withdrawal [cm]	Speed [cm/s]	Time scope of movement [s]	bins
84	8.7	-67.1	0.04-0.17	100
85	22.9	-163.5	0.02-0.16	100



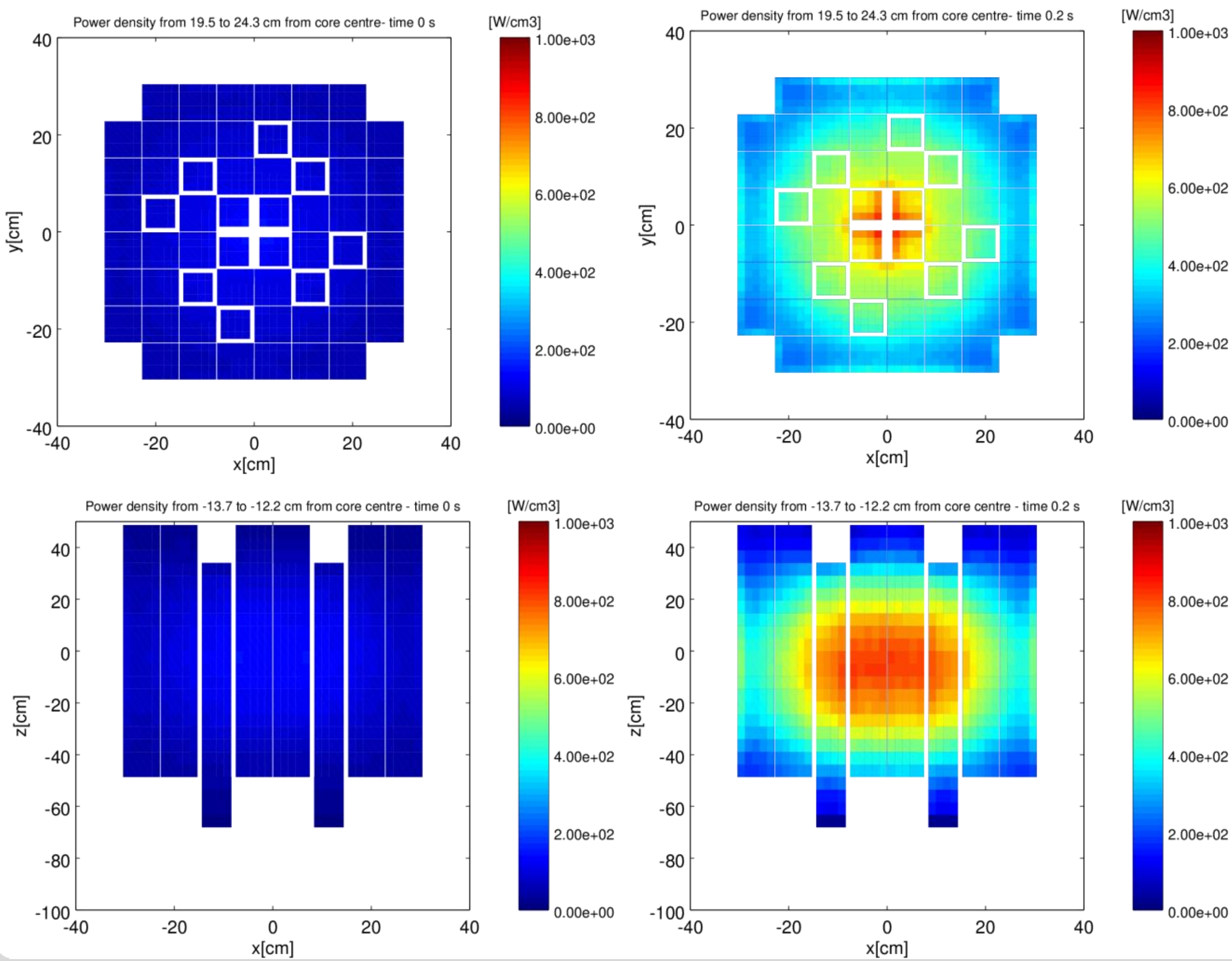


✓ Very good agreement both for power and reactivity.

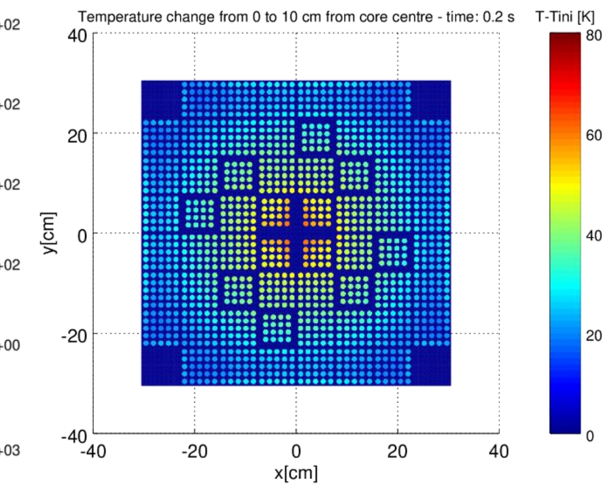
4.2 Validation for transients
SPERT-IIIE: High-fidelity results for T-85

- Results for coupled transient Serpent-SCF for test T-85 (pin-by-pin):

Power evolution (up to 0.2 s):



Temperature evolution (up to 0.2 s):



- ✓10h CPU @ 2.6 GHz for each run (in 1000 cpus)
- ✓SCF calculation time negligible

4.3 Validation for transients

Full scope RIA-kind in a realistic PWR

- Full-core pin-by-pin realistic applications?
- The OECD PWR MOX/UO2 transient benchmark was developed (Kozlowski & Downar).

¼ Core

	1	2	3	4	5	6	7	8
A	U 4.2% (CR-D) 35.0	U 4.2% 0.15	U 4.2% (CR-A) 22.5	U 4.5% 0.15	U 4.5% (CR-SD) 37.5	M 4.3% 17.5	U 4.5% (CR-C) 0.15	U 4.2% 32.5
B	U 4.2% 0.15	U 4.2% 17.5	U 4.5% 32.5	M 4.0% 22.5	U 4.2% 0.15	U 4.2% (CR-SB) 32.5	M 4.0% 0.15	U 4.5% 17.5
C	U 4.2% (CR-A) 22.5	U 4.5% 32.5	U 4.2% (CR-C) 22.5	U 4.2% 0.15	U 4.2% 22.5	M 4.3% 17.5	U 4.5% (CR-B) 0.15	M 4.3% 35.0
D	U 4.5% 0.15	M 4.0% 22.5	U 4.2% 0.15	M 4.0% 37.5	U 4.2% 0.15	U 4.5% (CR-SC) 20.0	M 4.3% 0.15	U 4.5% 20.0
E	U 4.5% (CR-SD) 37.5	U 4.2% 0.15	U 4.2% 22.5	U 4.2% 0.15	U 4.2% (CR-D) 37.5	U 4.5% 0.15	U 4.2% (CR-SA) 17.5	
F	M 4.3% 17.5	U 4.2% (CR-SB) 32.5	M 4.3% 17.5	U 4.5% (CR-SC) 20.0	U 4.5% 0.15	M 4.3% 0.15	U 4.5% 32.5	
G	U 4.5% (CR-C) 0.15	M 4.0% 0.15	U 4.5% (CR-B) 0.15	M 4.3% 0.15	U 4.2% (CR-SA) 17.5	U 4.5% 32.5		
H	U 4.2% 32.5	U 4.5% 17.5	M 4.3% 35.0	U 4.5% 20.0				

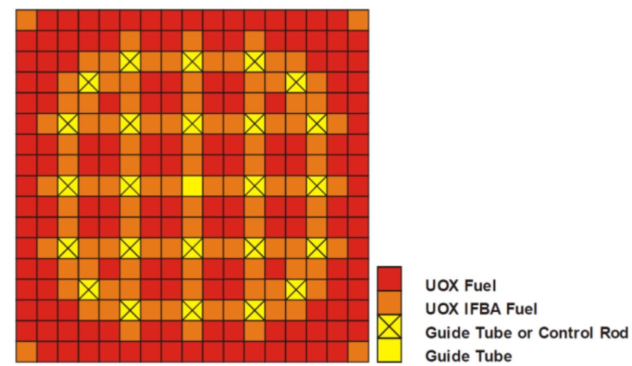
Assembly Type
CR Position
Burnup [GWd/t]

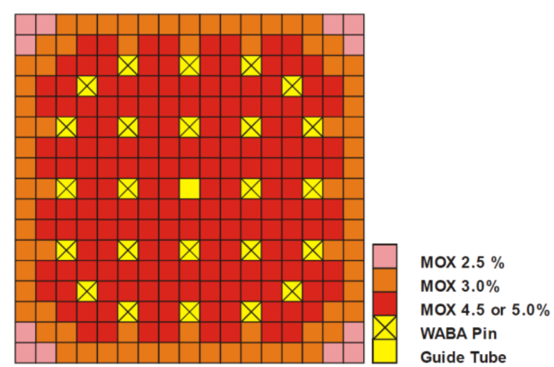
Fresh
Once Burn
Twice Burn

CR-A	Control Rod Bank A
CR-B	Control Rod Bank B
CR-C	Control Rod Bank C
CR-D	Control Rod Bank D
CR-SA	Shutdown Rod Bank A
CR-SB	Shutdown Rod Bank B
CR-SC	Shutdown Rod Bank C
CR-SD	Shutdown Rod Bank D
O	Ejected Rod

y z x

Fuel details



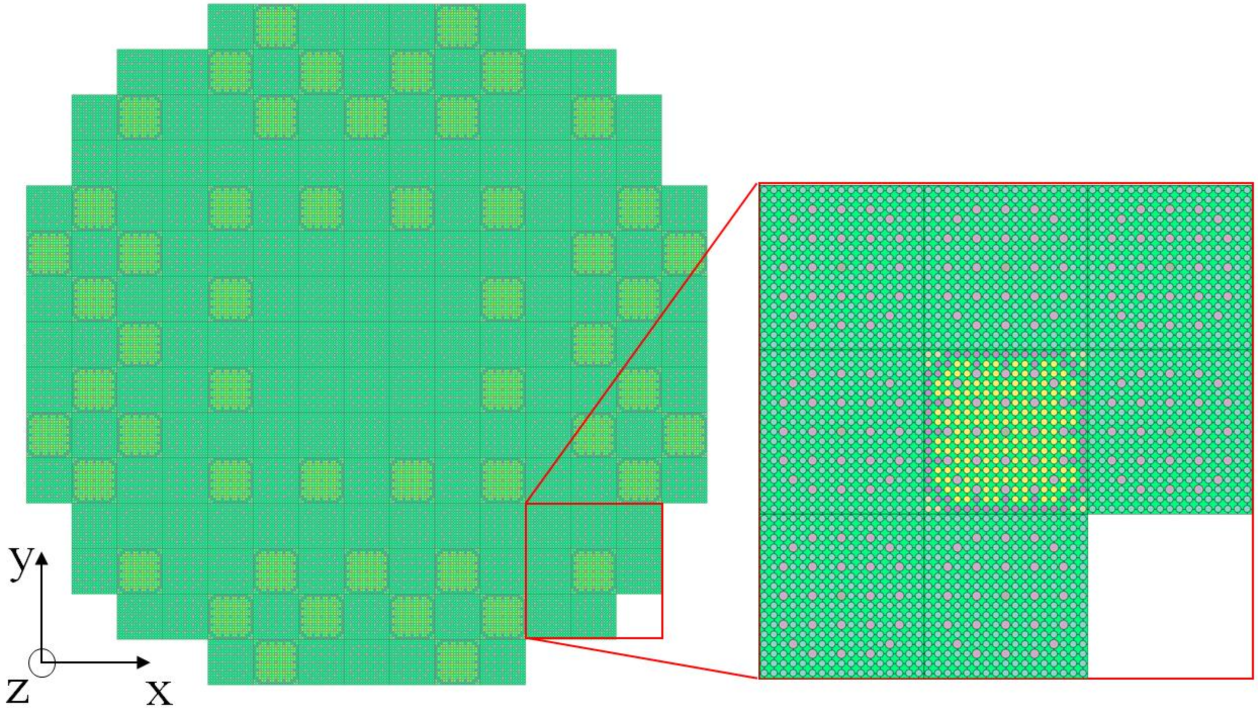


4.3 Validation for transients

Models for the OECD PWR MOX/UO_2 transient benchmark

- Models for Serpent-SCF were developed for Parts I to IV of benchmark (2D HZP, 3D HFP, 3D HZP, 3D HZP RIA) [2].
- Diverse key parameters compared with reported results (reference values also provided within the Benchmark).
- Pin-by-pin coupling.

SCF model



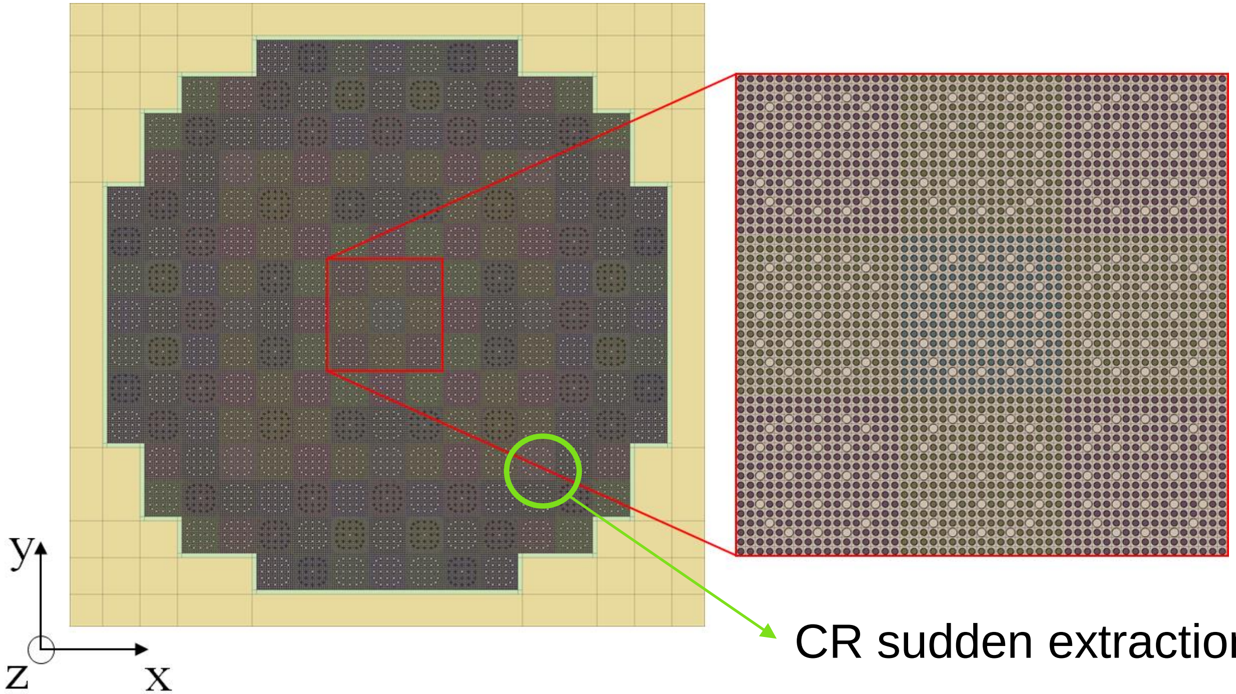
[2] D. Ferraro et al. "OECD/NRC PWR MOX/UO2 core transient benchmark pin-by-pin solutions using Serpent/SUBCHANFLOW" –Annals of Nuclear Energy 147:107745,2020.

4.3 Validation for transients

Models for the OECD PWR MOX/UO_2 transient benchmark

- Models for Serpent-SCF were developed for Parts I to IV of benchmark (2D HZP, 3D HFP, 3D HZP, 3D HZP RIA) [6].
- Diverse key parameters compared with reported results (reference values also provided within the Benchmark).
- Pin-by-pin coupling.

Serpent model



CR sudden extraction (0.1s).

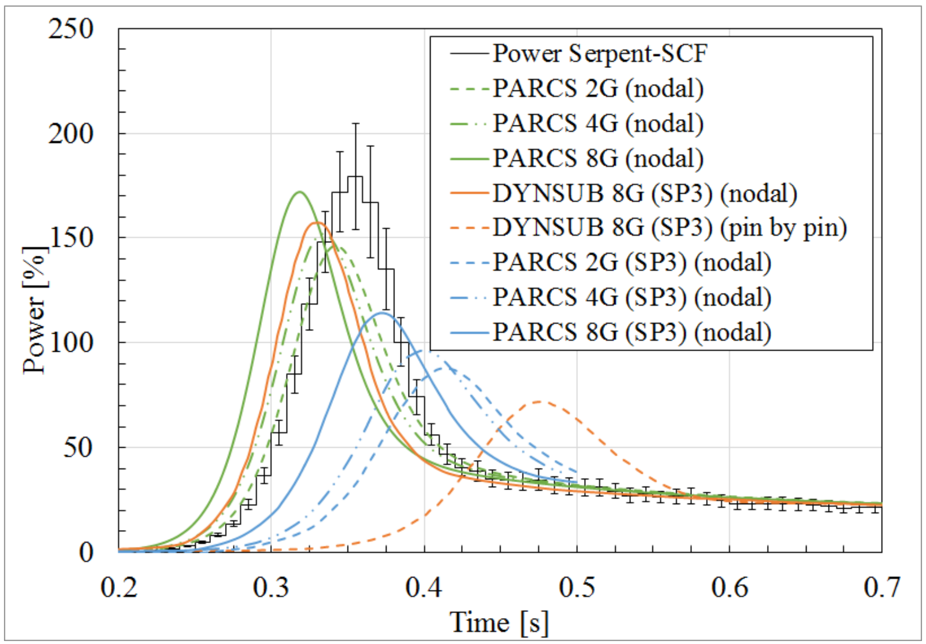
[2] D. Ferraro et al. “OECD/NRC PWR MOX/UO2 core transient benchmark pin-by-pin solutions using Serpent/SUBCHANFLOW” –Annals of Nuclear Energy 147:107745,2020.

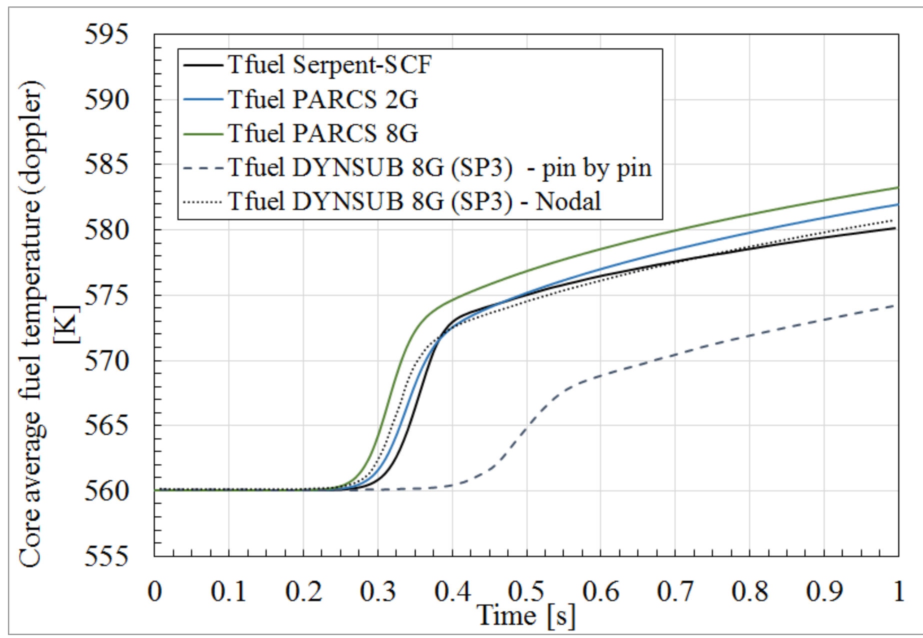
4.3 Validation for transients

Main results for the OECD PWR MOX/UO_2 transient benchmark

- Results for transient (RIA case) from HZP.

Code	Peak time [s]	Peak Power [%]	Peak ρ [$]	Integral power [%s]
EPISODE	0.33	160	1.13	26.9
PARCS 2G	0.34	142	1.12	27.2
PARCS 8G	0.32	172	1.14	29.1
Serpent-SCF	**0.355**	**179 ±26**	**1.18±0.02**	**27.7**



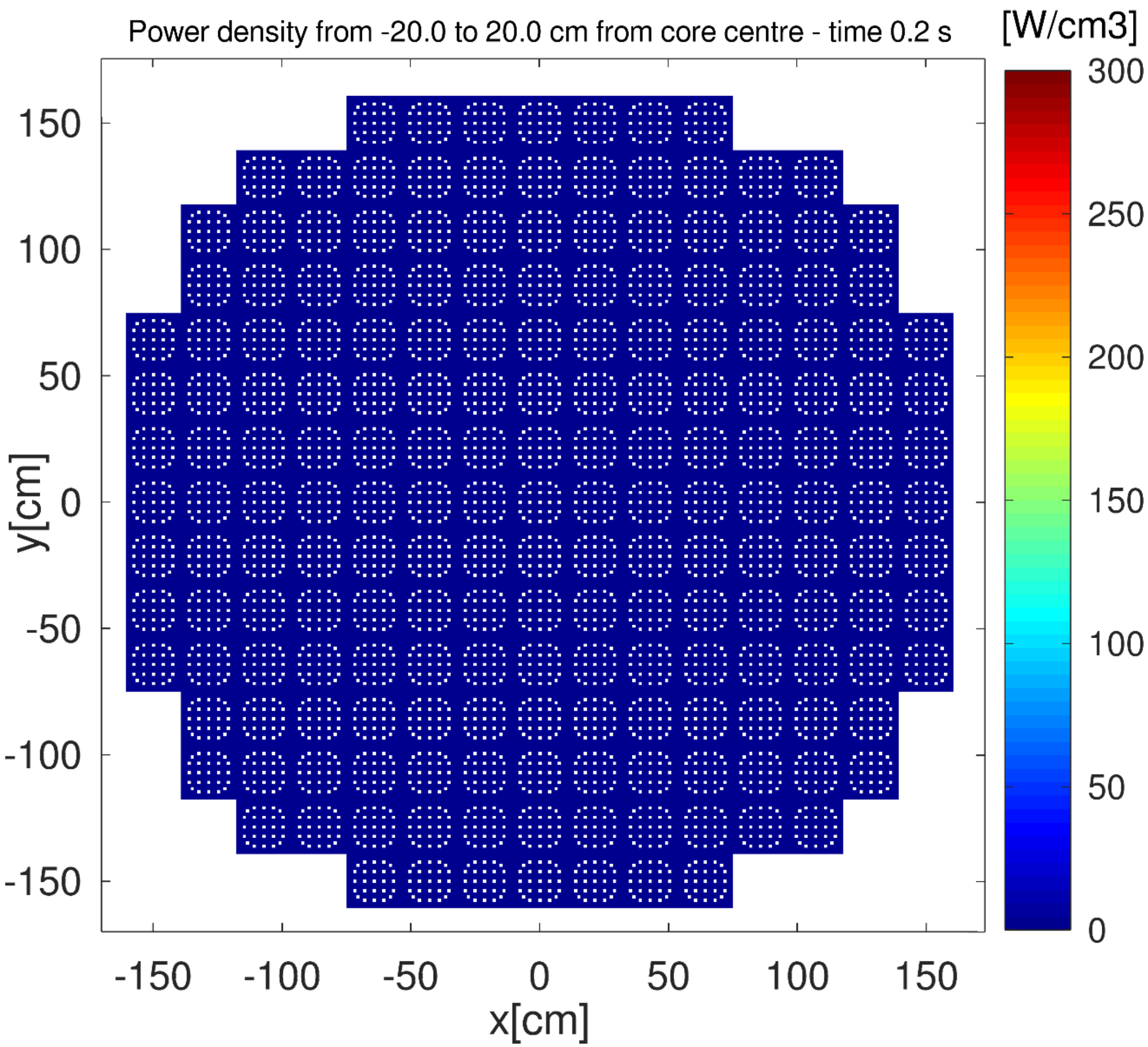


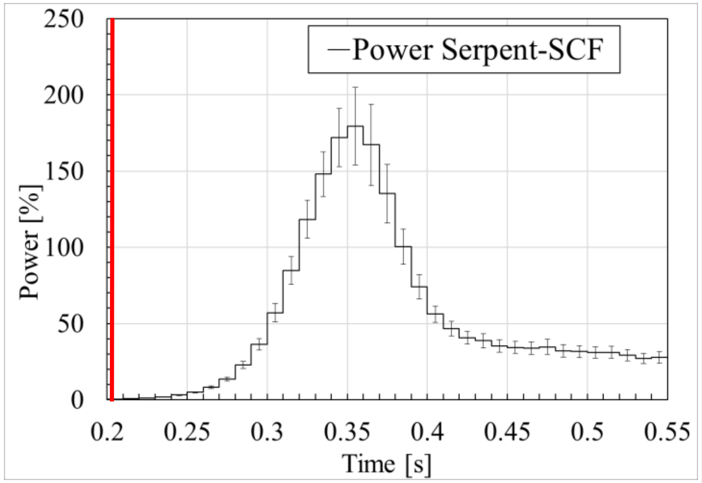
✓ 120 h in 1280 processors / SCF calculation time not negligible!

4.3 Validation for transients

Main results for the OECD PWR MOX/UO_2 transient benchmark

- Detailed results for power – time 0.2 s

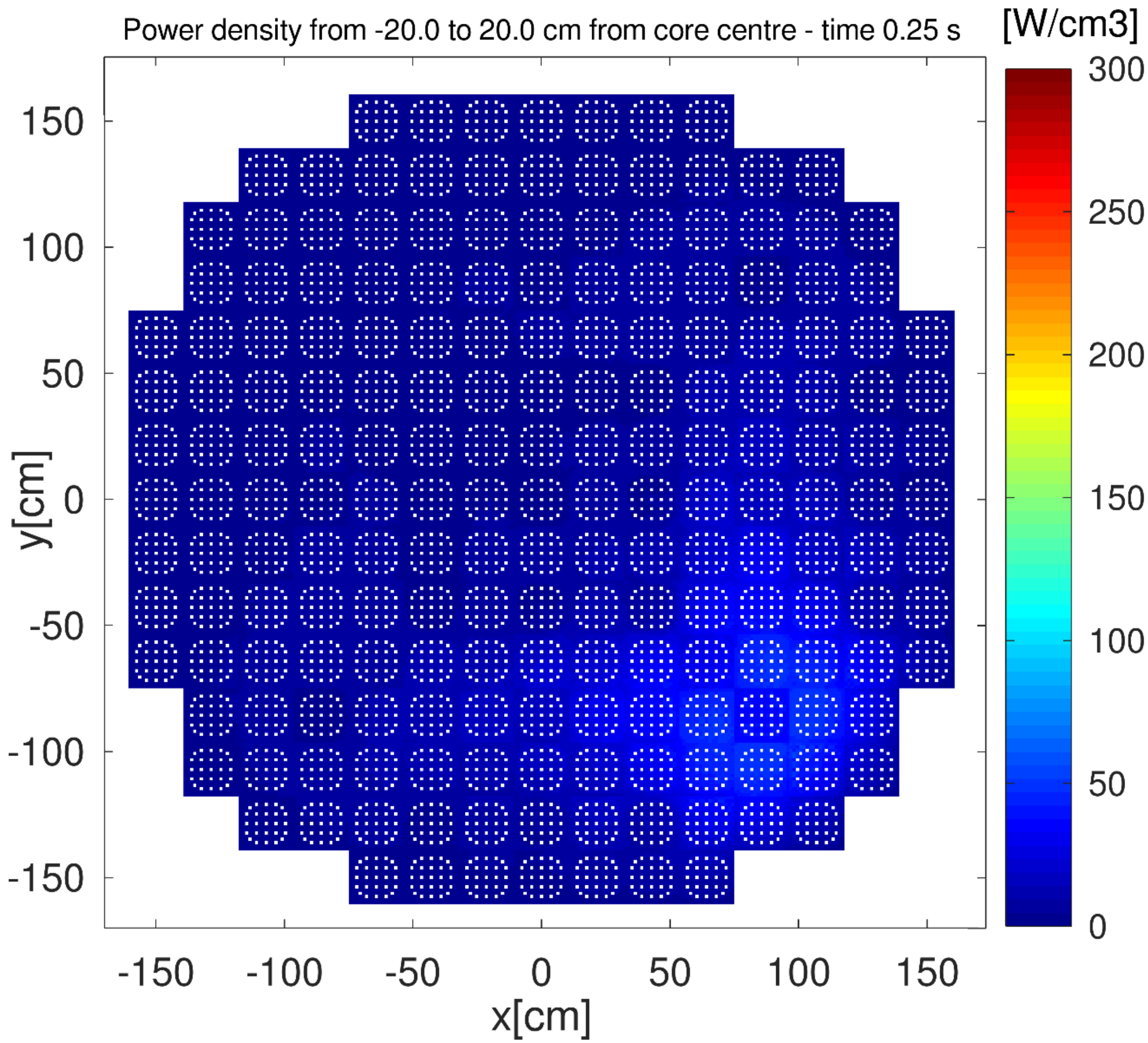


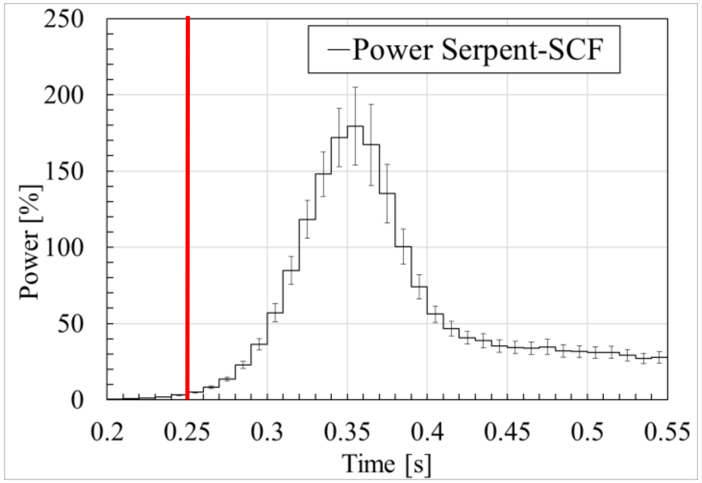


4.3 Validation for transients

Main results for the OECD PWR MOX/UO_2 transient benchmark

- Detailed results for power – time 0.25 s

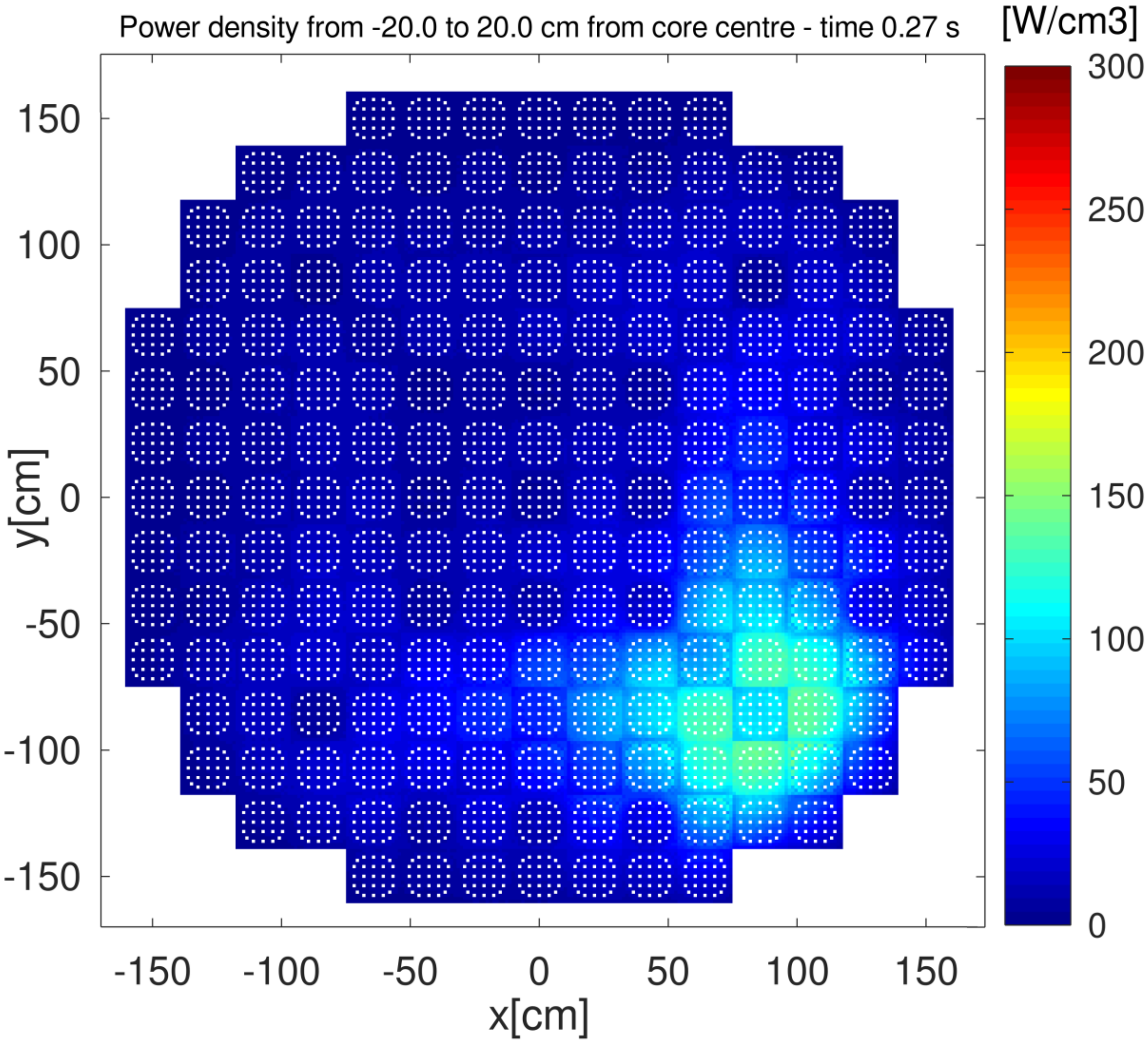


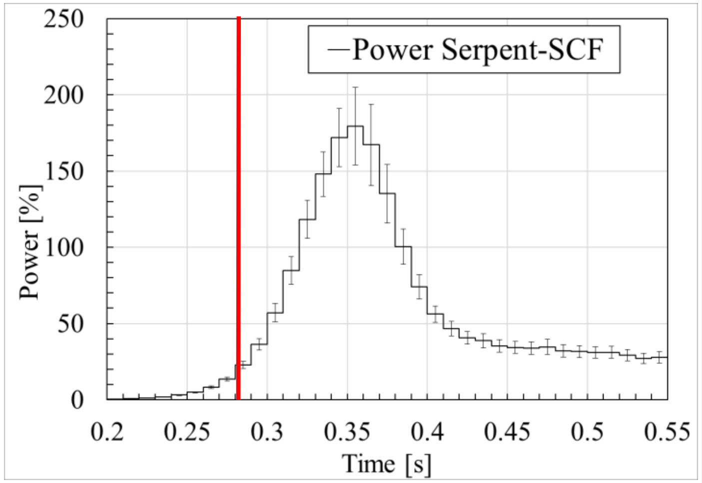


4.3 Validation for transients

Main results for the OECD PWR MOX/UO_2 transient benchmark

- Detailed results for power – time 0.27 s

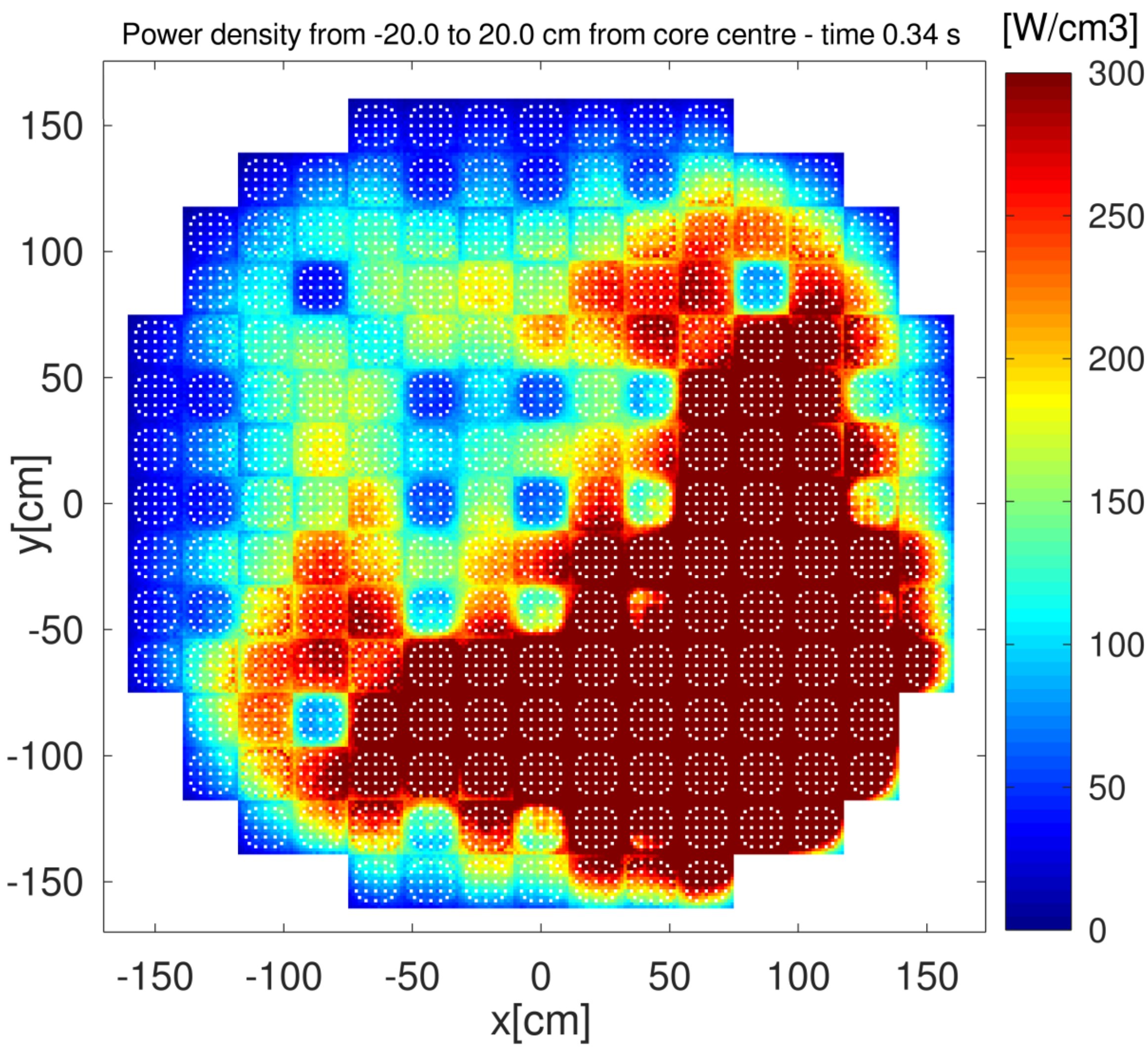


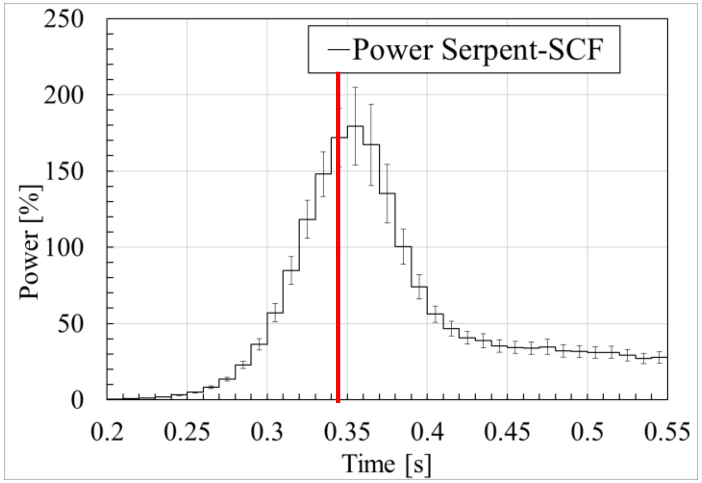


4.3 Validation for transients

Main results for the OECD PWR MOX/UO_2 transient benchmark

- Detailed results for power – time 0.34 s

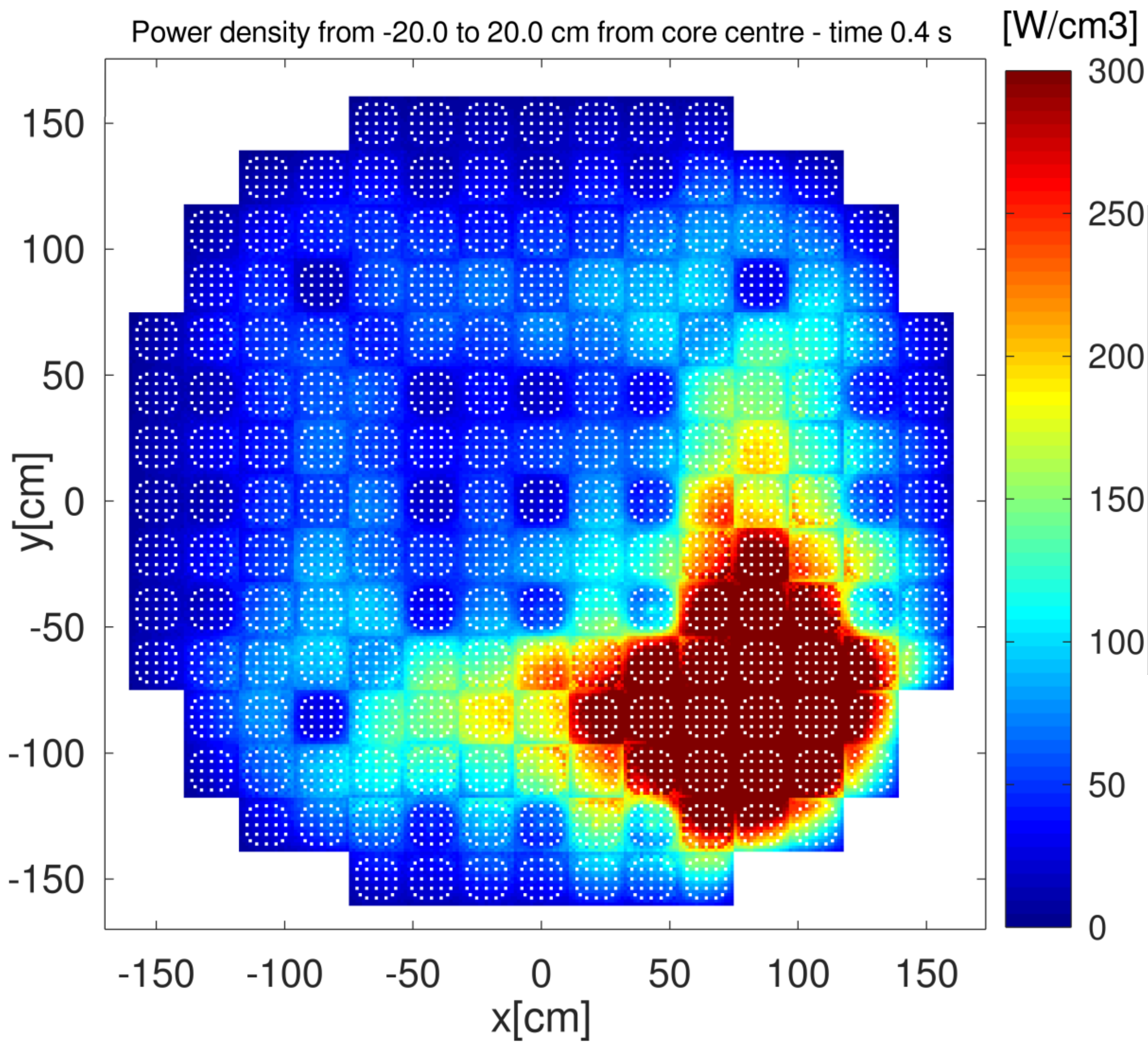


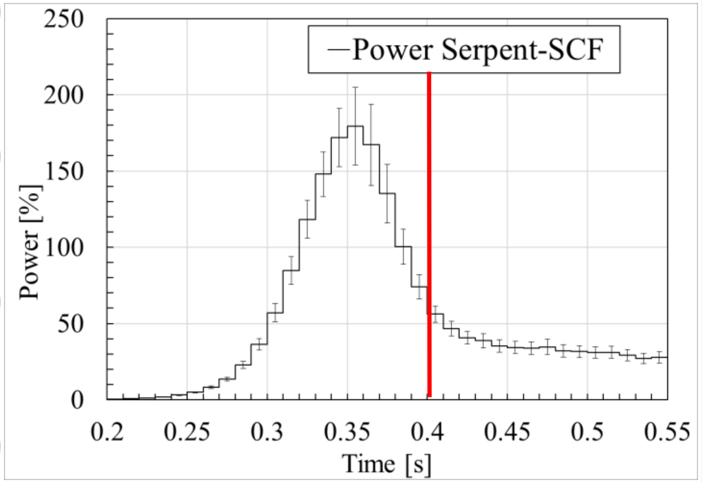


4.3 Validation for transients

Main results for the OECD PWR MOX/UO_2 transient benchmark

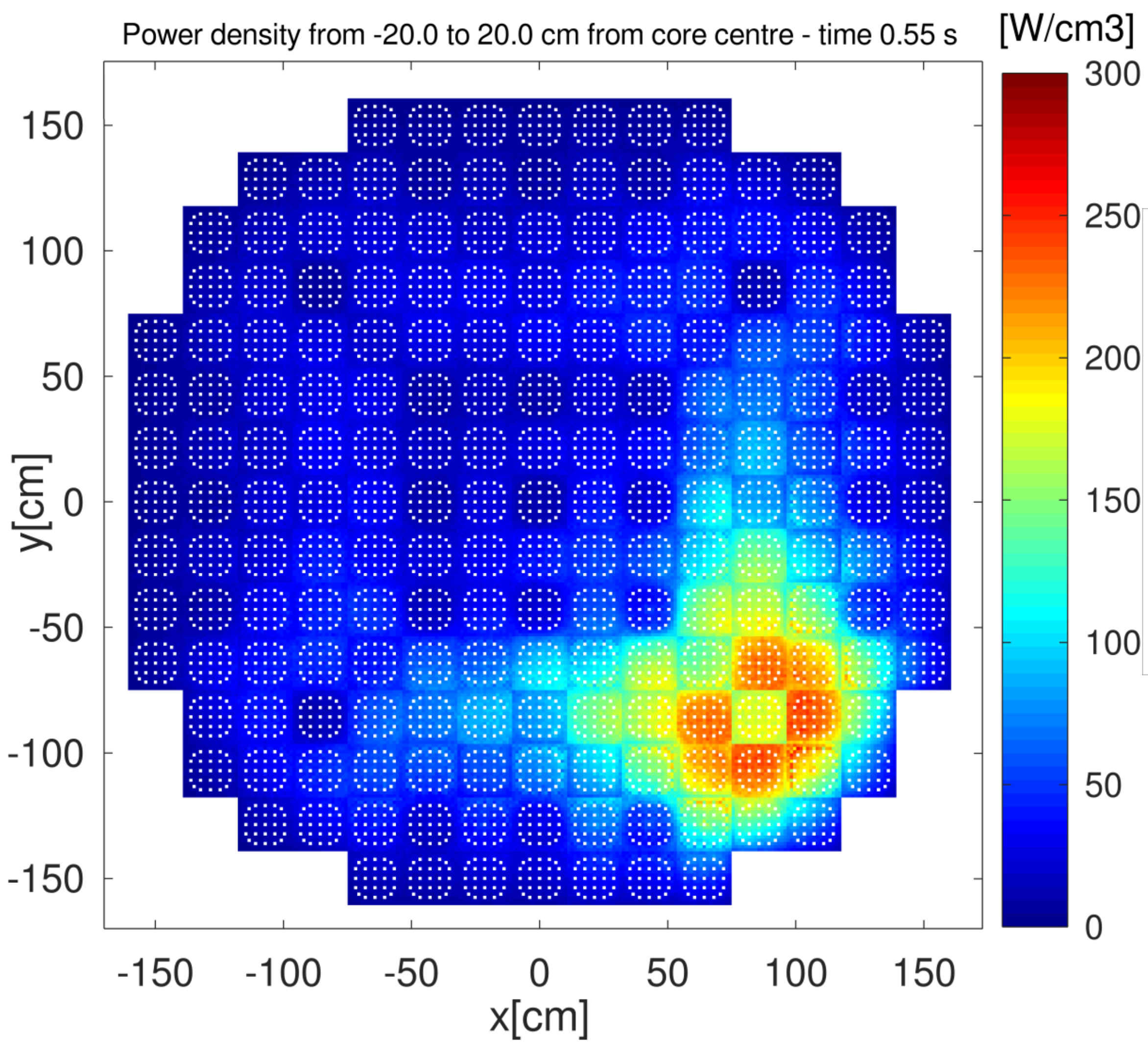
- Detailed results for power – time 0.4 s

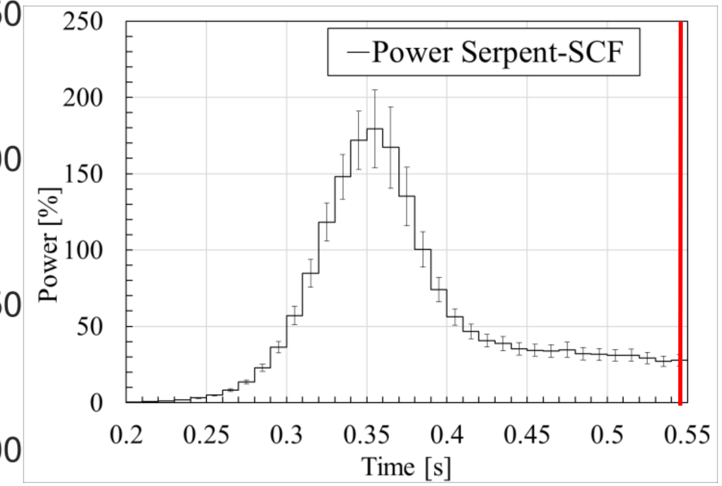




4.3 Validation for transients
Main results for the OECD PWR MOX/UO_2 transient benchmark

- Detailed results for power – time 0.55 s

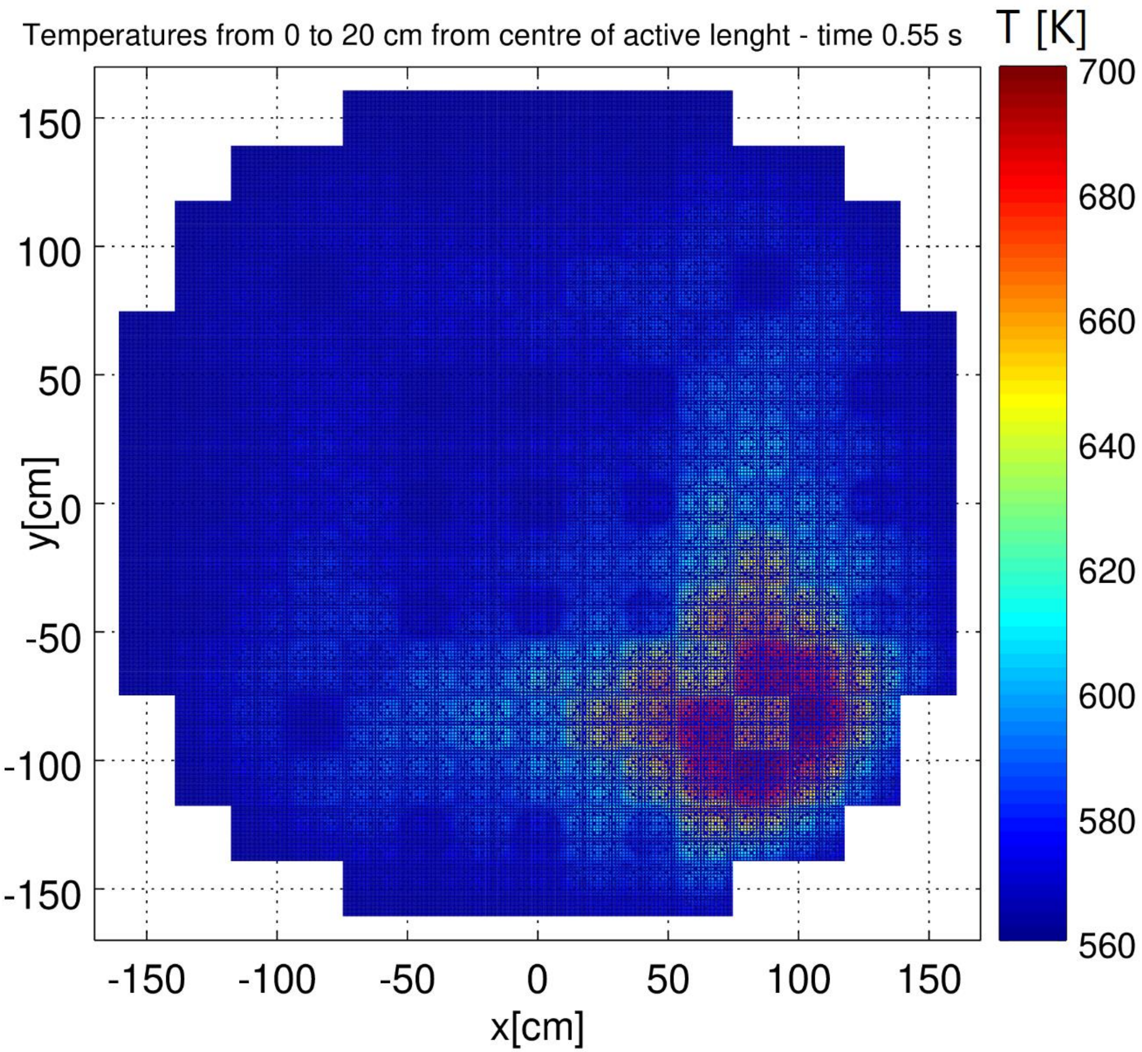


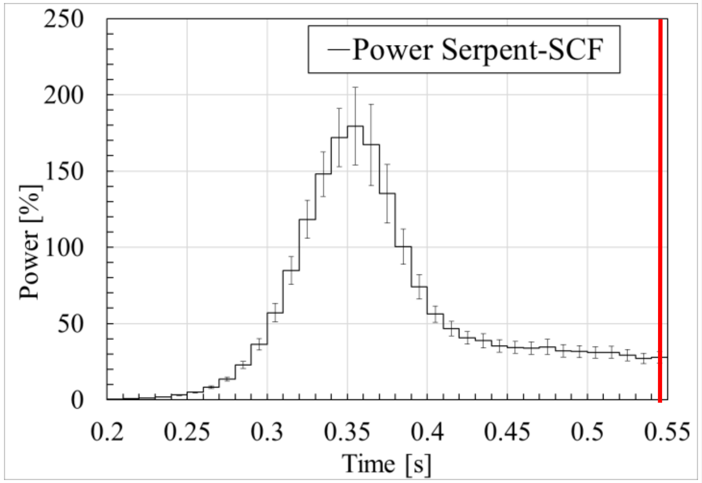


4.3 Validation for transients

Main results for the OECD PWR MOX/UO_2 transient benchmark

- Detailed results for temperature – time 0.55 s





✓ Direct pin-by-pin results.

✓ Consistent behavior.

5. Conclusions

- Alternative approach to industry-standard → most of cell-core approximations avoided.
- Serpent-SCF new internal coupling was → tested → verified → validated within realistic conditions.
- First validation of coupled transient capabilities successfully held using SPERT-IIIE.
- Full-scope within PWR geometries verified with MOX/UO_2 transient benchmark.
- Main coupled physics behaved as expected for all cases.
- Good agreement with reported experimental data / other codes.
- ***Serpent-SCF approach for coupled transients is proven to be feasible.***
- ***Results pave the path for industry-like applications.***

Further questions?
Thanks!