Karlsruhe Institute of Technology

Serpent and TRIPOLI-4® transient calculations comparisons for several reactivity insertion scenarios in a 3D PWR minicore benchmark

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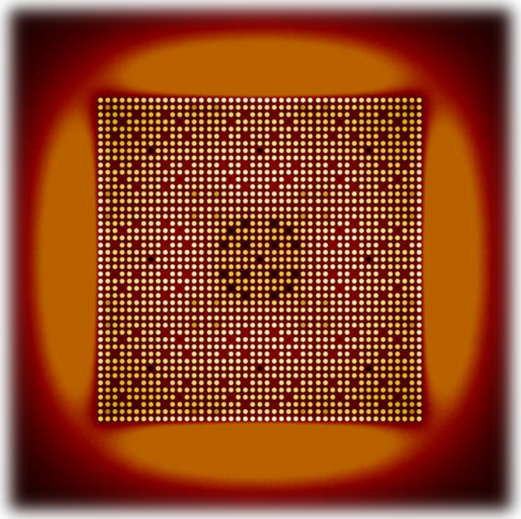


Presentation Overview

- Introduction & motivation: the McSAFE: high-fidelity Horizon 2020 multiphysics project
- Proposed verification scheme: Benchmark and scenarios
- Main results comparison and analysis
- Conclusions & further work

1.1 – Introduction & motivation

- ***Increasing effort*** to develop highly accurate multi-physics approaches for nuclear reactor analysis of complex phenomenology.
- ***Increasing demand*** from designers, operators, regulators and other stakeholders.
- Several projects around the world oriented to provide ***high-fidelity results*** → improvement of local phenomena calculation & provide reference solutions).
- Under this framework, the ***McSAFE*** project started in 2017 under Horizon 2020 (EU):

McSAFE*: High –Performance* ***M****onte****c****arlo Methods for* ***SAFE****ty Demonstration:*

- ✓ ***Cooperation*** between code developers, methods developers and industry stakeholders.
- ✓ **12 partners** from **9 countries** around EU and an extended community of users around world.

1.2 – Introduction & motivation

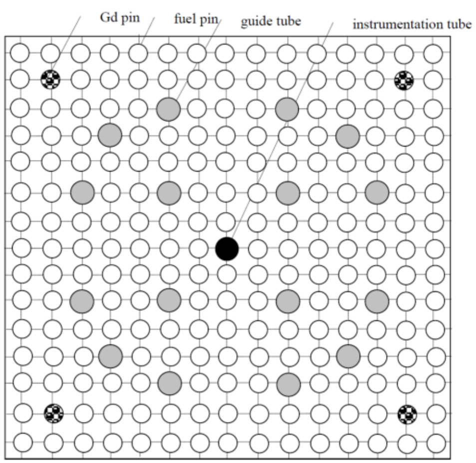
- Global McSAFE goal “move towards high fidelity calculations for steady state, burnup and ***transient*** calculations”
- Several MC codes involved within McSAFE for the diverse applications
- In this work we focus on ***Serpent and TRIPOLI-4*** for transients calculations
- How to do this → RIA-type scenarios based on a detailed 3D benchmark for a 3x3 PWR Minicore are proposed.
- Scenarios start from critical state and undergo a series of reactivity excursions transients through ***control rod (CR) withdrawals.***
  - **Scope of this work**:

✓ Analyze and compare ***combined capabilities*** (and identify potential bottlenecks or issues)

✓ Analyze performance and requirements (identify VR techniques required for a full scope case)

2.1 – PWR Minicore transients

- We need a well stated benchmark suitable for MC transient calculations → ***Not an easy task***: most oriented to Nodal diffusion codes or out of scope for this stage (full core PWR or not suitable scenarios).
- Here the UAM 3-D 15x15 FA PWR Minicore[1] is used ***as basis***:

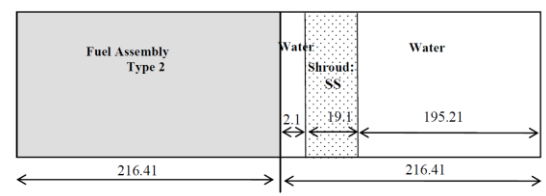


Fuel assembly
FR pitch ~1.44 cm

Reflector	Reflector	Reflector	Reflector	Reflector
Reflector	U	U	U	Reflector
Reflector	U	R	U	Reflector
Reflector	U	U	U	Reflector
Reflector	Reflector	Reflector	Reflector	Reflector

Minicore array

U= Unrodded
R= Rodded



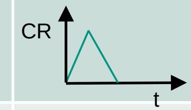
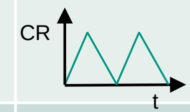
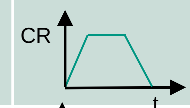
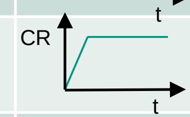
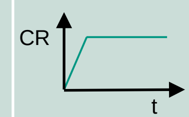
Lateral, Top & bottom reflector model

→ For this problem, rated power (141MWth) and TH fields for ***fuel pins and coolant are proposed*** → ***RIA based*** **transient scenarios** are proposed.

[1]*Benchmarks for Uncertainty Analysis in Modelling (UAM) for the Design, Operation and Safety Analysis of LWRs - Volume II: Specification and Support Data for the Core Cases (Phase II)*

2.2 – PWR Minicore transient scenarios

- Five scenarios are *proposed*:

#	Name	Main description		Time scope
1	A	**Start from critical state**. **Withdrawal of CR** at constant velocity 40 cm/s from 0.2 to 1.2s. **Further insertion** at same velocity from 1.2 to 2.2 s		0 to 5 s with 50 bins (0.1 s each)
2	B	**Start from critical state**. **Withdrawal of CR** at constant velocity 40 cm/s from 0.2 to 1.2s. **Further insertion** at same velocity from 1.2 to 2.2 s. Repeat procedure starting at 2.4s.		
3	C	**Start from critical state**. **Withdrawal of CR** at constant velocity 40 cm/s from 0.2 to 1.2s. **Further insertion** at same velocity from 3 to 4 s		
4	D.1	**Start from critical state**. **Withdrawal of CR** at constant velocity 40 cm/s from 0.2 to 1.2s.		
5	D.2	**Start from critical state**. **Withdrawal of CR** at constant velocity 40 cm/s from 0.2 to 1.2s, but **considering simplified TH feedback at fuel level**: Additional energy from steady state (E) deposited into the fuel for each time bin, increasing temperature of each **fuel level node** (with **10 axial levels**) as : $E^{i,j\ node}_{time\ bin} = m^{i,j\ node}_{fuel} c_p \Delta T^{i,j\ node}_{time\ bin}$		

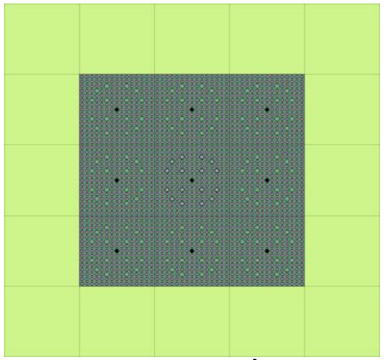
➡ For each scenario global and pin by pin powers are analyzed and compared

2.3 – PWR Minicore 3D Models

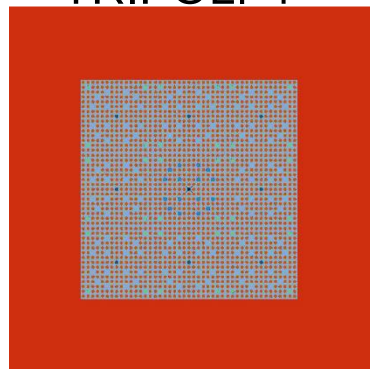
- Independent 3-D models were developed:

Serpent 2

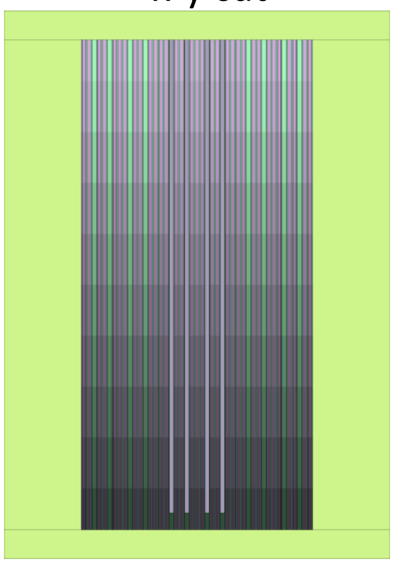
TRIPOLI-4®



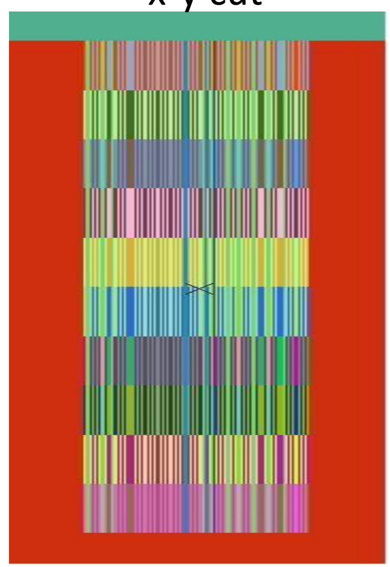
x-y cut



x-y cut



x-z cut (not-scale)



x-z cut (not-scale)

✓ Developed independently

✓ Transient handling implementation approach depends on code.

✓ JEFF 3.1.1 NDL

✓ Axial dependency of temperature and density for fuel and coolant

✓ Control rod movement

- For coupled D.2. case (only Serpent) → Python script

2.4 – Global behavior reference

- The most simple comparison possible → Point kinetics!
- A simplified point kinetic model[1] was developed for these scenarios **using kinetic parameters from Serpent** (obtained in critical calculations):

$$\dot{P} = \frac{\rho - \beta}{\Lambda} P + \sum_{i=1}^{8} C^i \lambda^i \quad \text{Eq. 1}$$

$$\dot{C^i} = \frac{\beta^i}{\Lambda} P - C^i \lambda^i \quad \text{Eq. 2}$$

$$\dot{T_{fuel}} = (P - P_0)K \quad \textit{Eq. 3}$$

$$\rho = \rho_{CR}(t) + \alpha_t (T_{fuel} - T_{fuel_0}) \quad \textit{Eq. 4}$$

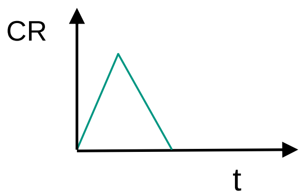
- ✓ **Fuel temperature feedback** coefficient was **calculated using Serpent** critical model (only for case D.2)
- ✓ **CR worth** was also **calculated using Serpent** critical model and converted to reactivity vs time

[1]Eq 1 to 4 solved using Wasora code: https://www.seamplex.com/wasora/

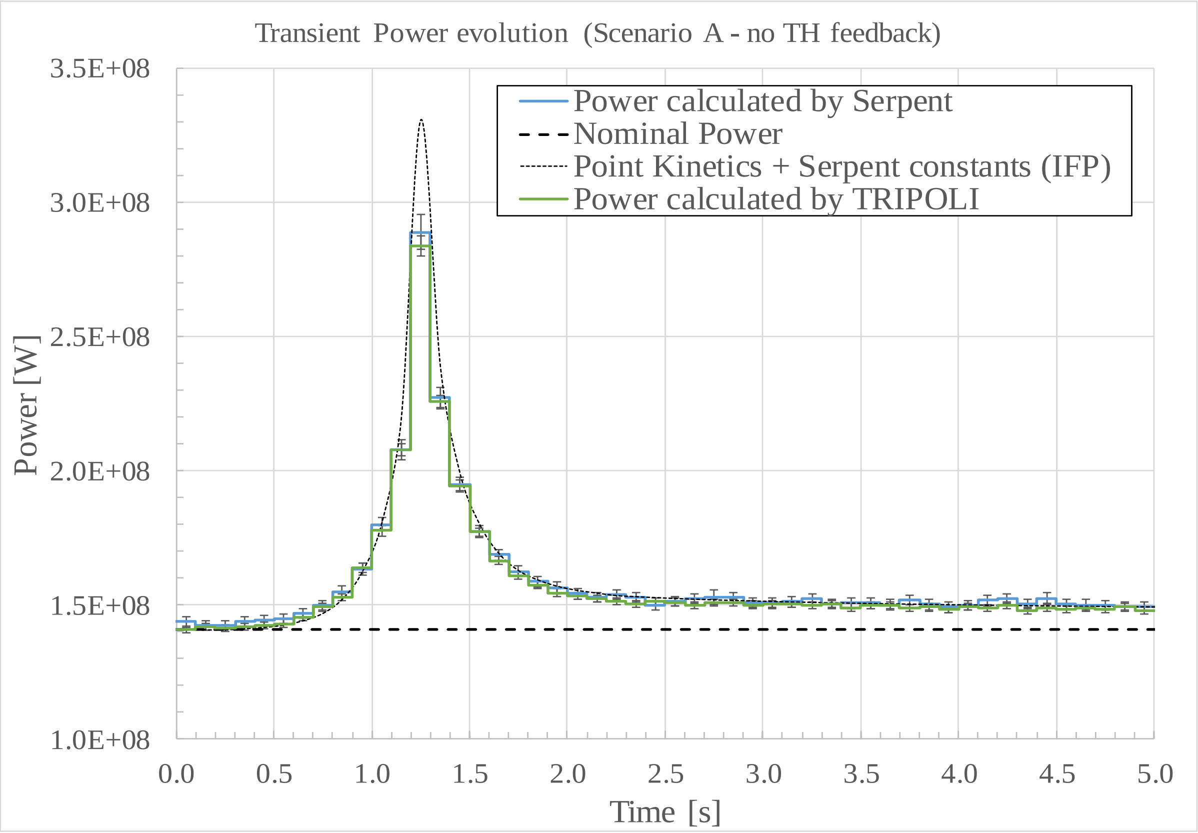
3.1 – Results comparison

Scenario A (no TH feedback)

- Scenario and global power from Serpent, TRIPOLI-4® and PK comparison:



Scenario A

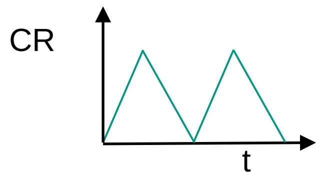


✓ Good and consistent global behavior for this RIA-kind transient
✓ Some differences (PK overshoot, probably due to leakage in real 3D case)

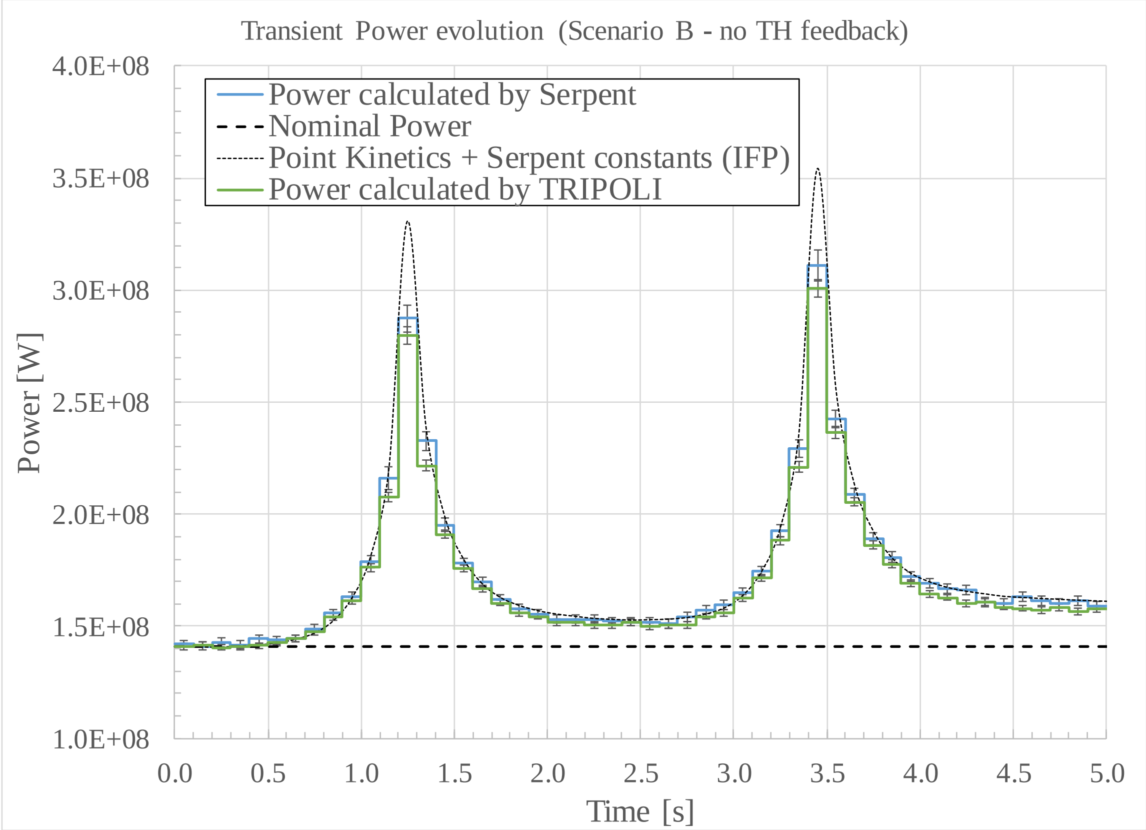
3.2 – Results comparison

Scenario B (no TH feedback) → Scenario A duplicated

- Scenario and global power from Serpent, TRIPOLI-4® and PK comparison:



Scenario B



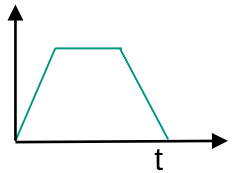
✓ Good and consistent global behavior for this **repeated** transient consistent for both codes

✓ Some differences (PK overshoot)

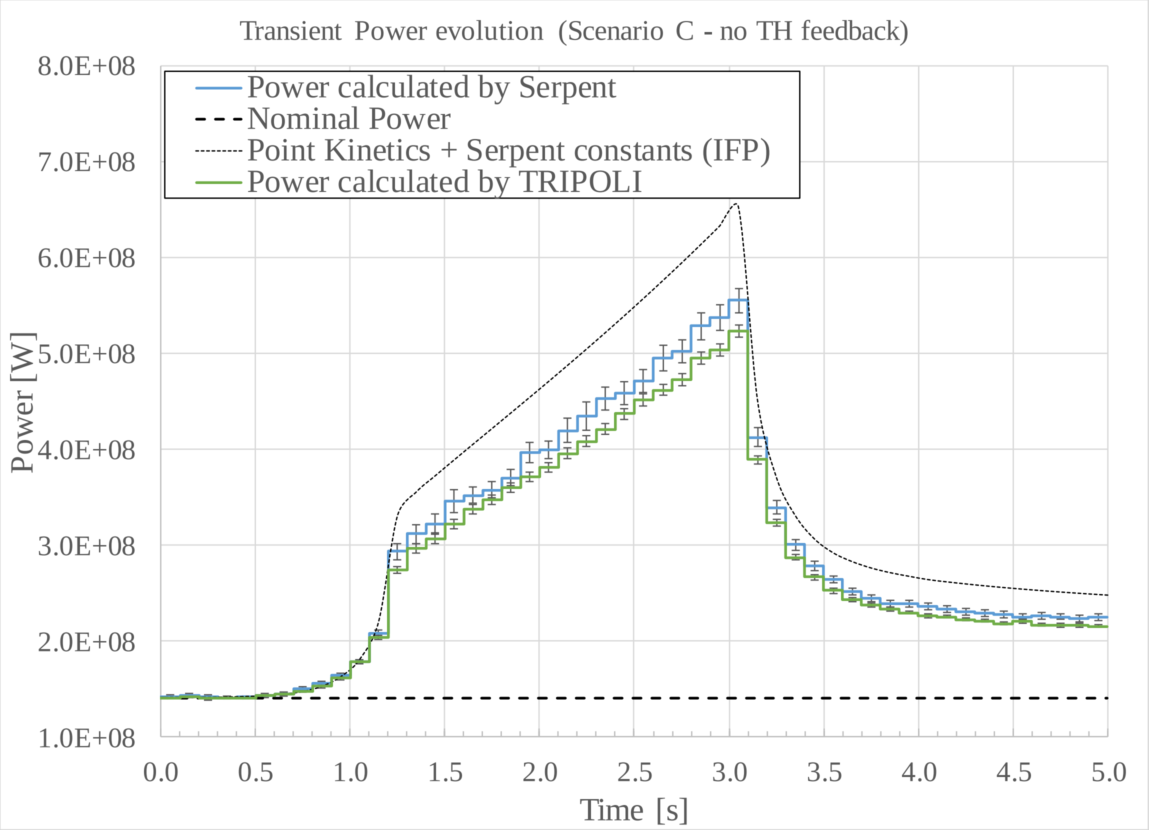
3.3 – Results comparison

Scenario C (no TH feedback) → Scenario A with flat top

- Scenario and global power from Serpent, TRIPOLI-4® and PK comparison:



Scenario C



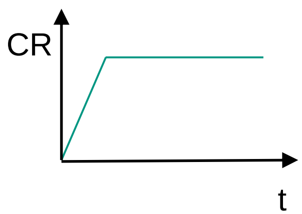
✓ Good and consistent global behavior for this flat top transient → Precursors buildup OK → Delayed neutrons OK

✓ Some differences (PK overshoot)

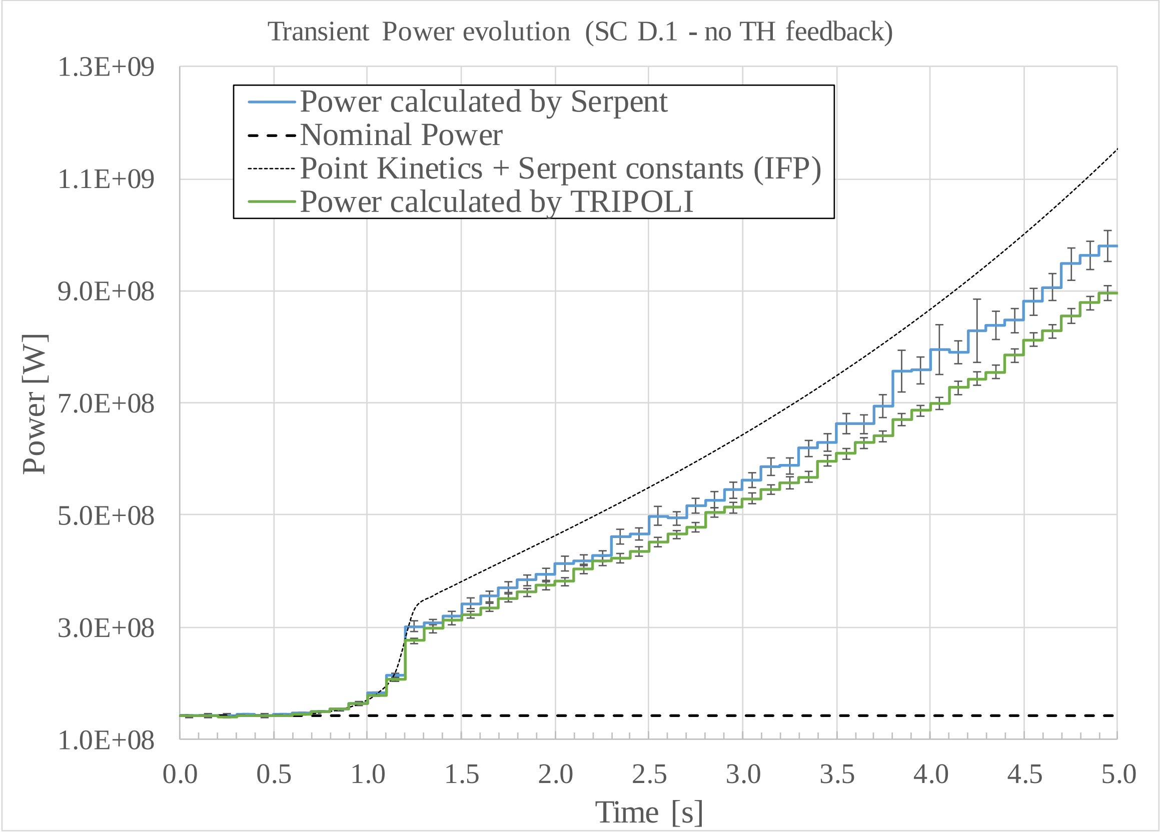
3.4 – Results comparison

Scenario D.1 (no TH feedback) → Scenario A without CR insertion

- Scenario and global power from Serpent, TRIPOLI-4® and PK comparison:



Scenario D.1



✓ Good and consistent global behavior for this supercritical transient for both codes

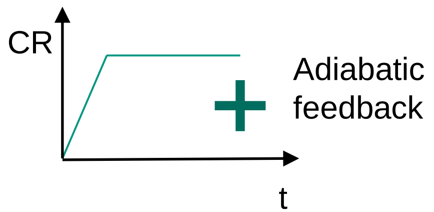
✓ Some cumulative differences

✓ What should we expect with TH feedback?

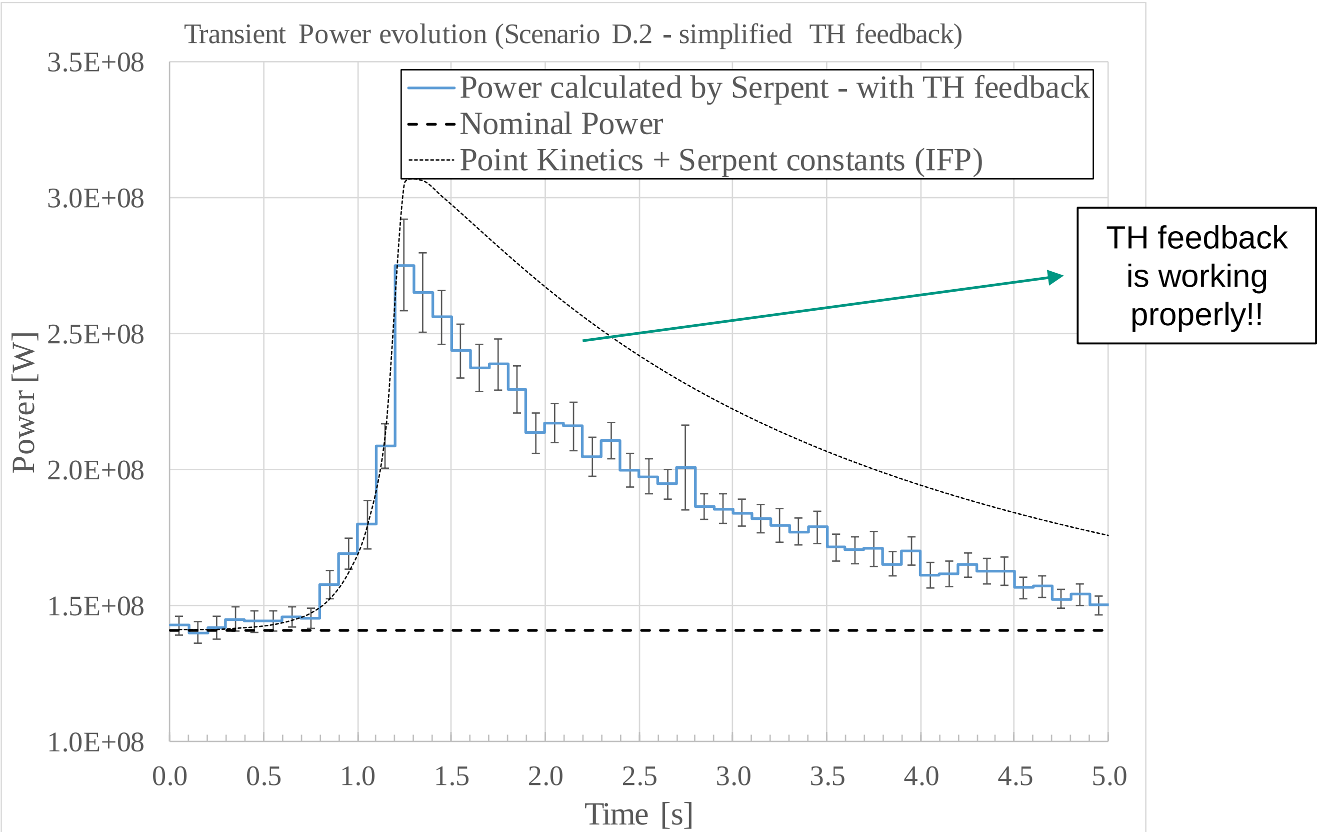
3.5 – Results comparison

Scenario D.2 (D.1 + simplified TH feedback)

- Scenario and global power from Serpent and PK comparison:



Scenario D.2



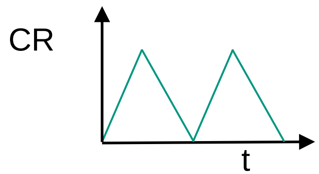
✓ Good global behavior for this supercritical transient → Feedback on TH fields is working properly!

✓ Some differences (PK overshoot, to be further analyzed)

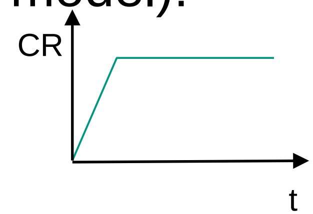
3.5 – Some remarks on results differences

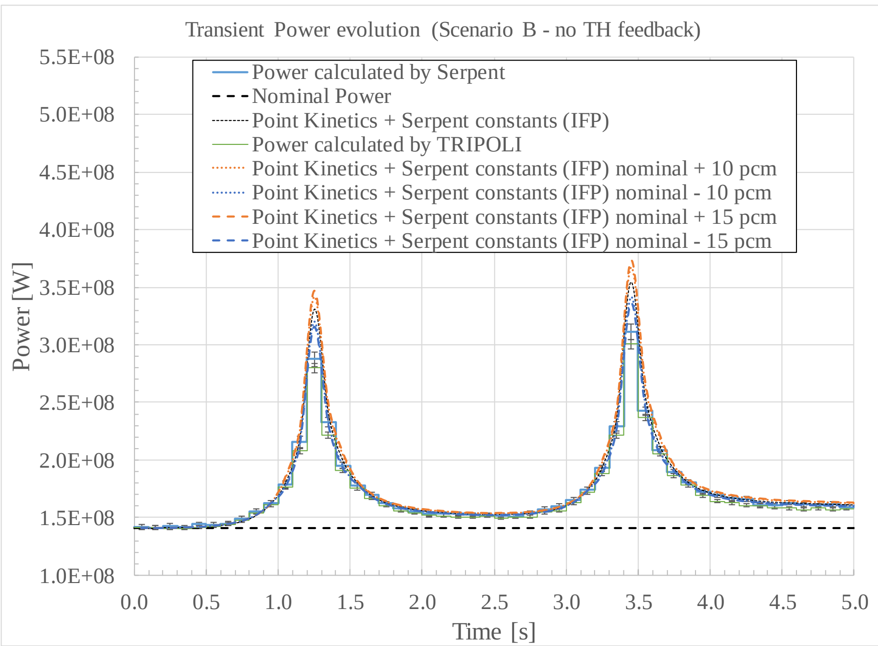
- Perturbation analysis of the proposed scenarios (PK model):

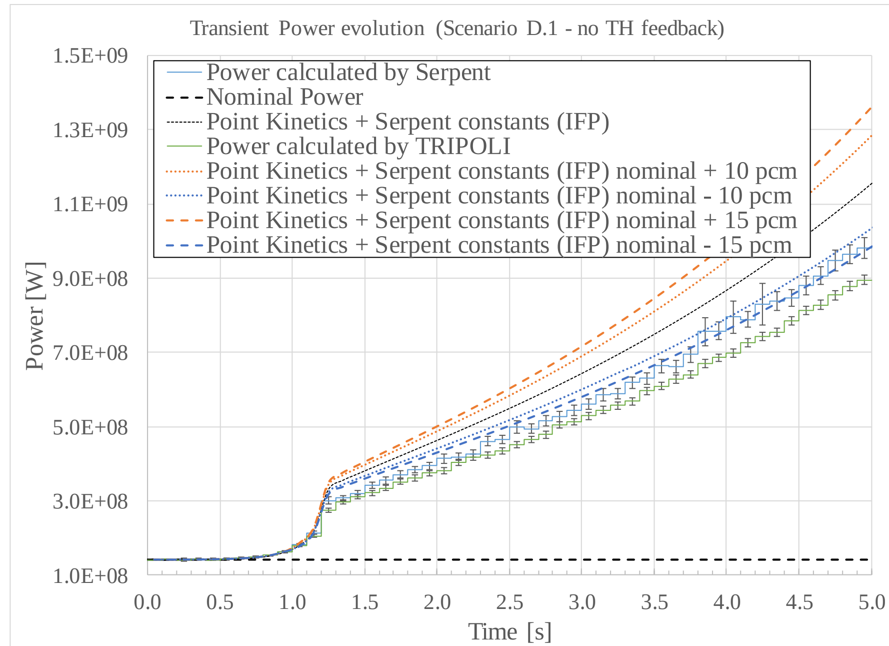
Scenario B



Scenario D.1





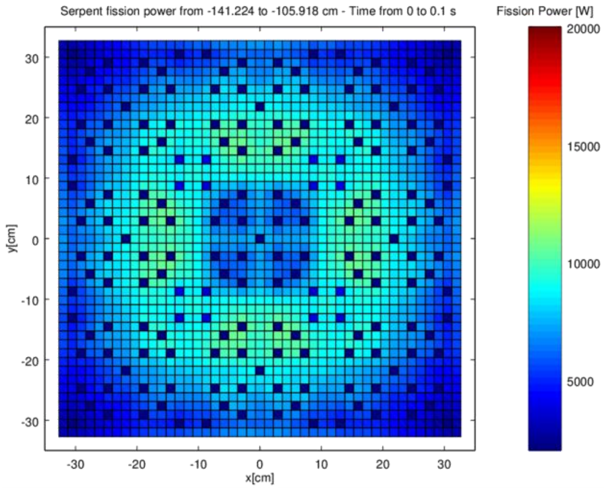


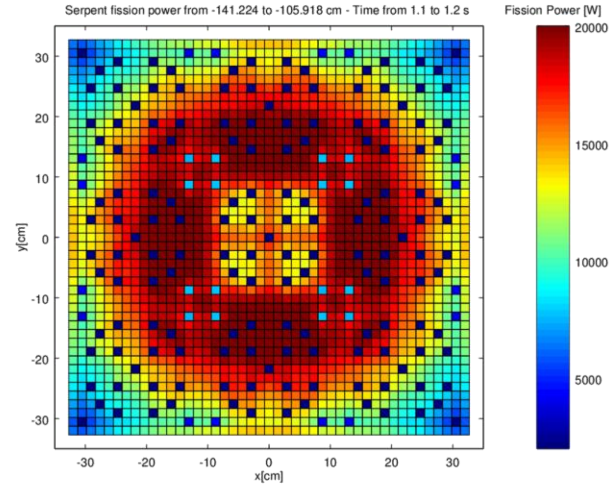
- ✓ Slight differences on reactivity have a clear impact in the long-term power evolution (cumulative).
- ✓ TH feedback will have a stabilizing effect on the discrepancies.
- ✓ Impact on further steps?

3.6 – Towards high-fidelity

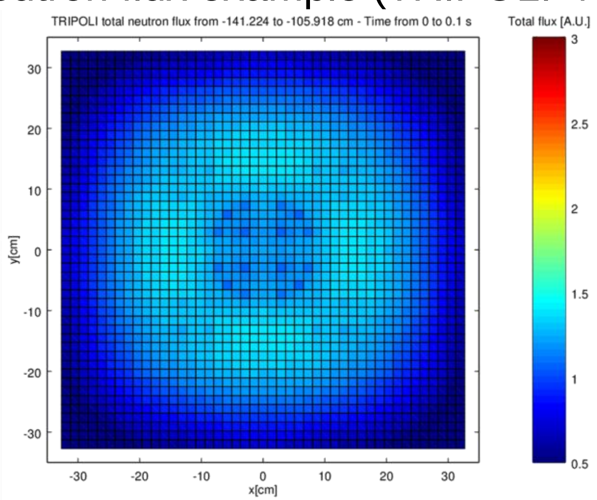
Spatially resolved tallies for scenario A

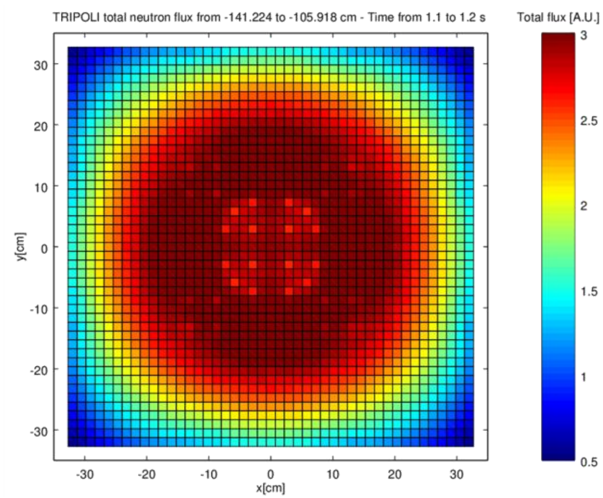
- Fission Power example (Serpent 2):





- Total neutron flux example (TRIPOLI-4®)





➡ Highly detailed (i.e. pin-by-pin) results feasible

3.7 – Requirements and performance

The computational costs and performance comparison

- Compared computational costs for Serpent and TRIPOLI-4®

Parameter / Scenario	A	B	C	D1
Serpent[1]				
Active neutron histories	1.00E+07	1.00E+07	1.00E+07	1.00E+07
Processors	1000	1000	1000	1000
Running wallclock time [min]	393	412	482	593
Average stdev [%] 1 sigma	0.65	0.68	0.96	1.26
Max stdev [%] 1 sigma	1.1	1.2	1.7	3.4
FOM [(1/(σ^2T)]	6.0E-02	5.3E-02	2.3E-02	1.1E-02
TRIPOLI-4®				
Active histories	1.00E+08	1.00E+08	8.00E+07	4.00E+07
Processors	1000	1000	1000	1000
Running wallclock time [min]	1006	1103	1388	1254
Average stdev [%] 1 sigma	0.46	0.47	0.55	0.85
Max stdev [%] 1 sigma	0.68	0.68	0.78	1.09
FOM [(1/(σ^2 T)]	4.8E-02	4.2E-02	2.4E-02	1.1E-02

[1] Run in hybrid MPI/OMP in cluster based on nodes with 2x10 intel Xeon processors E5-2660 v3 @ 2.6 GHz

[2] Run in pure MPI in cluster based on nodes with 2x14-cores Intel Broadwell @ 2.4GHz (AVX2)

✓ Highly detailed (i.e. pin-by-pin) results require high amount of resources

✓ Consistent performance for both codes

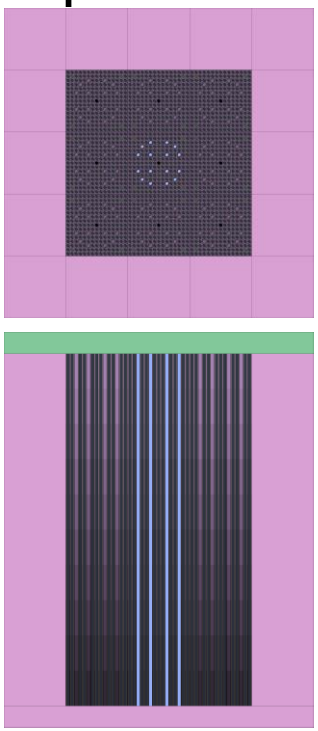
4 – Conclusions and further work

- The McSAFE is a *high-fidelity* project aimed at developing high-fidelity calculations, including transient analysis
- A detailed 3D benchmark for a 3x3 PWR Minicore is proposed as basis to develop a series of scenarios (RIA-type)
- Results obtained & compared with the Serpent 2 and TRIPOLI-4® MC codes → first code-to-code comparison for such RIA type transient simulations
- For all transient scenarios results from TRIPOLI-4® and Serpent 2 are in good agreement
- First step towards the verification and performance analysis.
- Further work:
  - Coupling with TH subchannel codes (SUBCHANFLOW)
  - Proper verification (code-to-code) and validation with experimental data

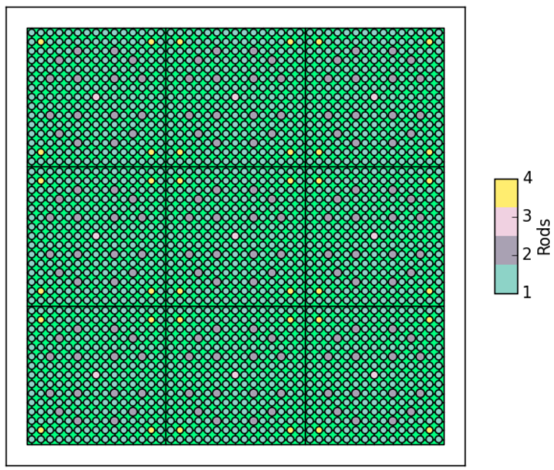
4 – Further work (under development)

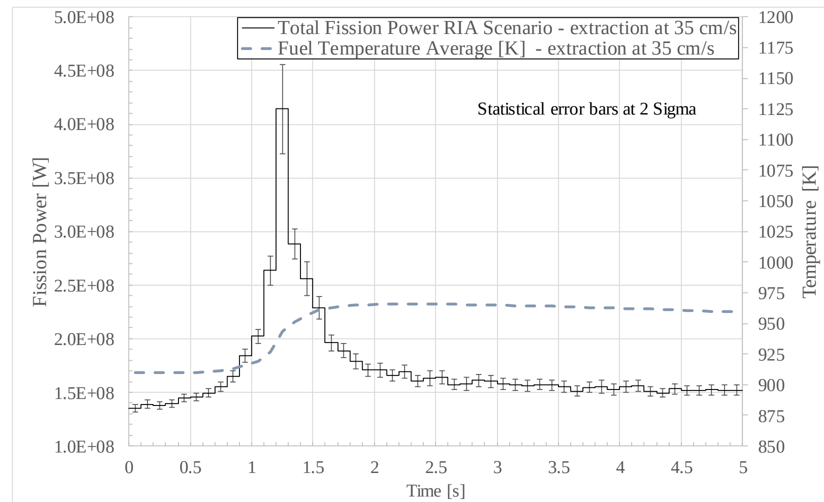
- Given the good obtained results, further coupling (master-slave) was developed with SERPENT+SUBCHANFLOW (COBRA-based subchannel thermalhydraulics).
- First verification results already available for Serpent+SCF (consistent behavior)

Serpent model



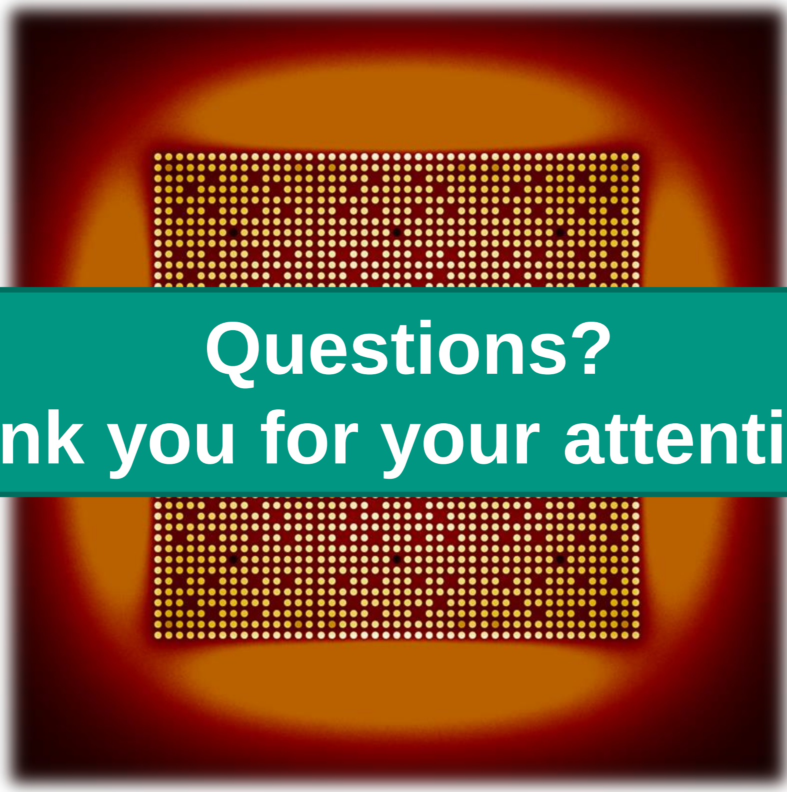
SCF model (coolant-centered)





Full paper submitted to ANE (May 2019): "Serpent/SUBCHANFLOW pin-by-pin coupled transient calculations for a PWR minicore" - *D. Ferraro et al.*

TRIPOLI/SUBCHANFLOW also under development

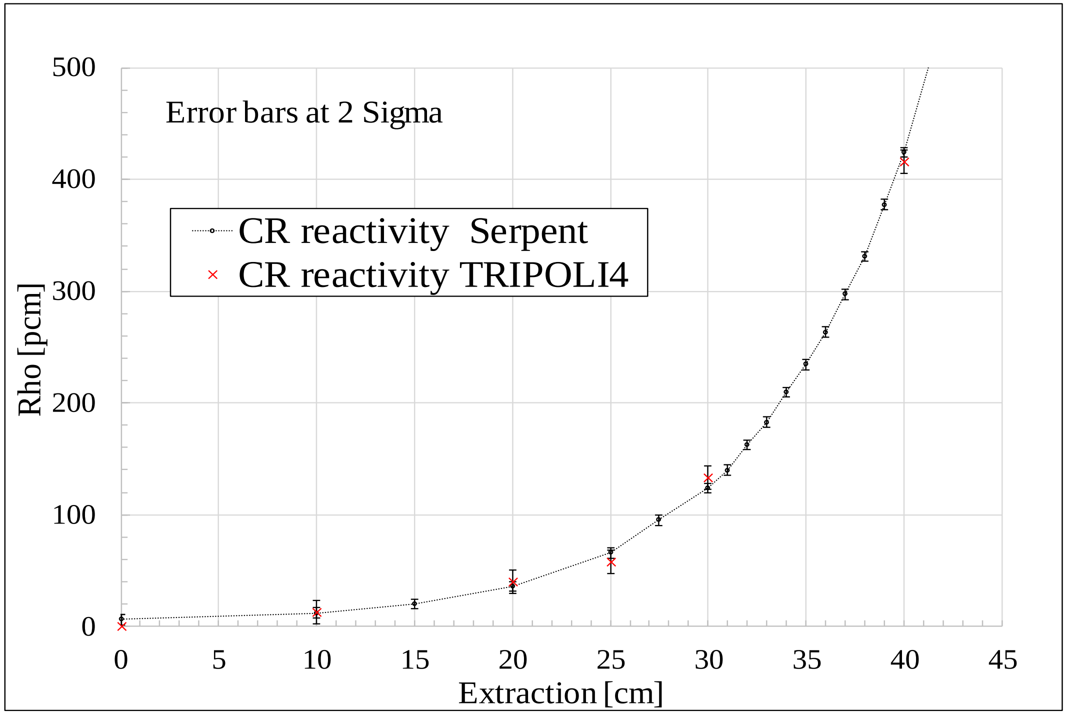


Questions?

Thank you for your attention!!!

Additional information

Static reactivity comparison between TRIPOLI and Serpent



Code	Boron concentration [ppm]	keff (+/- 1 σ)	Reactivity difference with Serpent [pcm]
Serpent	1480 (adjusted)	1.00006 +/ 2e-5	-
TRIPOLI-4®	1493 (adjusted)	0.99995 +/ -5e-5	-11
TRIPOLI-4®	1480	1.00124 +/ -17 e-5	117