Overcooling transient analysis in a CAREM-like SMR design using different simulation approaches

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This project has received funding from the Euratom research and training programme 2019-2020 under grant agreement No 945063.

Content

- The CAREM SMR
- Scenario description
- Core description
- Models and approaches
- Results
- Conclusion
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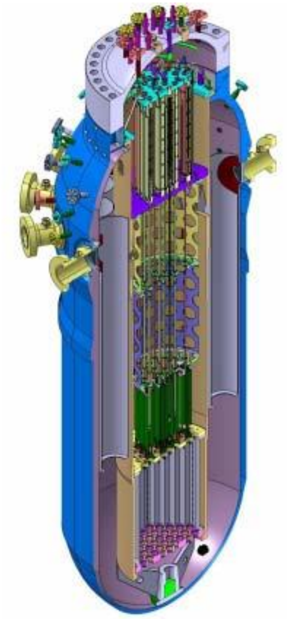
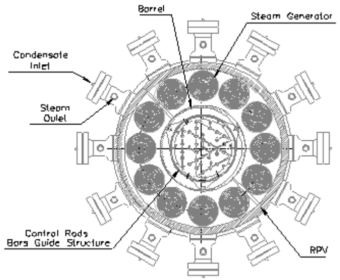
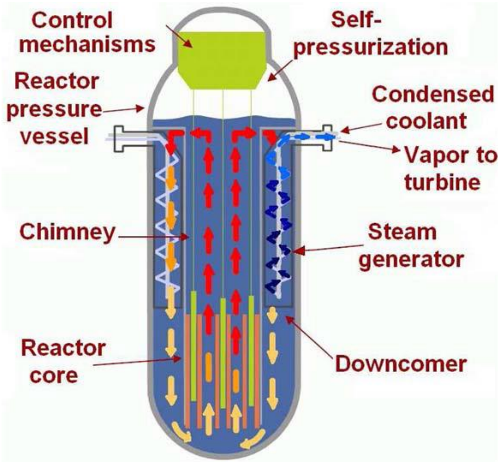
The CAREM design







Images extracted from [1] and [2].

- LWR 100MWth SMR
  - 32 MWe prototype (CAREM 25) under construction
- Integrated system inside the RPV
  - Coolant system
  - Control rod drive mechanism (Rod ejection accident not possible)
- Primary cooling by natural circulation
- Self-pressurized
- No soluble boron during normal operation
- Safety systems rely on passive features

CAREM-25 construction site (Lima, Buenos Aires, Argentina – November 2022) [3]

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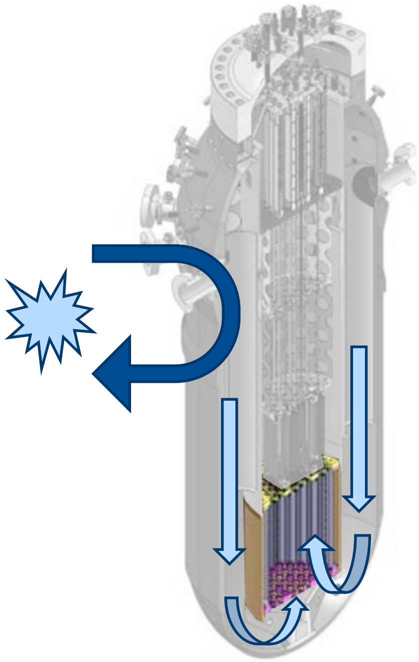
Scenario description



- Domain of analysis: only the reactor core
- Scenario
  - Reactivity insertion accident (RIA)
  - Perturbation of the initial state
  - Initial state: Full Power (100 MW)
  - Origin of the event: Secondary side
  - Effect in the primary coolant system: Cold front of coolant going through the downcomer and entering in the core, producing a rise in power.
  - Time-dependent boundary conditions for 50 seconds are provided

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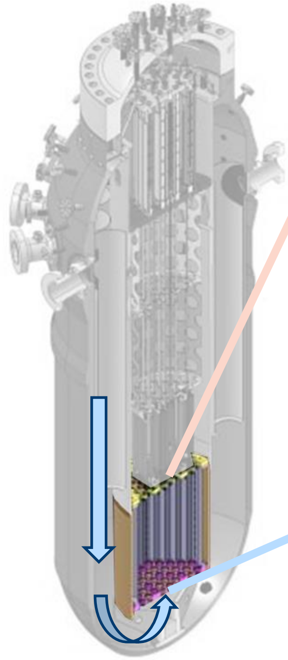

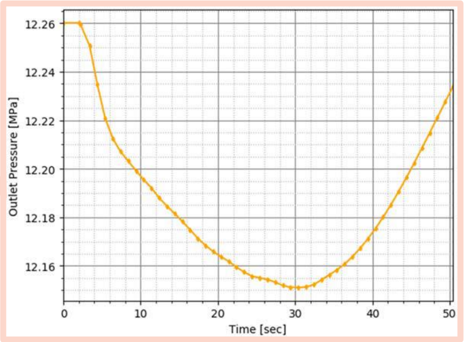

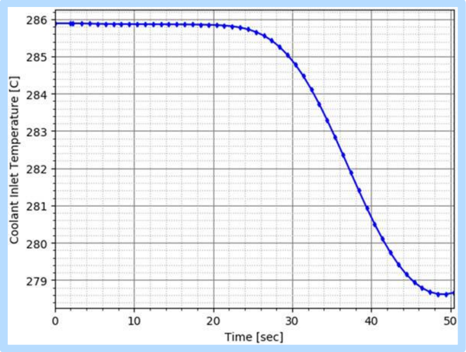

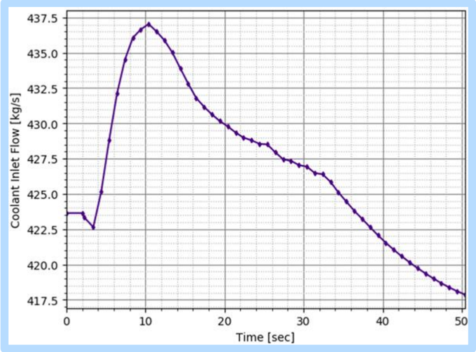

- 50 s transient problem
- Coolant inlet temperature
  - it takes ~25 s to the colder front to arrive at the core inlet
  - Decreases ~8°C (~3%) in the last 20 seconds.
- Mass flow rate
  - Increases ~ 14 kg/s (~3,3%) in the first 10 seconds.
- Core outlet pressure
- Decreases 0,11 Mpa (<0,03%)

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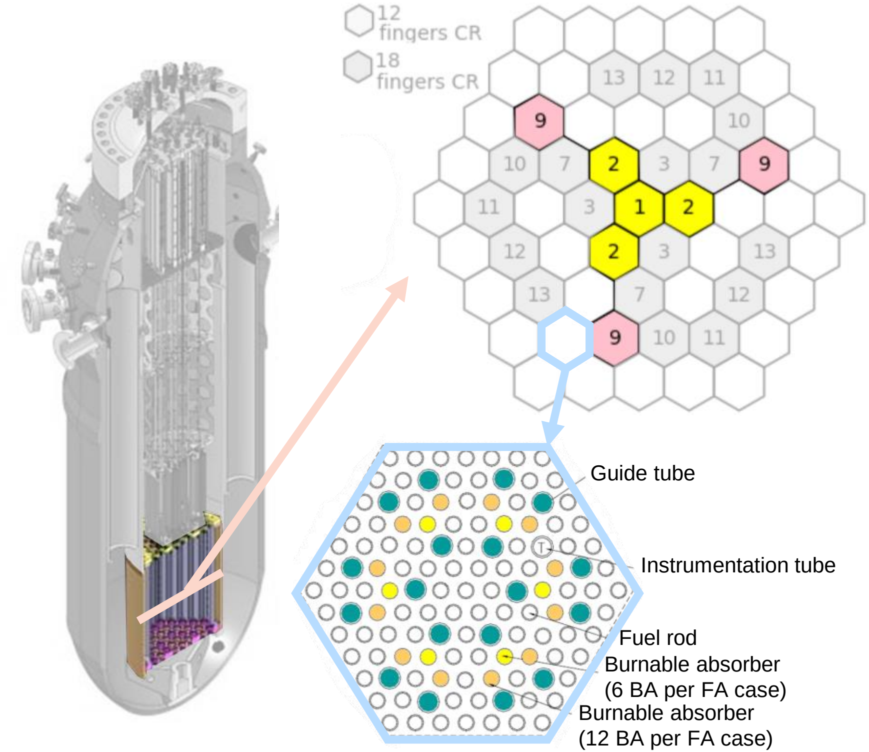
Reactor core



- CAREM-like core
  - 61 hexagonal fuel assemblies
  - 4 fuel assembly types
  - Fresh composition (BOC)
- Fuel assembly
  - 1,8% and 3,1% U235 enrichments
  - {0,6,12} burnable absorbers (UO2-nat + Gd2O3)
  - 18 guide tubes + 1 Instrumentation tube
- Control rods
  - 13 control rod banks
  - Fixed during the scenario
  - Bank1 50%, Bank2 86% and Bank9 68% extracted
  - All other banks out of the core

Some images extracted from [1]

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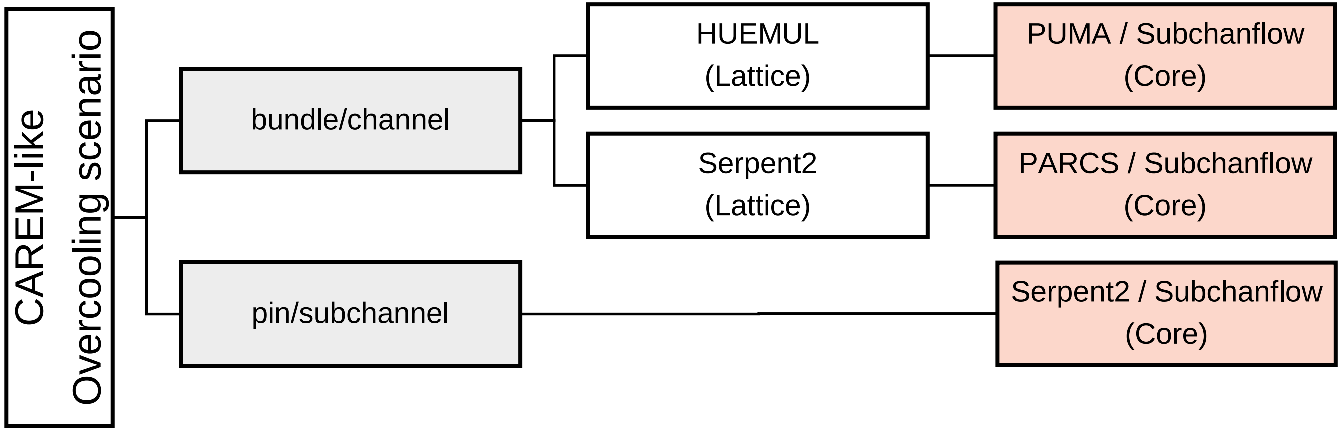
Simulation tools



- HUEMUL/PUMA deterministic chain developed at CNEA, Argentina.
- Serpent2 3D continuous-in-energy Monte Carlo code developed at VTT, Finland [4].
- PARCS nodal diffusion core solver developed currently at University of Michigan.
- Subchanflow is a subchannel TH code developed at KIT [5].
- Bundle/channel analysis is part of a dedicated deliverable [6].
- Pin/subchannel analysis is part of a dedicated deliverable.

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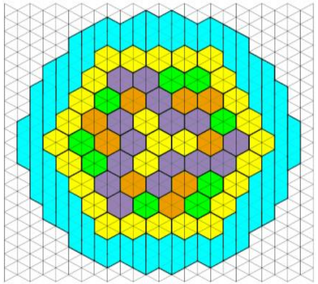
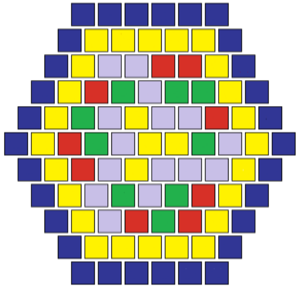
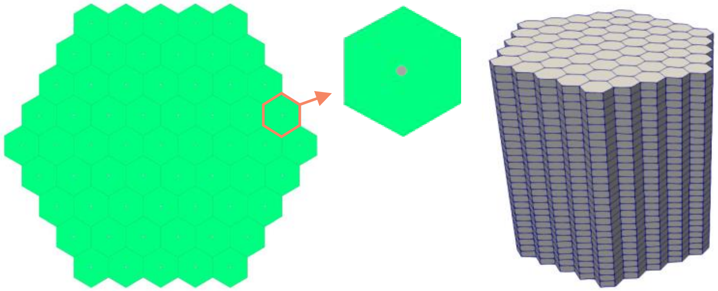
Bundle/channel models

	PUMA	PARCS
Core neutronic models		
Subchanflow model		

- Core neutronic model
  - Bundle homogenization
  - Few groups condensation
  - Diffusion approximation
  - Bundle feedback with TH

- Thermal hydraulic model
  - Rod equivalent model: 61 fuel rods
  - 1 channel with one rod per node: 61 channels
  - Rod equivalent model: 61 fuel rods
  - Axial discretization: 28 axial cells (5cm/cell)

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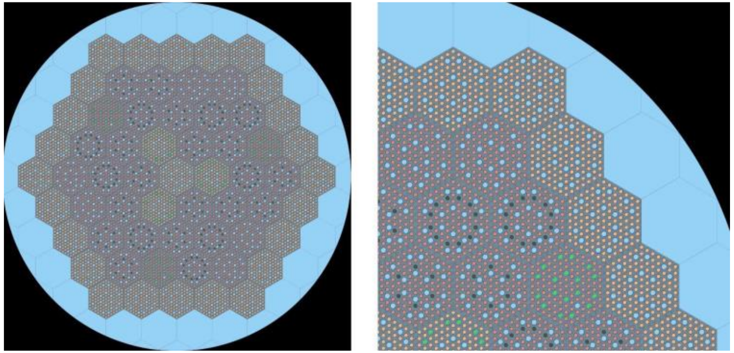
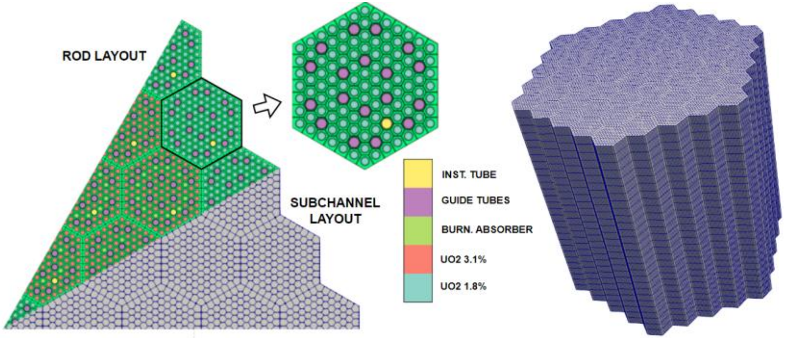
Pin/subchannel model

Serpent2 code model	
Subchanflow model	

- Neutronic core model
  - No homogenization/condensation
  - High geometry detail
  - Local pin-wise feedback with TH

- Thermal hydraulic model
  - All rods are modeled: 7747 rods in total.
  - Fuel-centered model -> 7747 subchannels.
  - Same axial discretization: 28 axial cells.

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Models summary

	Bundle/channel		Pin/subchannel
Neutronic / TH code	PUMA / Subchanflow	PARCS / Subchanflow	Serpent2 / Subchanflow
Neutronic method for the solution	Diffusion equation solved by finite differences.	Diffusion equation solved by TPEN nodal method.	Transport equation solved by Monte Carlo method.
Neutron data library		JEFF 3.1.1	
Energy groups in XS	5	2	Continuous ACE format
Code for cross section generation	Huemul	Serpent 2	-
Coupling type	Via Python script	ICoCo	Internally-coupled
Subchanflow version	3.1	3.7.1	3.7.1
TH model	Fuel-centered	Fuel-centered	Fuel-centered
Number of rods	61	61	7747
Number of fuel rods	61	61	6786
Number of channels	61	61	7747
Number of axial cells (Active length)	28	28	28

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  - Transient
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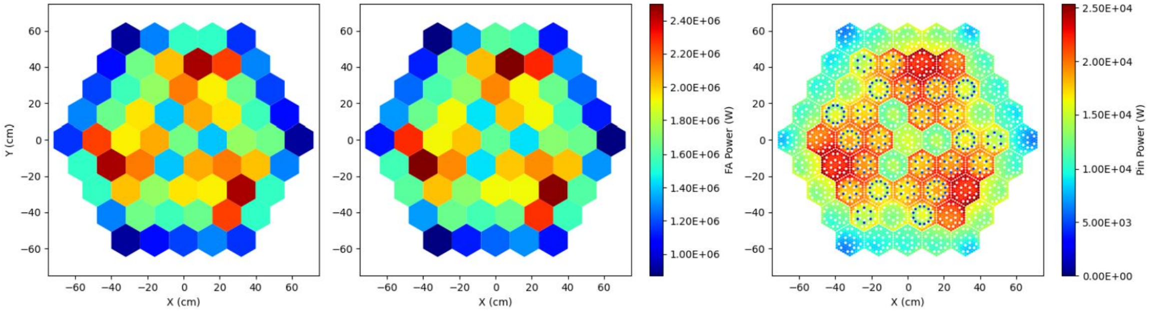
Steady-state results

- Full power with TH feedback
- ~4100 pcm excess reactivity (ARO)
- Initial condition for the transient is slightly subcritical
  - Fission source normalization with initial keff for transient simulation
- Taking Serpent2/SCF as reference
  - Overprediction of PARCS/SCF
  - Better agreement against PUMA/SCF

Control banks	Reactivity (pcm)			Difference (pcm)	
	PUMA/SCF	PARCS/SCF	SSS2/SCF	PUMA/SCF-SSS2/SCF	PARCS/SCF -SSS2/SCF
ARO	4084	4566	4185	-101	+381
'Critical position'	-611	-233	-758	+147	+525



Axial integrated power distribution for PUMA/SCF, PARCS/SCF and Serpent2/SCF, respectively.

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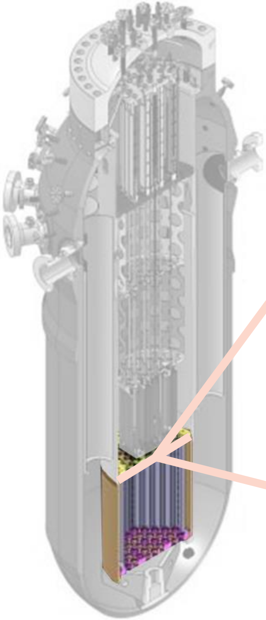
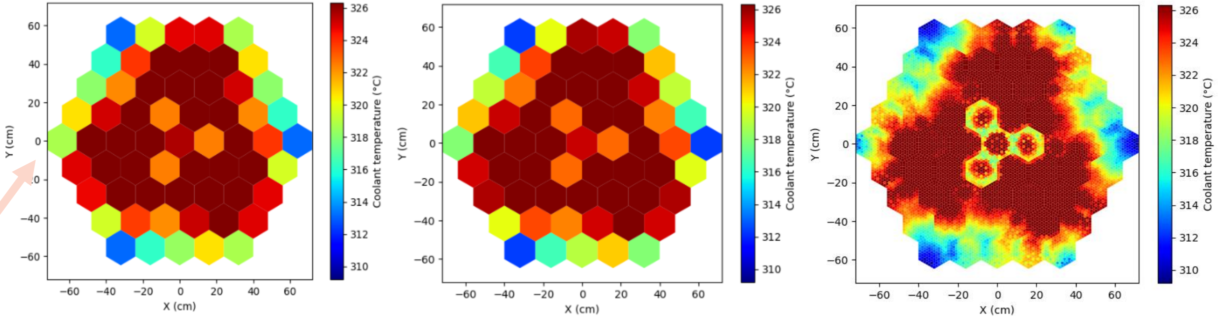
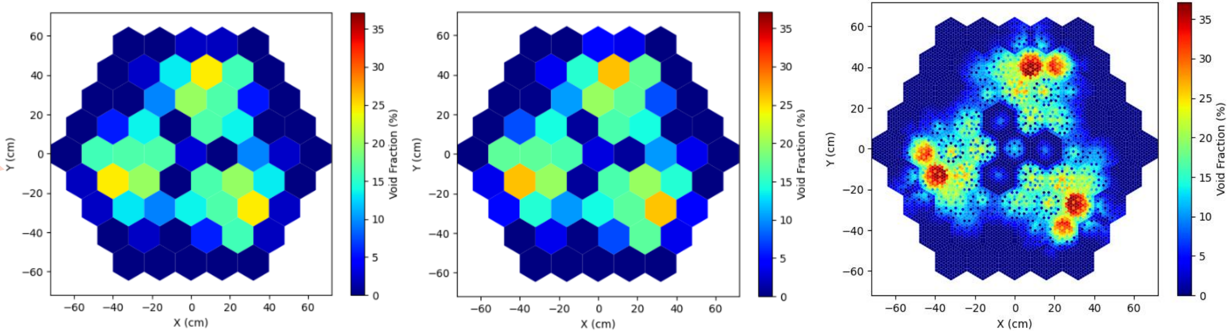
Steady-state results

Coolant temperature for PUMA/SCF, PARCS/SCF and Serpent2/SCF, respectively.







Void fraction for PUMA/SCF, PARCS/SCF and Serpent2/SCF, respectively.

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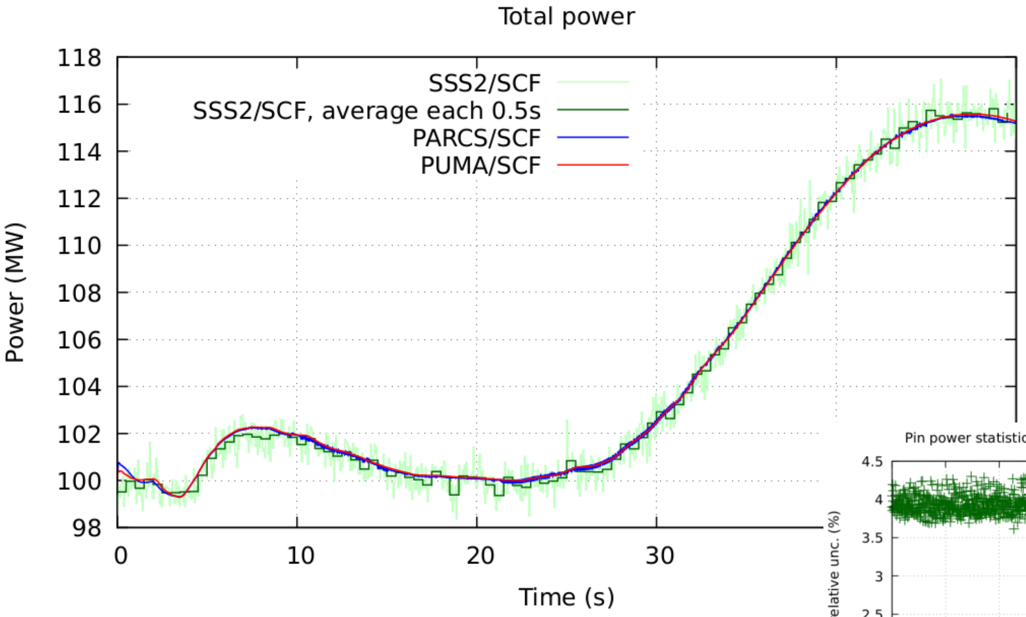
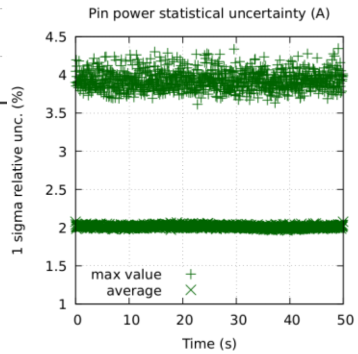
Transient results: Power





- Good agreement
- Noisy because of the Monte Carlo approach
- Initial rise in power [5-15s] due to increase in the mass flow rate
- Final rise [30-50s] in power due to the cold front.
- Serpent2/SCF
  - Total power uncertainty ~ 0,6%
  - Pin power uncertainty ~ 4%
  - KIT HOREKA supercomputer
  - 760 cores (10 nodes)
  - 19 days simulation time

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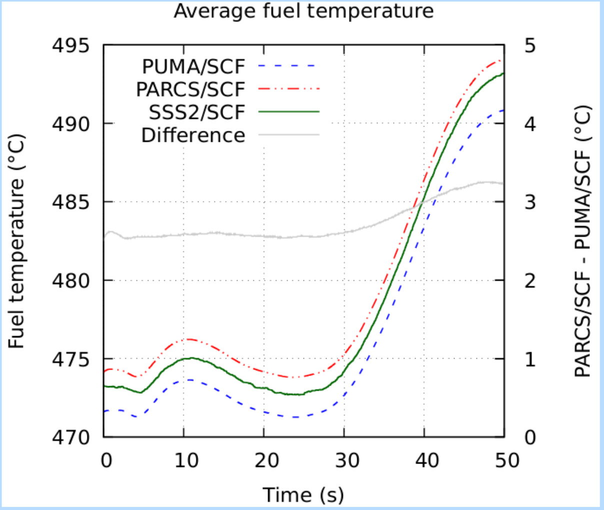
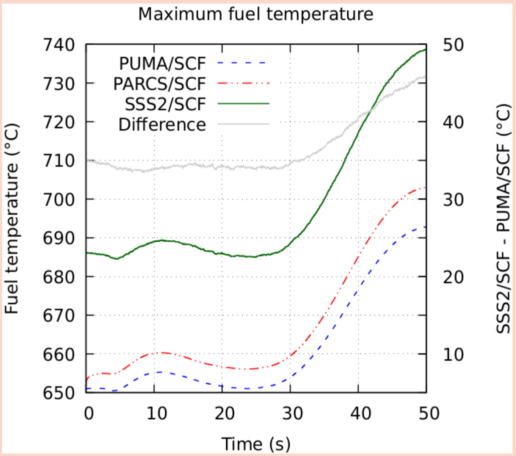
Transient results: Fuel temperature





- $T_{ik}^{fuel} = 0,3 \times T_{center} + 0,7 \times T_{outer}$
- Good agreement on core average
- Differences ~3°C
- Diff. bundle/channel ~ 10°C
- Higher peak values expected with Serpent2/SCF
  - ~35°C higher at t=0s
  - ~45°C higuer at t=50s

Parameter	Puma / SCF and Parcs / SCF	Serpent 2 / SCF
Fuel rod index	$i = \{1, 2, \dots, I\}; I = 61$	$i = \{1, 2, \dots, I\}; I = 6786$
Axial cell index	$k = \{1, 2, \dots, K\}; K = 28$	$k = \{1, 2, \dots, K\}; K = 28$
Average fuel temperature	$\frac{1}{I \times K} \sum_{i,k} T_{ik}^{fuel}$	$\frac{1}{I \times K} \sum_{i,k} T_{ik}^{fuel}$
Maximum fuel temperature	$max\{T_{ik}^{fuel}\}$	$max\{T_{ik}^{fuel}\}$

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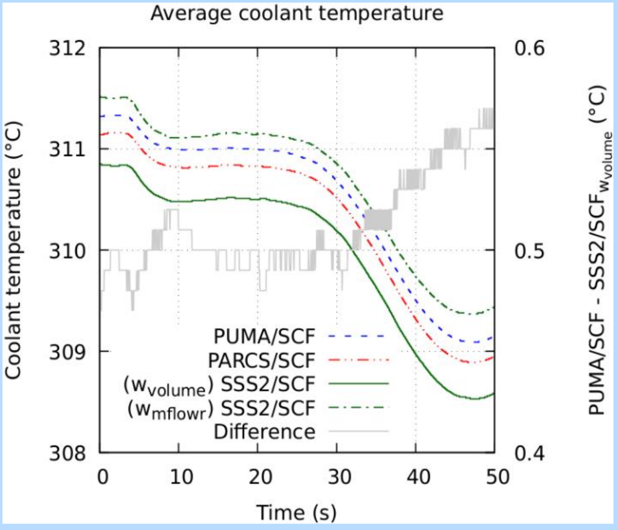
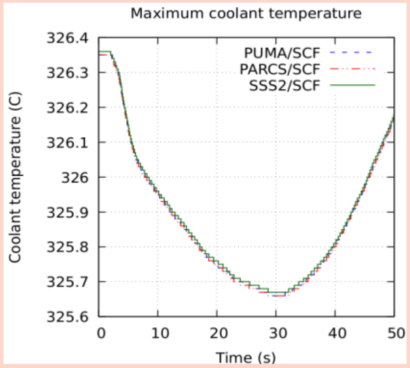
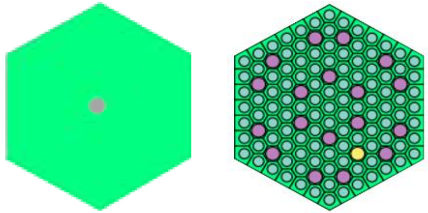
Transient results: Coolant temperature





- Good agreement
- Differences < 1°C
- Careful for Tcool core average

- Max. Tcool is at the core outlet
- Saturated water condition
  - Tcool = Tsat(P)



Parameter	Puma / SCF and Parcs / SCF	Serpent 2 / SCF
Channel rod index	$j = \{1, 2, \ldots, J\}; J = 61$	$j = \{1, 2, \ldots, J\}; J = 7747$
Axial cell index	$k = \{1, 2, \ldots, K\}; K = 28$	$k = \{1, 2, \ldots, K\}; K = 28$
Average coolant temperature	$\frac{\sum_{j,k} T_{jk}^{cool}}{J \times K} \equiv \frac{\sum_{j,k} V_{jk} \times T_{jk}^{cool}}{\sum_{j,k} V_{jk}}$ $\{V_{jk}\} = Weighted\ with\ volume$	$\frac{\sum_{j,k} V_{jk} \times T_{jk}^{cool}}{\sum_{j,k} V_{jk}}$ or $\frac{\sum_{j,k} \dot{m}_{jk} \times T_{jk}^{cool}}{\sum_{j,k} \dot{m}_{jk}}$ $\{V_{jk}\} = Weighted\ with\ volume$ $\{\dot{m}_{jk}\} = Weighted\ with\ mass\ flow\ rate$
Maximum coolant temperature	$max\{T_{jk}^{cool}\}$	$max\{T_{jk}^{cool}\}$

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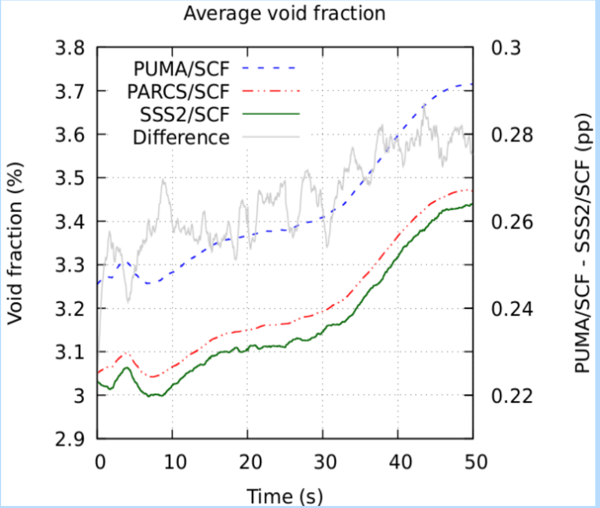
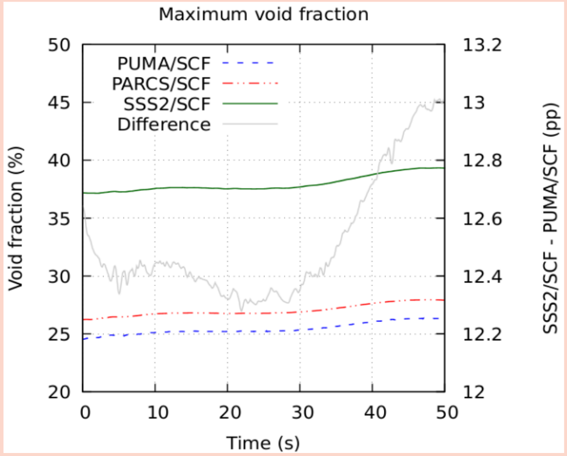
Transient results: Void fraction





- Core
  - ~ 3.1% void fraction
  - Differences < 0,3 pp
- Peak value
  - Bundle level ~25%
  - Pin/subchannel level ~38%

Parameter	Puma / SCF and Parcs / SCF	Serpent 2 / SCF
Channel rod index	$j = \{1, 2, \dots, J\}; J = 61$	$j = \{1, 2, \dots, J\}; J = 7747$
Axial cell index	$k = \{1, 2, \dots, K\}; K = 28$	$k = \{1, 2, \dots, K\}; K = 28$
Average void fraction	$\frac{\sum_{j,k} f_{jk}}{J \times K} \equiv \frac{\sum_{j,k} V_{jk} \times f_{jk}}{\sum_{j,k} V_{jk}}$	$\frac{\sum_{j,k} V_{jk} \times f_{jk}}{\sum_{j,k} V_{jk}}$
Maximum void fraction	$max\{f_{jk}\}$	$max\{f_{jk}\}$

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Conclusion

- Results of an overcooling transient in the CAREM-like SMR.
  - 2 state-of-the-art solutions
  - 1 high-fidelity solution
- Very good agreement
- High-fidelity
  - Higher peak values were identified
  - Requires high computational resources
- ‘Long’ transient with Serpent 2
  - Relative small changes in Power and THs
  - No big changes in the THs allow to choose bigger time steps

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Thank you for your attention.

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