N.IN.E.

Nuclear and INdustrial Engineering

10th Serpent User Group Meeting

FRM II, TUM, Garching, Germany,

October 27th-30th, 2020

Serpent application to Neutronics Benchmark of CEFR Start-Up Tests

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Outline

- Introduction
- Serpent geometrical model
  - Horizontal section
  - Vertical section
- Description of experiments
- Experiment simulation model
- Results

Introduction

- Framework
  - Coordinated research project
  - Proposed by the China Institute of Atomic Energy (CIAE)
  - Under the direction and support from International Atomic Energy Agency (IAEA)
- Overall objective
  - To improve the Member States' analytical capabilities in the field of fast reactor simulation and design by international validation and qualification of codes currently employed in the field of fast reactor neutronics

Introduction

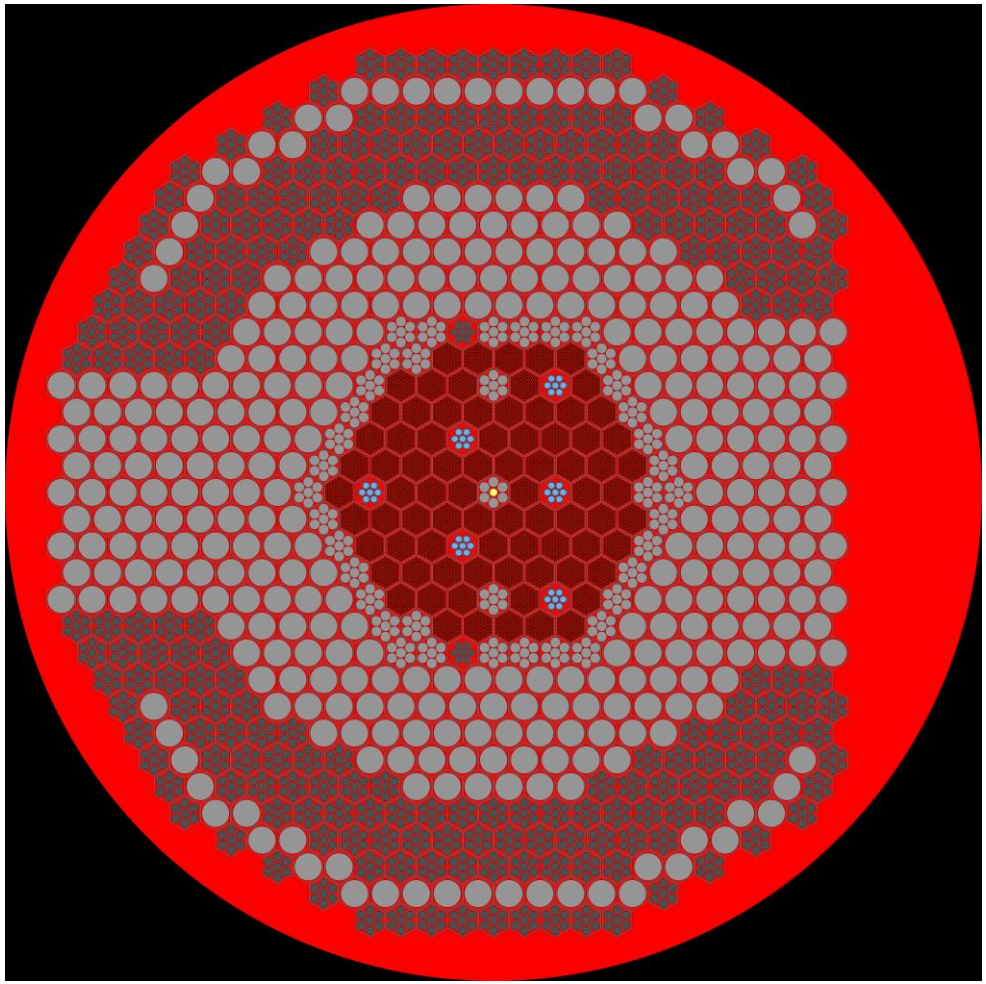
- China Experimental Fast Reactor (CEFR)
  - First Chinese fast reactor
    - ✓ 65 MW_{th}
    - ✓ Pool-type
    - ✓ Sodium cooled
  - First criticality 2010
- Start-up tests
  - Fuel loading and criticality
  - Measurement of control rod worth
  - Measurement of reactivity coefficients
  - Foil activation measurements

Serpent geometrical model

- Code
  - Serpent 2.1.31
- Nuclear data
  - Data provided by Alexey Stankovskiy (SCK-CEN) and based on the ENDF/B-VIII
    - ✓ Reprocessed at different experimental temperatures
- Computational Model
  - Full 3D core model
  - Fuel assemblies in full detail
    - ✓ Clad, Gap, hollow pellet and related characteristics
  - Control and safety assemblies, Reflector (different designs) assemblies and Shielding assemblies
  - Material characteristics and geometry from technical specifications
    - ✓ At operating temperature (thermal expansion considered)

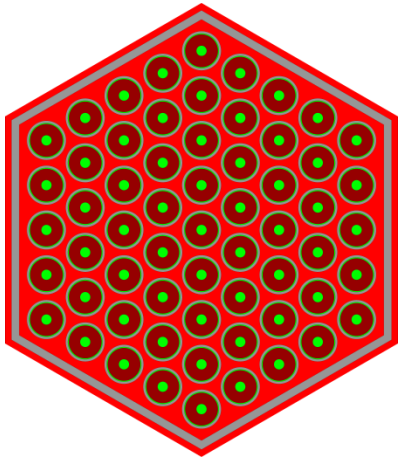
Serpent geometrical model

- Horizontal section
  - Modeled assemblies
    - ✓ Fuel assemblies
    - ✓ Control assemblies
    - ✓ Stainless steel reflector assemblies (two types)
    - ✓ Boron Shielding assemblies
    - ✓ Neutron source assembly
    - ✓ Mock-up fuel assemblies
    - ✓ Other assembly types for various experiments

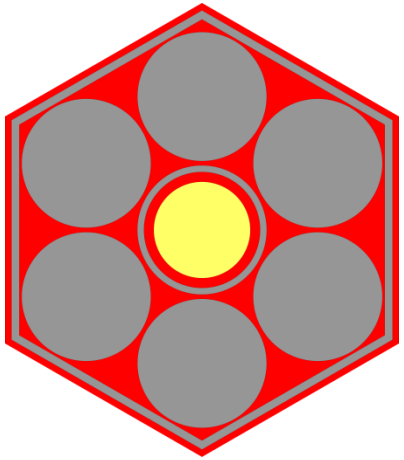


Serpent geometrical model

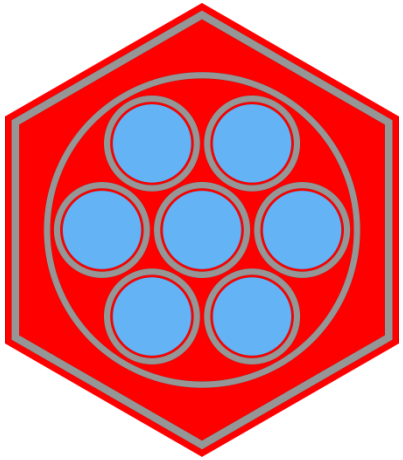
- Assemblies details



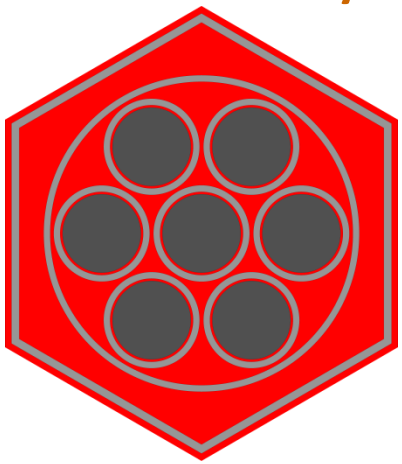
Fuel Assembly



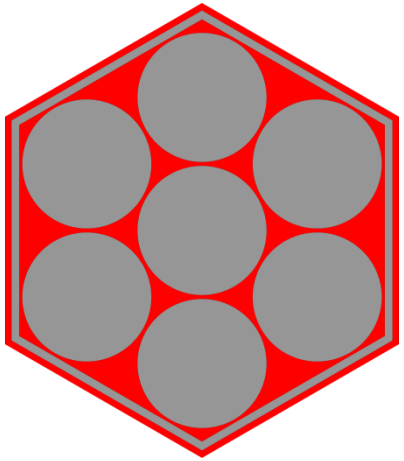
Neutron Source



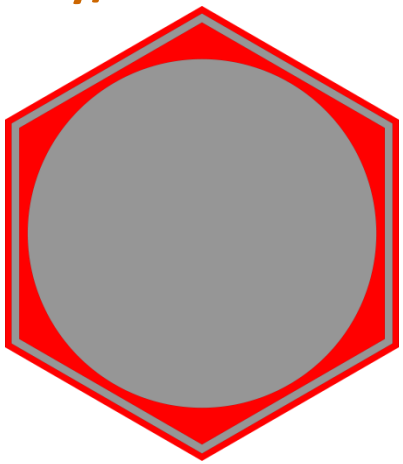
Safety/Shim Assembly



Regulating Assembly



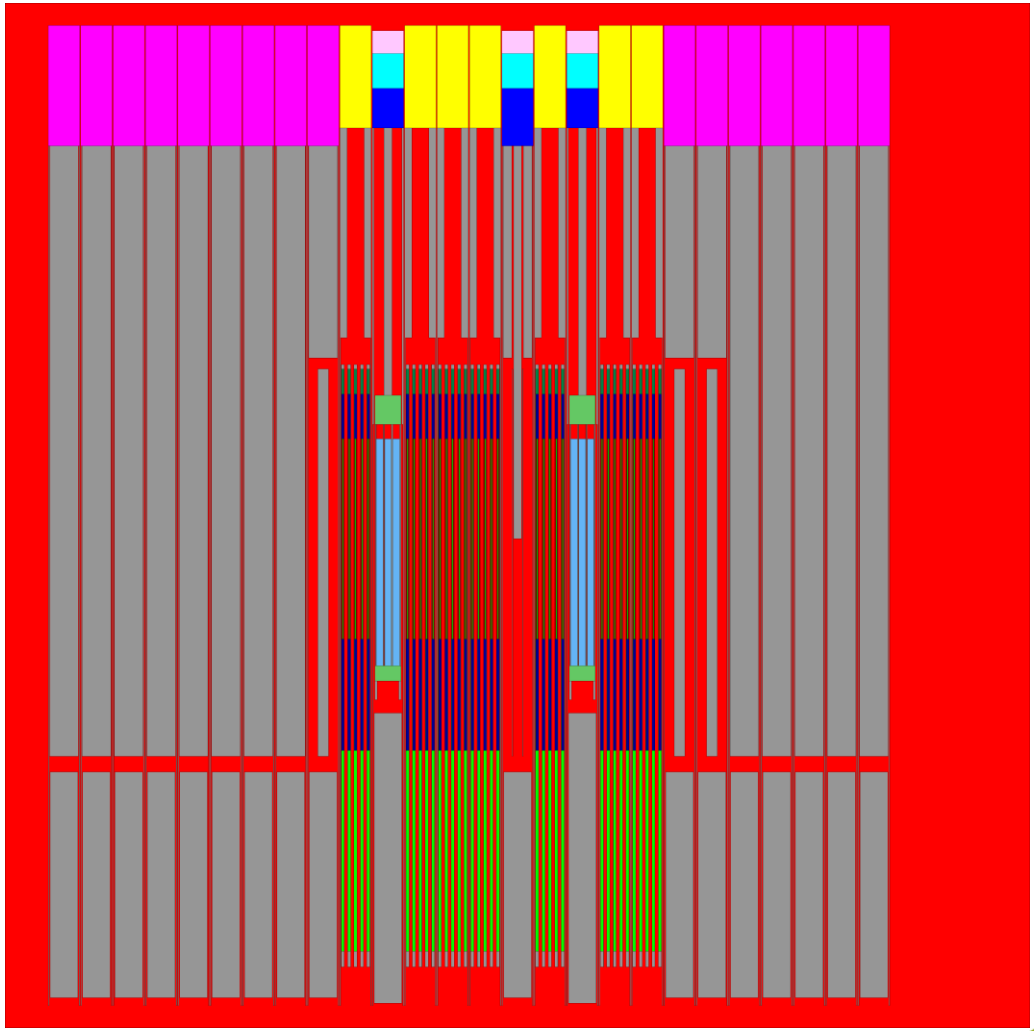
Stainless Steel Assembly (type I/II)

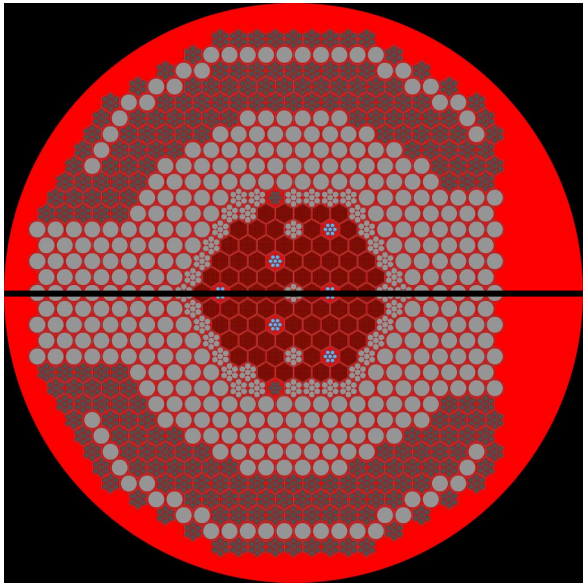


Stainless Steel Assembly (type III/IV)

Serpent geometrical model

- Vertical section:
  - Neutron Source Assembly
  - Fuel Assemblies
  - Shim Assembly
  - Safety Assembly
  - Stainless Steel Assemblies (both types)





Description of experiments

- Fuel loading and criticality
  - Loading phase
    - ✓ 10 steps of fuel assemblies load
  - Criticality phase
    - ✓ 4 measurement at different Regulating assembly position
- Measurement of control rod worth
  - Rod-drop measurement
    - ✓ Each assembly
    - ✓ 2 shutdown systems
      - With/without one assembly stuck
    - ✓ All control rods
      - With/without one assembly stuck

Description of experiments

- Measurement of reactivity coefficients
  - Void reactivity
    - ✓ Replacement of a fuel assembly with a voided ones
      - 5 different positions
  - Temperature reactivity coefficient
    - ✓ Temperature levels
      - 5 increasing temperature (250 °C → 302 °C)
      - 5 decreasing temperature (300 °C → 250 °C)
  - Swap reactivity
    - ✓ Replacement of a fuel assembly with a SS assemblies
      - 6 different positions
    - ✓ Swap of a fuel assembly with a SS assembly
      - 2 different SS assemblies position
      - Starting from a swapped fuel assembly case

Experiment simulation model

- Fuel loading and criticality (WP1)
  - 14 different cases
    - ✓ 10 steps of fuel loading
    - ✓ 3 Supercritical positions
    - ✓ 1 Critical position
  - Simulation set-up
    - ✓ 500k neutrons per generation
    - ✓ 500 active generations
    - ✓ 50 inactive generations
  - Boundary condition
    - ✓ Vacuum

Experiment simulation model

- Measurement of control rod worth (WP2)
  - 117 different cases
    - ✓ 28 rod worth experimental measurement (other rods partially inserted or out of the core)
    - ✓ 17 rod worth measurement (with other rods out of the core)
    - ✓ 72 for “S” curve evaluation (9 intermediate positions for each rod)
  - Simulation set-up
    - ✓ 500k neutrons per generation (except for regulating rods)
    - ✓ 1M neutrons per generation (for regulating rods)
    - ✓ 500 active generations
    - ✓ 50 inactive generations
  - Boundary condition
    - ✓ Vacuum

Experiment simulation model

- Measurement of reactivity coefficients, Void reactivity (WP4)
  - 10 different cases
    - ✓ 5 with original configuration
    - ✓ 5 with voided configuration
  - Simulation set-up
    - ✓ 500k to 2M neutrons per generation
    - ✓ 500 active generations
    - ✓ 50 inactive generations
  - Boundary condition
    - ✓ Vacuum

Experiment simulation model

- Measurement of reactivity coefficients, Temperature reactivity coefficient (WP3)
  - 18 different cases
    - ✓ 10 different temperatures
    - ✓ 8 intermediate steps (change of rod positions, before temperature change for 3 step method)
  - Simulation set-up
    - ✓ 500k neutrons per generation
    - ✓ 500 active generations
    - ✓ 50 inactive generations
  - Boundary condition
    - ✓ Vacuum

Experiment simulation model

- Measurement of reactivity coefficients, Swap reactivity (WP5)
  - 48 different cases
    - ✓ 8 assembly positions considered
      - Original case
      - Swapped case
    - ✓ Reactivity compensation
      - Single rod
      - Multiple rods
      - No compensation (rods out)
  - Simulation set-up
    - ✓ 500k neutrons per generation
    - ✓ 500 active generations
    - ✓ 50 inactive generations
  - Boundary condition
    - ✓ Vacuum

Results

- Fuel loading and criticality (WP1)
  - Loading phase (experimental k from counting rate)

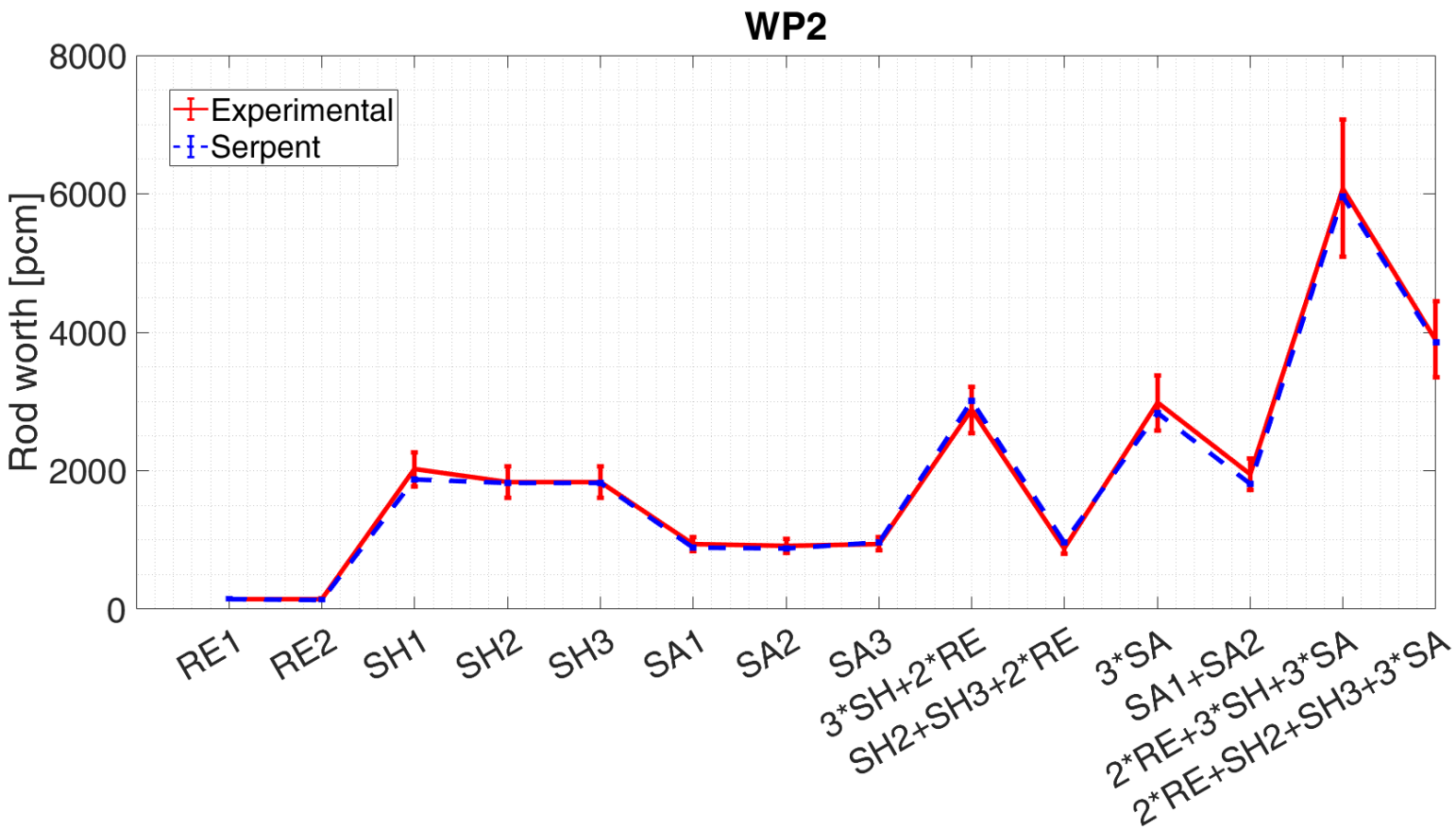
Fuel assemblies inserted	RE2 Control Rod Position [mm]	Serpent		Experimental	Relative error
		k_{eff}	Standard deviation	$k_{eff,exp}$	$\frac{k_{eff,exp} - k_{eff}}{k_{eff,exp}}$
24	Out	0.68447	0.0001	0.58799	16%
40	Out	0.83536	9.00E-05	0.77123	8.31%
46	Out	0.87669	8.80E-05	0.82454	6.32%
55	Out	0.92885	8.70E-05	0.89287	4.03%
61	Out	0.95349	8.30E-05	0.93168	2.34%
65	Out	0.96828	8.70E-05	0.95568	1.32%
68	Out	0.98183	8.30E-05	0.97694	0.50%
69	Out	0.98621	8.10E-05	0.98273	0.35%
70	Out	0.99064	8.70E-05	0.98891	0.17%
71	Out	0.99496	7.90E-05	0.99509	0.01%

Results

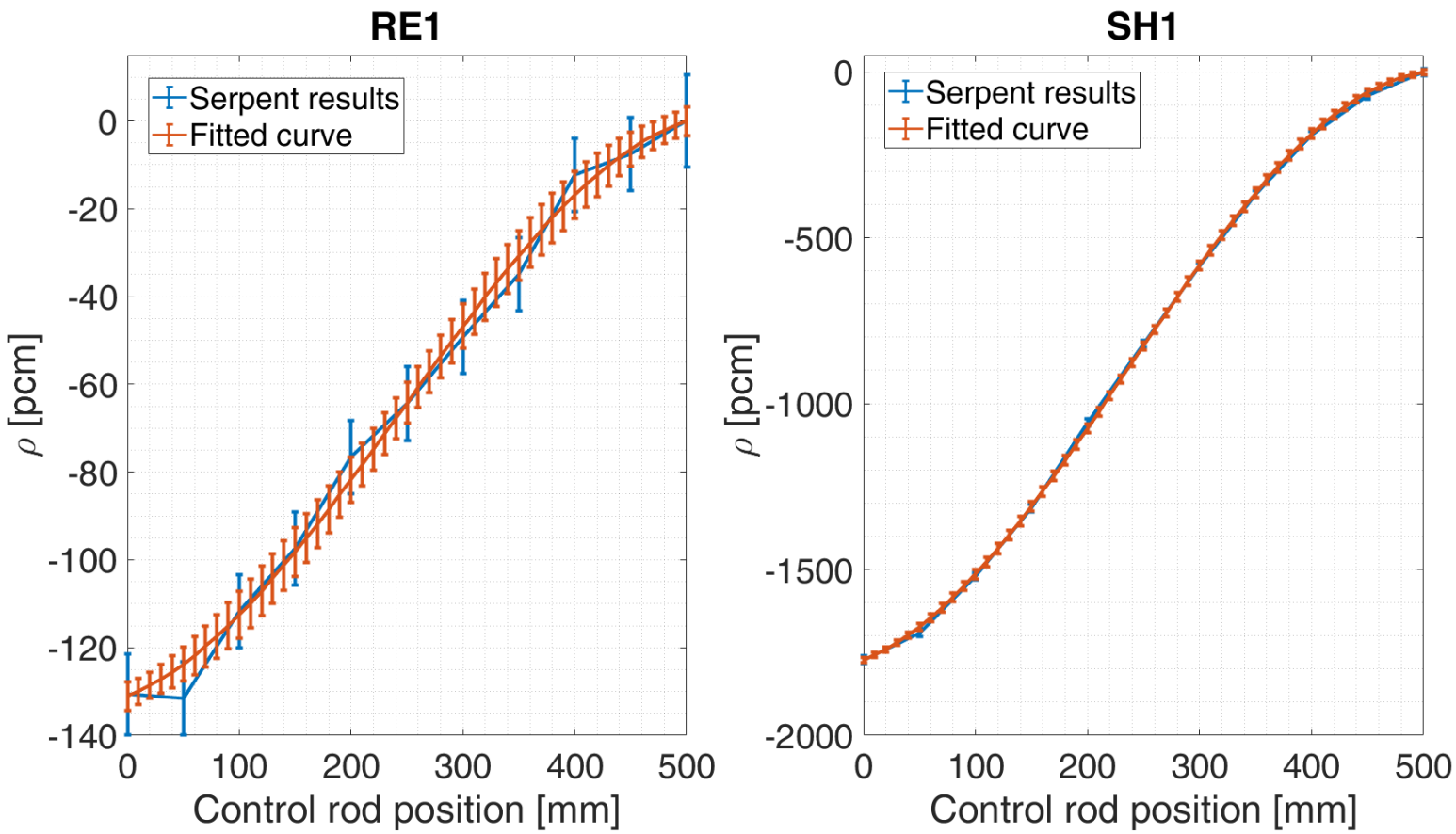
- Fuel loading and criticality (WP1)
  - Criticality phase
    - ✓ 3 supercritical steps
    - ✓ 1 extrapolated critical position

Fuel assemblies inserted	RE2 Control Rod Position [mm]	Serpent		Experimental	Relative error
		k_{eff}	Standard deviation	$k_{eff,exp}$	$\frac{k_{eff,exp} - k_{eff}}{k_{eff,exp}}$
72	70	0.99807	8.2E-05	1.000000	0.19%
72	151	0.99831	7.7E-05	1.000245	0.19%
72	170	0.99843	8.2E-05	1.000335	0.19%
72	190	0.99854	3.9E-05	1.000395	0.19%

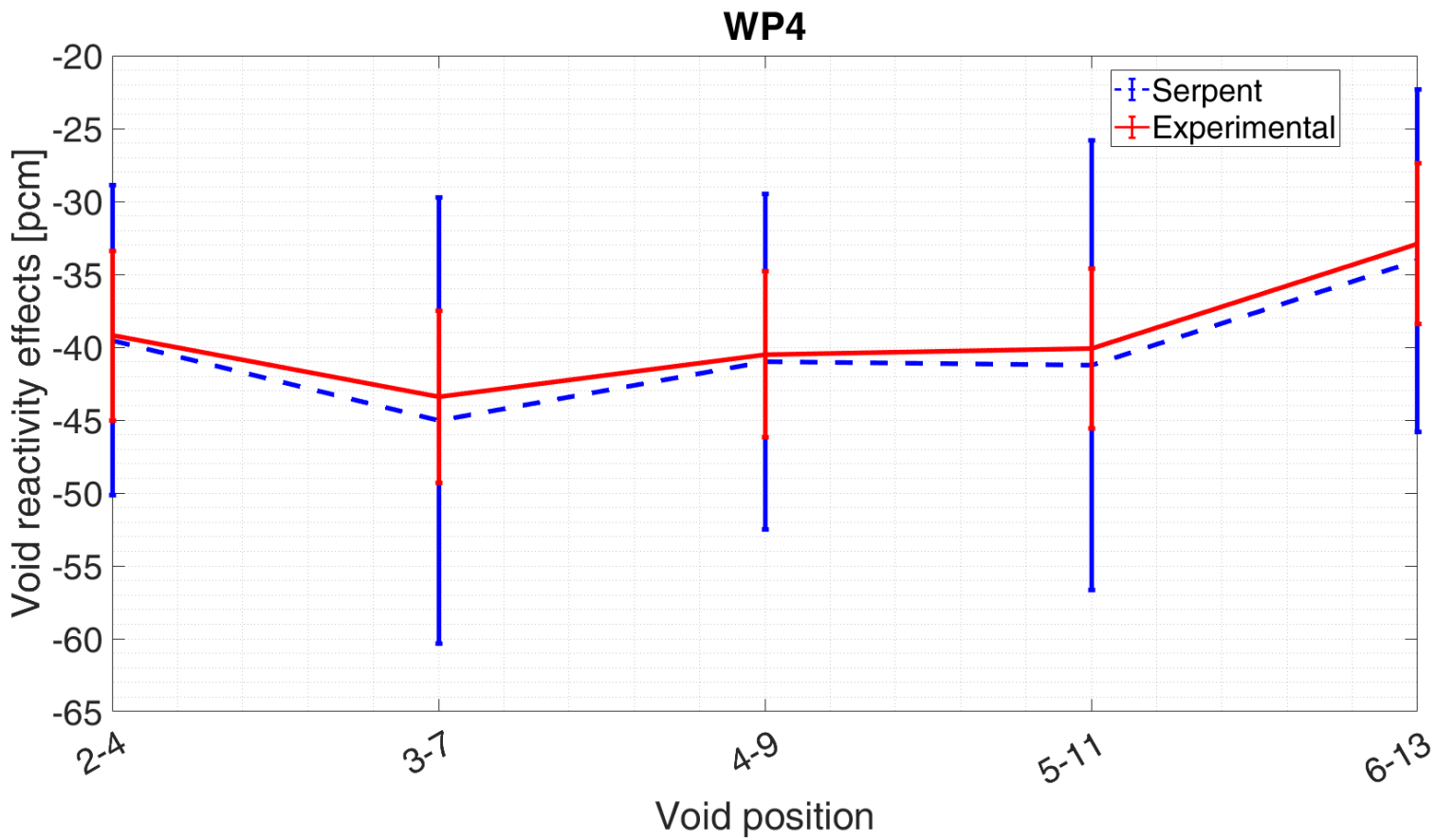
- Measurement of control rod worth (WP2)
  - Comparison with experimental results



- Measurement of control rod worth (WP2)
  - Fitted curve examples (fitting formula: $\rho = A + B * \sin(C \cdot x + D)$)



- Measurement of reactivity coefficients
  - Void reactivity (WP4)

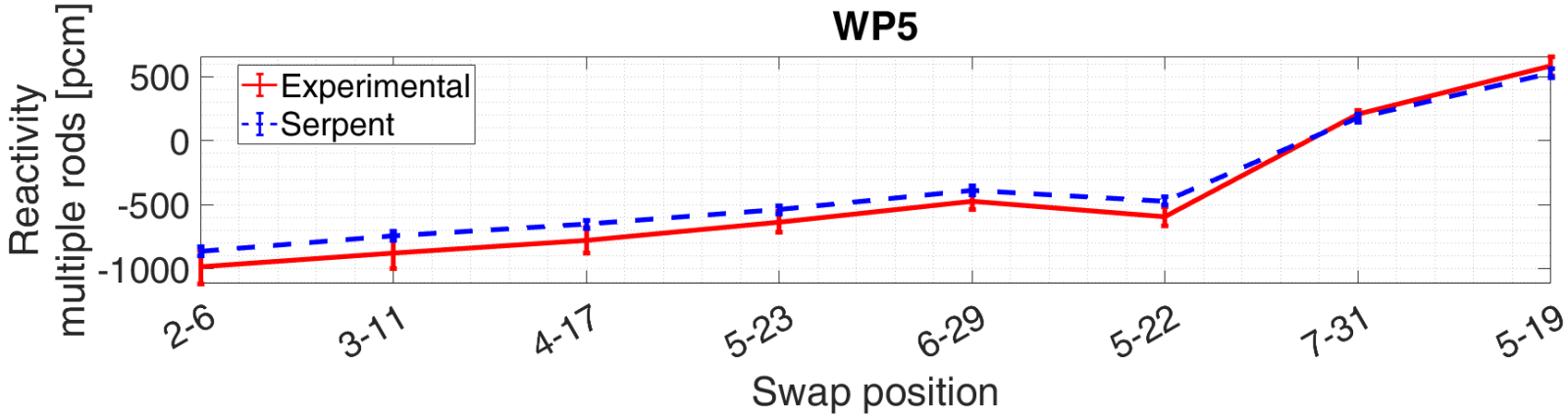


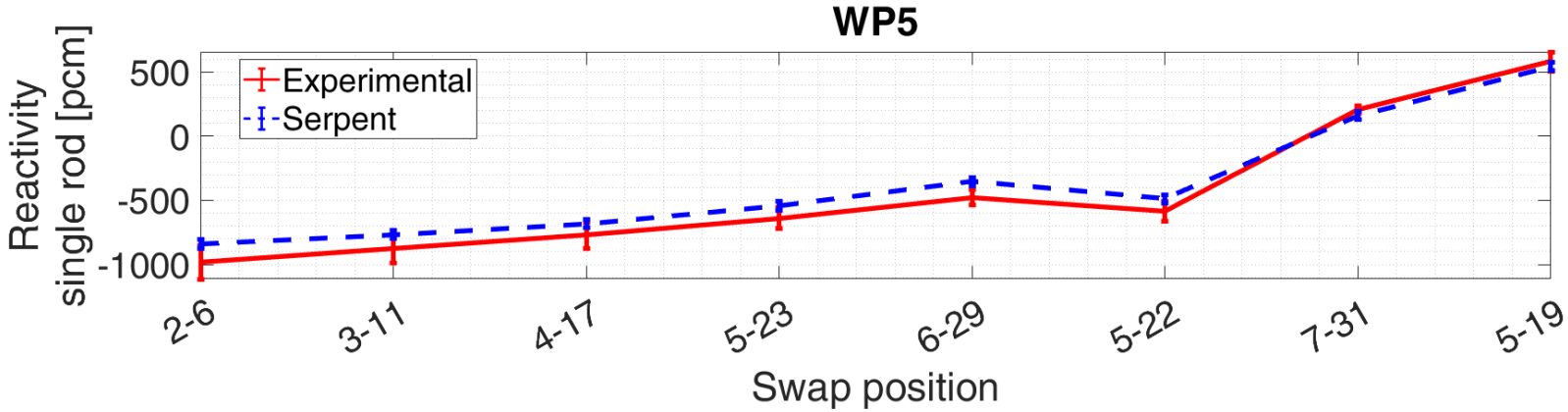
Results

- Measurement of reactivity coefficients
  - Temperature reactivity coefficient (WP3)

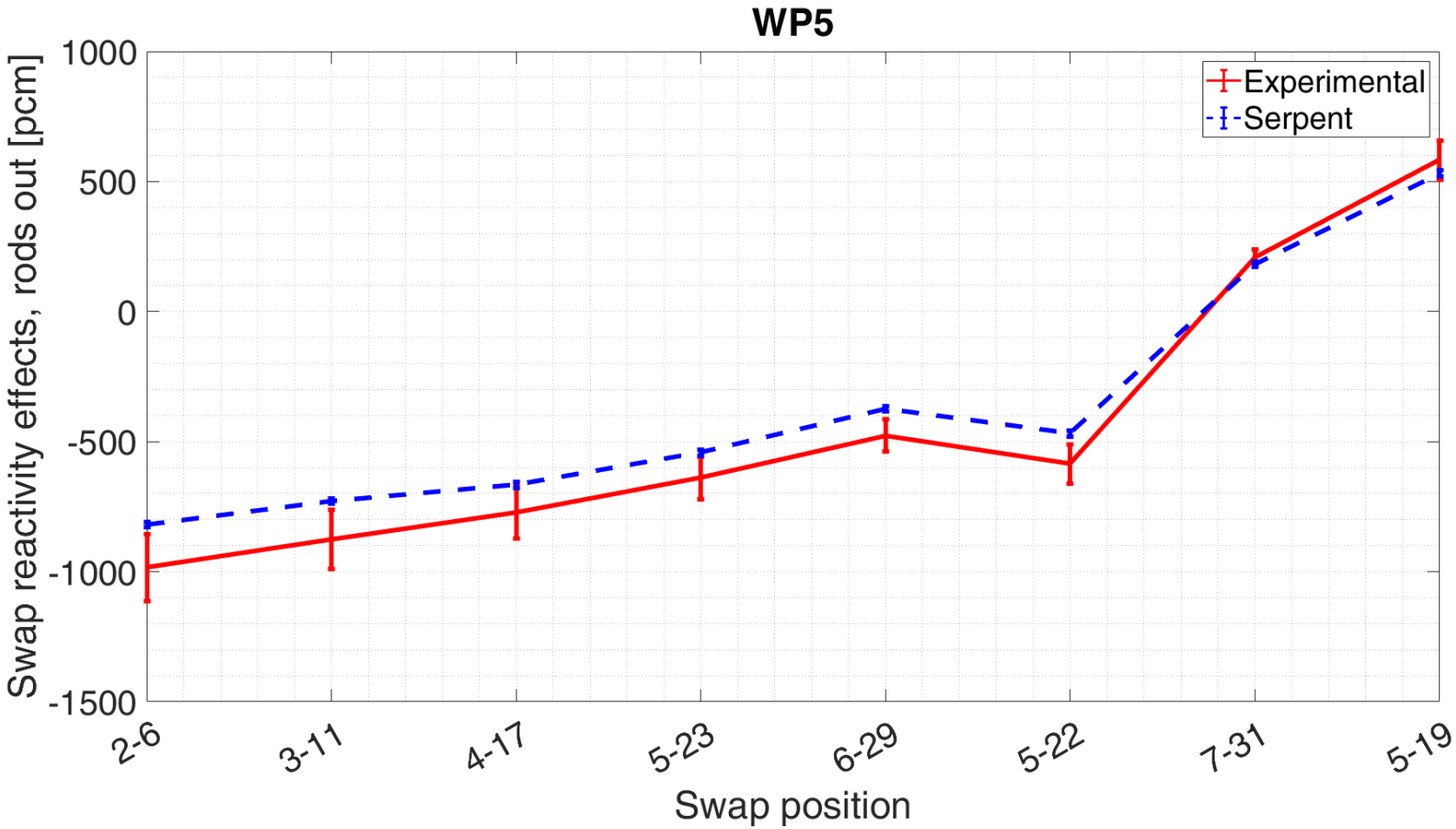
	Serpent				Experimental	
	3 step method		Experimental method			
	Reactivity coefficient [pcm/K]	Error [pcm/K]	Reactivity coefficient [pcm/K]	Error [pcm/K]	Reactivity coefficient [pcm/K]	Error [pcm/K]
Increasing process 250°C→302°C	-3.988	0.245	-3.793	0.632	-3.883	0.530
Decreasing process 300°C→ 250°C	-3.559	0.254	-3.820	0.681	-4.394	0.593

- Measurement of reactivity coefficients
  - Swap reactivity, multiple rods/single rod (WP5)





- Measurement of reactivity coefficients
  - Swap reactivity, rods out of the core (WP5)



Thank you for your attention!