Application of Serpent for Fuel Assembly Bowing

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and

SPERT III Static Calculations

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Serpent User Group Meeting,

Helsinki, Finland, 29.05. – 01.06.2018

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Introduction

The Bowing Phenomenon

- Fuel assembly bowing has been observed in PWR since the mid-90s
- Deformations in C-, S-, and W-shape have been observed
- Bowing caused by
  - Irradiation creep
  - Mechanical forces (hold down springs, interaction with neighboring fuel assemblies)
  - Thermal-hydraulic forces
- Mitigation achieved by use of stiffer structure materials and appropriate reshuffling

Fuel assembly bowing changes inter-assembly gap and local fuel/moderator ratio

→ impact on power of fuel pins of the first and second row

The power changes in the edge pin rows cannot be detected by the in-core detectors, therefore

- Calculations by operators necessary to confirm safety margins under bowing conditions
- Start of a research project at GRS in 2016

Mini core selection from a Pre-KONVOI cycle

Core Layout

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
				G	U	U	G	U	U	G					P
		G	U	U	G	U	U	U	G	U	U	G			O
	U	U	U	G	U	G	G	G	U	U	U	U	U		N
	U	U	U	G	G	G	G	G	G	G	U	U	U		M
G	U	U	G	G	G	U	U	U	G	G	G	U	U	G	L
U	G	U	G	G	G	U	G	U	G	G	G	U	G	U	K
U	U	U	G	U	U	G	U	G	U	U	G	U	U	U	J
G	U	G	G	U	G	U	G	U	G	U	G	G	U	G	H
U	U	U	G	U	U	G	U	G	U	U	G	U	U	U	G
U	G	U	G	G	G	U	G	U	G	G	G	U	G	U	F
G	U	G	G	G	G	U	U	U	G	G	G	G	U	G	E
	U	U	U	G	G	G	G	G	G	G	U	U	U		D
	U	U	U	U	U	G	G	G	U	U	U	U	U		C
		U	U	U	G	U	U	U	U	U	U	U			B
				G	U	U	U	U	U	G					A

■ fresh ■ once burnt ■ twice burnt ■ thrice burnt

U: UOX fuel assembly
G: UO2-Gd2O3 fuel assembly

Assembly Powers @BOC

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
				0.33	0.50	0.32	0.36	0.32	0.51	0.34					P
		0.34	0.81	0.96	0.84	1.02	0.89	1.01	0.86	0.97	0.81	0.33			O
	0.35	1.04	1.28	0.93	1.31	1.03	1.25	1.01	1.32	0.95	1.28	1.03	0.34		N
	0.84	1.30	1.07	1.35	1.19	1.33	1.15	1.33	1.19	1.35	1.06	1.28	0.82		M
0.36	1.03	0.98	1.37	1.24	1.36	1.00	1.38	0.99	1.35	1.22	1.34	0.94	0.98	0.35	L
0.59	0.93	1.38	1.22	1.38	1.12	1.11	1.10	1.10	1.10	1.34	1.17	1.31	0.87	0.55	K
0.48	1.12	1.04	1.36	1.01	1.12	1.39	1.29	1.38	1.09	0.98	1.30	0.96	1.06	0.46	J
0.37	0.96	1.29	1.18	1.41	1.12	1.31	1.28	1.29	1.09	1.36	1.14	1.24	0.92	0.36	H
0.48	1.11	1.04	1.36	1.03	1.13	1.41	1.30	1.39	1.10	1.00	1.33	1.02	1.08	0.47	G
0.57	0.90	1.36	1.21	1.39	1.14	1.14	1.11	1.11	1.11	1.35	1.19	1.34	0.91	0.57	F
0.35	1.00	0.96	1.37	1.25	1.38	1.01	1.39	1.00	1.35	1.22	1.34	0.94	0.99	0.35	E
	0.83	1.30	1.09	1.37	1.21	1.34	1.16	1.33	1.18	1.33	1.06	1.27	0.81		D
	0.35	1.05	1.30	0.97	1.35	1.02	1.26	1.03	1.31	0.93	1.26	1.02	0.33		C
		0.35	0.83	1.00	0.89	1.04	0.90	1.02	0.84	0.94	0.80	0.34			B
				0.34	0.52	0.33	0.38	0.32	0.48	0.27					A

FA power
(GRS core simulator KMACS)

Scenarios under examination

Burnup in the mini-core [MWd/kgHM]:

Fresh fuel – 0.0 MWd/kgHM

5	6	7	8	9	
U	U	G	U	G	J
U	G	U	G	U	H
U	U	G	U	G	G
G	G	U	G	U	F
G	G	U	U	U	E

0 EFPD (BOC)

5	6	7	8	9	
26.3	16.3	0.0	12.4	0.0	J
0.0	17.4	12.3	15.1	12.4	H
25.7	16.3	0.0	12.4	0.0	G
0.0	17.3	15.3	17.5	16.2	F
16.6	0.0	26.4	0.0	26.3	E

7 EFPD

5	6	7	8	9	
26.6	16.6	0.4	12.8	0.4	J
0.4	17.8	12.7	15.5	12.8	H
26.0	16.6	0.4	12.8	0.4	G
0.4	17.6	15.6	17.8	16.6	F
17.0	0.4	26.7	0.4	26.6	E

Scenario:	Fresh	BOC (no Xe)	7 EFPD (Xe equilibrium)
Boron concentration [ppm]	500.0	1576.5	1250.0
Moderator density [kg/m³]	730.62	724.833	724.833
Moderator temperature [K]	571.15	572.71	572.71
Fuel temperature [K]	950.0	779.89	779.89

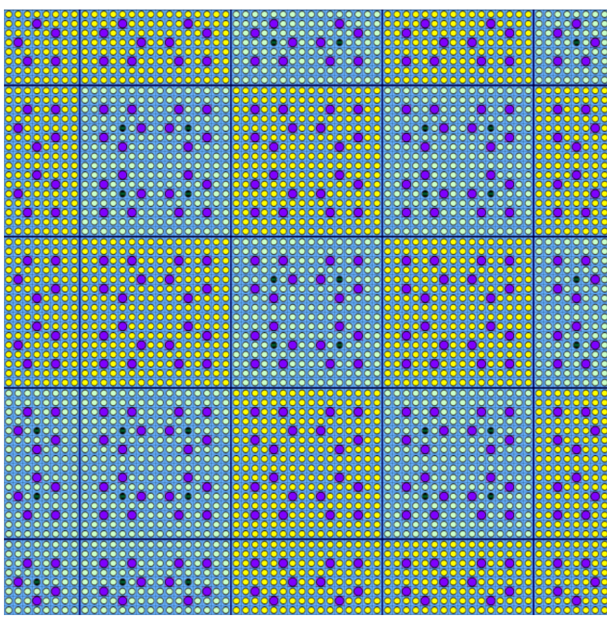
Scenarios under examination (2)

- Nominal case:
- Additional inter-assembly gap:
  - 5 mm
  - 10 mm
  - 15 mm
- Calculations with Serpent Monte Carlo

	5	6	7	8	9
J	U	U	G	U	G
H	U	G	U	G	U
G	U	U	G	U	G
F	G	G	U	G	U
E	G	G	U	U	U

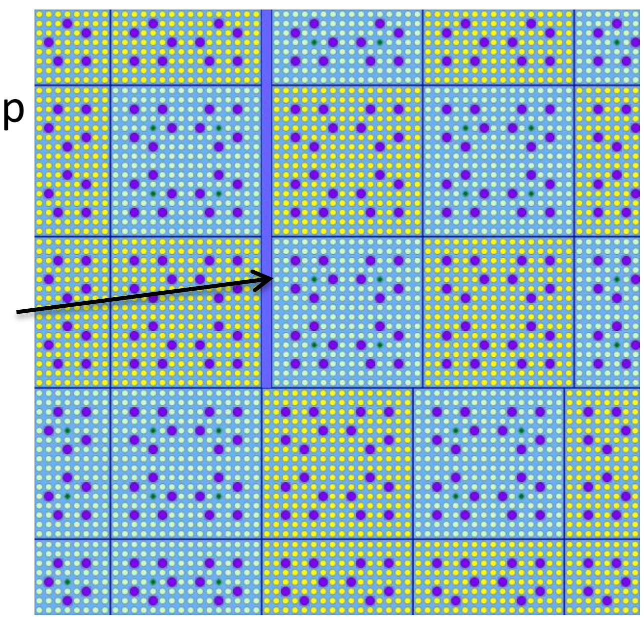
Additional inter – assembly gap in x direction

Nominal case



Nominal inter-assembly gap

Maximum gap in x direction

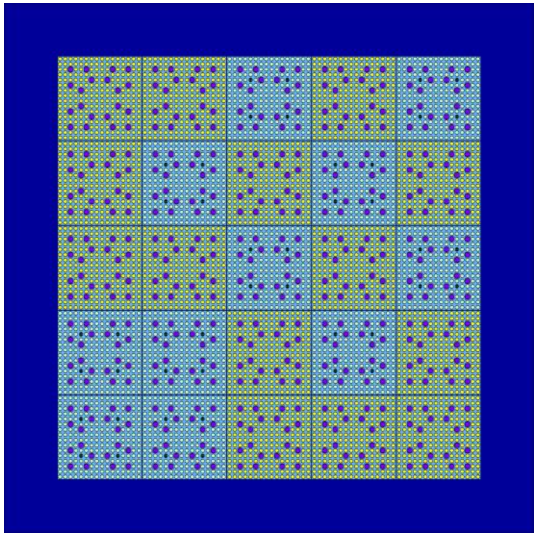


Additional gap

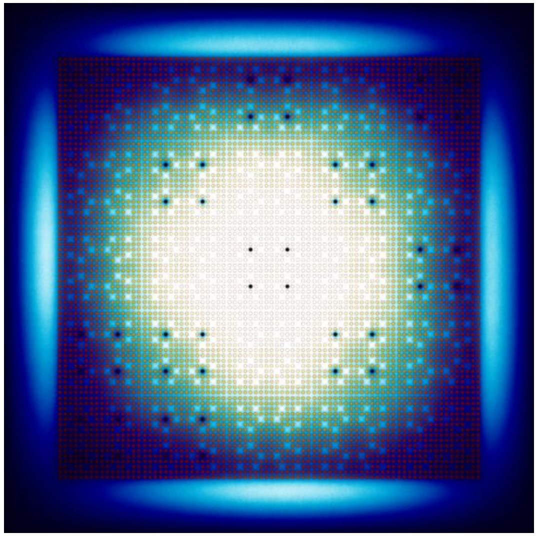
Mini-core Model – Boundary Conditions (1/3)

- Vacuum BDC:
  - Fuel mass conservation while fuel assemblies are shifted into the radial reflector
  - Problem: Significant depression of the neutron flux at the core periphery
    ⇒ unrealistic power distribution
    ⇒ unrealistic impact of the fuel assembly bowing in the centre of the core

MC-Model with fresh fuel:

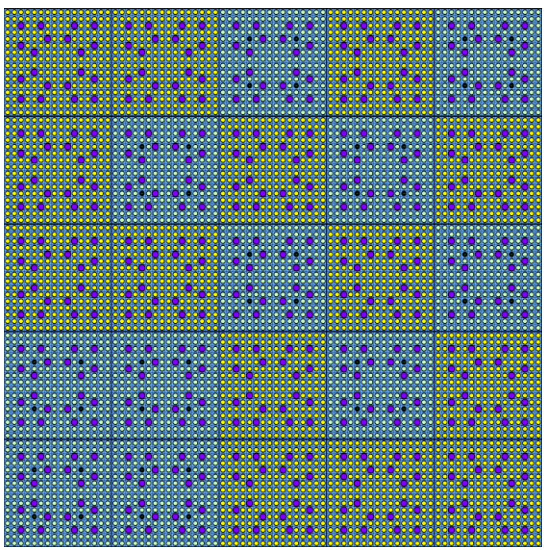


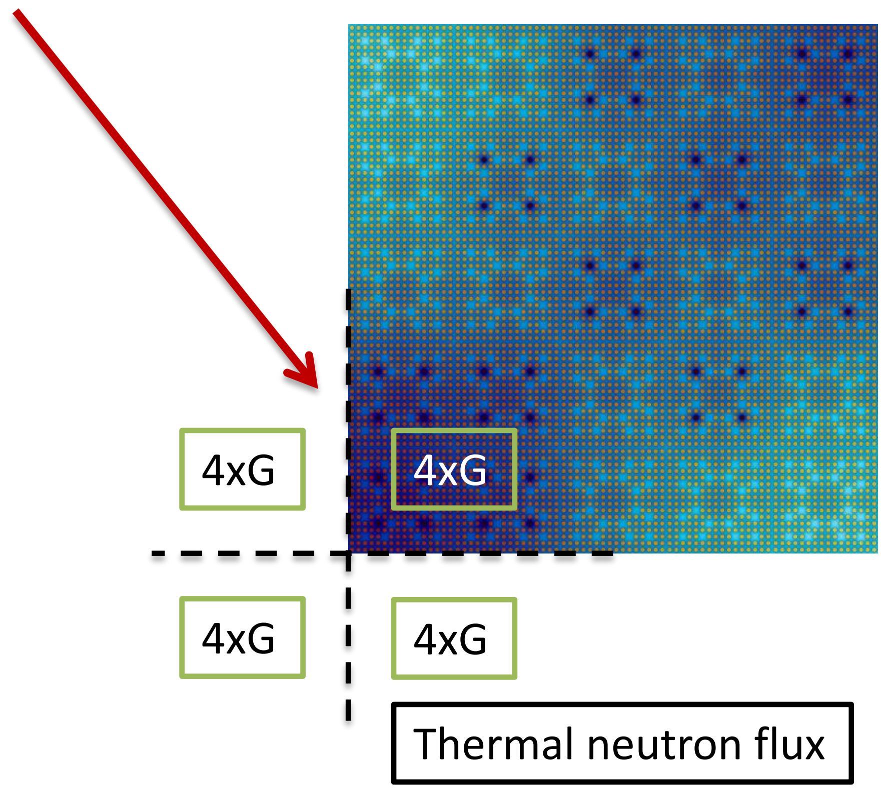
Thermal neutron flux



Mini-core Model – Boundary Conditions (2/3)

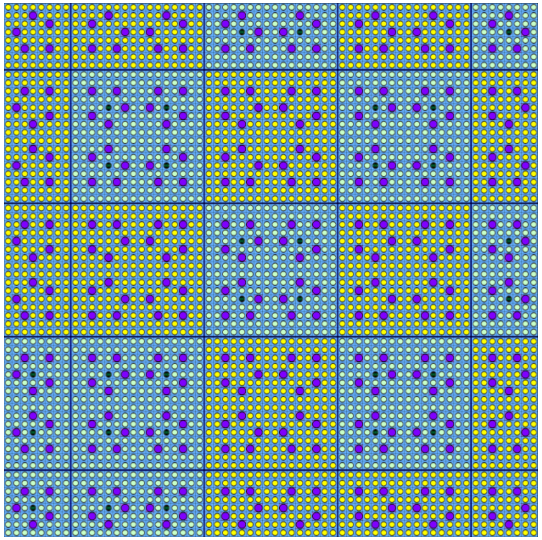
- Reflective BDC:
  - Uniform neutron flux distribution
  - Important for comparing power distributions:
    Fuel is shifted outside the model
  - Problem: Significant depression of the neutron flux
    at the corner with Gd fuel assemblies



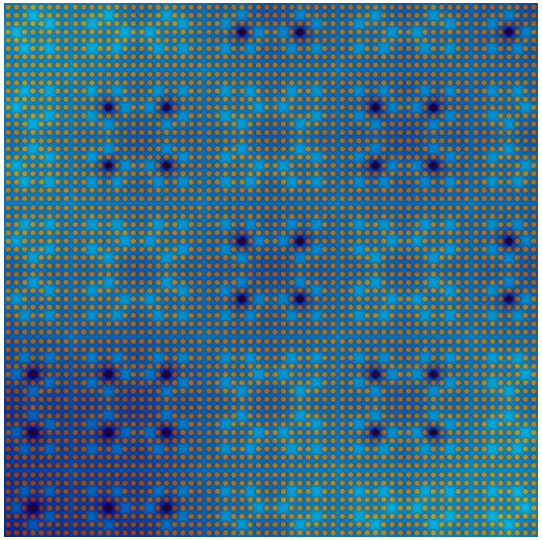


Mini-core Model – Boundary Conditions (3/3)

- Mini-core model truncated:
  - Only half of the outer assemblies is modelled
  - Reflective BDC
  - More uniform neutron flux distribution compared to the fully modelled 5x5 lattice
  - Important for comparing power distributions: Fuel is shifted outside the model



Half fuel assembly



Thermal neutron flux

Mini-core Model - Calculation Details

Monte Carlo calculation details:

- 1 000 000 Neutronhistories per cycle
- 1 000 active cycles, 60 inactive cycles
- 12.32 h run time with 10 MPI Jobs
- Stat. error ~0.2 % on pin power

Power normalisation:

- To ensure comparability, the total power of the bowed models is normalised by the total power of the nominal model

Pin power increase: ratio gap power / nominal power

Scencario BOC

Additional gap: 5 mm

	Left side		Right side	
	2nd pin Row	1st pin row	1st pin row	2nd pin row
Average increase	1.03	1.08	1.09	1.04
Maximum		1.11	1.12	

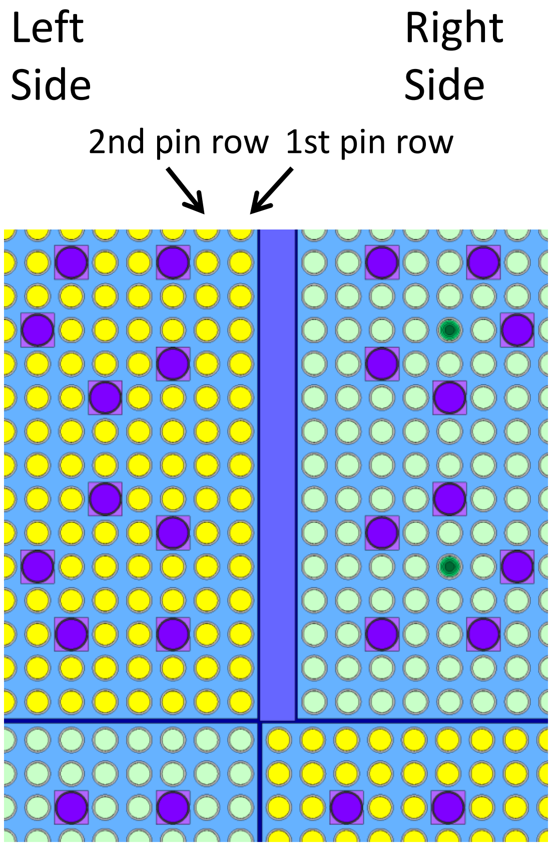
Additional gap: 10 mm

	Left side		Right side	
	2nd pin Row	1st pin row	1st pin row	2nd pin row
Average increase	1.06	1.15	1.17	1.08
Maximum		1.20	1.22	

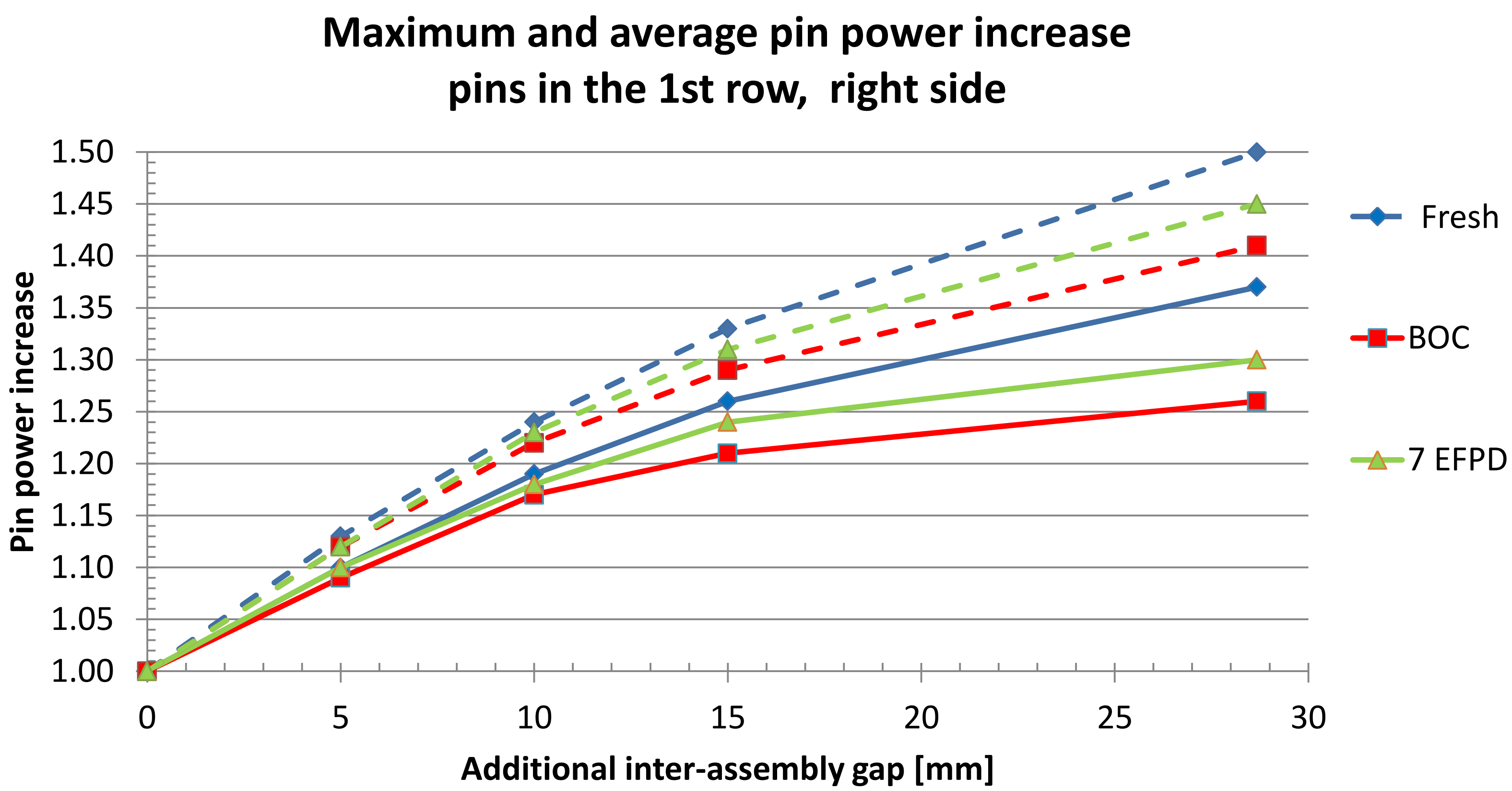
Additional gap: 15 mm

	Left side		Right side	
	2nd pin Row	1st pin row	1st pin row	2nd pin row
Average increase	1.07	1.19	1.21	1.09
Maximum		1.25	1.29	

Monte Carlo: relative statistical uncertainty of the increase approx. 0.3%.



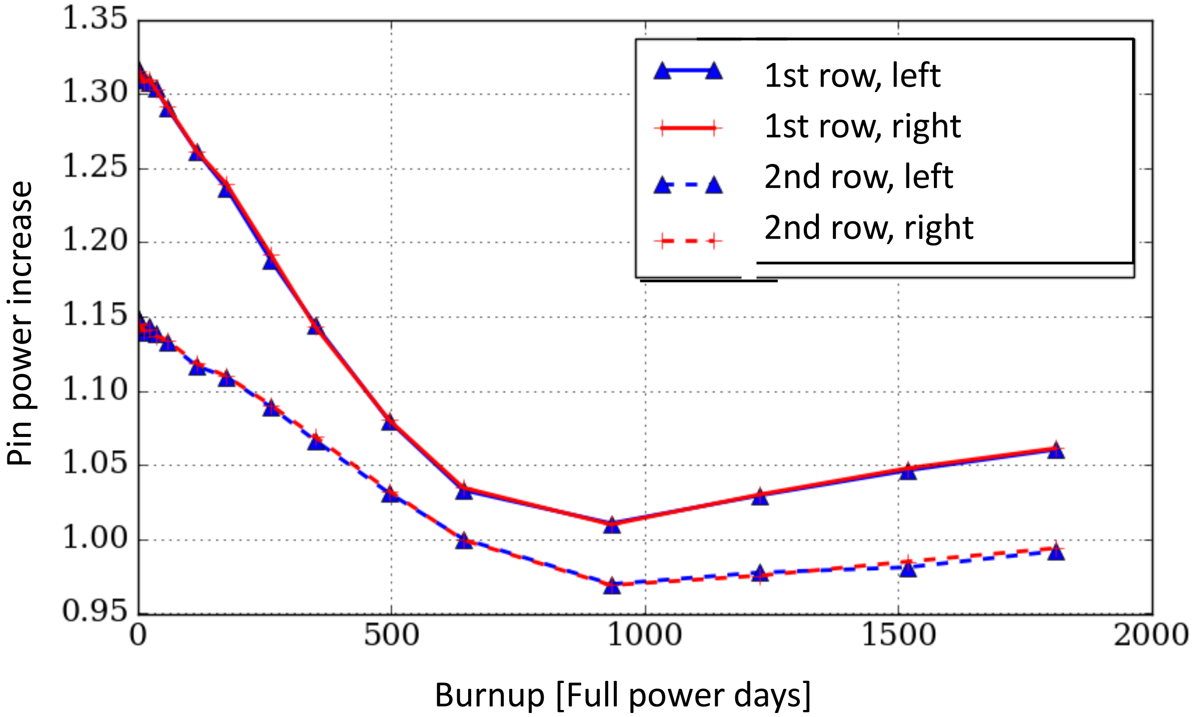
Pin power increase as a function of additional water gap



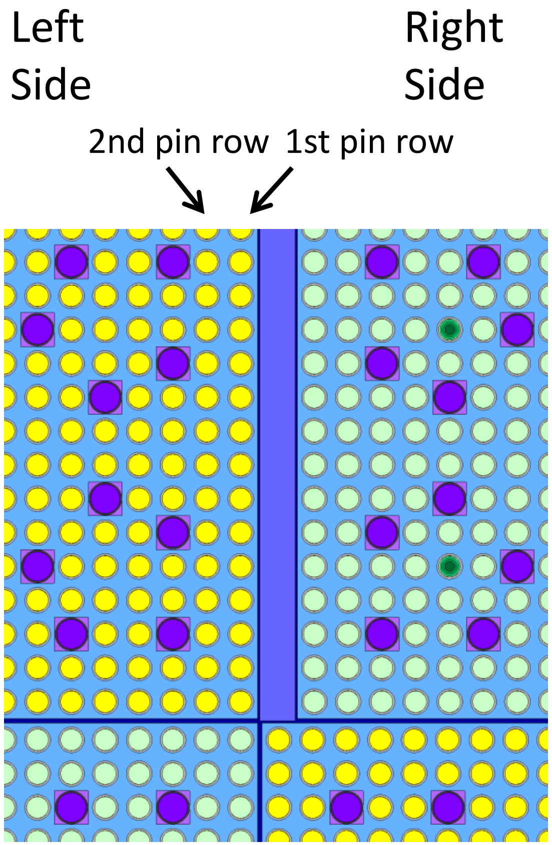
- - maximum pin power increase

– average pin power increase

Pin power increase as a function of burnup
Fresh fuel @ 15mm additional gap



Average values in 1st and 2nd row, respectively



Model Extensions for the GRS Core Simulator KMACS

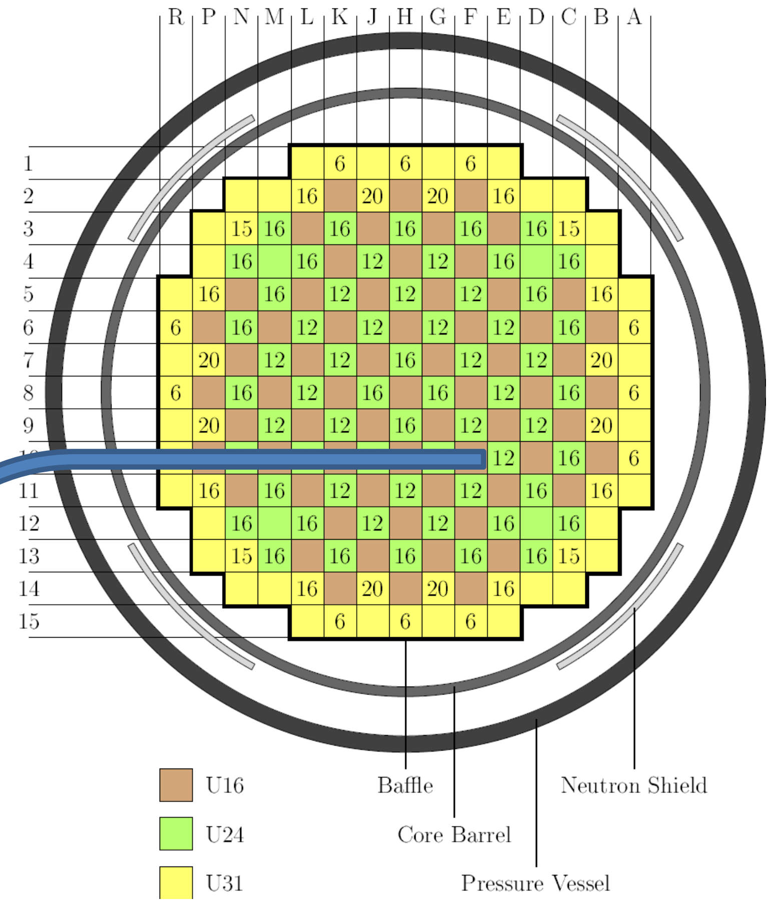
- 3d core simulations with TH feedback: Use of a core simulator is required

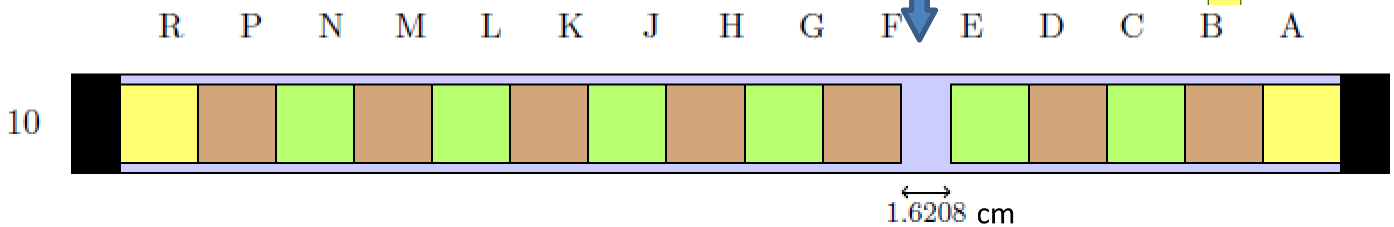
- KMACS is a classical 2-step core simulator
  1. XS generation for single fuel assemblies in infinite lattice
     Interfaces to codes SCALE-NEWT, HELIOS and Serpent (provisional)
  2. Full-core calculation by a 2-group diffusion code including core thermal hydraulics (GRS Codes QUABOX/CUBBOX-ATHLET)

- Modifications required to consider fuel assembly bowing
  1. Parametrization of XS according to inter-assembly gap
  2. Modification of the nodal power calculation for the nodal diffusion code (grid is no longer quadratic)

Testing gap-parametrized XS in KMACS: Single additional gap in 2D BEAVRS reactor model

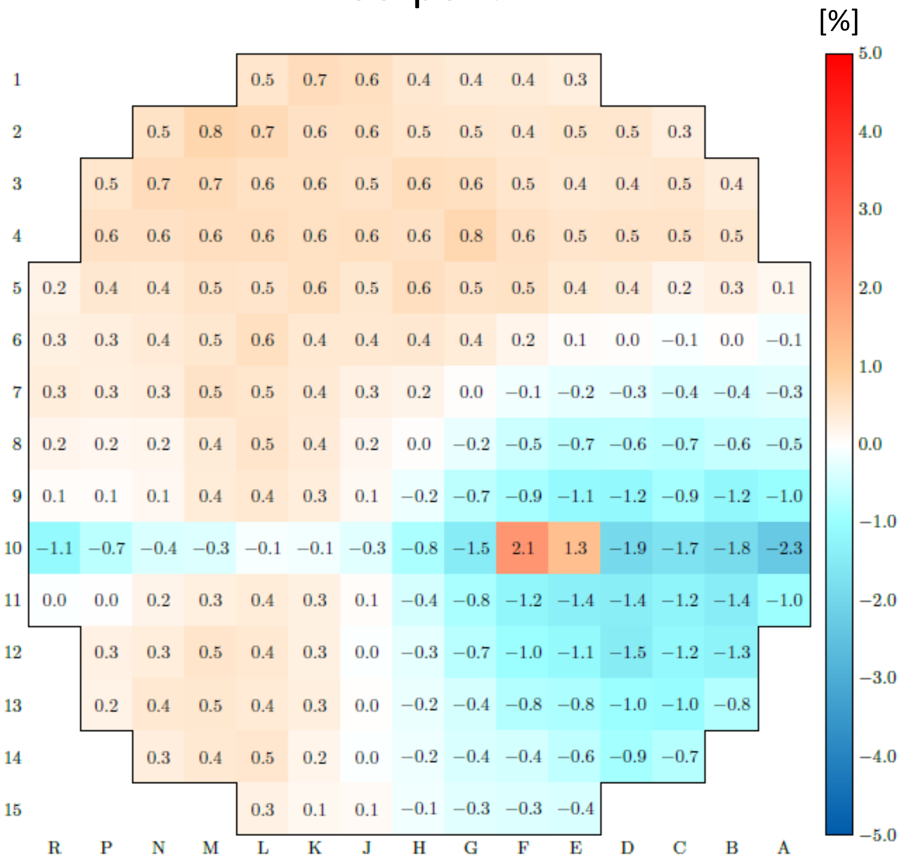
- Insertion of the maximum possible inter-assembly F and E
- Gap width:1.6208 cm
- All other inter-assembly gaps in row 10 close



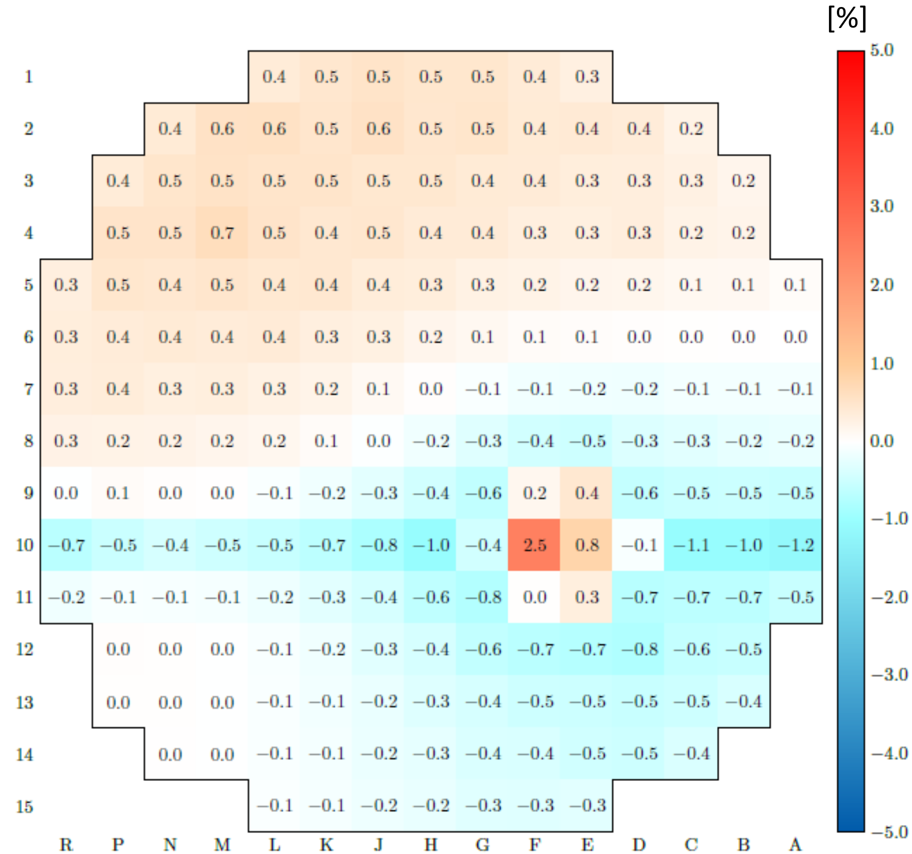


Testing gap-parametrized XS in KMACS:
2D assembly powers changes Serpent vs. KMACS

Serpent



KMACS



Assembly power changes in % of the average assembly power

Conclusions and Outlook

- Fuel assembly bow causes a change in inter-assembly gaps
- This results in
  - change of the local fuel-to-moderator ratio and
  - changes in pin powers
- Serpent Monte-Carlo Calculations yield a pin power increase of up to 34% for an additional 15mm flat gap between Pre-KONVOI UO_2/UO_2-Gd_2O_3 assemblies
- In approximately 400 full power days this increase burns out to 10%

- Gap-parametrized XS have been tested in GRS core simulator KMACS:
  - XS-behavior with varying inter-assembly gap similar for different UO_2 and UO_2-Gd_2O_3 assemblies
  - Qualitative agreement between Serpent and KMACS for assembly power changes in a 2D BEAVRS model with additional inter-assembly gap

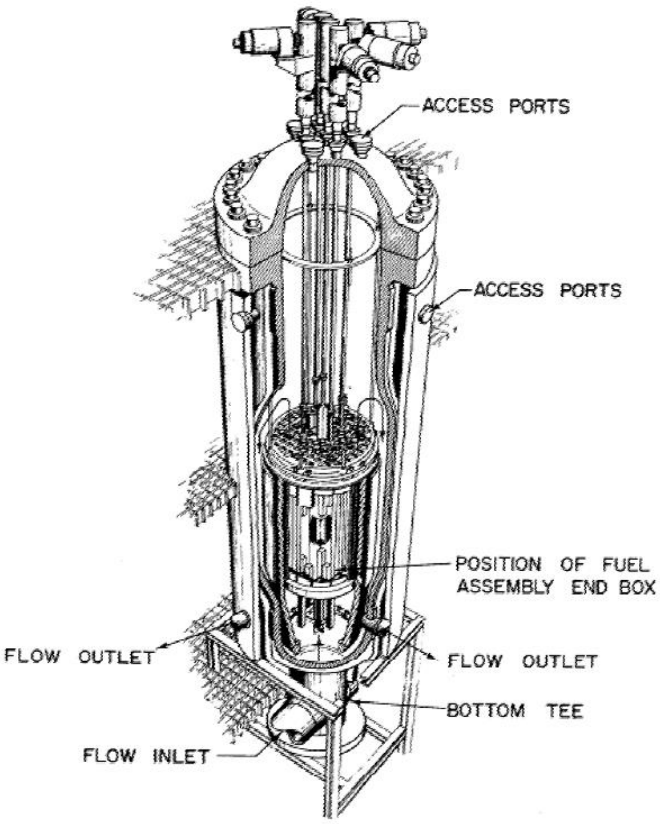
- Next steps:
  - Extensions to 3D and more complex inter-assembly gap patterns
  - Consideration of MOX assemblies

Supported by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety

Contents

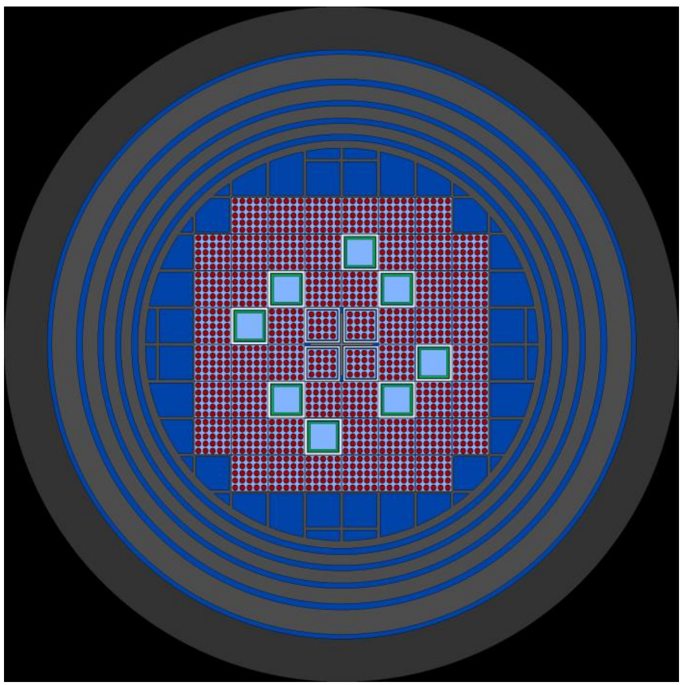
SPERT III Experiments

- Performed in the 1960's
- Analysis of reactor dynamic behaviour at rod ejection events
- PWR-like design
- Fuel: UO_2 with 4.8% enr. in U-235
- 60 fuel assemblies
  - 48 FAs with 5 x 5 fuel pins
  - 8 movable FAs: lower half 4 x 4 fuel pins, upper half absorber (stainless steel + 1.35% B-10)
  - 4 FAs with 4 x 4 fuel pins, controlled by transient rod
- Transients driven by ejection of a centrally located transient rod
- Experiments differ by inserted reactivity, reactor period and peak power
- Conditions: Cold Startup, Hot Startup, Hot Standby, Operating Power

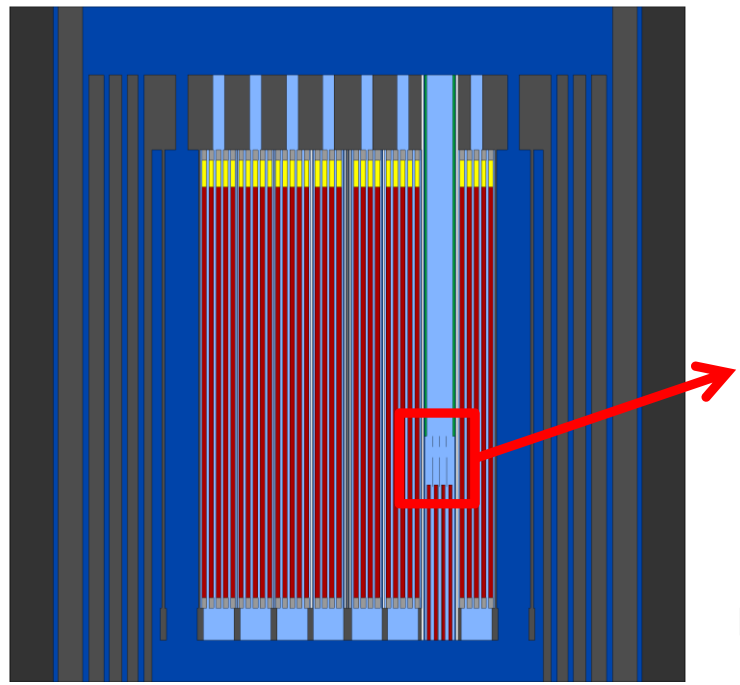


Models - Serpent and KMACS

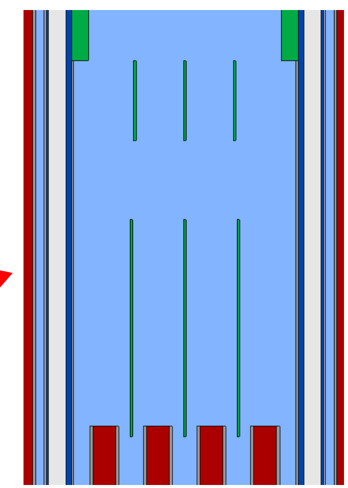
- Models were set up for the CZP state: 294 K, 0.99803 g/cm^3
  - **Serpent Reference** model with detailed modelling of flux suppressors (cross-shaped absorber plates made from stainless steel + 1.35% B-10)
  - **Serpent Simplified** model, flux suppressors replaced with absorber can → for better comparability with the KMACS model
  - **KMACS** model with few group constants from infinite lattice models



Top view of reference model



Side view of reference model



Detail view of the flux suppressors

Results - Integral Quantities

- Multiplication factors – Fuel Followers and Transient Rod withdrawn:

	Serpent Reference	Serpent Simplified	KMACS
Multiplication factor	1.11724(6)	1.11804(6)	1.11184

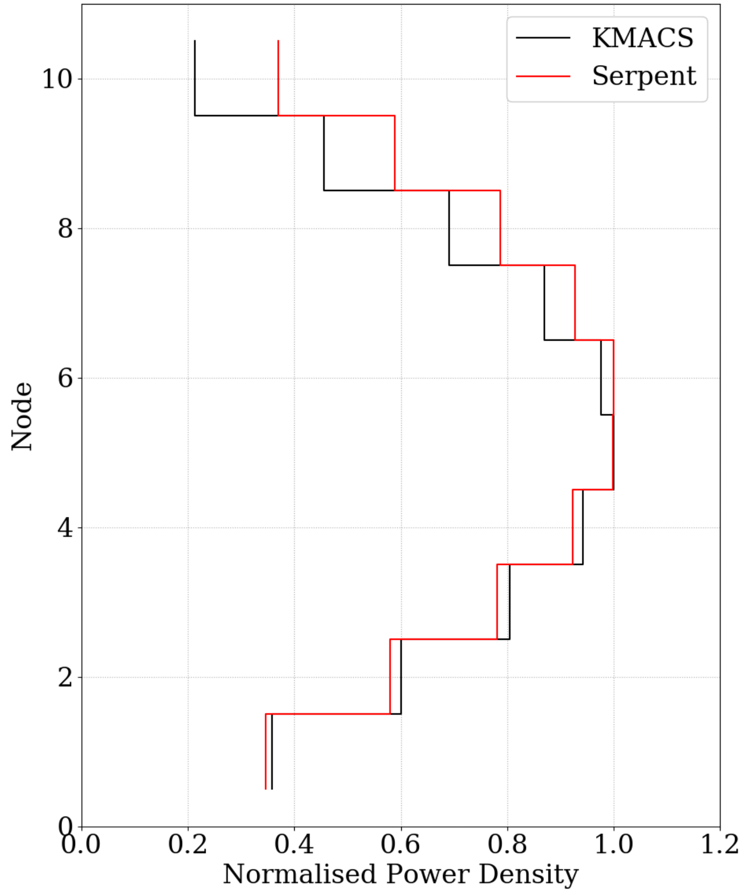
- Critical Position of the Fuel Followers (from bottom of active core):

	Serpent Reference	Experiment	Serpent Simplified	KMACS
FF Crit. Position [cm]	38.248	37.084	29.406	29.136

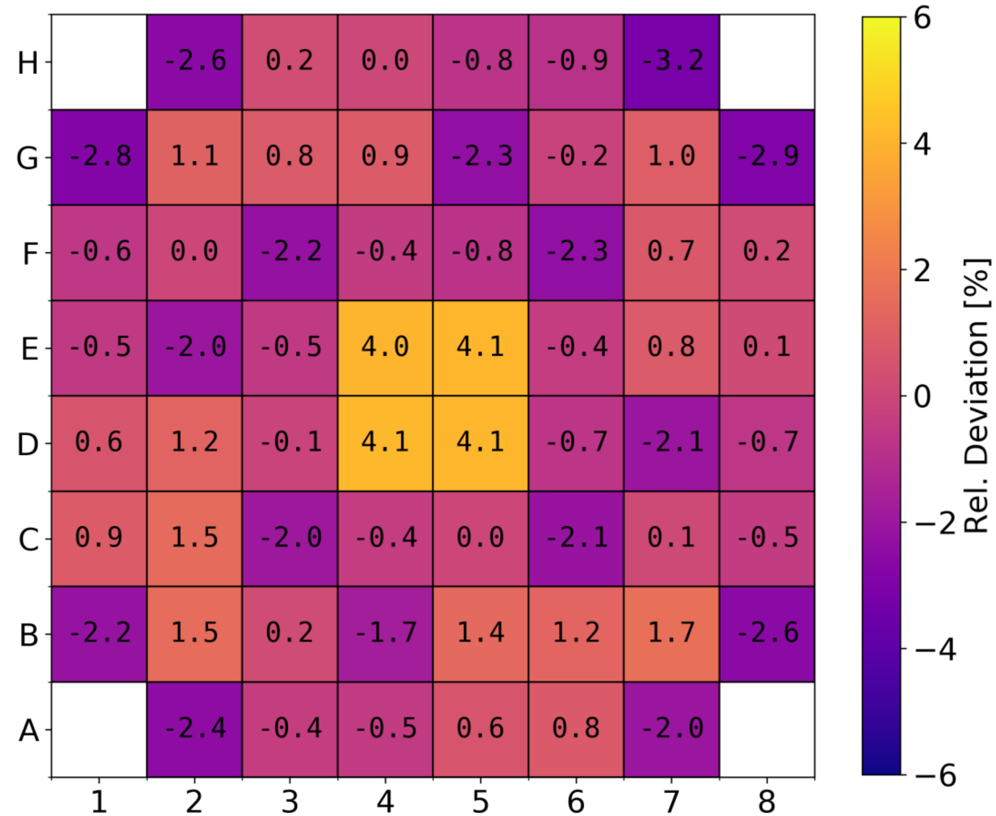
- Kinetic data from the reference model – FF and TR withdrawn:

Beta	2.355E-04	1.254E-03	1.226E-03	2.804E-03	1.239E-03	5.168E-04	Total: 0.00727574
Lambda	1.335E-02	3.261E-02	1.211E-01	3.056E-01	8.607E-01	2.892E+00	

Radial Power Distribution at All Rods Out State

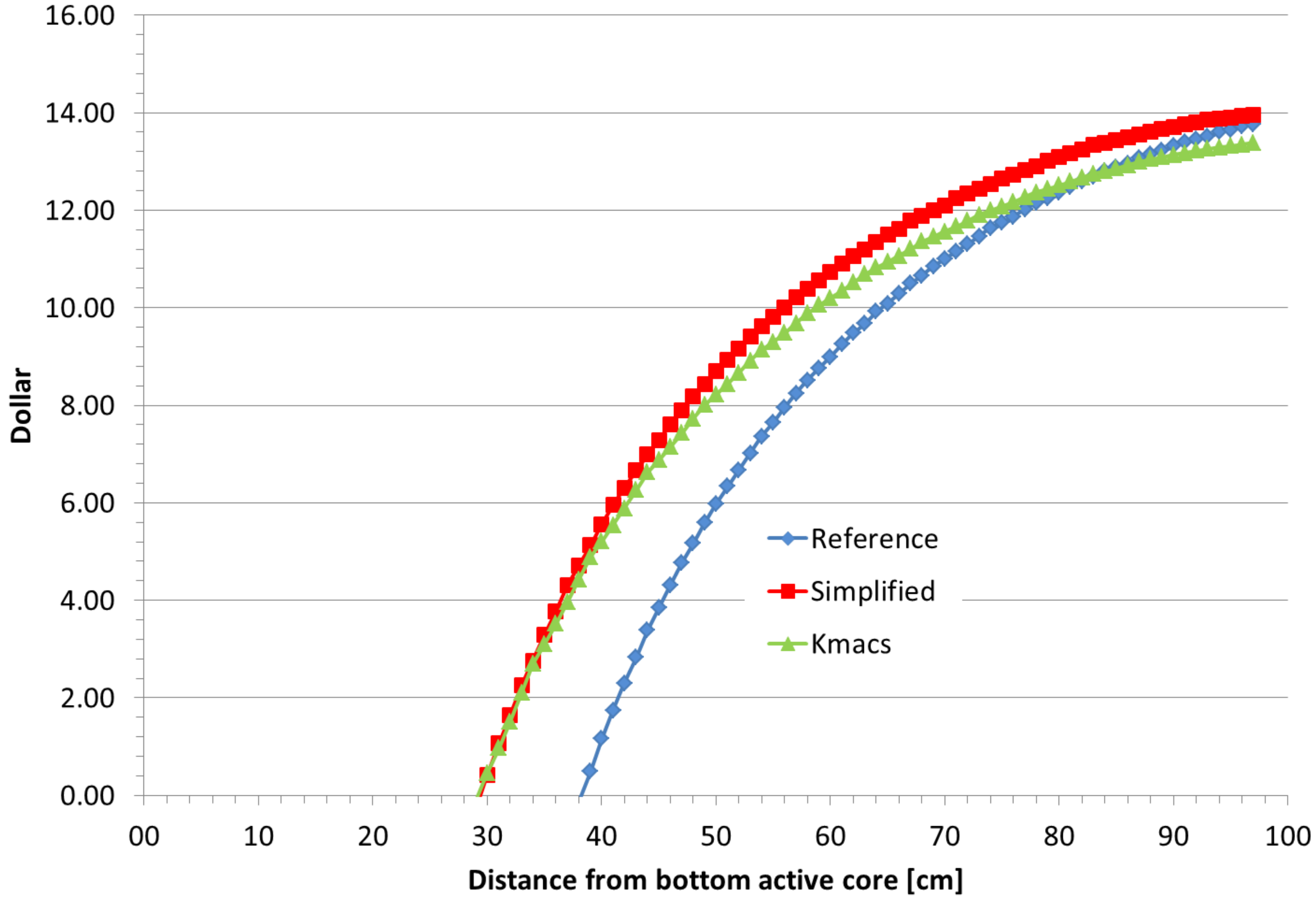


Axial distribution of normalised power density

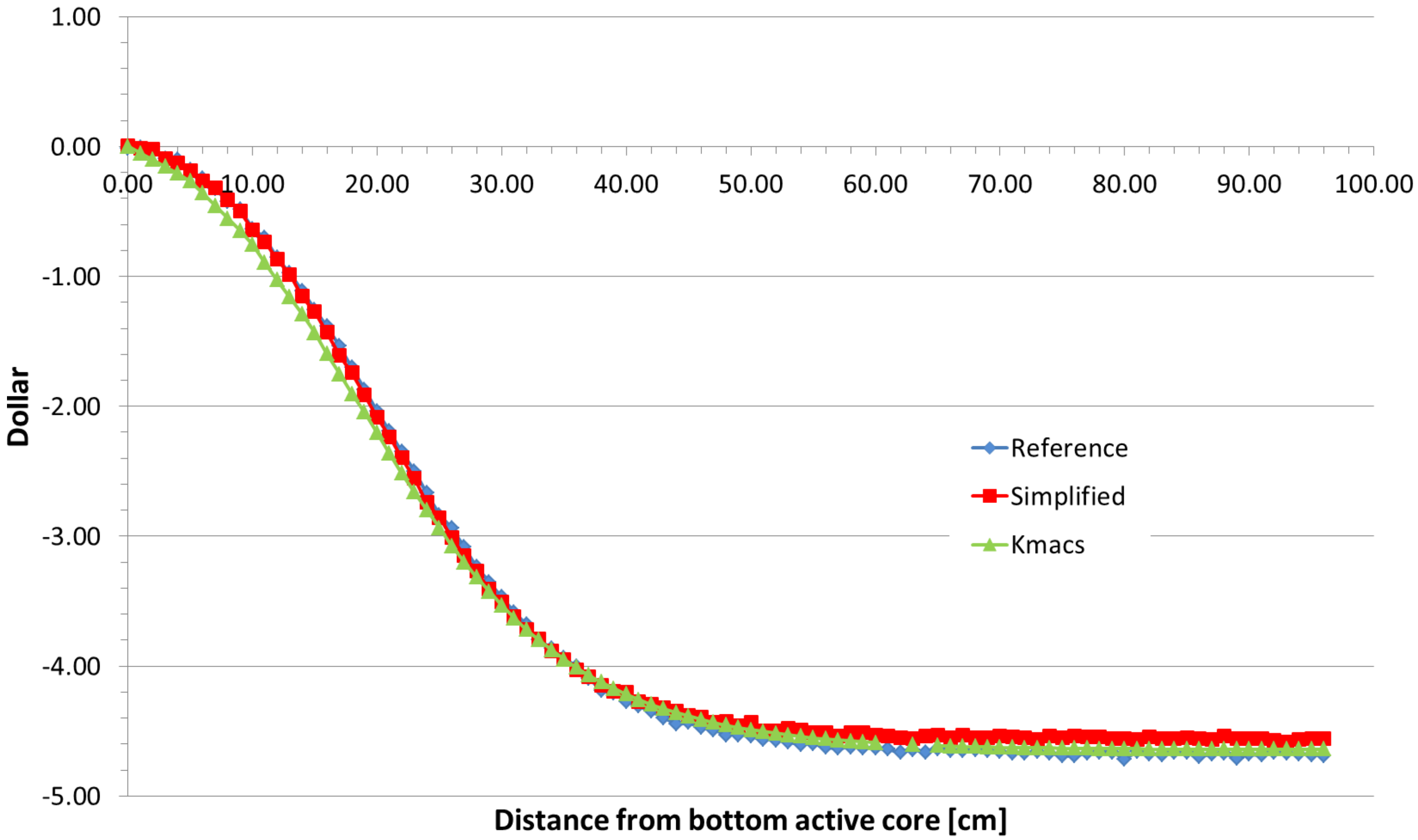


Rel. deviation between KMACS and Serpent

CR Worth – Fuel Followers



CR Worth – Transient Rod



Conclusions and Outlook

- Reference Serpent model and simplified Serpent model were built for CZP state
- Model built for the GRS core simulator KMACS with few-group constants from infinite-lattice calculations
- Preliminary results obtained:
  - Multiplication factors of the Serpent models and of the KMACS model at All Rods Out state → reasonable agreement
  - Critical position of the fuel followers:
    - About 1 cm deviation between the reference Serpent model and the experimental value
    - Good agreement between the simplified Serpent model and the KMACS model
  - Fuel followers worth and transient rod worth with the various models

Next steps:

- In-depth analyses of the static models for different reactor conditions
- Transient calculations

Supported by the German Federal Ministry for Economic Affairs and Energy