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Long-cycle, boron-free NuScale-like SMR core with radially zoned (Th,U)O_2 fuel and combined Gd/Er burnable absorbers

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Keywords: Small modular reactor, Thorium, Boron-free core, Burnable absorber, HIGA, Two-batch fuel management, Equilibrium cycle

Motivation and outline

Motivation

- Longer cycles mean **fewer refuelling outages** and less fuel handling over the plant lifetime [5, 6].
- Spent fuel is stored as whole assemblies, so **assemblies discharged per unit energy** measure the back-end burden [1].
- Without soluble boron, **burnable absorbers and control rods** alone must hold the excess reactivity.
- Thorium is about **3.9 times** more abundant than uranium [3]; Th-232 breeds fissile U-233.

Outline of this talk

Part 1 · Conference paper

All-fresh, single-batch core: 54 zoned cores screened, **B8/A52** selected. Open problem: **> 20,000 pcm** of excess reactivity without boron.

▼

Part 1 → 2 · Why two batches?

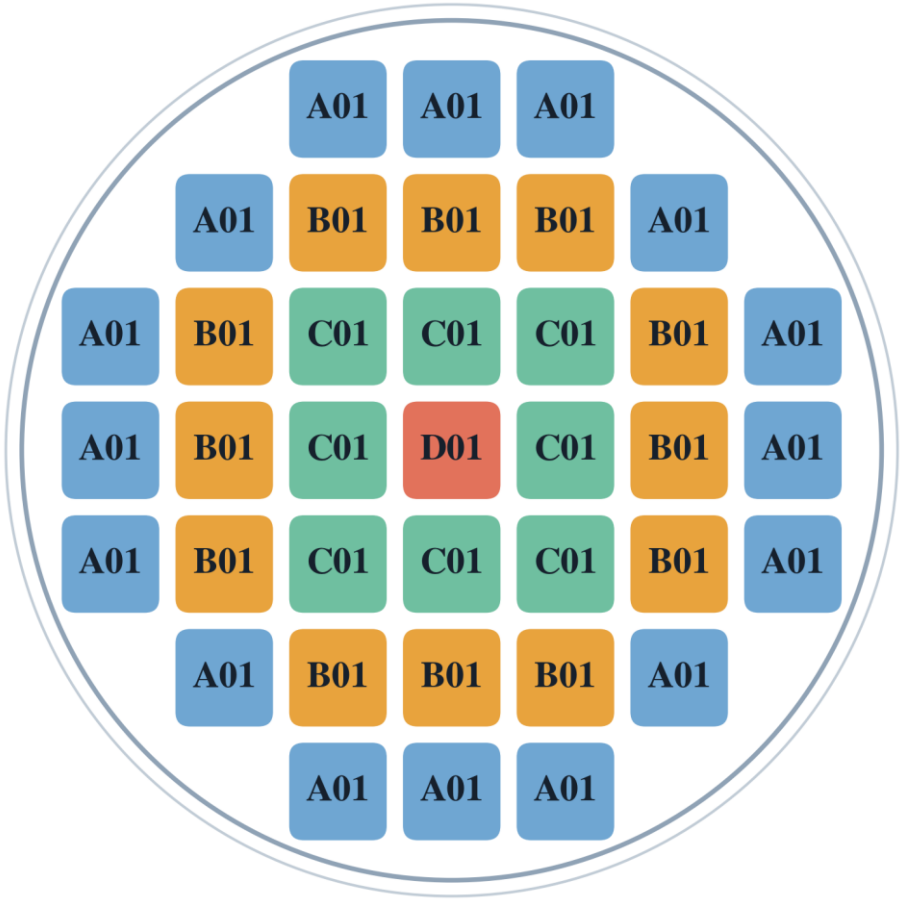
A plant reloads only **part of the core**. Each assembly stays two cycles: **64 instead of 52 GWd/tHM** from the same fuel, and the BOC excess drops from **22,400 to 16,300 pcm** (no absorbers). Due to longer cycles Thorium breeding effect is more visible.

▼

Part 2 · Current work

Two-batch, boron-free equilibrium core designed with the new CROMA/SPHINCS system.

All-fresh single-batch core with radial ThO_2 zoning



EOCS zones: A01 (16), B01 (12), C01 (8), D01 (1).

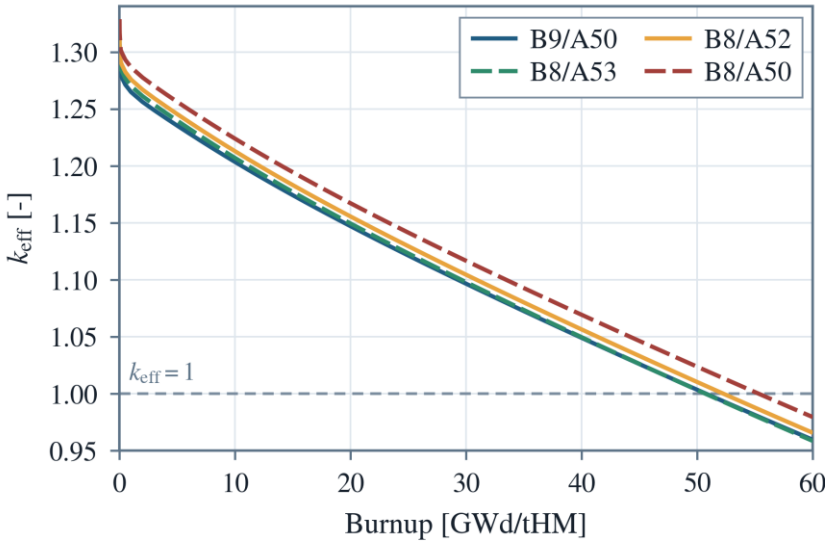
Model and calculation	
Core	NuScale-like [4]: 37 FAs (17 × 17), 160 MW_{th}
Fuel management	all fresh, single batch
Fuel	$(Th,U)O_2$, THW50–THW95, 20 wt% U-235 in U
Zoning	ThO_2 content rising towards the centre (EOCS)
Boron / absorbers	0 ppm / none
Calculation	static depletion, 900 / 600 K, no TH feedback
Codes	DeCART2D lattice → SPHINCS 3-D core
Design space	9 batches × 6 cores = 54 cores

Screening objectives adopted in this study (all four at once)

Critical burnup	Cycle length	PPF	F_r
> 50 GWd/tHM	**> 2800 EFPD**	**< 1.40**	**< 1.45**

Results of the 54-core screening

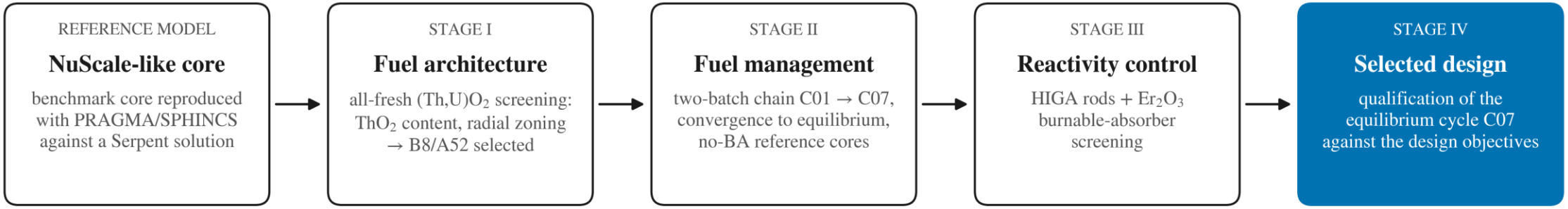
Core	A01/B01/C01/D01 [wt% ThO_2]	Critical burnup [GWd/tHM]	EFPD	PPF	F_r	k_{eff} at BOL
B9/A50	50/61/72/83	50.74	2808	1.225	1.380	1.3070
B8/A53	53/61/69/77	50.68	2803	1.266	1.404	1.3135
B8/A52	**52/60/68/76**	**52.24**	**2892**	**1.278**	**1.406**	**1.3188**
B8/A50	50/58/66/74	55.29	3067	1.300	1.422	1.3288



- Critical burnup follows the **core-average ThO_2**; radial peaking follows the **zone gradient**.
- Open problem: without boron they start at $k_{eff} \approx 1.31–1.33$, i.e. **23,500–24,700 pcm** of excess reactivity.

From the conference paper to the current work

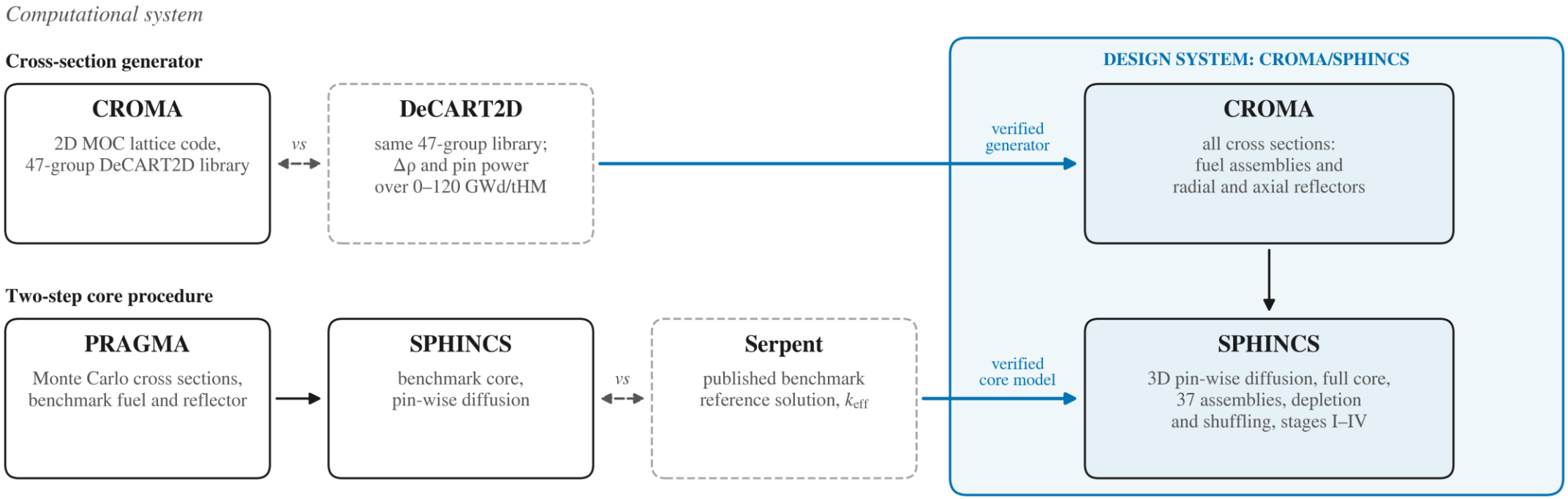
Design progression



	Conference paper	Current work
Fuel management	single batch, 37 fresh	two batches, 21 fresh + 16 once-burned
Excess reactivity	> 20,000 pcm, not controlled	100–1500 pcm with HIGA + Er_2O_3
Lattice code	DeCART2D	CROMA (new MOC code)
U-235 in uranium	20.00 wt%	19.95 wt%

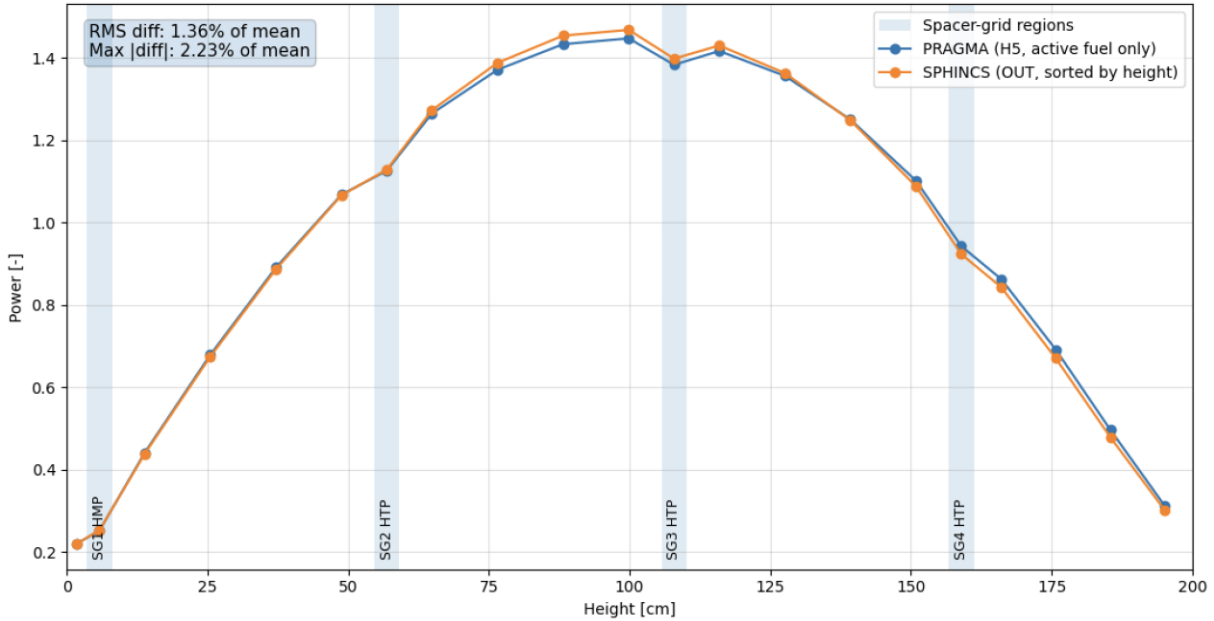
The B8/A52 zoning is carried over and turned into an **operable boron-free equilibrium core**.

Design system: CROMA and SPHINCS



- **CROMA is a GPU-accelerated MOC code combining CPU and GPU calculations: a few seconds where DeCART2D takes a few minutes.**
- **Thanks to KAERI, it uses the DeCART 47-group library; CROMA will be officially released in the near future.**

Verification of the core model against the benchmark



- PRAGMA and PRAGMA/SPHINCS reproduce the Serpent k_{eff} within **−38** and **+40 pcm**.
- SPHINCS reproduces the PRAGMA assembly powers within **1.1 %**; axial RMS difference **1.36 %**.
- This verifies the geometry and the two-step procedure.

Solution	k_{eff}	Δ vs Serpent
Serpent [4]	1.02768 (1)	–
PRAGMA [16]	1.02728 (3)	−38 pcm
PRAGMA/SPHINCS [10]	1.02811	+40 pcm

Benchmark reference state: 1000 ppm boron, all rods out, ENDF/B-VII.1.

(a) PRAGMA

1.137	0.821	0.882	0.982
0.821	0.890	1.169	1.056
0.879	1.167	0.952	
0.977	1.051		

(b) SPHINCS

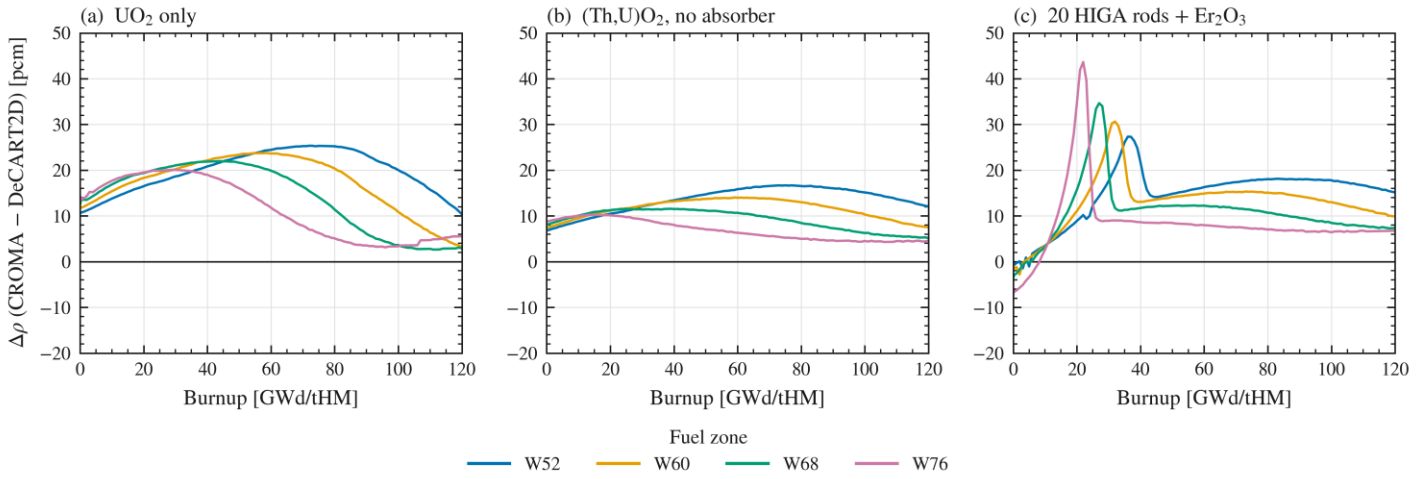
1.143	0.823	0.886	0.981
0.823	0.893	1.174	1.044
0.886	1.174	0.942	
0.981	1.047		

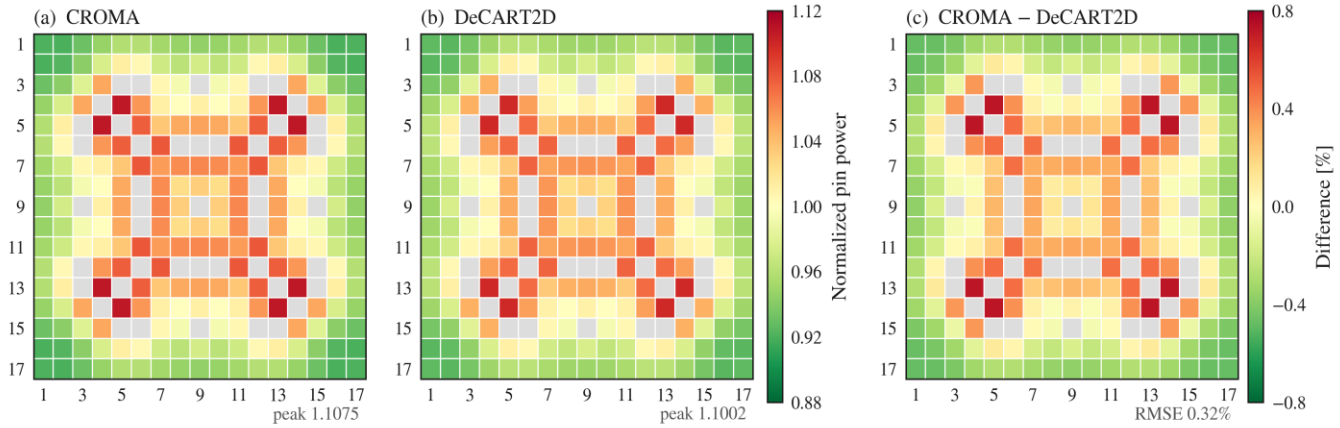
(c) difference [%]

+0.5	+0.2	+0.5	−0.1
+0.2	+0.3	+0.4	−1.1
+0.8	+0.6	−1.1	
+0.4	−0.4		

Relative assembly power, quarter core (centre at top left); (c) = (SPHINCS − PRAGMA) / PRAGMA × 100.

Verification of CROMA against DeCART2D



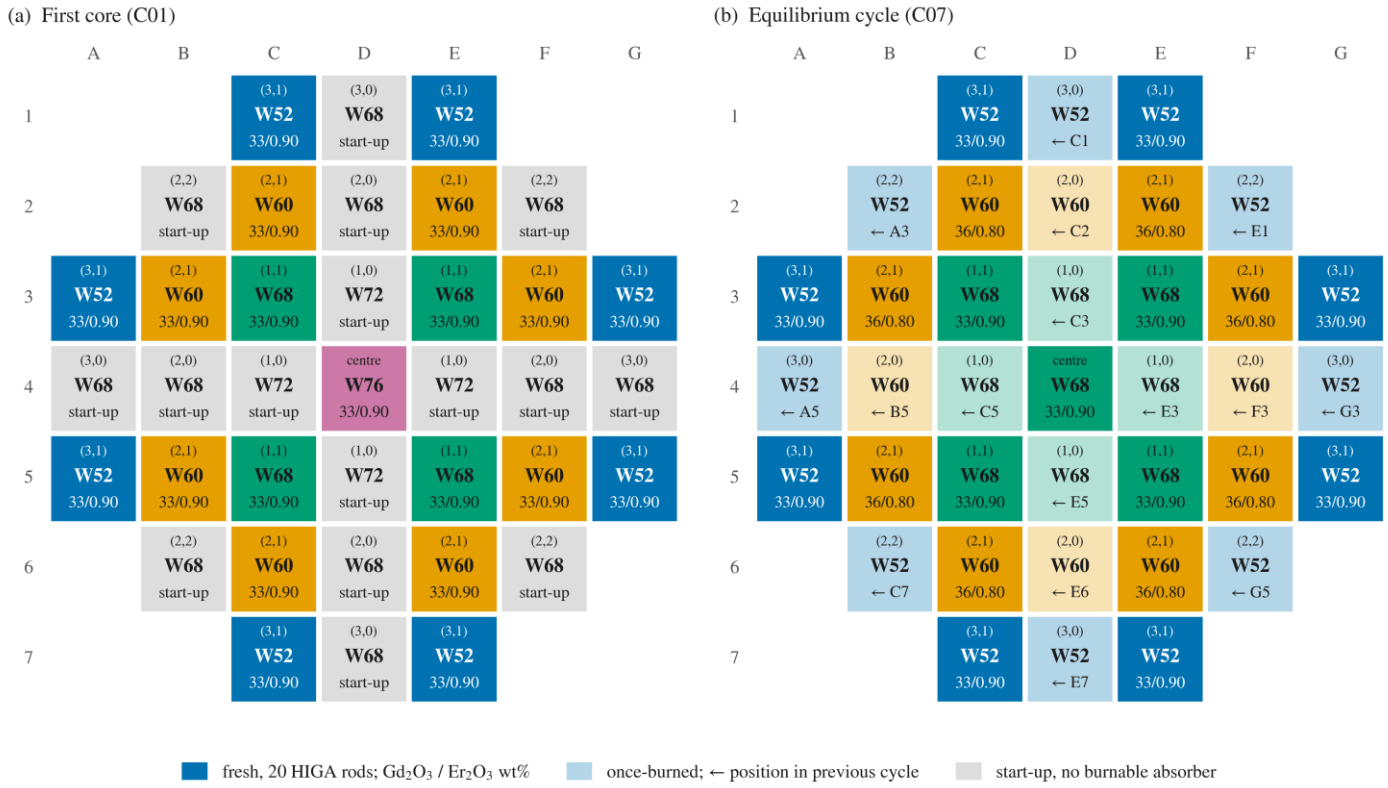


Δρ, 1500 points	[pcm]
Mean |Δρ|	12.4
RMS	13.9
95 % of points below	23.4
Maximum |Δρ|	**43.6**

DeCART2D [11, 14] with the same 47-group library as CROMA.

- 12 lattices × 125 burnup points: |Δρ| never exceeds **44 pcm**.
- Pin powers of a HIGA assembly at 60 GWd/tHM differ by at most **0.73 %** (mean 0.27 %).

Two-batch loading pattern and design objectives

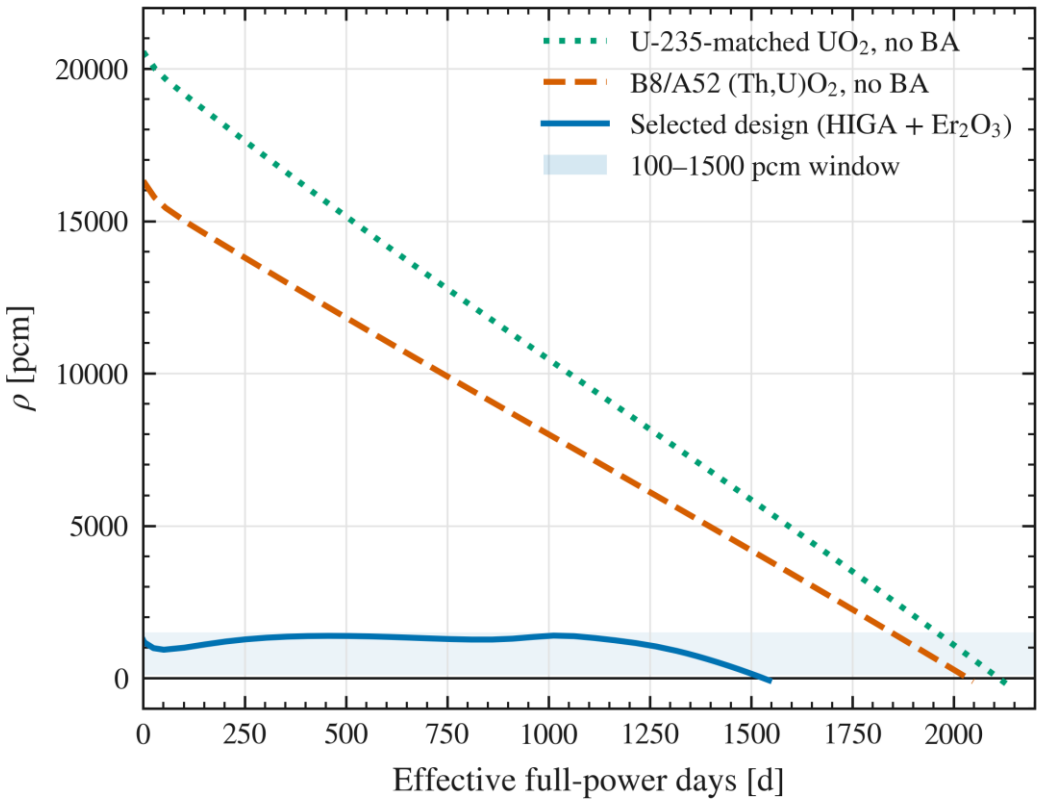


- **21** fresh assemblies per cycle: **16** reused, **5** discharged.
- The centre gets fresh thorium-rich fuel every cycle.

Objective, equilibrium cycle	Limit
Maximum excess reactivity	**≤ 1500 pcm**
Minimum excess reactivity	**≥ 100 pcm**
Cycle length	**≥ 1450 EFPD**
Assembly peaking, PPF	**≤ 1.40**
Pin peaking, F_r	**≤ 1.50**
Convergence, $\Delta\rho_{eq}$	**≤ 100 pcm**

- The 1500 pcm limit stays below the regulating-bank worths, **1975** and **2381 pcm** [4].
- 1450 EFPD is about **twice** the 720-day NuScale-like cycle [12].

Effect of thorium without burnable absorbers

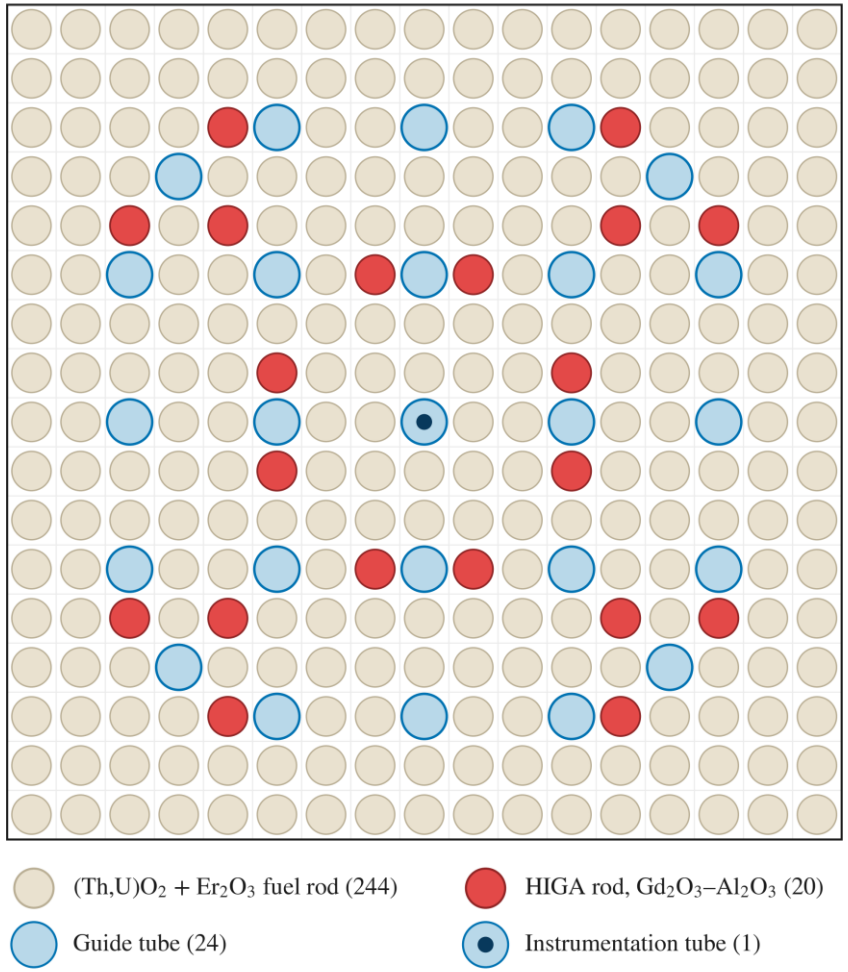


Same loading pattern and shuffling; UO_2 reference with the same U-235 inventory.

Equilibrium cycle	UO_2, no BA	$(Th,U)O_2$, no BA	Selected
ρ at BOC [pcm]	20,556	**16,316**	1242
Cycle length [EFPD]	2109	2021	1519
Cycle burnup [GWd/tHM]	36.0	36.5	30.0
Maximum F_r	1.601	1.511	1.499
Total Pu at EOC [kg]	102.4	**49.3**	39.7
U-233 fissions at EOC	–	23.6 %	20.4 %

- Same U-235: the thorium core starts **4200 pcm lower**.
- Absorbers must hold **15,100** instead of **19,300 pcm**.
- Plutonium is **halved** at the end of the cycle.
- Thorium cuts the control burden; the long cycle comes from **enrichment and fuel management**.

Burnable absorbers: HIGA rods and erbia

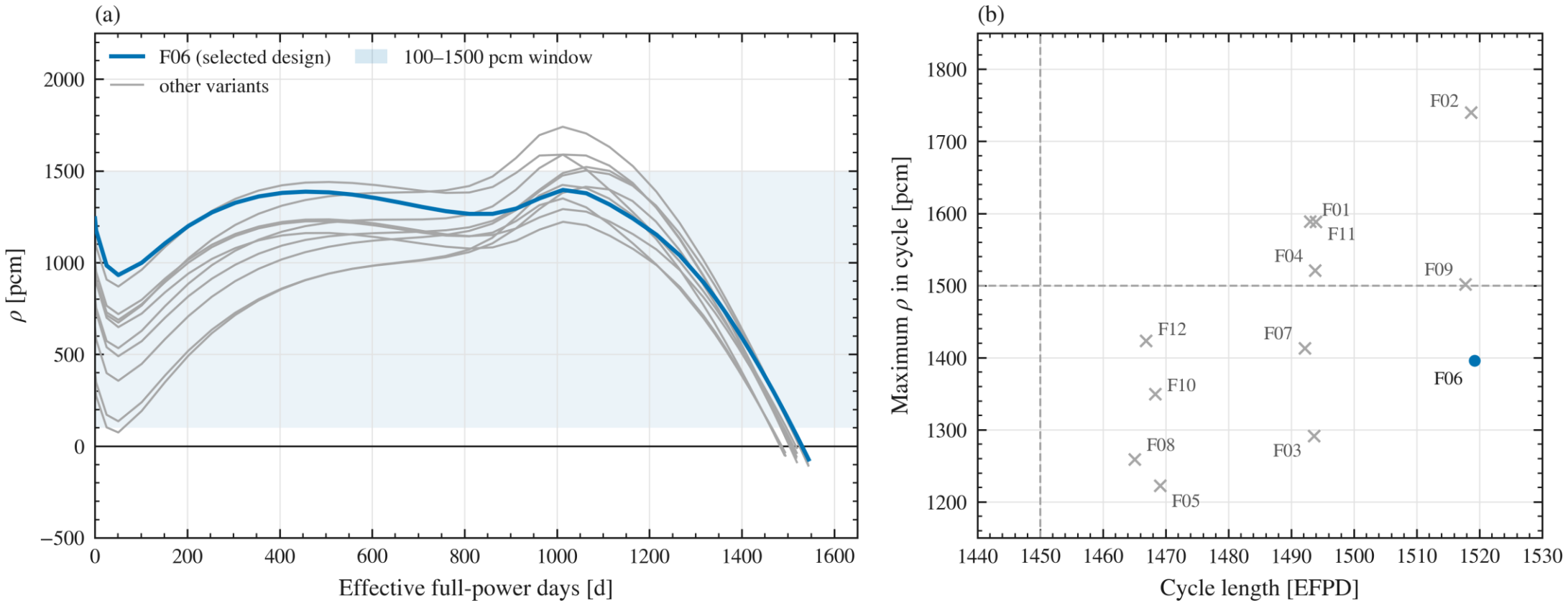


$\Delta\rho_\infty$ [pcm] at burnup [GWd/tHM]	0	10	20	30	40	60
Gd_2O_3 33 → 35 wt%	−201	−305	−497	**−1005**	−36	−31
Er_2O_3 0.90 → 0.95 wt%	**−539**	−332	−191	−113	−73	−48
33/0.90 → 36/0.80 (F06)	**+796**	+213	−349	**−1215**	+69	+50

THW60 lattice, 20 HIGA rods (CROMA); change from 33 wt% Gd_2O_3 / 0.90 wt% Er_2O_3.

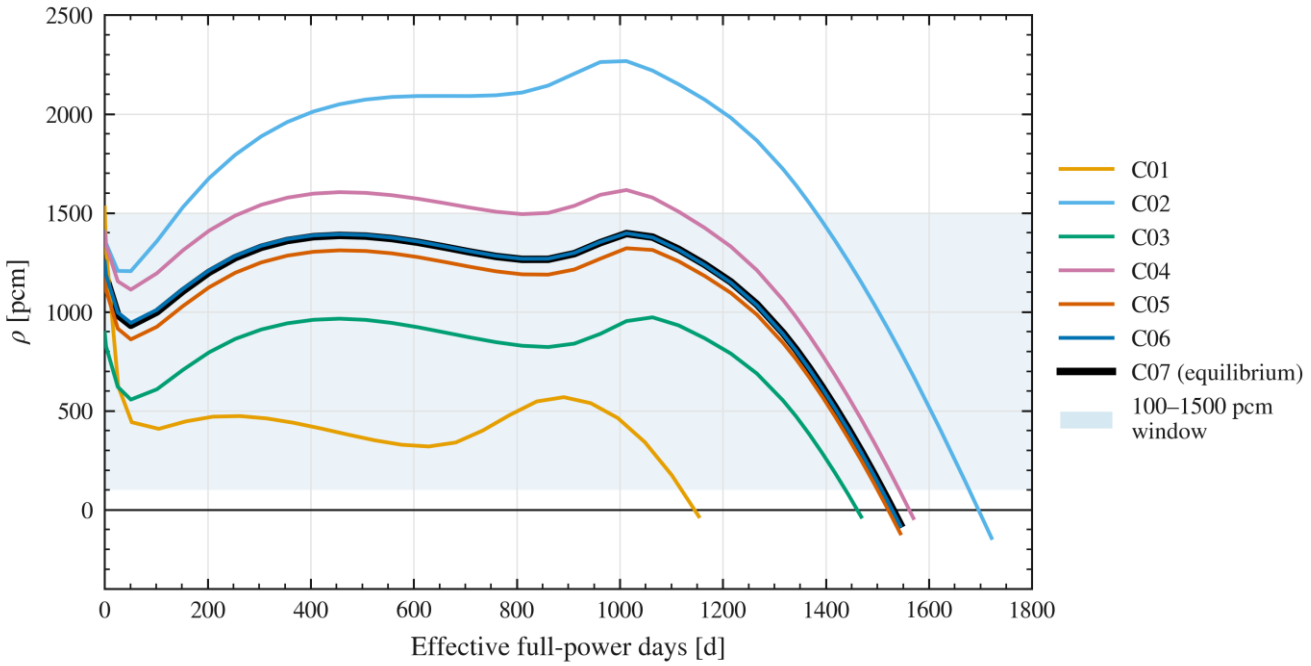
- **Erbia acts early**: it lowers the reactivity mostly at the start of the cycle.
- **Gadolinia acts late**: more Gd_2O_3 lowers the reactivity mostly around 30 GWd/tHM, before the HIGA rods burn out.
- **Less erbia and more gadolinia** on the (2,1) orbit **flattens the trajectory**.

Selection of the best obtained equilibrium cycle



Of the twelve absorber variants, only **F06** nominally satisfies all design objectives.

Selected design: approach to equilibrium

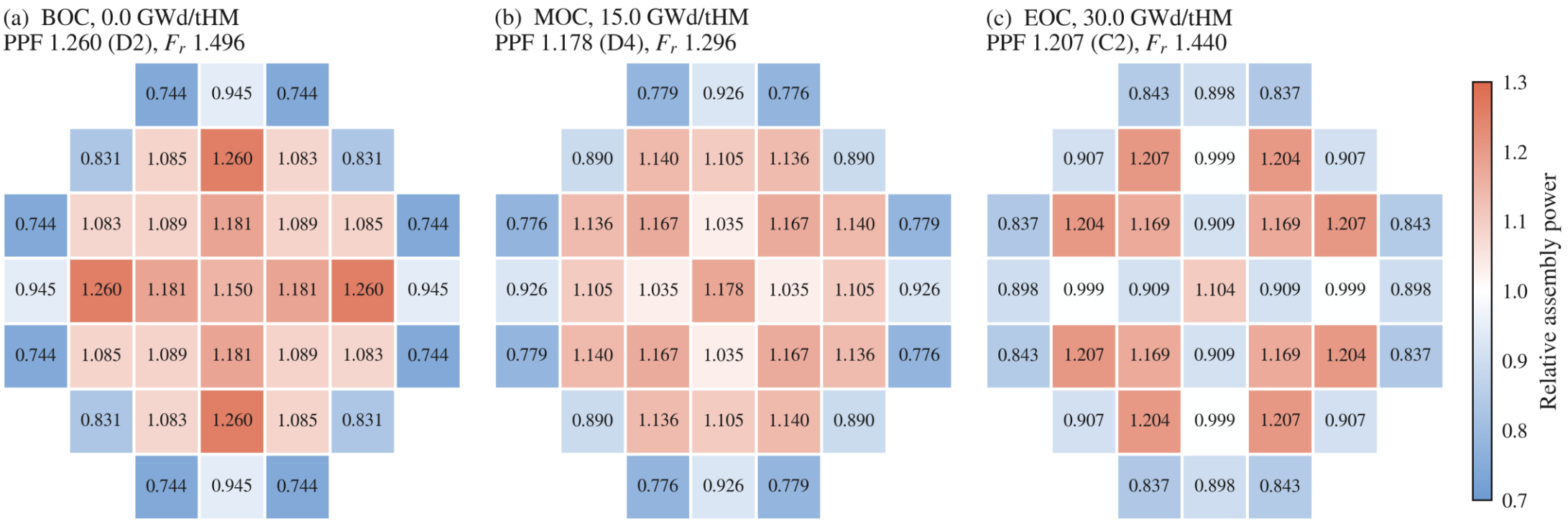


Cycle	Max ρ [pcm]	Min ρ [pcm]	EFPD	F_r	$\Delta\rho_{eq}$ [pcm]
C01	1528	320	1101	1.696	–
C02	2267	1206	1671	1.555	122.5
C03	972	557	1443	1.465	510.4
C04	1616	1112	1545	1.520	506.3
C05	1322	861	1519	1.492	225.5
C06	1397	944	1519	1.500	78.2
C07	**1396**	**932**	**1519**	**1.499**	**12.5**

Equilibrium is reached in C07: its BOC reactivity is within **13 pcm** of C06.

C07 stays within **932–1396 pcm** for **1519 EFPD**, with F_r = **1.499** and PPF = **1.26**.

Power distribution in the equilibrium cycle



- Assembly powers stay between **0.74 and 1.26** over the whole cycle: a flat, well-balanced distribution.

Comparison with the NuScale-like base design core

Per cycle / per unit energy	NuScale-like, 720 d	Selected design	Change
Cycle length [EFPD]	720	1519	+111 %
U-235 loaded per cycle [kg]	134.5	378.3	+181 %
Discharged assemblies per GWd	**0.113**	**0.086**	**−23 %**
Discharged heavy metal (initial mass) per GWd [kg]	**28.5**	**18.9**	**−34 %**
U-235 per GWd [kg]	1.17	1.56	+33 %
Natural uranium per GWd [kg]	238	333	+40 %

- The cycle is more than **twice as long**: 1519 vs 720 EFPD.
- Per unit energy: **23 % fewer** discharged assemblies and **34 % less** heavy metal.
- About **90 fewer** spent assemblies per module over 60 years.

NuScale-like cycle and reload scheme from [12]; its fresh-batch masses reconstructed from the benchmark fuel data [4].

Conclusions

- Radial ThO_2 zoning sets both cycle length and power peaking; **B8/A52** is the balanced choice.
- The boron-free two-batch core reaches **1519 EFPD**, more than twice the NuScale-like cycle, within **100–1500 pcm**.
- Thorium **eases reactivity control** and halves plutonium; the long cycle discharges **23 % fewer assemblies** per unit energy.

Remaining limitation

- Peak rod burnup of **76.9 GWd/tHM** requires fuel qualified for extended burnup.

Future work

- Full-core calculations with **thermal-hydraulic feedback**.
- **Shutdown margin** and reactivity coefficients.

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Thank you for your attention

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