First Criticality and Uncertainty Analysis of the HTR-PM using MCS

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Overview of HTR-PM

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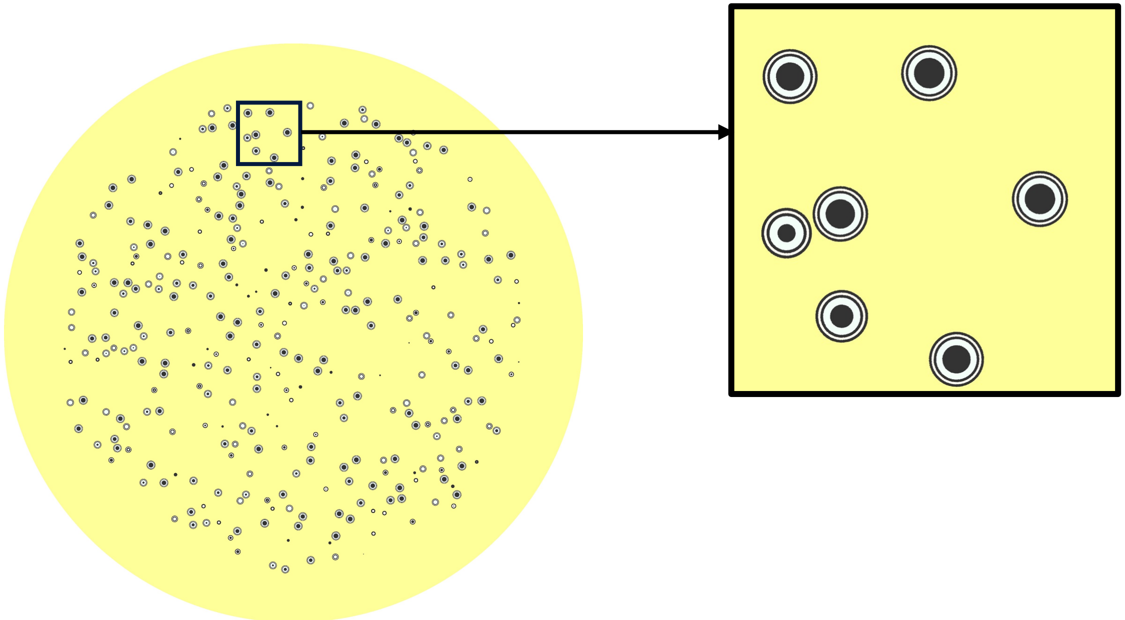
- The HTR-PM is high-temperature reactors pebble-bed modular with 250 MW_{th} built at the Shidao Bay site in Rongcheng, Shandong Province, China.
- The HTR-PM is scale-up of the HTR-10 that is one of the generation-IV nuclear reactors.
- The results of computer calculations used as the benchmarks of HTR-10 are far from a well-established art.
- The HTR-PM has reached its first criticality on September 12, 2021.
- This work presents the multiplication factor (k_{eff}) as a function of core loading height. Some parameters, including the cross-section library, graphite material, radius of the fuel zone, and the randomness of the mixed pebbles, were analyzed to study the uncertainty.

The Model and Simulation by MCS

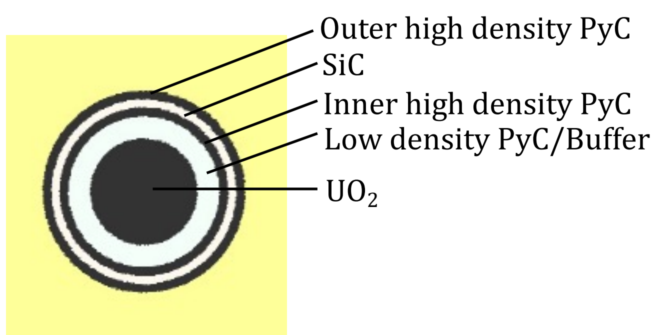
The Model: The TRISO, Pebbles, and Packing Fraction

- The fuel pebble consists of randomly packed of 11672 TRISO particles embedded in a graphite matrix.
- For simplicity, the TRISO positions are considered to be fixed.
- For the initial core loading, graphite pebbles will be first loaded into the discharge tube and the bottom region of the reactor. Then, the mixed pebbles, which are a mixture of fuel pebbles and graphite pebbles, will be loaded until the reactor reaches the first criticality.
- The packing fraction of the entire pebbles is 0.61. The positions of TRISO and pebbles are externally determined by python scripts using random sequential packing for TRISO and close random packing for pebbles.
- There are no overlapping particles and pebbles in this packing.
- The fuel pebbles and graphite pebbles are randomly selected with a ratio of 7:8 by the python numpy random module.

The Model: The TRISO and Fuel Pebble modeled by MCS

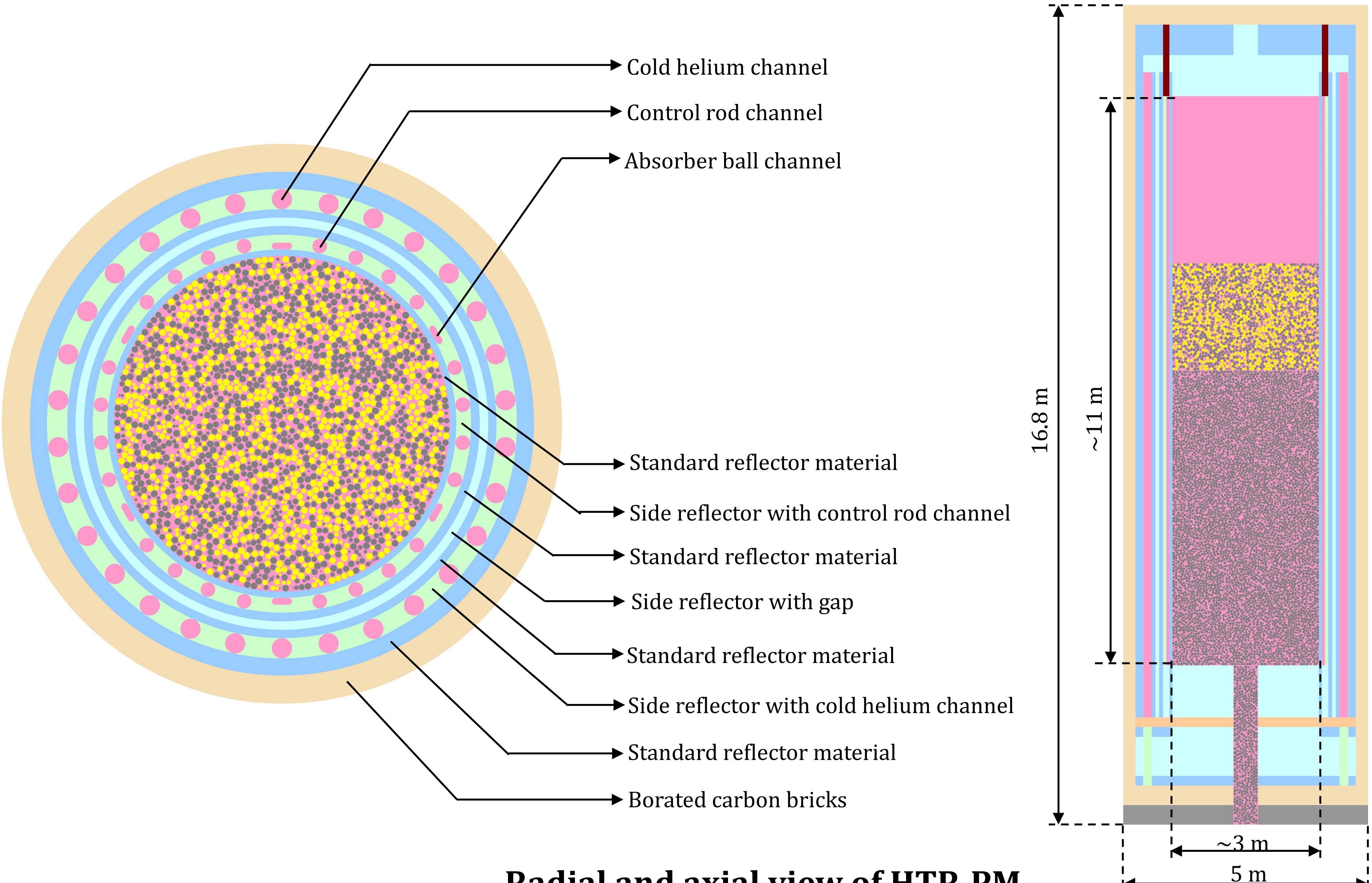


TRISO particles in fuel pebble



TRISO particle

The Model: The HTR-PM modeled by MCS



Radial and axial view of HTR-PM

The simulations: The Materials [1]

Material	Physical parameter	Value	Unit
Fuel pebble	Uranium weight in single pebble	7	g
	Enrichment of ^{235}U	4.2	%
	Diameter of the fuel pebble	6	cm
	Diameter of fuel zone in the fuel pebble	5	cm
	Density of graphite (including matrix and outer shell)	1.74	g/cm^3
	Impurities represented by EBC in uranium	0.5 *	ppm
	Impurities represented by EBC in graphite	0.795	ppm
Coated fuel particle	Radius of the kernel	250	μm
	Thickness of low density PyC	95	μm
	Thickness of inner high density PyC	40	μm
	Thickness of SiC	35	μm
	Thickness of outer high density PyC	40	μm
	Density of UO_2	10.4	g/cm^3
	Density of low density PyC	1.05	g/cm^3
	Density of high density PyC	1.9	g/cm^3
	Density of SiC	3.18	g/cm^3
	Impurities represented by EBC in graphite	0.795	ppm
Graphite pebble	Diameter of the graphite pebble	6	cm
	Density of graphite	1.74	g/cm^3
	Impurities represented by EBC in graphite	1.0	ppm

- *The impurity represented by equivalent boron concentration (EBC) in uranium is 0.5 ppm. The percentage of boron is as follows 19.9% ^{10}B and 80.1% ^{11}B.
- The reactor is in an air atmosphere, 10% porosity graphite material, and the components are at room temperature.

[1] D. She, B. Xia, J. Guo, C. L. Wei, J. Zhang, F. Li, L. Shi, and Z. Y. Zhang, Prediction calculations for the first criticality of the HTR-PM using the PANGU code, NUCL SCI TECH, 2021.

The simulations:

- MCS Code is a 3D continuous-energy neutron physics code for particle transport based on the Monte Carlo method, and it has been under development since 2013 at UNIST.
- The MCS simulations were executed on a Linux cluster (Intel(R) Xeon(R) CPU E5-2680 v4 @ 2.40GHz) with 28 cores.
- The simulations were performed for:

Cycles	: 500 active and 50 inactive
Histories	: two-million neutron
Time	: <32 hours/loading height.

- Results from the MCS code with ENDF/B-VIII.0 are compared with preliminary benchmarks of the HTR-PM from the RMC Monte Carlo code and PANGU.

Results

MCS vs RMC & PANGU as the Preliminary Benchmark and the Uncertainty

Result 1: Comparison Calculation with the Preliminary Benchmarks

Loading height of mixed pebbles (cm)	Number of mixed pebbles	k_{eff}			Δρ (%) with RMC	Δρ (%) with PANGU
		RMC (±10 pcm)	PANGU	MCS (±2 pcm)		
220	84182	0.94760	0.94648	0.94674	-0.10	0.03
250	95662	0.98130	0.98083	0.98075	-0.06	-0.01
275	105228	1.00432	1.00358	1.00321	-0.11	-0.04
300	114794	1.02293	1.02232	1.02201	-0.09	-0.03
330	126274	1.04095	1.04075	1.04003	-0.08	-0.07
385	147319	1.06638	1.06634	1.06534	-0.09	-0.09
440	168365	1.08496	1.08485	1.08385	-0.09	-0.09

$$\Delta\rho = \frac{1}{k_{eff}^{reference}} - \frac{1}{k_{eff}^{MCS}}$$

- By using interpolation, the first criticality achieves with the height of mixed pebbles equals 271.4 cm with the corresponding number of mixed pebbles is 103861.
- The experimental data [2] shows the first criticality has achieved when the number of mixed pebbles is approximately 102300.

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[2] R. Li, Z. Liu, Z. Feng, J. Liang, and L. Zhang, High-Fidelity MC-DEM Modeling and Uncertainty Analysis of HTR-PM First Criticality, Frontiers in Energy Research, 2022.

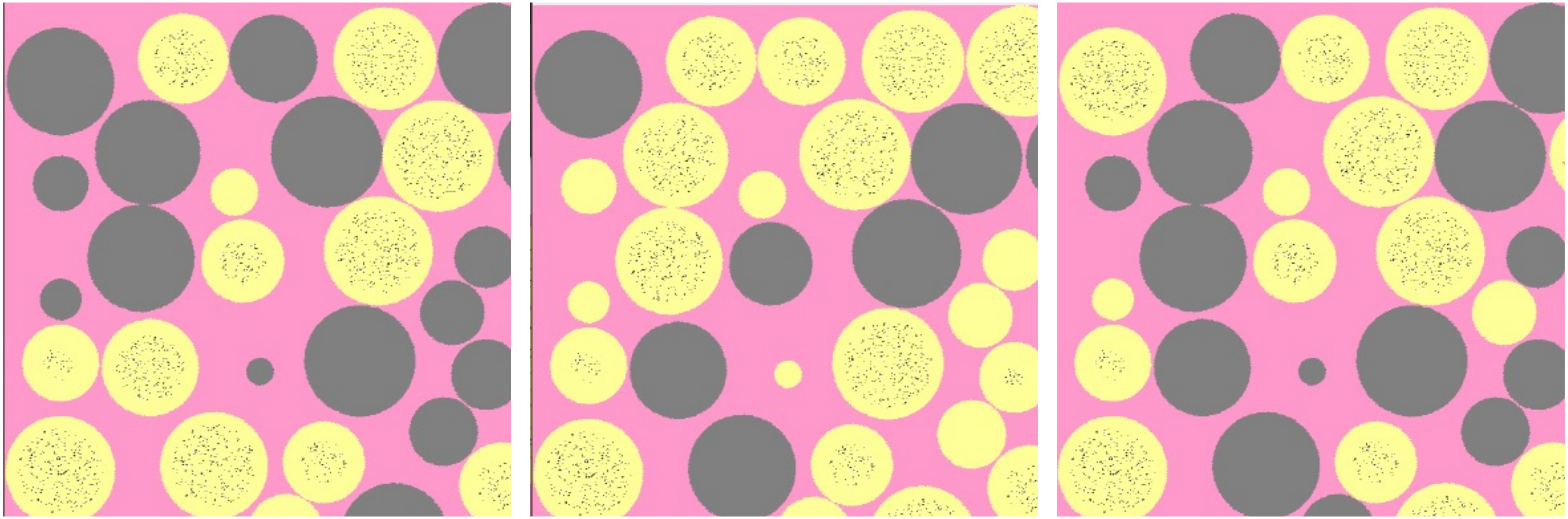
Result 2: Uncertainty Caused by Several Parameters

The HTR-PM with 275 cm loading height of mixed pebbles was analyzed

Parameters	Change from/to	Δρ (%)
Library ENDF/B	VIII.0/ VII.0	1.39
Graphite porosity (%)	0/10	0.34
The radius of fuel zone (cm)	2.5 /2.3	0.09

- Library ENDF/B: The crystalline graphite is used for both library ENDF/B VII.0 and ENDF/B VIII.0. The result given by ENDF/B VII.0 overestimated the k_{eff} by 1.39% or in this case is 1412 pcm. This caused by the significant change of the capture cross-section of graphite in ENDF/B VIII.0.
- Graphite porosity: The result showed that graphite with 10% porosity has higher k_{eff} by 0.34% or in this case is 344 pcm. The difference is likely caused by the thermal neutron scattering cross-section.
- The radius of fuel zone: Reducing the radius of the fuel zone from 2.5 cm to 2.3 cm can increase the k_{eff} by 0.09% or in this case is 94 pcm. As a matter of fact, X-Ray radiograph shows that the actual fuel zone radius is slightly less than 2.5 cm.

Result 3: Uncertainty Caused by Randomness of the Mixed Pebbles



- The mixed pebbles with 250 cm loading height was chosen.
- The numbers of fuel and graphite pebbles are the same for all samples, which are 44642 and 51020.
- The simulations were performed with black boundary condition for 120 active and 30 inactive cycles with one million neutrons.

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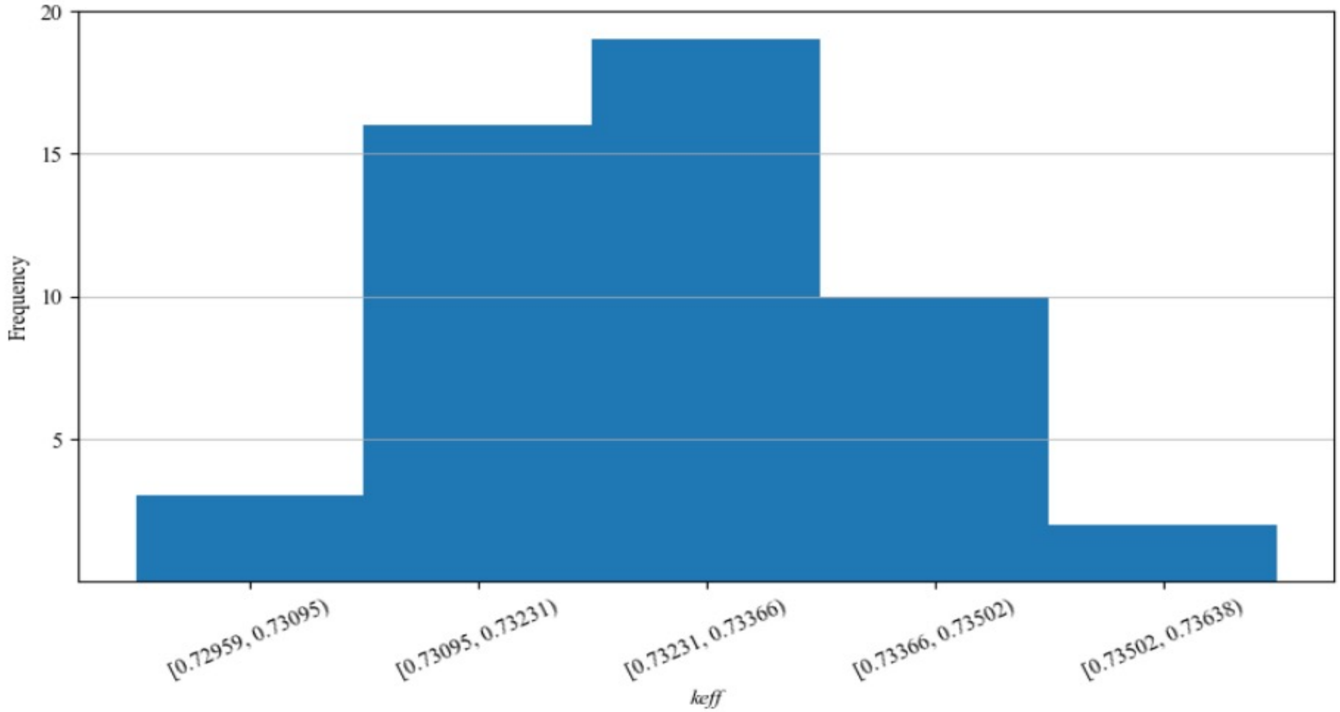
Result 3: Uncertainty Caused by Randomness of the Mixed Pebbles



Histogram of k_{eff} with a different selection of fuel and graphite

- Mixed pebbles: k_{eff} are ranged between 0.72959 - 0.73638 (± 8 pcm)
- Whole reactor: k_{eff} are ranged between 0.97773 - 0.98075 (± 2 pcm)
- An uncertainty of 302 pcm is given by the whole reactor model.

Conclusion

A model of the HTR-PM can be simulated by MCS. The results of k_{eff} agree well with various loading heights compared with the preliminary benchmarks. The number of mixed pebbles is also close compared with the experimental result. However, the effects of the cross-section library, graphite material and radius of the fuel zone cannot be ignored.

Further study found that the randomness of mixed pebbles significantly affects the k_{eff}. So, it would be challenging to accurately find a k_{eff} that agrees well with experimental data without knowing the details position of the pebbles.

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