Geometric Optimization of Micro-sized Stationary Pebble Bed Reactor

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1. Introduction

High-temperature gas-cooled reactors (HTGRs) are attractive Generation IV concepts for microreactor applications due to their high thermal efficiency, capability for hydrogen and process-heat production, and the inherent safety of TRISO fuel. However, conventional fuel-shuffling schemes used in pebble-bed and prismatic reactors can complicate operation, maintenance, and inspection, which is undesirable for microreactors.

Another key challenge is increased neutron leakage caused by the small core size and high surface-to-volume ratio, which can degrade neutron economy and fuel utilization. Possible approaches to mitigate this include optimizing the core height-to-diameter (H/D) ratio, increasing the uranium inventory, and introducing an inner graphite reflector.

Accordingly, this study investigates geometric optimization of a 25 MWth micro-sized stationary pebble bed reactor (SPBR), with emphasis on improving neutron economy and overall core performance. Neutronic analyses were performed using the Serpent 2.2.1 Monte Carlo code with the ENDF/B-VII.1 nuclear data library.

2. Description of the TRISO particle

Figure 1 illustrates the configuration of a conventional TRISO particle and pebble, consisting of a 500 μm UCO fuel kernel surrounded by a porous graphite buffer, inner pyrolytic carbon (IPyC), silicon carbide (SiC), and outer pyrolytic carbon (OPyC) layers [1, 2]. The pebble is 6 cm diameter with 5 cm diameter of fuel graphite matrix. The dimensions and material densities of the TRISO particle components are summarized in Table I.

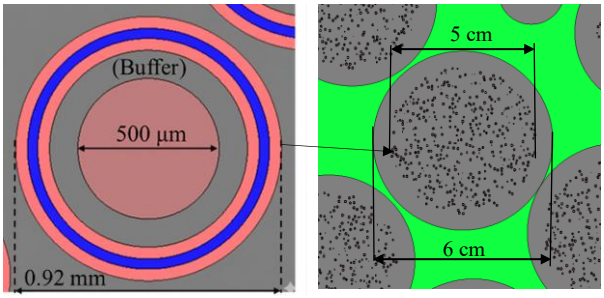


Fig. 1. Conventional TRISO and pebble [3]

Table I: Material densities [1, 2]

Material	■ $UC_{0.5}O_{1.5}$	■ Buffer	■ PyC	■ SiC
ρ (g/cm^3)	10.8	1.05	1.9	3.18
Size	500 μm	95 μm	40 μm	35 μm

3. Neutronic Analysis of Micro-sized Stationary Pebble Bed Reactor

3.1. Conventional cylindrical core

To investigate the neutronic effects associated with the number of TRISO particles per pebble, a series of sensitivity analyses was performed using a simplified cylindrical reactor geometry. The reference active core dimensions were set to a height of 300 cm and a diameter of 150 cm, as illustrated in Fig. 2. The core was surrounded by an 80-cm-thick graphite reflector with a density of 1.85 g/cm³. For the fuel specification, a uranium enrichment of 12 wt.% HALEU was adopted as the reference composition for the 3D reactor model. Using this configuration, the influence of varying the number of TRISO particles per pebble on the neutronic performance of the core was evaluated [1, 2].

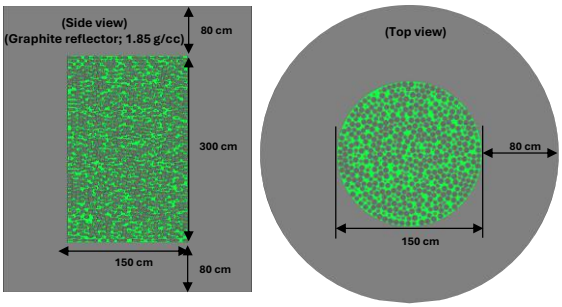


Fig. 2. Description of conventional cylindrical core

Table II present the depletion results for various particles per pebble in the 1.5 m-diameter, 3 m-high core at 25 MWth (60% bed packing fraction). Depletion was modeled as an average across the fuel zone without subdivision. The maximum lifetime with meaningful discharge burnup was 511 days at 15,000 particles per pebble. The lifetime could be extended to beyond 600 days, but the burnup decreased due to less moderation. The initial effective multiplication factor depends on the number of particles per pebble, with the maximum achieved around 15,000 particles per pebble.

Table II: Depletion analysis of 1.5 m active core diameter size PBR

Particles/pebble	Initial k-eff	Lifetime (d)	Discharge Burnup (MWd/kgU)	HALEU inventory (kg)
10,000 (6.03% PF)	1.21834	324	45.678	178
15,000 (9.04% PF)	1.22276	511	47.685	268
20,000 (12.06% PF)	1.20682	616	42.721	361
25,000 (15.07% PF)	1.18998	664	37.029	449
30,000 (18.09% PF)	1.17150	679	31.646	537
40,000 (24.11% PF)	1.14098	673	23.555	715
45,000 (27.13% PF)	1.12766	652	20.475	797
50,000 (30.14% PF)	1.11629	641	18.214	881

*PF (TRISO packing fraction) is only considered fuel matrix only
** As reference Xe-100 use around 19,000 particles per pebble [3]

Table III: Depletion analysis of sensitivity analysis of the core height-to-diameter (H/D) ratio

Height (cm)	Diameter (cm)	H/D	Burnup (MWd/kgU)	Lifetime (d)
100	259	0.39	48.438	514
150	212	0.71	50.379	531
200	183	1.09	49.902	532
250	164	1.52	48.742	514
300	150	2.00	46.633	496
350	138	2.54	44.526	473
400	129	3.10	42.363	450
450	122	3.69	39.429	419
500	116	4.31	37.074	396
550	110	5.00	34.123	366
600	106	5.66	31.898	341

Based on the neutronic characteristics obtained from the sensitivity analysis of particles per pebble, a sensitivity analysis for the core height-to-diameter ratio was conducted. In this case, the core volume is kept constant, and a 60% bed packing fraction is used. As shown in Table III, depletion calculations for 15,000 particles per pebble show that the maximum lifetime and burnup occur at a height of 150 cm and a diameter of 212 cm, with an H/D ratio of 0.71. For an idealized bare, homogeneous cylindrical reactor, the optimum H/D ratio is around 0.92. However, because this case uses a reflector, the optimum H/D ratio shifts due to differences in axial and radial leakage compared with the idealized bare homogeneous cylindrical reactor.

3.2. Annular core

To achieve optimal burnup performance with a compact core design, the inner reflector was implemented as illustrated in Fig. 3. The sensitivity analysis was conducted using a core with H = 300 cm and Diameter = 150 cm as the volume reference for H/D sensitivity analysis. In this case, to achieve similar fuel mass with the conventional cylindrical core, 45,000 to 60,000 particles per pebble, a 60% bed packing fraction, and 25 MWth are used. The diameter of the inner reflector is called D_{in}. To identify the near-optimal inner diameter (D_{in}) for each H/D configuration, D_{in} was varied from 60 to 140 cm in increments of 10-20 cm. D_{out} is diameter of outer core.

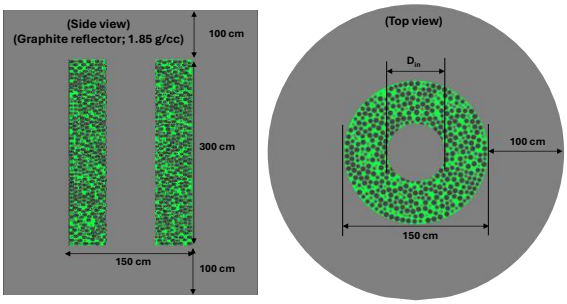


Fig. 3. Description of annular core

Table IV: Depletion analysis of the annular core

H / D	D_{in} (cm)	Lifetime (days)	Discharge Burnup (MWd/kgU)	HALEU Inventory (kg)	Power Density (W/cc)
20,000 particles per pebble					
1.52	60	682	56.214	303	5.44
2.00	60	666	55.963	298	5.61
2.53	60	631	55.342	285	5.89
3.07	60	597	53.936	277	6.10
30,000 particles per pebble					
1.52	100	709	53.955	328	7.49
2.00	80	836	55.622	376	6.59
2.53	80	788	56.217	351	7.19
3.07	80	731	55.864	327	7.77
40,000 particles per pebble					
1.52	110	821	53.488	384	8.55
2.00	100	861	55.701	387	8.49
2.53	100	753	55.886	337	10.06
3.07	80	993	57.166	434	7.77

**The H/D 1.52, 2.00, 2.53, and 3.07 corresponds to the 250/164, 300/150, 350/138, and 400/129

Table IV shows that the near-optimal lifetime and burnup occur at D_{in} = 80 cm, H/D = 3.07 and 40,000 particles per pebble, resulting in a discharge burnup of 57.166 MWd/kgU and a core lifetime of 993 days for the annular case. Higher the number of particles per pebble can achieve similar burnup compared to the lower particles per pebble in the conventional cylindrical core by implementing the inner reflector which enhances the neutron moderation. In the next case, the number of particles per pebble will be reduced to a level compatible with current TRISO fuel fabrication technology.

3.3. Inner cylinder and outer annular core

Based on previous neutronic characteristics, introducing an inner reflector reduces the fuel inventory. To further increase the fuel inventory, an inner cylinder core is installed within the inner reflector. To see how the effect on the neutronic performance based on the particles per pebble, inner cylinder core size and inner reflector size, a more detailed sensitivity analysis was conducted using 20,000, 30,000, and 40,000 particles per pebble with varied height 200, 250, 300, and 350 cm, with corresponding diameters of 183, 164, 150, and 138 cm based on a conventional cylindrical core with the volume kept constant. Similar to the previous annular core sensitivity analysis to find near-optimum D_{in}, in this

case, the diameter of the inner active core (D_{ic}) was varied from 30 to 60 cm using increments of 10 cm, while D_{out} is the diameter of the outer core, as illustrated in Fig. 4. In addition, the thickness reflector for all case uses 100 cm of thickness to decrease neutron leakage and enhance burnup performance.

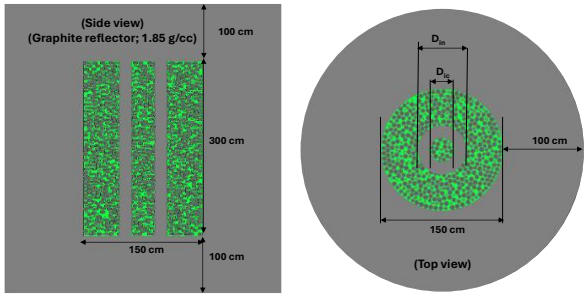


Fig. 4. Description of inner cylinder and outer annular core

Table V: Depletion analysis of inner cylinder and outer annular core

D_{ic} (cm)	D_{in} (cm)	Lifetime (d)	Discharge Burnup (MWd/kgU)	HALEU inventory (kg)	Power density (W/cc)
20,000 particles per pebble					
D_{out} =138 cm, H = 350 cm					
40	80	658	62.264	264	6.38
D_{out} =150 cm, H = 300 cm					
60	100	656	64.567	254	6.59
D_{out} =164 cm, H = 250 cm					
60	100	704	65.816	267	6.21
D_{out} =183 cm, H = 200 cm					
80	120	711	66.165	268	6.24
30,000 particles per pebble					
D_{out} =138 cm, H = 350 cm					
50	100	859	67.235	320	7.88
D_{out} =150 cm, H = 300 cm					
60	110	895	68.300	328	7.58
D_{out} =164 cm, H = 250 cm					
60	110	981	68.536	358	6.92
D_{out} =183 cm, H = 200 cm					
70	120	1013	67.256	376	6.24
40,000 particles per pebble					
D_{out} =138 cm, H = 350 cm					
40	100	1099	69.814	394	8.54
D_{out} =150 cm, H = 300 cm					
50	110	1134	70.433	403	8.23
D_{out} =164 cm, H = 250 cm					
60	120	1169	69.892	418	7.91
D_{out} =183 cm, H = 200 cm					
80	140	1167	68.214	427	7.84

Table V summarizes depletion results for near-optimal lifetime and burnup for each case sensitivity analysis. With 20,000 particles per pebble, the discharge burnup can exceed 60 MWd/kgU. This is because introducing an inner cylinder core increases the total fuel inventory relative to the previous annular-core design analysis. In addition, 20,000 particles per pebble provide more moderation than higher particle counts per pebble, which increases burnup and lifetime performance. For 30,000 particles per pebble, the discharge burnup ranges from 63 to 68 MWd/kgU, and the lifetime ranges from 700 to 1000 days, both of which are higher than in the 20,000 particles-per-pebble case. This is because the total fuel inventory increases due to a higher number of particles per pebble. For 40,000 particles per pebble, a similar increasing trend is noticeable for the discharge burnup range of 64 to 70 MWd/kgU, the lifetime of 900 to 1200 days, and the volumetric power density of 6 to 9 W/cc, which is higher than that of conventional HTGR [4].

3.4. Double-annular core

To achieve an optimum burnup performance with a compact core design, the inner reflector inside the inner cylindrical core was introduced as shown in Fig. 5. The sensitivity analysis was conducted using the near-optimal from the inner cylinder and outer annular core with varying diameter of innermost reflector (D_{in_ic}) with an increment of 10 cm.

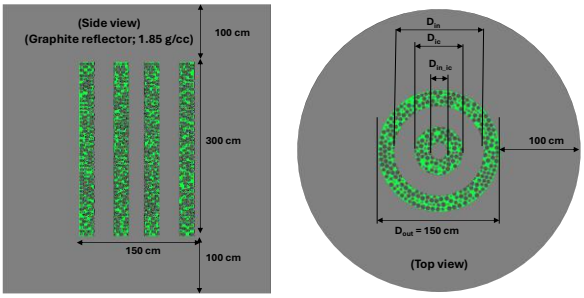


Fig. 5. Description of double annular core

The power distribution double annular configuration as shown in Fig. 6 with 40,000 particles per pebble shows a more pronounced spatial variation in power density due to the presence of the inner graphite reflector. the power peaking near the inner reflector becomes increasingly significant. This behavior is primarily attributed to enhanced neutron moderation and thermalization in the vicinity of the inner reflector, which increases the local thermal neutron flux and consequently the fission rate in the adjacent fuel region. Therefore, although the inner reflector can improve neutron utilization by reducing neutron leakage, its effect on the local neutron spectrum can also lead to increased radial power peaking, which should be carefully considered in the thermal-hydraulic and fuel-temperature evaluation of the core.

Across all simulation cases, as the number of particles decreases, the spectrum becomes softer. More neutrons are captured in the thermal region, and neutron capture in the resonance region becomes less. Thus, the conversion ratio becomes lower. The reactivity will fall off much more rapidly. As the burnup progresses, the fission-product poisoning becomes overwhelming relative to the fuel fission cross section. As shown in Table VI, since there is less fuel in the core, the mean free path becomes larger, which means the increase in neutron leakage outweighs the beneficial effect of enhanced thermalization. Moreover, comparing with the optimized conventional cylinder case, using double annular core decrease a lot of neutron leakage.

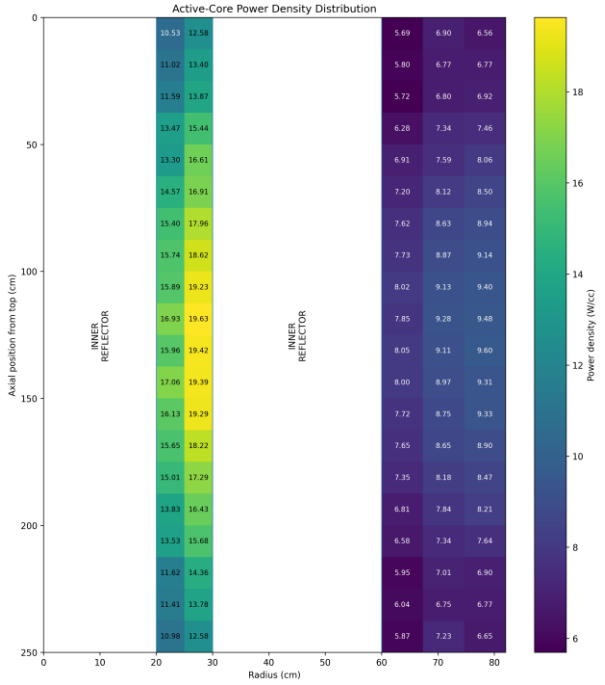


Fig. 6. Power distribution of double annular core for near optimum case (40,000 particles per pebbles)

Table VI: Leakage rates at varying particles per pebbles for each near optimum case

D_{in_ic} (cm)	D_{ic} (cm)	D_{in} (cm)	H / D	Top & Bottom (#/s)	Radial (#/s)	Total (#/s)
15,000 particles per pebble (conventional cylinder)						
-	-	-	0.7	7.63E+16	1.28E+17	2.05E+17
20,000 particles per pebble						
20	60	100	1.5	2.87E+16	1.18E+17	1.47E+17
30,000 particles per pebble						
30	60	110	1.5	2.62E+16	1.09E+17	1.35E+17
40,000 particles per pebble						
40	60	120	1.5	2.49E+16	1.06E+17	1.31E+17

*Leakage to the outside the reactor system
**The H/D 0.7 corresponds to the 150/212

Table VII: Depletion analysis of double annular core

40,000 particles per pebble and H/D 1.5						
D_{in_ic} (cm)	D_{ic} (cm)	D_{in} (cm)	Lifetime (d)	Discharge Burnup (MWd/kgU)	HALEU inventory (kg)	Power density (W/cc)
30	70	128	1100	72.889	376	8.78
40	80	131	1112	73.846	376	8.78
50	80	127	1125	74.542	376	8.78
60	90	130	1109	73.852	376	8.78

*The H/D 1.5 corresponds to the 250/164

Table VII summarizes depletion results with 40,000 particles per pebble. In this case, the sensitivity analysis conduct with change inner and outer annular core volume with keeping the total volume of both annular core is same using previous near optimum case. Comparing the double annular core with the first optimization, overall, the discharge increases. The highest burnup occurs at 74.542 MWd/kgU with 1125 lifetime days using 40,000 particles per pebble.

4. Conclusion

The neutronic feasibility of the SPBR has been evaluated for micro-reactor applications. The challenge of HTGR miniaturization, driven by neutron leakage and low fissile inventory, can be addressed with simple stationary fuel. The highest burnup reached 74.542 MWd/kgU with 1125 lifetime days using an H/D ratio of 1.5, D_{in_ic} 50 cm, D_{ic} 80 cm, D_{in} 127 cm, and 40,000 particles per pebble. However, a key challenge for the SPBR is its relatively high volumetric power density of approximately 6-9 W/cc, resulting from the compact core enabled by the improved inner-reflector configuration. The power density should therefore be appropriately reduced, for example by increasing the core size, to ensure the structural integrity of the TRISO particles and pebbles under loss-of-coolant accident conditions.

ACKNOWLEDGEMENTS

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