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MONTE CARLO EQUILIBRIUM CYCLE ANALYSIS OF A DEEP-BURN MHR CORE CHARGED WITH DILUTED-KERNEL-BASED TRISO FUEL

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ABSTRACT

Neutronic analyses of TRU deep-burn (DB) have been performed for a 600 MWth MHR (Modular Helium Reactor) by using a continuous energy Monte Carlo code, MCCARD. In order to improve the neutronics and reduce the fuel self-shielding effect, a carbon-diluted kernel is introduced in this work. The double-heterogeneity of TRISO fuels are handed with the aid of the RPT (Reactivity-equivalent Physical Transformation) method. It is shown that the RPT method provides a very accurate solution for the diluted-kernel TRISO fuel. Instead of conventional radial fuel shuffling, an axial-only block shuffling strategy is used to reduce the axial neutron leakage. Based on a 4-batch axial-only fuel block shuffling scheme, equilibrium cycle is directly searched with repeated 3-D Monte Carlo depletion calculations. For an equilibrium cycle, TRU transmutation performance is evaluated and core power distributions are analyzed. In addition, core performance of a diluted kernel is compared with that of a concentrated kernel in terms of TRU transmutation capability and the reactivity swing. It is found that a diluted kernel results in a noticeable increase in the TRU discharge burnup, compared with a concentrated kernel and a much smaller reactivity swing.

Key Words: MHR, TRU Deep-burn, Monte Carlo analysis, Diluted kernel, Axial fuel shuffling

1. INTRODUCTION

It is generally perceived that the spent nuclear fuel problem should be appropriately resolved for a sustainable development of nuclear energy and the transmutation of TRUs (transuranics) contained in the LWR spent fuels is a potential solution. A conventional transmutation concept is to burn TRUs from LWRs in fast reactors (either critical or subcritical) based on a repeated reprocessing of spent fuels.

As an alternative, the deep-burn (DB) concept has been proposed by General Atomics (GA), in which a graphite-moderated modular helium reactor (MHR) is used to achieve an ultra high TRU burnup without costly reprocessing and re-fabrication of TRU fuels[1,2]. In the DB-MHR concept, TRUs from LWRs are fabricated into ceramic-coated particulate fuels (TRISO) and

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irradiated in an MHR core, and the spent fuels of MHRs are either fed synergistically into fast reactors[3] or directly disposed of in a final repository.

For a successful implementation of a DB-MHR approach, the TRU discharge burnup should maximized as much as possible, regardless of the back-end options (either synergy with fast reactors or direct disposal). In MHRs, a ceramic-coated particle fuel (TRISO) is used to achieve a high degree of passive safety. It was experimentally demonstrated that TRISO fuels can accommodate an extremely high burnup of ~750 GWD/tHM[4].

The moderation by graphite in an MHR produces valuable opportunities for thermal and epithermal neutrons to interact with fissionable and non-fissionable materials, respectively. In particular, the moderation by graphite allows effective use of the resonance absorption of ^{241}Am, ^{237}Np, and ^{240}Pu to counteract the reactivity loss by depletion of ^{239}Pu, which is a major fissile nuclide in an LWR TRU vector. Additionally, a full 100% TRU-loaded core is feasible since MHR's safety characteristics are exceptionally good. Consequently, an MHR has a high potential as a TRU transmuter from the physics points of view.

Previously, Talamo et. al.[5] evaluated the deep-burn potential of a 600 MWth MHR core by using a Monte Carlo method. They considered a two-pass Deep Burn irradiation mode, in which irradiated TRUs fuels are recycled into the same MHR core after a reprocessing treatment (removal of fission products). The work showed the final TRU discharge burnup to be about 53% for an LWR-derived TRU vector fuel in an three-region annular MHR core. Also, Talamo and Gudowski[6] evaluated the deep-burn of a weapon-grade plutonium in a similar MHR and achieved over 92% transmutation of Pu-239. Recently, Kim et al.[7] applied deterministic methods to evaluate the deep-burn physics of a 600 MWth annular MHR core with five fuel rings. They showed that the TRU consumption rate is about 58% (58.6% fissile content in TRU vector) in a one-pass irradiation campaign based on a four-batch fuel management, while the burnup can be increased up to ~62% in a two-pass concept.

A small kernel size is usually adopted for deep-burning of TRU in MHRs and a kernel diameter of ~200μm is typically used. Kim and Noh[8] showed that the kernel size should be minimized to enhance the fuel burnup. However, it is challenging to fabricate a very small fuel kernel for the TRISO fuel. Therefore, we have introduced a new kernel concept, carbon-diluted kernel, in which small fuel particles are dispersed in a carbon matrix[9].

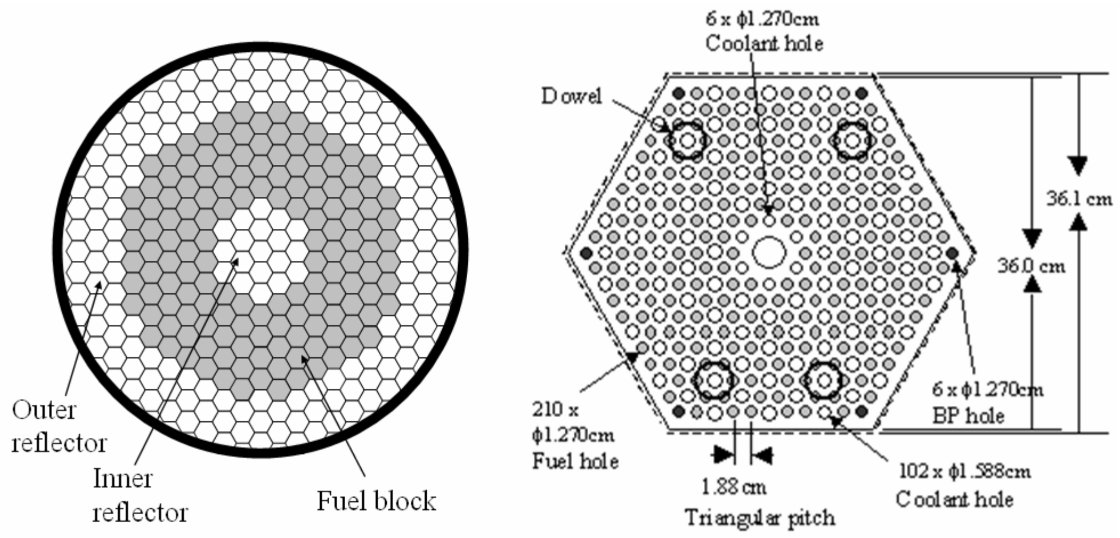
The objective of the work is to evaluate the deep-burn capability of an MHR core loaded with TRU TRISO fuels with a diluted kernel. All the neutronic analyses are done with the continuous energy Monte Carlo code MCCARD[10] in order to reduce the calculational uncertainties.

2. DESIGN OF THE DB-MHR CORE

2.1. Core Layout

Figure 2 shows the schematic configurations of the DB-MHR core considered in this study. The core was modified from the original GT-MHR[11] of General Atomics. In Table I, the major design parameters of the core are provided. This modified MHR core is comprised of 144 fuel columns and 8 axial layers, while the original design has 102 fuel columns and 10 axial layers. The number of fuel columns was increased to improve the neutron economy of the core. Because of the lower power density and the smaller decay heat production from TRU-based fuel, the increased number of fueled columns does not result in a significant increase of the fuel temperature during the loss of coolant heat-up incident, with respect to the original 104-column fueled with LEU.

In the fuel block, dowels are not modeled and the burnable poison (BP) holes are assumed to be filled with graphite. The control assemblies are not considered, either. Thus, all the fuel blocks are identical in the core. It is assumed that each fuel block has a 2.9cm-thick non-fuel graphite zone at both top and bottom.



a) Core layout with 144 fuel columns b) Fuel block design

Fig. 1. Core configurations of DB-MHR.

Table I. Major design parameters of the DB-MHR core

Parameter	Value
Thermal power, MWt	600
Coolant inlet/outlet temperature, °C	490/850
No. of fuel columns	144
Active core height, cm	792.9
Core radius, cm	340
Top/bottom reflector thickness, cm	120/120
No. of axial layers	8
Average power density, W/cm^3	4.66
Graphite block density, g/cm^3	1.74

2.2. TRISO Fuel with a Diluted Kernel

In order to accommodate a very high fuel burnup and reduce the fuel self-shielding, a relatively small fuel kernel is used in the one-pass DB-MHR core. In this work, instead of a conventional concentrated small-diameter kernel, a relatively larger carbon-diluted kernel is used to reduce the amount of fuel in each TRISO particle and to reduce the self-shielding effect. Figure 2 shows the model of the TRISO fuel with a carbon-diluted kernel. As shown in Fig. 2, in a diluted kernel, very small fuel particles (20~40μm diameter) are randomly dispersed in a carbon matrix with a small volume fraction. Note that a concentrated kernel is a pure fuel.

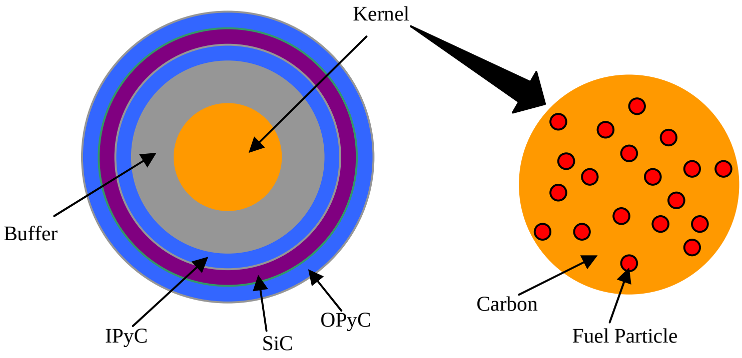


Fig. 2. TRISO particle with a carbon-diluted kernel.

A TRISO particle with a diluted kernel has a one extra level of heterogeneity compared with a concentrated kernel. Two kinds of randomness exist in a diluted-kernel TRISO fuel: random distribution of fuel particles in the kernels and random distribution of TRISO particles in the fuel compacts. It is very difficult to accurately analyze such a TRISO fuel by using conventional methods.

Table II shows the specifications of TRISO fuel and fuel compact used in this paper. The specific design parameters that were used for the diluted kernel fuel are as follows: diameter of kernel-embedded fuel particles = 30μm, volume fraction of kernel-embedded fuel particles = 20%, kernel diameter = 300μm, density of kernel carbon matrix = 1.70g/cm^3. The optimization of the parameters that can influence self-shielding (such as fuel and kernel diameter, fuel volume fraction, etc.) was not attempted in this study.

Table II. TRISO fuel and compact

TRISO fuel	
Fuel type	TRUO$_2$
Fuel density, g/cm^3	10.0
Buffer layer (thickness, μm/density, g/cm^3)	100/1.05
IPyC layer (thickness, μm/density, g/cm^3)	35/1.9
SiC layer (thickness, μm/density, g/cm^3)	35/3.18
OPyC layer (thickness, μm/density, g/cm^3)	40/1.9
Fuel Compact	

Radius, cm	0.6225
Matrix density, g/cm^3	1.70
TRISO Packing fraction, %	35

Regarding the TRU fuel, we calculated a TRU composition from LWR spent fuels by assuming a future equilibrium condition, a 50GWD/MTU burnup and a 5-year cooling. The TRU compositions are given in Table III. In Table III, it is assumed that Cm isotopes (mostly Cm-244) are removed, due to the fact that they are very radioactive and ultimately decay rather rapidly into Pu-240, a much easier and more desirable isotope to use in the DB-MHR. If it were carried into the DB-MHR fuel, the neutronic impact of Cm nuclides on the core behavior would be negligible.

Table III. TRU compositions (50 GWD/MTU, 5-yr cooling)

Nuclides	Fraction, wt%
^{237}Np	6.8
^{238}Pu	2.9
^{239}Pu	49.5
^{240}Pu	23.0
^{241}Pu	8.8
^{242}Pu	4.9
^{241}Am	2.8
^{242m}Am	0.02
^{243}Am	1.4

3. COMPUTATIONAL METHODS

The continuous energy Monte Carlo code MCCARD is used for the neutronic analysis of DB-MHR cores. It has a built-in depletion routine, thus it can be used in a stand-alone mode for the reactor depletion analysis. In the MCCARD depletion calculation, all actinides and over 160 fission products nuclides are considered. MCCARD can directly handle the double-heterogeneous fuel used in MHRs. In particular, the randomness of the TRISO fuel particles can also be taken into consideration. MCCARD code can be run on parallel computers. A Linux cluster computer (20 CPUs) was used for a parallel Monte Carlo calculation in this work. The cross section libraries are generated from the ENDF-B/VI data.

The double-heterogeneity effect is very large in a reactor-grade, TRU-loaded MHR. The direct modeling of the TRISO for 3-D core depletion calculations fuel requires a huge memory requirement and an extremely long computing time. Therefore, in this work, the RPT[12,13,14,15] (Reactivity-equivalent Physical Transformation) method is adopted to convert a double-heterogeneous fuel compact into a conventional single-heterogeneous material. Figure 3 shows the concept of the RPT method: TRISO particles are dispersed in a smaller fuel zone with a higher packing fraction and a smaller surface area, and then the new fuel region is simply homogenized (volume-weighted homogenization, VWH). The new fuel radius (RPT radius) is determined so that the neutron multiplication factor is equivalent to the reference value. The reference reactivity is obtained by MCCARD in this paper.

With the aid of the RPT method and a Monte Carlo depletion method, the MHR core can be analyzed very efficiently. The application of the RPT method to a diluted kernel can be found in Ref. 15. As illustrated in Fig. 5, the RPT model shows an extremely good agreement with the reference solution although the double-heterogeneity is very large, ~7144pcm.

The core performance is evaluated for an equilibrium cycle. To find the equilibrium cycle, repeated 3-D depletion calculations are performed until a convergence is reached. In this work, a 1/6th core is considered for the depletion calculation. Even using the RPT model, the Monte Carlo depletion calculation is still very challenging if all the fuel compact should be depleted independently. Thus, we grouped 210 fuel regions (compact-filled holes) into 19 depletion groups for each fuel block, as depicted in Fig. 5. The sensitivity of the analysis to the number of depletion zones was evaluated for a 2-D DB-MHR core and the results are presented in Fig. 6. The 19-group depletion analysis shows a very good agreement with a pin-wise depletion, while one depletion group results in a noticeable error.

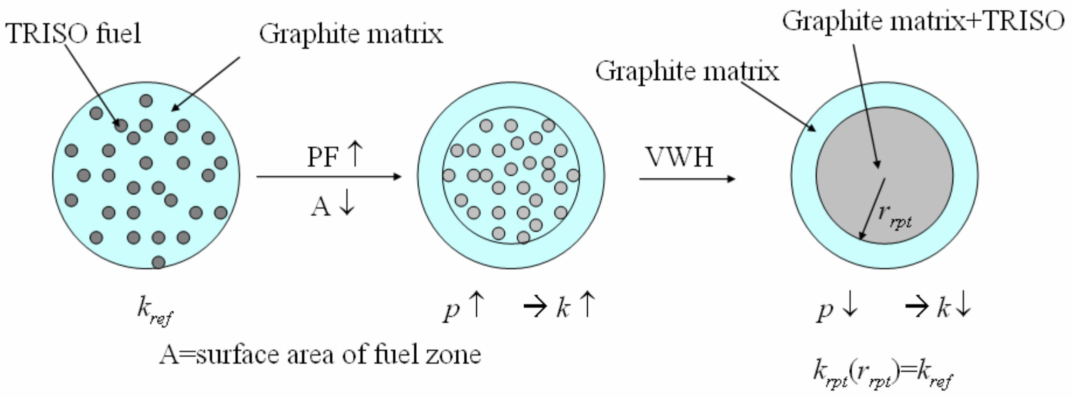


Fig. 3. Concept of the RPT method.

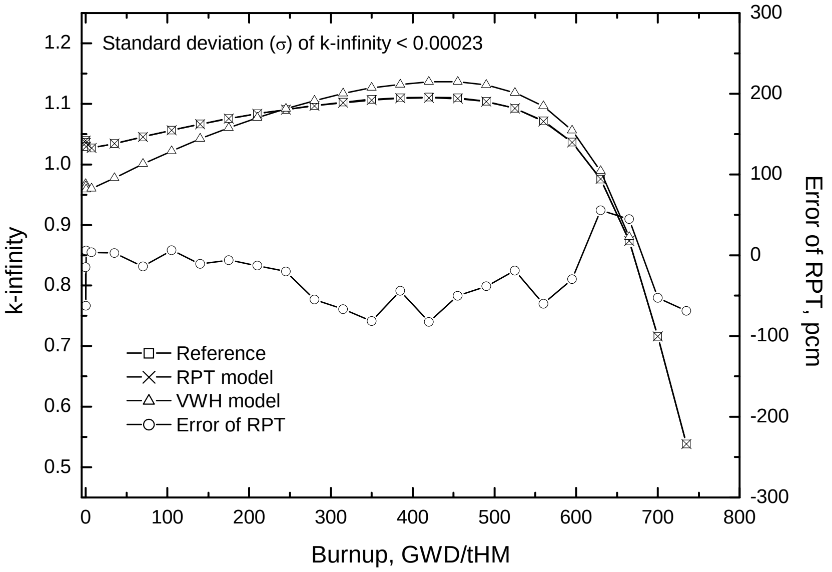


Fig. 4. Accuracy of the RPT model of a diluted-kernel-based TRISO fuel.

The temperature feedback is not considered in the current neutronic analysis. Instead, the core temperature assumed to remain constant: active core at 1200°K; inner, outer, and top reflectors at 900°K; bottom reflector at 1200°K. When the coolant inlet and outlet temperatures are 763°K and 1123°K, respectively, as in the current DB-MHR core, the core average fuel temperature should be much lower than 1200°K. Thus, we think that the current evaluation of the fuel burnup is rather conservative since the MHR core has a negative temperature feedback effect, as was indicated in Ref. 7.

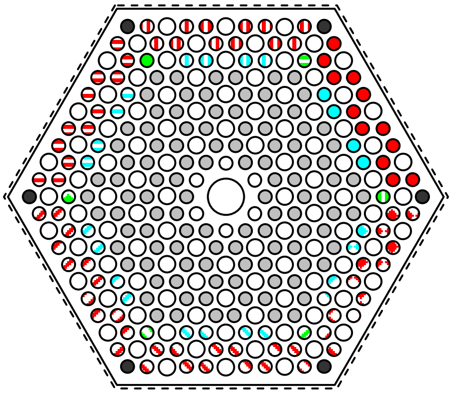


Fig. 5. 19 depletion groups in a fuel block (each color denotes a group).

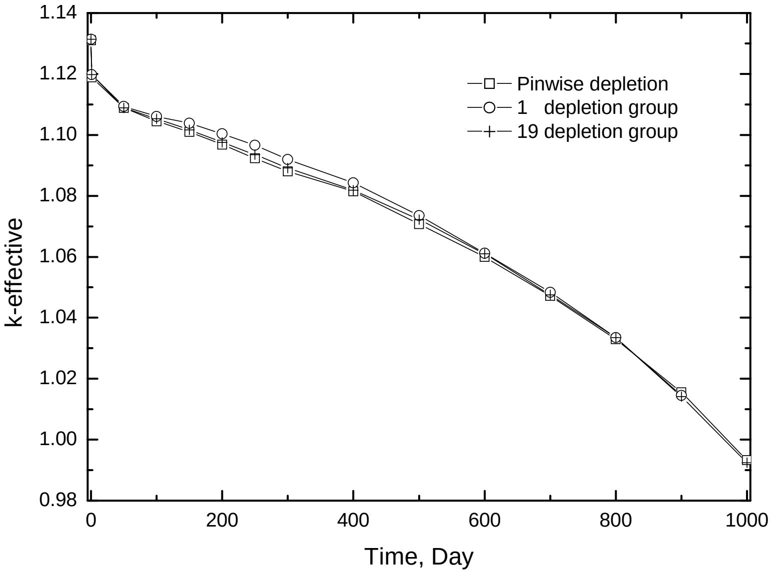


Fig. 6. Impact of the number of depletion groups per fuel block.

4. EQUILIBRIUM CYCLE ANALYSIS

4.1. Equilibrium Cycle Search

In order to evaluate the deep-burn performance in an equilibrium cycle, a direct search of an equilibrium cycle was done with the MCCARD code. For the fuel management, an axial-only fuel block shuffling scheme is introduced, instead of conventional radial shuffling to reduce the axial neutron leakage. Figure 7 shows a 4-batch fuel shuffling scheme used in this paper. It is worthwhile to note that the axial leakage can be reduced by placing highly burned blocks at both top and bottom of the column. There are many other axial shuffling schemes since each fuel column has 4 fuel types. In this work, we did not do any optimization of the shuffling scheme. In actual core design, the axial shuffling scheme should be optimized by taking into account the fuel temperature, neutron leakage etc.

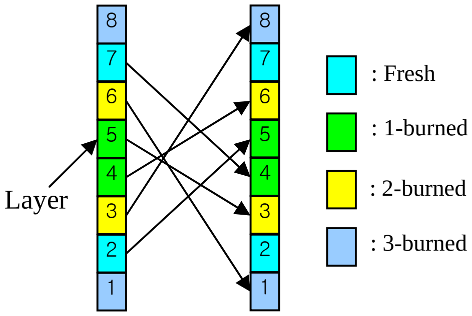


Fig. 7. Axial shuffling scheme in DB-MHR core.

Based on the fuel shuffling in Fig. 7, an equilibrium cycle was searched for the DB-MHR core through repeated Monte Carlo depletion calculations. Figure 8 shows the evolution of the cycle-wise reactivity during the calculations. Between each cycle, a 40-day shutdown period was considered. The equilibrium cycle length is 320 days and the residual reactivity is about 300pcm. The reactivity swing is about 6200pcm over the 320 cycle length. Using this transition scheme, the number of required cycles for an equilibrium cycle is about 3 times the batch size.

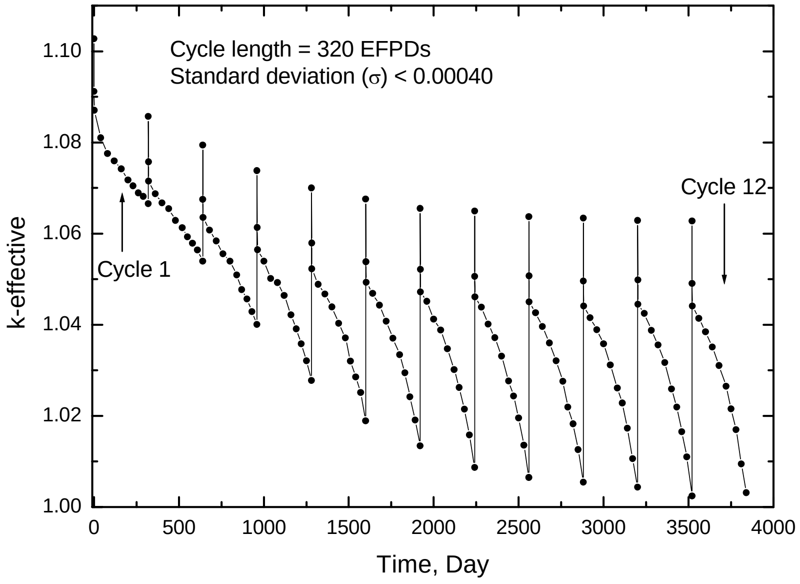


Fig. 8. Equilibrium cycle search by MCCARD.

4.2. Deep-Burn Performance

Table IV summarizes the TRU transmutation performance of the DB-MHR core. One can see that a very high discharge burnup can be achieved, 63.2%, with the 4-batch axial shuffling scheme. In the axially shuffled DB-MHR core, the neutron leakage is quite small, 2.5-2.6%. It is about 3.5% in a conventional radial fuel shuffling scheme.

Table IV. TRU transmutation performance

Region	Heavy metal, kg		Burnup, %	
	BOC	EOC	BOC	EOC
Fresh	303.8	244.3	0	19.6
1-time-burned	244.3	169.4	19.6	44.2
2-time burned	169.4	123.9	44.2	59.2
3-time burned	123.9	111.9	59.2	63.2
Core	841.4	649.5		
Neutron leakage: 2.5% at BOC and 2.6% at EOC Cycle length=320 EFPDs				

Table V and Fig. 9 show the axial and radial power distributions, respectively. From the axial power distribution, it is clear that power density is very low at bottom and top of the core. This is because the most burned-up fuel blocks are placed at the core boundaries, resulting in a reduced axial neutron leakage.

Table V. Axial power distributions

Layer	BOC	EOC
8 (top)	0.30	0.24
7	1.23	1.36
6	1.03	0.82
5	1.46	1.59
4	1.47	1.58
3	1.03	0.80
2	1.20	1.36
1 (bottom)	0.28	0.25

From Fig. 9, it is observed that the radial power distribution is well balanced over the whole core except that the inner-most ring has a relatively high power sharing at BOC and a low power density at EOC. This is because the neutron spectrum is softer due to the inner reflector and the flux level is higher. Consequently, the fuels in the inner-most ring undergo a faster depletion rate. The higher power can be easily controlled by applying a zoning of the fuel packing fraction. Also, it should be mentioned that the power distribution at BOC can also be effectively controlled by using burnable poisons since every fuel column has two fresh blocks.

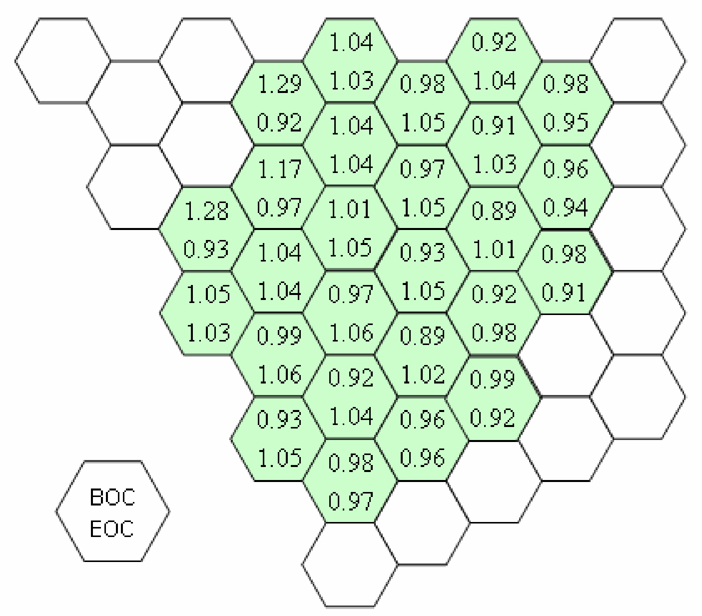


Fig. 9. Radial power distribution.

Table VI. TRU compositions before and after deep-burn (diluted kernel)

Nuclide	Charge		Discharge		
	Mass, kg	Fraction, %	Mass, kg	Fraction, %	Consumption, %
U-234			0.4	0.4	
U-235			0.06	0.05	
U-236			0.02	0.02	
Np-237	20.7	6.8	8.0	7.1	-61
Pu-238	8.7	2.9	18.8	16.8	+116
Pu-239	150.3	49.5	3.1	2.7	-98
Pu-240	69.9	23.0	10.9	9.8	-84
Pu-241	26.7	8.8	14.4	12.9	-46
Pu-242	14.8	4.9	34.0	30.5	+130
Am-241	8.5	2.8	1.7	1.5	-80
Am-242m	0.07	0.02	0.08	0.07	+14
Am-243	4.2	1.4	11.3	10.1	+169
Cm-242			0.6	0.5	
Cm-243			0.04	0.04	
Cm-244			7.9	7.0	
Cm-245			0.5	0.5	
Cm-246			0.1	0.1	

Pu	270.3	88.8	81.2	72.7	-70.0
TRU	303.8	100	111.9	100	-63.2

Table VI shows the discharge composition after deep-burn of 63.2% in DB-MHR. The burnup of plutonium isotopes is 70%, in particular, Pu-239 is almost completely transmuted. Also, Np-237 and Am-241 undergo large transmutation rates. On the other hand, Pu-238 and Pu-242 are significantly accumulated, as well as Am-243 and Cm-244.

4.3. Comparison with Concentrated Kernel

For comparison, similar analyses have been performed with MCCARD describing a conventional concentrated kernel. In this case, the diluted kernel was replaced by a concentrated kernel with a diameter of 200μm. The packing fraction of TRISO was reduced from 35% to 18% so that fuel loading in a fresh block is similar in the two cases.

With the same axial fuel shuffling strategy, an equilibrium cycle was determined for the concentrated kernel, with the results summarized in Table VII. The cycle length is slightly shorter and the fuel burnup smaller.

Table VII. Transmutation performance with a concentrated kernel

Region	Heavy metal, kg		Burnup, %	
	BOC	EOC	BOC	EOC
Fresh	303.7	232.0	0	23.6
1-burned	232.0	173.7	23.6	42.8
2-burned	173.7	132.5	42.8	56.4
3-burned	132.5	117.0	56.4	61.5
Core	841.9	655.2		
Neutron leakage: 2.5% at BOC and 2.7% at EOC Cycle length=310 EFPDs				

More importantly, Figure 10 compares the equilibrium cycle reactivity change in the case of the concentrated kernel with that of the diluted kernel. The reactivity rundown is rather linear with a concentrated kernel, while it is relatively non-linear and more extended with a diluted kernel**.** The reactivity swing is much smaller (6200pcm vs. 8432pcm) with a diluted kernel due to the reduced self-shielding of fuel.

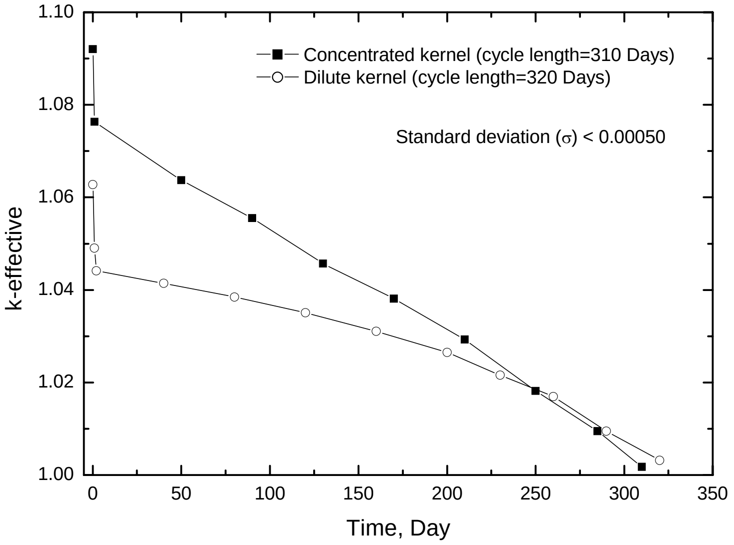


Fig. 10. Comparison of equilibrium cycle reactivity change.

5. CONCLUSIONS

A Monte Carlo equilibrium cycle analysis has been done for a prismatic MHR core loaded with a TRU TRISO fuel. It is confirmed that the RPT method can be successfully applied to a diluted-kernel-based TRISO fuel and 3-D Monte Carlo depletion calculations can be done very efficiently with the aid of the RPT method.

Compared with a conventional concentrated kernel, a diluted kernel provides a noticeably higher TRU discharge burnup in DB-MHR cores. A diluted kernel results in a much smaller burnup reactivity swing than a concentrated kernel. The TRU burnup in a single-pass DB-MHR core can be over 60% either with a diluted or a concentrated kernel.

In this work, optimization of fuel design and management scheme was not considered. It is expected that a substantially higher fuel burnup would be achieved through an optimized diluted kernel design.

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