Preliminary Study on Neutronics Characteristics of Thorium-based Supercritical Water-cooled Fast Reactor

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Abstract

Thorium is a hopeful alternative fuel resource for nuclear power to meet the sustainable development requirement based on its abundance. Besides, it can help to minimize the production of transuranium, as plutonium (and thus the minor actinides) is not a byproduct in the thorium chain. Previously, thorium utilizations in LWR, PHWR and HTGR have been reviewed. As a Generation IV reactor, Supercritical Water-cooled Reactor has some different characteristics, especially for the fast spectrum case (SCFR). To better understand the neutronics characteristics of SCFR and the thorium utilization in SCFR, a preliminary study was carried out based on the pin cell analysis. The work mainly concentrates on the comparisons of spectrums and the burnup effects analysis.

1 Introduction

As one of the six Generation-IV nuclear systems, supercritical water cooled reactor is the only one adopting light water as coolant. With high steam parameters (pressure ~25MPa, temperature 500-550℃) and a single-loop scheme it is possible to obtain a thermal efficiency of ~44%. Besides, due to the high heat transfer performance of supercritical water, the amount of coolant required in the core can be greatly reduced, which makes it possible to arrange the fuel elements in closely-spaced lattices, and the reactor will have a fast neutron spectrum. Supercritical water-cooled fast reactor (SCFR), like the other fast reactor designs, is thought to have some unique advantages, such as breeding capability and transmutation of MAs and LLFPs, etc.

On the other side, thorium is thought to be the most hopeful substitution of uranium as the future nuclear fuel, since the uranium resource is getting used out. Besides, the use of thorium-based fuel would tend to attain high fuel utilization and minimize wastes, i.e., it would conserve uranium and lessen the plutonium (and thus minor actinides) production within the fuel, while allowing a higher destruction rate of any initial charged plutonium and minor actinides.

2 Modelling parameters and computational tools

As for the preliminary study, the pin cell model is adopted, as shown in Figure 1. The pin cell is divided into 12 equal segments along the axial direction, and the coolant densities are calculated with a single-channel code. In order to compare SCFR with the traditional LWRs and FRs, a standard PWR (Pressured Water-cooled Reactor) pin model and a SFR (Sodium-cooled Fast Reactor) pin model are also constructed. Some fixed parameters are listed in Table 1. The fuel composition is changed for different comparison studies.

The Monte Carlo code RMC is used to do the criticality calculation and spectrum analysis, while the MCBurn code is used to analyze the reactivity limited burnup and isotopic contents of the fuel through each burnup step. MCBurn is a coupling system of RMC, which calculates eigenvalues, flux distributions and reaction rates distributions, and ORIGEN, which calculates the generation and depletion of isotopes with a given power or flux.

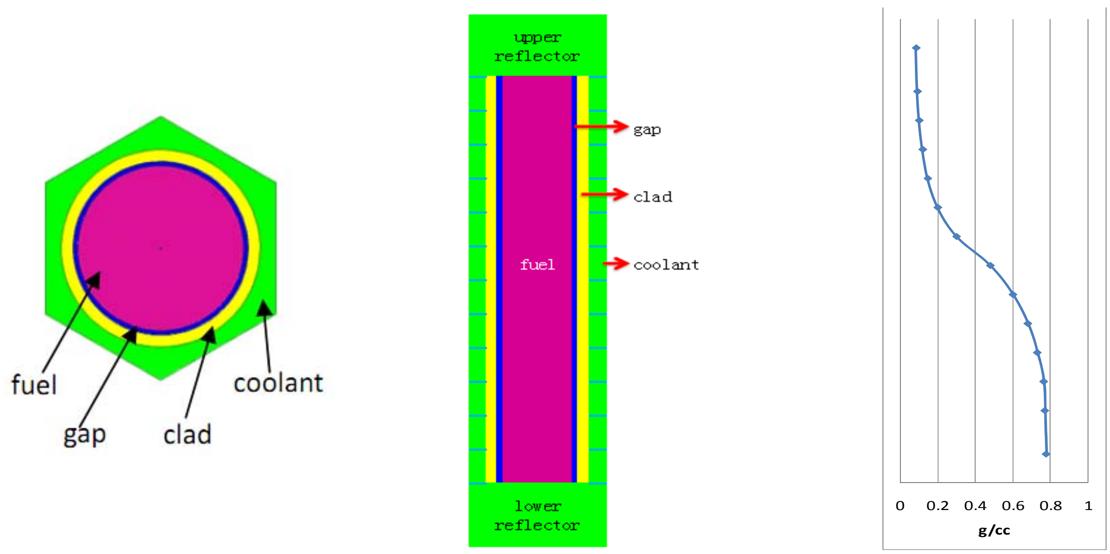


Figure 1 SCFR pin model and the coolant density distribution

Table 1 Cell parameters of PWR, SCFR and SFR

Parameters	PWR	SCFR	SFR
pellet outer diameter (cm)	0.4095	0.368	0.368
clad inner diameter (cm)	0.418	0.388	0.388
clad outer diameter (cm)	0.475	0.44	0.44
active height length (cm)	365.76	120	120
pitch (cm) (geometry style)	1.26 (square)	1.02 (hexagon)	1.02 (hexagon)
reflector height (cm)	26.0	40.0	40.0
inlet/outlet coolant temperature (℃)	286/324	280/510	330/500
clad material	stainless steel	stainless steel	stainless steel

3 Calculations and analyses

3.1 Spectrum comparisons

Supposing the fuel type is 5% enriched UO_2 in the 3 aforementioned pin models, the corresponding spectrums are shown in Figure 2. To better understand the influence of coolant density to the spectrum, a 2D SCFR pin model is analyzed with different coolant densities (DC), and the results are illustrated in Figure 3.

As we can see, the spectrum of SCFR is quit different from PWR and SFR. It's hard to say that it is a fast spectrum, but it is more close to a thermal spectrum. While the coolant density decreases, the spectrum of SCFR is getting harder. We can infer that the differences of spectrums in different axial segments of a SCFR pin cell are big since the coolant density changes a lot along the axial direction. Only when the coolant is nearly void, the spectrum of SCFR is close to the traditional fast spectrum. The large differences of spectrums among not only SCFR, PWR and SFR, but also the different axial segments of a SCFR fuel element, suggest that we should pay special attention to the multi-group neutron data libraries when analyzing SCFR with traditional deterministic codes in future.

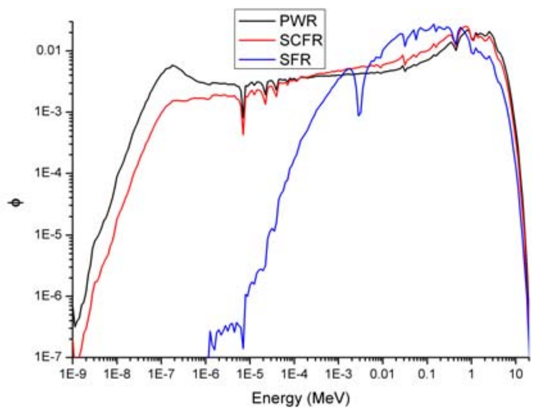


Figure 2 Spectrums of PWR, SCFR and SFR pin models

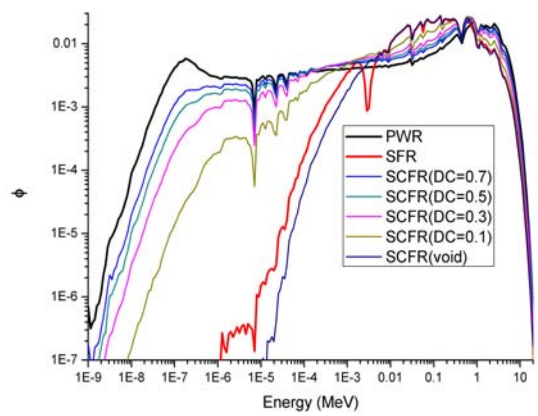


Figure 3 Spectrums of SCFR 2D-pin model with different coolant densities

3.2 The effects of direct homogenization

Due to the long transport distance of fast neutrons, the heterogeneous effects of detailed geometrical description of fuel elements in fast reactors are negligible. We tried to homogenize the whole pin model while keeping the total amounts of nuclides conserved. Comparisons are made between SFR and SCFR pin models, as illustrated in Table 2. It confirms that the influence of direct homogenization in traditional fast reactors is totally negligible, while it is never negligible in SCFR even with low coolant densities. It confirms also that the spectrum of SCFR is not like a traditional fast spectrum, but more close to a thermal spectrum. In addition, it is suggested that the space homogenization effects should be considered, as in the homogenization process of traditional LWRs.

Table 2 Differences between the non-homogeneous and homogeneous cells

Pin types	**Calculation conditions**	**Non-homogenization kinf**	**Homogenization kinf**	**Deviation**
SFR	——	1.25438 ±0.00024	1.25428 ±0.00024	0.008%
SCFR-3D	average coolant density 0.415g/cc	1.22790 ±0.00024	1.11924 ±0.00027	9.7%
SCFR-2D	coolant density 0.101g/cc	1.30604 ±0.00021	1.30192 ±0.00021	0.3%

3.3 The burnup characteristics of Th-SCFR

We still considered PWR and SFR for comparisons. Some burnup calculation parameters are listed in Table 3. Three models have nearly the same specific power and initial kinf. Results are shown in Figure 4, from which we can see: the attainable burnup ratio of PWR, SCFR and SFR is about 1:2:4; the fissile survival ratio (FSR, the ratio of fissile materials over initial loaded fissile materials) of SCFR is much higher than PWR, but a little lower than SFR, which indicates that the conversion ability of SCFR is between PWR and SFR; the U233 accumulation in SCFR is a little slower than SFR due to its softer spectrum; the final depletion of TRU nuclides in SCFR and SFR is close, but the TRU depletion speed of SCFR is faster, considering that the attainable burnup of SCFR is only about half of SFR.

Table 3 Burnup calculation parameters of PWR, SCFR and SFR cells

Pin types (fuel)	**Fuel composition (%wt)**	**Fuel density (g/cm3)**	**Initial loaded HM (g)**	**Specific power (W/gHM)**	**Initial kinf**
PWR (UO2)	U235 (3.1) U238 (96.9)	10.42	1770.02	43.136	1.21477 ±0.00154
SCFR (MN)	Th (80) Pu* (20)	11.55	556.3772	43.135	1.21464 ±0.00171
SFR (MN)	Th (80) Pu* (20)	11.55	556.3772	43.136	1.21844 ±0.00144

*: Isotopic concentrations of Pu: 2.7%Pu238, 47%Pu239, 26%Pu240, 15%Pu241 and 9.3%Pu242.

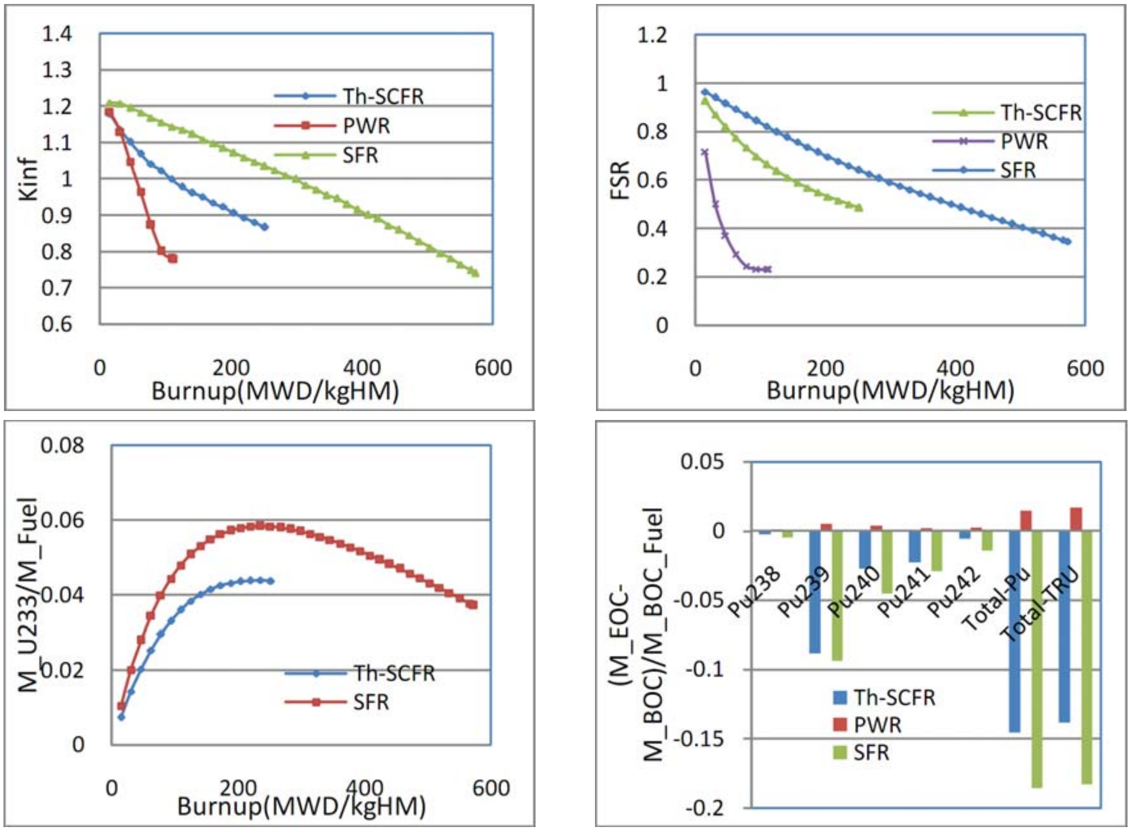


Figure 4 Cell burnup calculation results

3.4 The effects of specific power to burnup characteristics

The burnup characteristics of Th-SCFR are compared under different specific power densities. Some calculation parameters and results are given in Table 4 and Figure 5. Very small increase of attainable burnup is observed while increasing the specific power, but the requirements for materials and reactivity control would be much higher.

Table 4 Attainable burnup of SCFR cell at different specific power densities

Pin types	Pin power (kW)	Specific power (W/gHM)	Attainable burnup (MWD/kgHM)
SCFR	10	17.973	213.6309
	20	35.947	247.3247
	24	43.136	252.3421
	30	53.92	258.6479
	40	71.891	265.9823
SFR	24	43.136	573.489

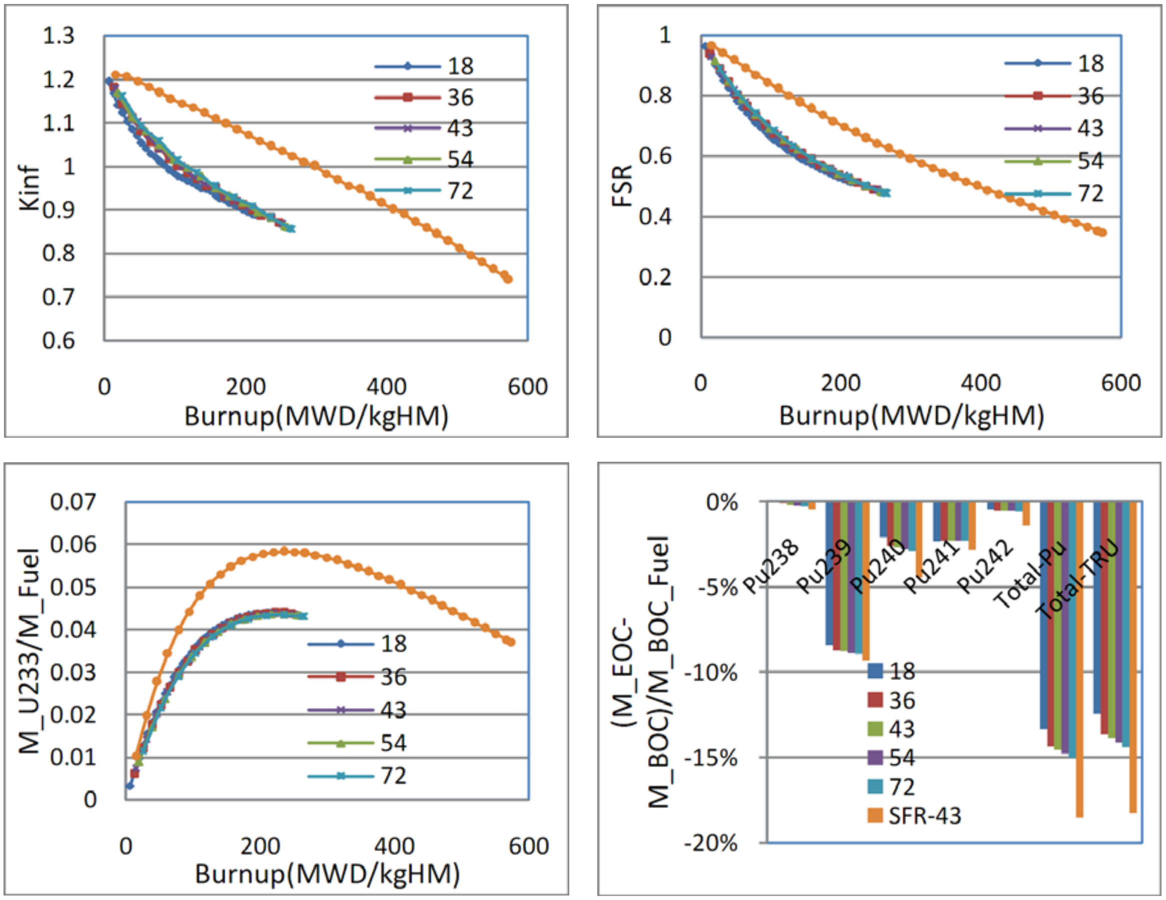


Figure 5 Burnup results of Th-SCFR cell at different specific power densities

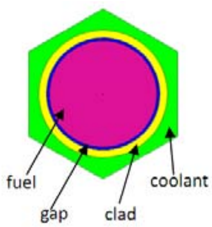
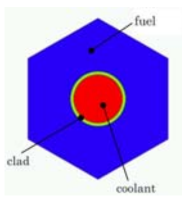
3.5 The effects of fuel volume fraction to burnup characteristics

The burnup characteristics of Th-SCFR cell are compared with different fuel volume fractions. Two pin cell types, the rod-type and briquette-type, are studied. The burnup calculation results are shown in Table 5 and Figure 6. From the results it can be seen that the attainable burnup increases with fuel volume fraction, and when the fuel volume fraction increases to over 80%, the attainable burnup of SCFR is comparable to SFR. One of the obvious disadvantages is that the coolant void coefficient increases with the fuel volume fraction, and when the fuel volume fraction goes over 50%, the coolant void coefficient would be positive.

3.6 The effects of heterogeneous load patterns to burnup characteristics

Here we want to discuss briefly the heterogeneous effects of different load patterns based on the pin cell model. In the above studies, the fuel type of SCFR pin cell is the homogeneous mixture of thorium nitride and plutonium nitride. The heterogeneous effects are studied with thorium nitride and plutonium nitride loaded separately, as shown in Figure 7, and the calculation results are given in Table 6, Figure 8 and Figure 9.

Table 5 Attainable burnup of SCFR cells at different fuel volume fractions

Pin types	Pitch or inner diameter of coolant tube (cm)	Fuel volume fraction (V_fuel/V_Total)	Attainable burnup (MWD/kgHM)
 Rod-type SCFR pin (coolant out)	0.94	0.556	351.9753
	0.98	0.512	295.4671
	1.02	0.472	252.3421
	1.06	0.437	223.167
	1.10	0.406	200.8093
	1.20	0.341	168.0444
 Briquette SCFR pin (coolant in)	0.1	0.821	584.1955
	0.15	0.733	503.4403
	0.2	0.647	419.8197
	0.25	0.566	336.2619
	0.3	0.472	251.9642
SFR pin	1.02	0.472	573.489

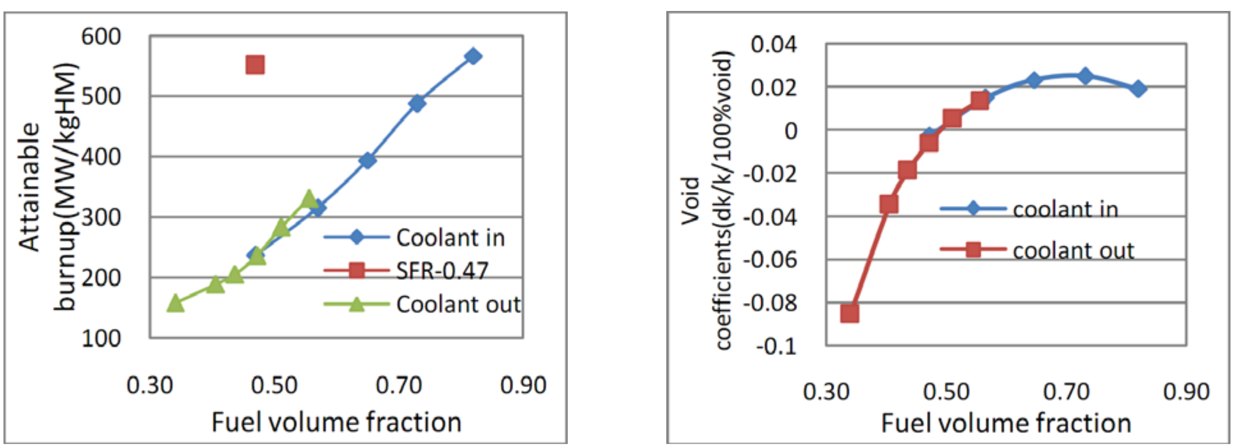


Figure 6 The attainable burnups and coolant void coefficients with different fuel volume fractions

From Table 6 we can see that the heterogeneous load patterns can significantly increase the attainable burnup, which is about 60%~100% higher than the homogeneous load pattern.

From Figure 8 it can be seen that when Pu is loaded together, the initial k-inf would be too big, and the k-inf decreases quicker with burnup, which may be undesirable for reactivity control. When heterogeneously loaded, the amount of U233 increases at the beginning, then decreases, which indicates that U233 is burned on site, and so the attainable burnup is higher than the homogeneous load pattern.

The most obvious one disadvantage of the heterogeneous load patterns is that the local power factors are too high, as can be seen from Figure 9. This would limit the average power density of SCFR, so it should be checked carefully for the heterogeneous designs, or means of flattening the power distribution should be considered.

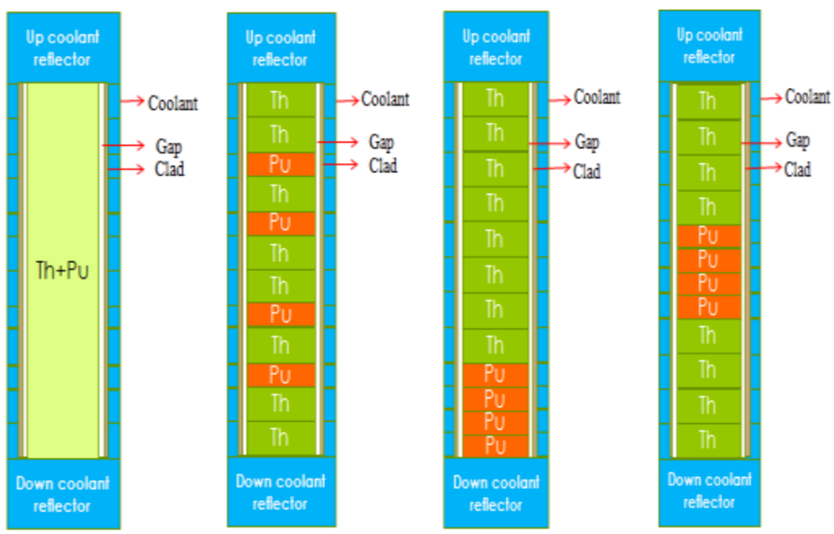


Figure 7 Different load patterns (from left to right): Th-Pu Homo-Loading; Th-Pu Hetero-Loading 1; Th-Pu Hetero-Loading 2; Th-Pu Hetero-Loading 3.

Table 6 Burnup calculation results of different load patterns

Load patterns	**Initial loaded Th (g)**	**Initial loaded Pu (g)**	**Specific power (W/g)**	**Attainable burnup (GWD/tHM)**
Th-Pu Homo-Loading	445.099	111.2748	43.13647	250.215
Th-Pu Hetero-Loading 1	441.792	110.5481	43.45149	422.4587
Th-Pu Hetero-Loading 2	441.792	110.5481	43.45149	409.817
Th-Pu Hetero-Loading 3	441.792	110.5481	43.45149	503.2508
SFR with Th-Pu Homo-Loading	445.099	111.2748	43.13647	573.489

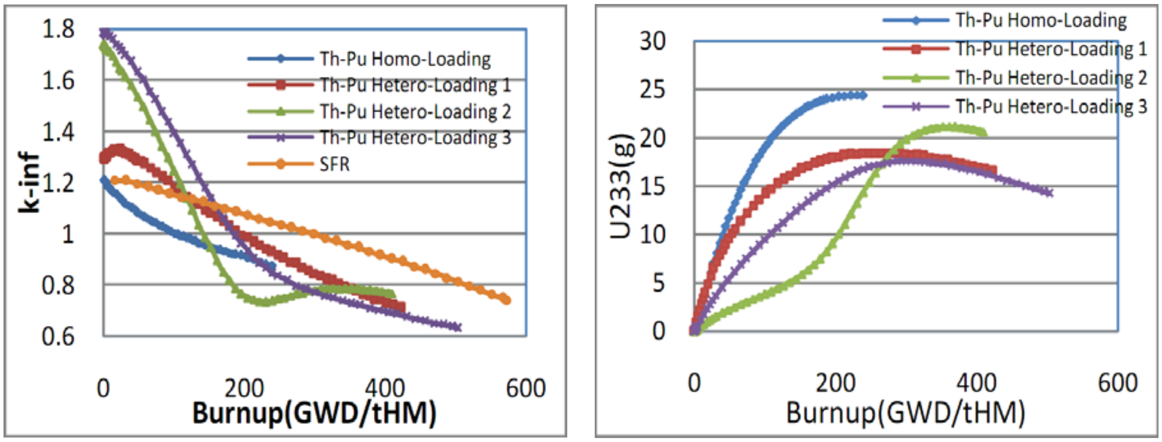


Figure 8 K-inf and U233 buildup versus burnup with different load patterns

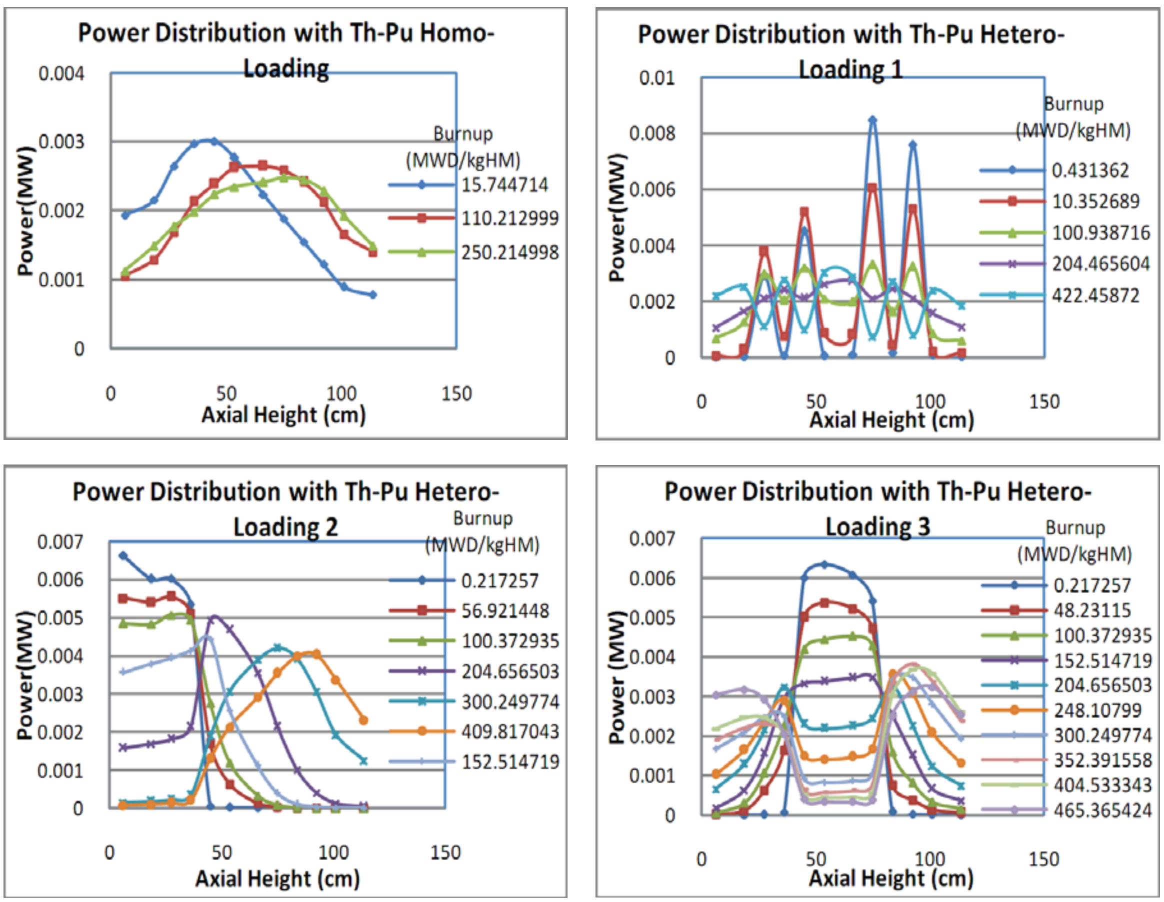


Figure 9 Axial power distribution of SCFR cells with different load patterns

4 Conclusions

The preliminary neutronics analyses of Th-SCFR were carried out based on the pin cell model. Some conclusions are obtained as follows:

a. The spectrum of SCFR is not a traditional fast spectrum, but more close to a traditional thermal spectrum, and it gets harder with the decreasing of coolant density.

b. The direct volume weighted homogenization would introduce big errors in SCFR analysis, which indicates that the space homogenization processes in traditional LWRs should be considered.

c. The burnup characteristics of SCFR are not sensitive to the specific power density, but sensitive to the fuel volume fraction. The attainable burnup increases with fuel volume fraction, but the coolant void coefficients also increase, which should be carefully checked.

d. With heterogeneous load patterns, the attainable burnup could be significantly increased. But the heterogeneous designs should be optimised so as to avoid the big initial k-inf, the quick changing of reactivity with burnup, and the high local power factors.

The further study of SCFR core designs will be carried out in the near future. Special attentions would be paid to the multi-group neutron data libraries due to the uniqueness of SCFR's spectrum.

5 References:

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