

# Neutronics physics analysis of a large fluoride-salt-cooled solidfuel fast reactor with Th-based fuel

Yu Peng<sup>1,2</sup> · Gui-Feng Zhu<sup>1</sup> · Yang Zou<sup>1</sup> · Si-Jia Liu<sup>1,2</sup> · Hong-Jie Xu<sup>1</sup>

Received: 1 April 2017/Revised: 4 May 2017/Accepted: 9 May 2017/Published online: 26 October 2017 © Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Chinese Nuclear Society, Science Press China and Springer Nature Singapore Pte Ltd. 2017

Abstract Fast reactors based on thorium fuel have enhanced inherent safety. Fluoride salt performs well as a coolant in high-temperature nuclear systems. In this paper, we present a reference core for a large fluoride-salt-cooled solid-fuel fast reactor (LSFR) using thorium-uranium fuel cycle. Neutronics physics of the LSFR reference core is investigated with 2D and 3D in-core fuel management strategy. The design parameters analyzed include the fuel volume fraction, power density level and continuous removal of fission products with 3D fuel shuffling that obtains better equilibrium core performance than 2D shuffling. A self-sustained core is achieved for all cases, and the core of 60% fuel volume fraction at 50 MW/m<sup>3</sup> power density is of the best breeding performance (average breeding ratio 1.134). The LSFR core based on thorium fuel is advantageous in its high discharge burn-up of 20-30% fissions per initial heavy metal atom, small reactivity swing over the whole lifetime (to simplify the

This work was supported by the "Strategic Priority Research Program" of the Chinese Academy of Sciences (No. XDA02010200) and the Frontier Science Key Program of Chinese Academy of Sciences (No. QYZDY-SSW-JSC016).

Yang Zou zouyang@sinap.ac.cn

 Hong-Jie Xu xuhongjie@sinap.ac.cn
 Yu Peng pengyu@sinap.ac.cn

<sup>1</sup> Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China

<sup>2</sup> University of Chinese Academy of Sciences, Beijing 100049, China reactivity control system), the negative reactivity temperature coefficient (intrinsically safe for all cases) and accepted cladding peak radiation damage. The LSFR reactor is a good alternative option for the deployment of a self-sustained thorium-based nuclear system.

**Keywords** Fluoride salts · Thorium cycle · Fast reactor · Core characteristics · Equilibrium

## **1** Introduction

Breeder reactors are considered as a unique tool for fully exploiting natural nuclear resources. Thorium is 3-4 times more abundant than uranium, widely distributed in nature as an easily exploitable resource in many countries. As <sup>232</sup>Th is the only isotope present in the thorium ore, enrichment of Th is not necessary for a thorium-fueled reactor [1, 2]. Ever since the inception of nuclear power program, it has been recognized that <sup>232</sup>Th is of immense potential for efficiently breeding fissile isotope <sup>233</sup>U in a thermal neutron reactor. MSR is the best candidate thermal reactor for thorium-uranium breeding, but researches show that a self-breeder MSRs requires a fast removal fission products (FP) and actinide metals (MA) online and the extraction of Pa and the re-introduction of the formed U [3]. Limited studies were carried out on the use of thorium in fast reactors (FRs), historically conceived as breeder reactors, due to the superiority of the uranium-plutonium fuel cycle. The thorium fuel cycle is known to offer a better neutron economy than the uranium fuel cycle at epithermal energies and does not have a large positive reactivity feedback upon spectrum hardening at high neutron energies because  $\eta(^{233}\text{U})$  does not vary with neutron energy as sharply as  $\eta$ <sup>(239</sup>Pu), and the fission cross section of <sup>232</sup>Th has a higher threshold energy and smaller magnitude than those of <sup>238</sup>U [1, 4, 5]. Also the use of thorium-based fuel endures FRs with enhanced inherent safety.

The attractive features of fluoride salts, as a coolant for new reactor types, include lower pressure, higher boiling temperature, optical transparency, higher volumetric heat capacities and lower chemical reactivity [6–16]. MSFR systems with favorable features (large negative temperature and void reactivity coefficients) are perceived as a candidate fast reactor for thorium–uranium breeding. However, since fissile material is dissolved in the molten fluoride salt in an MSFR system, the following problems have been reported [17, 18]:

- 1. Low fuel loading: poor breeding performance caused by limited fuel solubility in the molten salt;
- 2. Difficulties in separating Th, MA and FP from the liquid fuel with immature electrochemical separation technology;
- 3. Risk of radioactive leakage from the pump and heat exchanger due to lack of radioactive inclusion barrier; and
- 4. Necessary development of advanced neutronic and thermal-hydraulic coupling models in the system design.

Thorium breeder reactors using fluoride salt as a coolant based on solid fuel can avoid these problems. The concept of liquid-salt-cooled solid-fuel fast reactor (LSFR) was proposed by Forsberg in 2005 [19], who promoted the development of advanced high-temperature reactor (AHTR) in 2003 [20] and described the preliminary investigations of LSFRs which combined the AHTR plant design with traditional metal-clad-fuel fast reactor cores and the use of liquid salt coolants to improve fast reactor economics [6]. An LSFR uses solid fuel and a clean liquid salt as coolant. It has two implications [19, 21]:

- Salt selection. Existing fluoride salt coolants are based on thermal spectrum, and they may not be suitable for fast spectrum. Studies show that 57%NaF-43%BeF2 (FNaBe) salt is a suitable coolant for LSFR core.
- 2. Material selection. It is necessary to evaluate the structure materials and fuel materials for LSFR core. Two coolants, helium and liquid fluoride salts, have been demonstrated in high-temperature nuclear systems. In the material selection of LSFR, the design of European GFR2400 [22] is used as a reference. The feed fuel is UC/ThC. Carbides have higher heavy metal density than oxides and nitrides, hence better breeding performance. SiC/SiC is used as a cladding material, due to the low neutron absorption rate, high

temperature and irradiation resistance, and compatibility with liquid salt.

However, there is not enough research about comprehensive LSFR core neutronics characteristics, due to the lack of a concrete core layout and equilibrium physics analysis. Due to moderating ability of molten salt, Th-Ufuelled FRs possess breeding capability for a soft spectrum, hence the possibility of designing fluoride-salt-cooled fast breeder reactor.

In a typical low-leakage large fast breeder reactor, the breeding fissile material builds up faster near the axial center of the fuel assembly than the bottom and top of the fuel assembly. In researching Breed and Burn (B&B) reactors, Hou et al. at UCB [23] developed a three-dimensional in-core fuel management strategy and the engineering solution for the 3D shuffling by axially relocating the fuel. The 3D fuel shuffling reduced peak burn-up and increased uranium utilization of B&B reactors. In this paper, we present a large LSFR reference core with detailed information on the geometry and dimensions. Both 2D/3D shuffling methods are used for the reference LSFR core based on thorium-uranium fuel, to investigate the thorium breeding ability and analyze the equilibrium physics for important design parameters, such as fuel volume fraction, process parameters for removing fission gases and power density level.

Section 2 is a detailed description of the reference LSFR, including the 2D/3D fuel shuffling strategies and the modeling methodology used. In Sect. 3, equilibrium of core neutronics with 2D and 3D fuel shuffling is given, and the LSFR core parameters of equilibrium state for different influencing factors are presented. Section 4 is conclusion of the study.

### 2 LSFR core modeling

### 2.1 LSFR core description

The concept core is a large fluoride-salt-cooled fast reactor of low leakage rate. This LSFR core of Th-U cycle is designed in reference to the experience accumulated in the international development and design of fast reactors. As shown in Fig. 1, the cylindrical core is in similar geometry to the UCB B&B reactor [20], the core dimensions and composition of the regions modeled for the LSFR core are given in Table 1. The effective core height is 300 cm, with equivalent diameter of 504.6 cm, giving a total active core volume of  $60.0 \text{ m}^3$ . The upper and radial reflectors are made of  $Zr_3Si_2$ . The lower and radial shields are made of  $B_4C$ . The fuel compositions are given in Table 2. The fuel volume fraction of active zone is 0.45.



Fig. 1 Schematic layout of cylindrical LSFR core

### 2.2 Fuel management strategy

In order to breed <sup>233</sup>U in low-reactivity assemblies and to decrease power peaking factor (ppf), a twelve-batch scheme is adopted to promote reactivity sharing between low-reactivity assemblies and high-reactivity assemblies. The 12-batch reload sequence is designed to optimize three competing goals. First, the scheme must promote reactivity sharing between partially burnt and fresh fuel assemblies. Second, the reduction of core leakage shall be minimized to improve the neutron economy. Third, a radial power shape shall be as flat as possible to minimize the ppf. After the comprehensive comparison for many different shuffling schemes, an optimal radial shuffling scheme for the reference LSFR core is shown in Fig. 2a. It minimizes the ppf and the burn-up reactivity swings at acceptable low core leakage. To maintain the low core leakage while minimizing the ppf, the 3D shuffling scheme optimization is the same with the principles of Ref. [23]. Figure 2b shows the optimized 3D shuffling scheme.

As the neutron mean free path in typical FRs is larger than the lattice pitch, it is common to represent each burnup node for neutronic analysis as homogenized fuel, cladding, other structural materials, and the coolant are mixed by their volume fractions. A heterogeneous structure of a fuel assembly with the same fuel composition as the LSFR active zone is shown in Fig. 3, and its geometrical properties and materials are given in Table 3. Table 4 compares results from  $k_{inf}$ , mean free path (MFP) and one-group cross section of  $^{232}$ Th and  $^{233}$ U for various residence

Table 1 Dimensions and composition of the regions modeled for the LSFR core

Region	Height (cm)	Thickness (cm)	Fraction (vol%)	Density (g/cm <sup>3</sup> )
Upper reflector	34.9	293.3	50% Zr <sub>3</sub> Si <sub>2</sub> -50% FNaBe	3.44550
Upper end plug	2.5	252.3	22% Zr <sub>3</sub> Si <sub>2</sub> -78% FNaBe	2.64218
Plenum	209.4	252.3	22% Zr <sub>3</sub> Si <sub>2</sub> 28% FNaBe	1.63668
Enriched fuel	300.0	252.3		
Lower end plug	90.4	252.3	22% Zr <sub>3</sub> Si <sub>2</sub> -78% FNaBe	2.64218
Grid plate	5.2	293.3	50% Zr <sub>3</sub> Si <sub>2</sub> -50% FNaBe	3.44550
Coolant inlet	60.0	293.3	22% Zr <sub>3</sub> Si <sub>2</sub> -78% FNaBe	2.64218
Lower shield	20.0	293.3	43.1% B <sub>4</sub> C-29.7% Zr <sub>3</sub> Si <sub>2</sub> -27.2% FNaBe	3.08247
Radial reflector	511.7	41.0	50% Zr <sub>3</sub> Si <sub>2</sub> -50% FNaBe	3.44550
Radial shield	722.4	20.5	43.1% B <sub>4</sub> C–29.7% Zr <sub>3</sub> Si <sub>2</sub> –27.2% FNaBe	3.08247

Table 2         Enriched fuel
composition for the LSFR core
studied

Constituents	Material	Density (g/cm <sup>3</sup> )	Vol. fraction (%)
Fuel	UC/ThC <sup>a</sup>	11.56/9.01	45
Gap	He	0.00179	3.24
Cladding	Porous SiC	0.936	25
Wire	Compact SiC	3.18	0.92
Active coolant	FNaBe	2.011	20
Duct	Compact SiC	3.18	4.04
Inter-assembly coolant	FNaBe	2.011	1.8

<sup>a</sup>Values include the 15% porosity of the ceramic fuel



Fig. 2 Schematics of an optimal 2D (a) and 3D (b) shuffling schemes for the reference LSFR core. The batch numbers are 1-12



Fig. 3 Cross-sectional view of the fuel assembly for the calculations

time between the 0D mixture model and assembly model. The results obtained using a homogenized core model are usually in acceptable agreement with those obtained using a heterogeneous model, but the use of the homogenized model saves computational time significantly [24]. For further reducing the computational time, the numerical modeling adopts a 1/32 symmetry core model in  $\theta$  direction. The model is divided into 12 equal volumes radially and 8 axially for a total of 96 burn-up zones, each subbatch is axially divided into 2 burn-up zones. This is

acceptable for burn-up calculation and effectively reflecting the axial discharge difference.

### 2.3 Calculation procedure

The calculation is based on MCNP5 and MOBAT [25]. MOBAT is a MCNP5-ORIGEN2 coupled program developed at Shanghai Institute of Applied Physics with ENDFB-VII database. Its role is to couple ORIGEN2 with MCNP5 for burn-up analysis for arbitrary core models, and the correctness and its effectiveness has been verified.

The design objectives for fast breeder reactors can be formulated as [1]: (1) high breeding ratio, (2) low fissile inventory and (3) high burn-up fuel. Previous research based on 0D model for the neutron balance equation unique solution could achieve these design objectives. The <sup>233</sup>U atom percentage  $\epsilon$  in heavy metal (HM) and discharge burn-up for various leakage rates in the previous results [26] can initialize the parameters:  $\epsilon$  and cycle length *T* for the core fuel management. The initial concentration of nuclides for different batches in MCNP5 input card implies a hypothesis that the fuel burn-up intervals for different batches are uniform, and therefore, the concentration of nuclides at the same burn-up level in 0D calculation can initialize the core material composition.

Figure 4 shows the flowchart of the equilibrium calculation method for the reference LSFR core. First, the active zone leakage rate can be obtained from the estimate for MCNP5 calculation with the fuel shuffling. Second, according to estimated leakage rate for active zone, the

 Table 3 Geometrical

 properties of fuel element and

 assembly

Fuel element			Fuel assembly			
Region	Material	Radius (mm)	Parameters	Value		
Pin	UC/ThC	3.5677	Wrapper material	Compact SiC		
Gap	He	3.6939	Coolant (outside FA)	FNaBe		
Clad	Porous SiC	4.5515	Active height (cm)	150		
Liner	Compact SiC	4.5800	No. of pins (pcs)	271		

Table 4 Physical parameters of 0D model (0 M) and assembly model (AM) for various fuel residence time

Residence time/year	k <sub>inf</sub>		MFP (cm)		<sup>232</sup> Th			<sup>233</sup> U				
					(n,g)/barn		(n,f)/bar	n	(n,g)/barn		(n,f)/barn	
	0M	AM	0M	AM	0M	AM	0M	AM	0M	AM	0M	AM
0	0.93635	0.94459	3.905	4.063	0.411	0.392	0.0112	0.0114	0.412	0.389	3.093	2.976
4.172	1.00743	0.99052	3.893	4.066	0.403	0.387	0.0116	0.0116	0.392	0.378	2.985	2.920
14.986	1.04482	1.04573	3.852	4.036	0.404	0.383	0.0116	0.0118	0.382	0.368	2.931	2.865



Fig. 4 Flowchart of the equilibrium calculation method for the core

initial  $\epsilon$  and *T* can be interpolated from the results of 0D model. Third, burn-up analysis is calculated by MOBAT. It is worth noting that using the 0D burn-up calculation to initialize the materials for different batches in MOBAT input card can save computing time for accelerating into equilibrium state. Fourth, the minimum effective multiple factor for equilibrium  $k_{eq,min}$  should be greater than unity to maintain criticality; 1.001 is assumed for the upper permissible  $k_{eq,min}$  at equilibrium to reduce  $\epsilon$  value. Or the calculation will modify  $\epsilon$  and *T* according to existing results. The whole calculations are terminated if the requirements are satisfied.

An additional term FMR (fissile material ratio from *t* to  $t_0$ ) is proposed for the <sup>233</sup>U fissile material mass at any time *t* for multiple recycling of recovered thorium and uranium with FMR > 1.0 to a self-sustained core at least. FMR is defined as:

$$FMR(t) = \frac{^{233}U \text{ fissile material}(t)}{^{233}U \text{ fissile material}(t_0)}$$
(1)

Table 5 LSFR core parameters using 2D and 3D fuel shuffling at 50  $\ensuremath{\text{MW/m^3}}$ 

Core parameters	2D	3D
Cycle length (EFPD)	1530	1530
<sup>233</sup> U atoms percentage in HM (%)	7.964	7.664
Average FMR at discharges	1.013	1.090
Reactivity swing (% \delta k/k)	0.607	0.542
Average discharge burn-up (% FIMA)	23.22	23.60
Peak discharge burn-up (% FIMA)	29.06	25.78
Peak radiation damage (DPA)	164.35	144.91
Leakage rate at BOEC (%)	3.19	2.75
Leakage rate at EOEC (%)	3.70	3.00
Power peaking factor at BOEC	2.97	3.25
Power peaking factor at EOEC	2.12	2.12

### **3 Results**

### 3.1 2D and 3D fuel shuffling

LSFR core parameters with a volumetric power density of 50 MW/m<sup>3</sup> for a total core power of 3000 MW<sub>th</sub> using 2D and 3D fuel shuffling are given in Table 5. The reactivity swing for LSFR core based on thorium–uranium fuel cycle is 0.607% with 2D fuel shuffling and 0.542% with 3D fuel shuffling, obviously less than the reactivity of FRs based on U–Pu fuel. With 3D fuel shuffling, the initial <sup>233</sup>U  $\varepsilon$  was reduced to 7.664% due to <sup>233</sup>U build up in the axial direction more uniformly.

Figure 5 compares the fuel sub-zone average FMR at EOEC for different fuel batches of the two cores. The position of sub-zone represents batch number from Batch 1 to Batch 12 in horizontal direction and initial fresh fuel subassembly from the bottom to the top of core in vertical direction, which reflects the FMR evolution with fuel batch. Figure 6a shows the <sup>233</sup>U content peaks at Batch 6 with FMR = 1.154, while Fig. 6b shows the peaks at Batch 8 with FMR = 1.182. This indicates 3D fuel shuffling improves the utilization of nuclear fuel. Moreover, the average FMR at discharges is 1.090 for 3D shuffling versus 1.013 for 2D shuffling.



Fig. 5 FMR evolution of fuel sub-zone with fuel batch for 2D (a) and 3D (b) fuel shuffling



Fig. 6 Discharge burn-up of half-subassemblies using 2D and 3D fuel shuffling. A–B are of one subassembly, and so are the other pairs

The discharge burn-up of eight half-subassemblies with 2D and 3D fuel shuffling is shown in Fig. 6. The 3D discharge burn-up peaking factor is only 1.09, allowing the discharge burn-up distributed quite uniformly over the axial fuel. The maximum–minimum discharge burn-up ratio is close to 2. The 3D fuel management strategy can reduce the peak burn-up and corresponding radiation damage of fuel cladding.

3D fuel shuffling requires maintaining the low core leakage, while minimizing the power peaking. The leakage rate at EOEC is 3.0% with 3D shuffling, while it is 3.7% with 2D shuffling. The ppfs of 2D and 3D fuel shuffling are close to each other. The axial flux distribution along the core at EOEC with 2D and 3D fuel shuffling is presented in Fig. 7. The flux peak occurs in the center position of the core for both the fuel shuffling, but the 3D shuffling has higher flux peak and lower flux at both ends, hence lower leakage rate.

As 3D shuffling offers better breeding capability, the parameters using just 3D shuffling are given in following sections.



Fig. 7 Axial flux distribution along the core at EOEC with 2D and 3D fuel shuffling

# **3.2** Equilibrium core for different design parameters

### 3.2.1 Fuel volume fraction

Many of the inter-connected parameters of the fast reactor core design can be attributed to the fuel volume fractions which affect the spectrum and parasitic absorption. LSFR core parameters for various fuel volume fractions are given in Table 6 with the total percentage of the fuel and active coolant volume percentage fixed as 65%.

From Table 6, the core of high fuel volume fractions requires low <sup>233</sup>U fissile inventory and achieves good breeding performance. Taking the core of 0.60 fuel volume fraction for example, the initial <sup>233</sup>U atoms percentage in HM is 5.0%, the breeding ratio is 1.153 at BOEC and 1.114 at EOEC, which leads to high average FMR at discharge of 1.433. The core of high fuel volume fraction reduces the parasitic absorption rate, hence low leakage rate and good neutron economy. At the fuel volume fractions of 0.45, 0.50 and 0.60, the leakage rates at EOEC of active zone are 3.00, 2.67 and 2.07%, respectively. However, at high fuel volume fraction, the reactivity swing, discharge burn-up peaking factor, peak radiation damage and ppf are greater.

Table 6	LSFR	core	parameters	for	various	fuel	volume	fractions
with 3D	fuel sh	ufflin	g					

 Table 7
 LSFR core parameters at 100 MW/m<sup>3</sup> power density level with 3D fuel shuffling

Fuel volume fraction	0.45	0.50	0.60
Cycle length (EFPD)	1530	1920	2370
<sup>233</sup> U atoms percentage in HM (%)	7.664	6.688	5.000
Average FMR at discharges	1.090	1.166	1.433
Reactivity swing (% δk/k)	0.542	0.710	0.968
Average discharge burn-up (% FIMA)	23.60	26.63	27.30
Peak discharge burn-up (% FIMA)	25.78	29.64	32.94
Peak radiation damage (DPA)	144.91	194.05	285.23
Leakage rate at BOEC (%)	2.75	2.37	1.78
Leakage rate at EOEC (%)	3.00	2.67	2.07
Power peaking factor at BOEC	3.25	3.70	5.67
Power peaking factor at EOEC	2.12	2.33	3.00

0.45	0.50	0.60
600	870	1140
8.352	7.454	5.777
1.018	1.051	1.202
0.687	0.812	1.138
19.02	24.16	26.29
20.47	26.24	29.85
103.98	176.48	276.03
3.10	2.60	1.93
3.39	3.01	2.51
2.67	3.26	4.74
1.99	2.09	2.50
	0.45 600 8.352 1.018 0.687 19.02 20.47 103.98 3.10 3.39 2.67 1.99	0.45     0.50       600     870       8.352     7.454       1.018     1.051       0.687     0.812       19.02     24.16       20.47     26.24       103.98     176.48       3.10     2.60       3.39     3.01       2.67     3.26       1.99     2.09

The axial discharge burn-up becomes more uneven as the fuel volume fraction increases.

Figure 8a shows the discharge burn-up of eight halfsubassemblies for fuel volume fractions of 0.45–0.60. The discharge burn-up peaking factors are 1.09, 1.11 and 1.21 for fuel volume fractions of 0.45, 0.50 and 0.60, respectively. The ppf at BOEC reaches up to 5.67 at 0.60 fuel volume fraction, and this is obviously unacceptable. Moreover, at 0.60 fuel volume fraction, the peak cladding radiation damage is 285.23 dpa (displacements per atom), which exceeds the presently demonstrated clad radiation damage limit of 200 dpa. Figure 8b shows the normalized neutron flux for fuel volume fraction of 0.45–0.60. It can be seen that the core with high fuel volume fraction has hard energy spectrum.

### 3.2.2 Power density level

At 50  $MW/m^3$  power density and 0.45 fuel volume fraction, the cycle length is 1530 EFPD due to long retention time in the core for fuel assembly. Improving

power density can reduce cycle length and increase the plant economy. Table 7 lists the LSFR core parameters at 100 MW/m<sup>3</sup> power density level for fuel volume fraction of 0.45–0.60. The initial <sup>233</sup>U atoms percentage in HM for the core at 100 MW/m<sup>3</sup> power density is slightly larger due to smaller average FMR at discharges. The average discharge burn-up is 18.20% FIMA at 100 MW/m<sup>3</sup>, while it is 23.60% FIMA at 50 MW/m<sup>3</sup>. At 100 MW/m<sup>3</sup> power density, the leakage rate is slightly larger, but the ppf and peak radiation damage are smaller. The difference of average discharge burn-up for the two power density levels diminishes as the fuel volume fraction increases. This indicates that the core for high fuel volume is conducive to the operation of the reactor at large power density level.

Figure 9 shows the axial flux distribution along the core at EOEC for power densities of 50 and 100 MW/m<sup>3</sup> at 0.45 fuel volume fraction. The flux at 50 MW/m<sup>3</sup> is more flatting than at 100 MW/m<sup>3</sup>. The peak flux for 50 MW/m<sup>3</sup> is  $2.31 \times 10^{14}$  at 135 cm from the bottom, while it is  $4.26 \times 10^{14}$  at 145 cm for 100 MW/m<sup>3</sup>.



Fig. 8 Discharge burn-up of eight half-subassemblies (a) and normalized neutron flux (b) for fuel volume fractions of 0.45–0.60



Fig. 9 Axial flux distribution along the core at EOEC for power density of 50 and 100 MW/cm<sup>3</sup> at 0.45 fuel volume fraction

 
 Table 8
 LSFR core parameters using 3D fuel shuffling with continuous removal of fission gases

Power density (MW/m <sup>3</sup> )	100	50
Cycle length (EFPD)	840	1980
<sup>233</sup> U atoms percentage in HM (%)	7.788	6.922
Average FMR at discharges	1.006	1.100
Reactivity swing (% 8k/k)	0.817	0.574
Average discharge burn-up (% FIMA)	25.75	30.54
Peak discharge burn-up (% FIMA)	27.65	33.43
Peak radiation damage (DPA)	159.51	183.55
Leakage rate at BOEC (%)	2.82	2.48
Leakage rate at EOEC (%)	3.24	2.95
Power peaking factor at BOEC	3.05	3.46
Power peaking factor at EOEC	2.10	2.24

### 3.2.3 Continuous removal of fission gases

Removal fractions for a variety of volatile fission products in FRs have been studied [27]. In this section, the continuous 100% (except for I, 75%) removal of fission product noble gases (Xe and Kr) and volatile gases at high temperatures (Cs, Cd, Rb and I) is assumed in every burnup calculation through a nuclear process off-gases system, possibly helium bubbling [28]. Table 8 lists the LSFR core parameters using 3D fuel shuffling with continuous removal of fission gases at 0.45 fuel volume fraction. With continuous removing volatile fission products, LSFR core achieves a good breeding performance, with increased nuclear fuel utilization. There is little difference between the average FMR at discharges with and without removing fission gases, but clearly the average discharge burn-up and the peak FMR become greater with removing fission gases. At 50 MW/m<sup>3</sup> power density, the initial <sup>233</sup>U atoms percentages in HM are 30.54 and 23.6% FIMA, and the peak FMRs are 1.294 (at Batch 6) and 1.182, without removing fission gases, respectively. With the removal fractions for a variety of volatile fission gases, the leakage rate decreases slightly due to the reduction in the neutron parasitic absorption of fission products.

#### **3.3** Temperature reactivity coefficients

The temperature coefficients include the reactivity coefficient of fuel (or Doppler coefficient)  $T_{\rm F}$ , the coolant  $T_{\rm C}$ , the structure material in active zone  $T_{\rm S}$  and the reflector regions  $T_{\rm R}$ . The results for 0.45 fuel volume fraction at

Table 9 LSFR core temperature reactivity coefficients for 0.45 fuel volume fraction at BOEC and EOEC with 3D shuffling

Power density (MW/m <sup>3</sup> )	State	$T_{\rm F}$ (PCM/K)	$T_{\rm C}$ (PCM/K)	$T_{\rm S}$ (PCM/K)	T <sub>R</sub> (PCM/K)	Total (PCM/K)
100	BOEC	- 1.949	0.756	0.050	- 0.299	- 1.442
	EOEC	- 1.679	0.718	0.199	0.224	- 0.537
50	BOEC	- 2.012	0.848	0.025	- 0.125	- 1.264
	EOEC	- 1.761	0.917	0.058	0.199	-0.587



Fig. 10 Coolant (a) and fuel (b) coefficient at EOEC as a function of fuel volume fraction

BOEC and EOEC with 3D shuffling are presented in Table 9. It can be seen that although the coolant displays a foremost positive reactivity coefficient part, the overall value is negative due to the large negative contribution of the fuel. The  $T_{\rm F}$  value decreases with burn-up, but  $T_{\rm C}$  has little relationship from BOEC to EOEC. The coolant and fuel reactivity coefficient as a function of fuel volume fraction at EOEC with 3D shuffling are shown in Fig. 10. The total temperature reactivity coefficient for all cases is negative which shows the enhanced inherent safety of the LSFR core with thorium–uranium fuel.

### 4 Conclusion

Both 2D and 3D in-core fuel management strategies are adopted for equilibrium analysis of the LSFR core. The 3D fuel shuffling method for the LSFR core equilibrium analyzes parameters such as fuel volume fractions, power density level and continuous removal of fission gases. The main conclusions are as follows:

Both 2D and 3D shuffling strategies can achieve a selfsustaining core, but 3D fuel shuffling can reduce the initial fissile inventory, flatten discharge burn-up and achieve a good breeding performance.

At 50 MW/m<sup>3</sup>, comparing to the core of 0.45 fuel volume fraction, the core of 0.60 fuel volume fraction offers about 35% reduction in  $^{233}$ U fissile inventory, 15.7% increase in the average discharge burn-up, 31% reduction in the leakage rate of active zone and 31.5% increase in average FMR at discharges, but brings larger discharge burn-up peaking factor, larger cladding peak radiation damage and the obvious ppf increase. The core of 0.60 fuel volume fraction at 50 MW/m<sup>3</sup> power density has the best breeding performance of all cases, with an average breeding ratio of 1.134, while it is 1.062 for the core of 0.45 fuel volume fraction. It explains that the breeding capacity of the LSFR core based on thorium fuel is limited.

By doubling the power density level, the LSFR core has more than half reduction in cycle length and receives a 10–15% reduction in ppf and 21% reduction in cladding peak radiation damage for 0.45 fuel volume fraction. The peak cladding radiation damage for the core of 0.60 fuel volume fraction at 50 MW/m<sup>3</sup> power density is 285.23 dpa, while at 100 MW/m<sup>3</sup> it is 276.03 dpa, which exceeds the presently demonstrated clad radiation damage limit of 200 dpa. Moreover, low power density promotes the breeding behavior and is beneficial to smaller reactivity swing.

The employment of continuous removal of fission gases processing can reduce the <sup>233</sup>U fissile inventory, increase discharge burn-up and obtain a good breeding performance significantly.

The design of a large fluoride-salt-cooled fast breeder reactor based on thorium–uranium fuel is feasible, but the breeding capacity is limited. It achieves: (1) a high discharge burn-up of 20–30% FIMA, (2) small reactivity swing over whole lifetime to improve the safety and simplify the reactivity control system, (3) the negative reactivity temperature coefficient for all cases with intrinsically safe and (4) the accepted cladding peak radiation damage. These characteristics of LSFR core provide a good alternative option for the deployment of a self-sustained thorium-based nuclear energy system in the future.

Future studies will give a simple thermal hydraulic analysis and the final reference design for LSFR core.

### References

- 1. A.E. Waltar, D.R. Todd, P.V. Tsvetkov (eds.), *Fast Spectrum Reactors* (Springer, New York, 2012)
- A. Demirbas, Options and trends of thorium fuel utilization. Energy Source 27, 597–603 (2005). doi:10.1080/ 00908310490448596
- K. Nagy, J.L. Kloosterman, D. Lathouwers et al., Van der Hagen, Parametric studies on the fuel salt composition in thermal molten salt breeder reactors, in *The International Conference on Physics* of *Reactors 2008 (PHYSOR 08)*, Interlaken, Switzerland, 14–19 September 2008
- C. Fiorina, J. Krepel, A. Cammi et al., Analysis of thorium and uranium fuel cycles in an iso-breeder lead fast reactor using extended-EQL3D procedure. Ann. Nucl. Energy 53, 492–506 (2013). doi:10.1016/j.anucene.2012.09.004
- G.C. Li, Y. Zou, C.G. Yu et al., Influences of 7Li enrichment on Th–U fuel breeding for an Improved Molten Salt Fast Reactor (IMSFR). Nucl. Sci. Tech. 28, 97 (2017). doi:10.1007/s41365-017-0250-7
- C.W. Forsberg, Use of liquid salt coolants to improve fast-reactor economics. Paper presented at the economic analysis of fast reactors American nuclear society annual meeting, Boston, Massachusetts, 24–28 June 2007
- D.F. Williams, L.M. Toth, K.T. Clarno, Assessment of Candidate Molten Salt Coolants for the Advanced High Temperature Reactor (AHTR), 1st edn. Technical Report ORNL/TM-2006/12 (United States, Department of Energy, 2006), pp. 1–69
- A. Acır, Neutronic analysis of the laser inertial confinement fusion-fission energy (LIFE) engine using various thorium molten salts. J. Fusion Energy **32**, 634–641 (2013). doi:10.1007/s10894-013-9628-7
- A. Acır, Improvement of the neutronic performance of the PACER fusion concept using thorium molten salt with reactor grade plutonium. J. Fusion Energy 32, 11–14 (2013). doi:10. 1007/s10894-012-9518-4
- M. Übeyli, A. Acır, Neutronic investigation on the ARIES-ST fusion reactor with fissionable molten salts. Energy Convers. Manag. 51, 2531–2534 (2010). doi:10.1016/j.enconman.2010.05. 018
- J.X. Zuo, J.P. Jing, J.S. Bi et al., Framework analysis of fluoride salt-cooled high temperature reactor probabilistic safety assessment. Nucl. Sci. Tech. 26, 050602 (2015). doi:10.13538/j.1001-8042/nst.26.050602

- C. Xue, Z.Y. Zhu, H.Q. Zhang et al., In-core fuel management strategy for the basket-fuel-assembly molten salt reactor. Nucl. Sci. Tech. 28, 130 (2017). doi:10.1007/s41365-017-0286-8
- J. Ruan, B. Xu, M.H. Li et al., A specialized code for operation transient analysis and its application in fluoride salt-cooled hightemperature reactors. Nucl. Sci. Tech. 28, 119 (2017). doi:10. 1007/s41365-017-0268-x
- K. Yang, W. Qin, J.G. Chen et al., Neutron excess method for performance assessment of thorium-based fuel in a breed-andburn reactor with various coolants. Nucl. Sci. Tech. 27, 99 (2016). doi:10.1007/s41365-016-0096-4
- Z.B. Liu, Y. Liu, G.M. Liu et al., Reactor protection system testing for the solid fuel thorium molten salt reactor. Nucl. Sci. Tech. 27, 123 (2016). doi:10.1007/s41365-016-0091-9
- G.M. Sun, M.S. Cheng, Development of a MCNP5 and ORI-GEN2 based burnup code for molten salt reactor. Nucl. Sci. Tech. 27, 65 (2016). doi:10.1007/s41365-016-0070-1
- C. Behar, Technology roadmap update for Generation IV nuclear energy systems. (IOP Publishing Physics Web, 2014), https:// www.gen-4.org/gif/upload/docs/application/pdf/2014-03/giftru2014.pdf. Accessed March 2014
- G. Locatelli, M. Mancini, N. Todeschini, Generation IV nuclear reactors: current status and future prospects. Energy Policy 61, 1503–1520 (2013). doi:10.1016/j.enpol.2013.06.101
- C.W. Forsberg, P.F. Peterson, D.F. Williams, Practical aspects of liquid-salt-cooled fast-neutron reactors, in *The International Congress on Advances in Nuclear Power Plants 2005: ICAPP 05*, Seoul, Korea, 15–19 May 2005
- 20. C.W. Forsberg, P.F. Peterson, P.S. Pickard, Molten-salt-cooled advanced high-temperature reactor for production of hydrogen

and electricity. Nucl. Technol. **144**, 289–302 (2003). doi:10. 13182/NT03-1

- C.W. Forsberg, C.L. Brun, D.F. E.M. Lucotte et al., Practical aspects of liquid-salt-cooled fast-neutron reactors, in *The International Congress on Advances in Nuclear Power Plants 2007: ICAPP 07*, Nice, France, 13–18 May 2007
- Z. Perkó, S. Pelloni, K. Mikityuk et al., Core neutronics characterization of the GFR2400 gas cooled fast reactor. Prog. Nucl. Energy 83, 460–481 (2015). doi:10.1016/j.pnucene.2014.09.016
- 23. J. Hou, S. Qvist, E. Greenspan, 3-D fuel shuffling for reduced peak burnup and increased uranium utilization of breed-and-burn reactors, in *The International Congress on Advances in Nuclear Power Plants 2015: ICAPP 2015*, Nice, France, 03–06 May 2015
- F. Heidet, E. Greenspan, Neutron balance analysis for sustainability of breed-and-burn reactors. Nucl. Sci. Eng. 171, 13–31 (2012). doi:10.13182/NSE10-114
- G.F. Zhu, Dissertation, University of Chinese Academy of Sciences, 2015
- Y. Peng, G.F. Zhu, Y. Zou et al., in *Progress in Nuclear Energy*, ed. by N. Vishwaraj (Elsevier, Amsterdam, 2017). (in press)
- R.C. Hoyt, B.W. Rhee, Review of the literature for dry reprocessing oxide, metal, and carbide fuel: The AIROX, RAHYD, and CARBOX pyrochemical processes. Technical Report ESG-DOE—13277 ON: DE92004038 (1979). doi:10.2172/10108445
- S. Delpech, E.M. Lucotte, D. Heuer et al., Reactor physic and reprocessing scheme for innovative molten salt reactor system. J. Fluor. Chem. **130**, 11–17 (2009). doi:10.1016/j.jfluchem.2008. 07.009