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Analysis on fuel cycle schemes in the dual-cooled waste transmutation blanket for the FDS-I

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Abstract

The fusion-driven subcritical system (FDS-I) which consists of the fusion neutron driver with feasible and easy-achieved plasma parameters and the multifunctional subcritical blanket (DWT) was proposed as an intermediate step toward the final application of fusion energy. In this contribution, fuel configuration and chemical form to be adopted in the FDS-I and possible fuel cycle schemes are clarified and analyzed based on the general survey. The influences of initial fuel loadings on the fuel cycle parameters are presented. Optimal analysis on the in-pile operation length is discussed and some recommendations are given to guide the design of optimized fuel cycle scheme on the basis of comprehensively considering the balance of the spent fuel loadings and the transmutation capacity.

Keywords: Subcritical; Blanket; Fuel cycle; Transmutation

1. Introduction

The conventional fission nuclear industry has been problematic as there has been no conclusion about how to solve the shortage of nuclear resources and how to effectively deal with the high level waste (HLW) in addition to nuclear safety issues and proliferation. The fusion-driven subcritical system (FDS) proposed as an intermediate step toward the final application of fusion energy has been widely studied [1–3].

In this contribution, the preliminary analyses of fuel configurations and chemical forms, fuel initial loadings and in-pile cycle length have been given based on the main constraints and objectives so as to achieve the balance of possible fuel supports and consistent fuel consumptions. The detailed design constraints and objectives are in ref. [4]. The specified unit of spent fuel compositions and quantities, i.e. UPWR, according to the annual production from a 3000 MW_{th} PWR with fuel burned to 33GWD/t after 10 years decay is presented in refs. [5,6]. The FDS-I model, code and data are briefly introduced in Section 2. The fuel configuration and chemical forms are discussed in Section 3. Some optimal analyses on

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initial fuel loading by different fuel compositions and appropriate spatial distribution are given in Section 4. In Section 5, the optimal analysis on the in-pile operation length is discussed. Finally, in Section 6, some conclusions and recommendations are given.

2. Model, code and data

FDS-I system consists of inboard and outboard blankets. The inboard blanket mainly used for tritium production is composed of tritium breeding zone, reflector and shielding. The outboard blanket has the actinide (AC) zones and fission product (FP) zones arranged radially. The liquid LiPb eutectic has been seriously considered in the fusion field including FDS team as tritium breeder, neutron multiplier and good coolant whose liquid property is adapted to the complex blanket structure [2]. The detailed transmutation model is in ref. [4]. Accordingly, the simplified 1D spherical geometry model is listed in ref. [7].

The home-developed code VisualBUS integrating the SN multigroup neutron transport solution, burnup solution and genetic algorithm optimization solution has been introduced to perform the neutronics calculations and analyses. The multigroup Hybrid Evaluated Nuclear Data Library (HENDL) has been applied in the code system. The code VisualBUS and HENDL have been largely evaluated and validated in refs. [8,9].

3. Fuel configurations and chemical forms

3.1. AC fuel configuration and chemical forms

The fuel configuration like PIN or plate will bring the problems such as assembling and unloading due to the complicated geometrical structure of fusion blanket. TRISO (Tri-ISOtropic)-like coated fuel particle is considered as one of the options in the design of FDS-I AC fuel form for the maturity of high temperature gas cooled reactor (HTGR) fuel fabrication. As for the fuel chemical forms, it is important not only to evaluate the compatibility of AC fuel, cladding and coating material, but also to satisfy the chemical and thermal compatibility of LiPb. The carbide fuel is considered as an option for fuel chemical form which is preferable for its good neutron economy and superior thermal conductivity [10–12]. Furthermore, silicon carbide (SiC) as the peripheral cladding is considered the most compatible material with LiPb. In the current design, only spent plutonium (Pu) is loaded as neutron multiplier which results in a fertile-free blanket. So the fuel chemical forms in this study include minor actinide carbide (MAC) and plutonium carbide (PuC) fuels with the UPWR isotopic vector. The committed coated particle fuel proposed in ref. [2] contains a tiny spherical fuel kernel encapsulated in the carbon buffer. As one of the blanket concepts, carbide heavy nuclide particle fuel in circulating liquid LiPb coolant named FDS/DWT-CPL is presented in this contribution. The detailed fuel data is under developed [4].

3.2. LLFP chemical forms and the moderator

The fission products that deserve most attention are ^{99}Tc($T_{1/2}^{99\mathrm{Tc}} \sim 2.1 \times 10^5 y$), ^{129}I($T_{1/2}^{129\mathrm{I}} \sim 1.6 \times 10^7 y$) and ^{135}Cs($T_{1/2}^{135\mathrm{Cs}} \sim 2.3 \times 10^6 y$).The partitioning level shows that the separation technology for these three isotopes is feasible but only on laboratory level for both aqueous and pyrochemical reprocessing [13].

Preliminary results have shown that a pure metallic form of technetium (Tc: mp ~2250 °C, d ~11.5 g/cm^3) is the most desirable one for ^{99}Tc. The fabrication route for casting the Tc metal has been developed and relevant irradiation experiments did not show any evidence of the swelling or disintegration of the metal [14]. ^{129}I, which is not incorporated in the vitrified HLW, is the dominant isotope in the radiological effects of reprocessing effluents or even from spent fuel in the certain geological formation.

The elemental form of iodine (I) is found to be unacceptable because of its volatility and chemical reactivity. Sodium iodide (NaI: mp ~651 °C, d ~3.67 g/cm^3) is being considered for its high melting point and good compatibility with claddings [14–17]. Cesium (Cs) separated from spent fuel is not a single isotope but the mixture of long-lived ^{135}Cs which we are interested in, the stable ^{133}Cs and the short-lived ^{137}Cs. Especially for ^{135}Cs, its isotopic separation has not been envisaged since the high activeness of ^{137}Cs. Furthermore, parasitic capture in ^{133}Cs occurring during the process of irradiation will decrease the neutron economy to some extent. As a conceptual design on the basis of elemental separation, the cesium chloride (CsCl: mp ~645 °C, d ~3.99 g/cm^3) was chosen as the chemical form because Cs is remained as chlorides in the electromigration process for salt from the electro-refining cell of LLFP recovering process. However, the transmutation in the form of ^{135}Cs isotope will be re-envisaged due to the feasibility and availability of isotopic separation [12,14].

Most optimized environment of LLFP transmutation includes high flux and well thermalized spectrum. $\sigma_{(n,\gamma)}$ of three isotopes in fast and thermal spectra is listed in ref. [18]. Some moderators have been considered such as $ZrH_{1.7}$, CaH_2, graphite and D_2O, etc. Although previous survey has shown that $ZrH_{1.7}$ has better moderating performance than graphite for higher material density (5.6 g/cm^3), the graphite also has some attractive features of cheapness and industrial scale. As a result, the calculations below are based on graphite as the moderator and hydrides ($ZrH_{1.7}$, CaH_2) can be the candidate.

4. Optimization of initial loading

The objective of optimization about initial loading is achieving LLMA and Pu consistent consumptions in a fuel cycle length on the basis of possible spent fuel supports (reference upper limit ~300 UPWR) and the balance of possibly maximizing transmutation capacity and minimizing the initial loading based on the main design objectives. In this study, homogeneous fissile core is considered as the reference core concept in which the single fuel composition of MAC and PuC is distributed in AC zones, respectively. After each fuel cycle, all fuels are removed from blanket, then reprocessed and recycled for the next step. The influence of LLFP loading in the peripheral FP zones is discussed on the basis of referenced homogeneous case. However, the analysis of heterogeneous core is also performed to search the effects in comparison with the referenced homogeneous one.

4.1. Homogeneous loading

4.1.1. LLMA and Pu loading

For homogeneous loading, the blanket reactivity level is mainly determined by the Pu content due to its considerable neutron multiplication. Firstly, the amount of initial Pu is adjusted to satisfy the objectives and different design constraints. Comparatively, the initial loading of LLMA is less dominant than Pu with respect to reactivity level. As a result, the initial LLMA loading is given randomly based on the upper limit of initial loading, and 200 $UPWR_{LLMA}$ (~0.53% MAC volume fraction) is assumed for the calculations and analyses below. The influence of peripheral FP zones is ignored temporarily and will be analyzed detailedly in the next sub-section. Main parameters as a function of different initial loadings are shown in Fig. 1. As shown in this figure, the amount of initial Pu has the dominant influence on the system reactivity level because the K_{eff} is approximately proportional to the initial loading. Although high power density will bring the problems of heat transferring and safety, considering the influence of 1D geometry simplified from 3D geometry, Fig. 1 also gives the neutronics parameters of relatively high power density limit in the range of 200–300 MW/m^3 as the reference cases, in which the balance of initial loading and annually transmutation capacity for LLMA and Pu can be achieved, approximately 48 transmutation capacity of 210 $UPWR_{LLMA,Pu}$ loading and 67 of 215 $UPWR_{LLMA,Pu}$, respectively. The case with initial PuC loading of 4.3% (~197 $UPWR_{Pu}$), which achieves the K_{eff} ~0.93, power density ~100 MW/m^3 is chosen as the reference case by the comprehensive considerations of objectives and constraints [4].

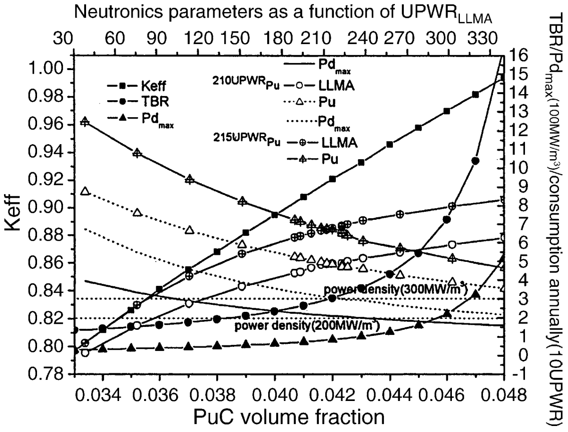

Fig. 1. Main parameters as a function of different initial loadings.

The initial LLMA loading has been great concerned in transmutation systems which need to meet the demand of transmutation efficiency as high as possible while minimizing the initial supports. From the result above, the initial PuC loading of 4.3% volume fraction

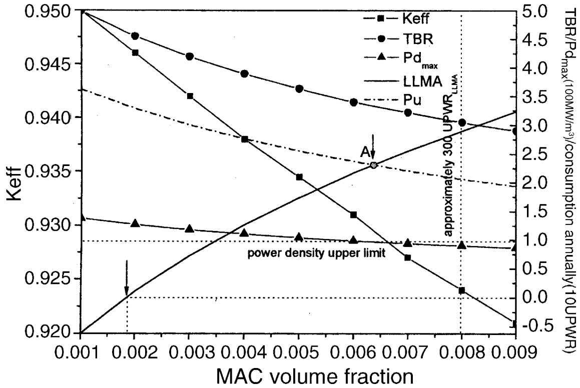

Fig. 2. Main parameters as a function of MAC volume fraction.

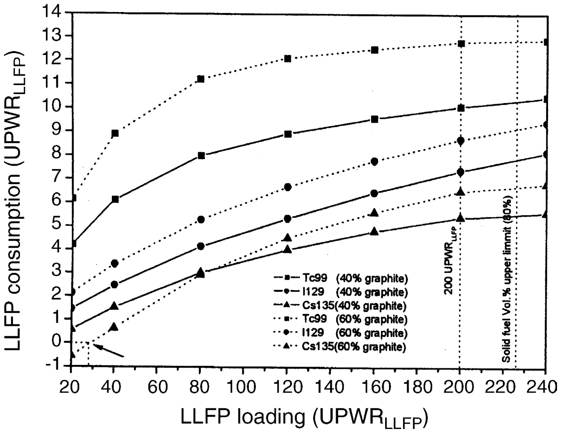

Fig. 3. Transmutation of LLFP isotopes as a function of $UPWR_{LLFP}$ loading.

is chosen as the reference case, based on which the main parameters as a function of MAC volume fraction are shown in Fig. 2. As we expect, the initial loading of LLMA has minor influence on the reactivity level and power density. The reactivity swing $\Delta k\%$ is only 2.4 from 60 to 300 $UPWR_{LLMA}$ range. Annual consumptions of LLMA and Pu are also given as a function of MAC initial fraction in the figure. It indicates that when the initial MAC volume fraction is set 0.2%, the transmutation of LLMA in the system is close to the internal balance, i.e. the net transmutation capacity of LLMA is about zero due to the large amounts of fresh LLMA produced by the Pu isotopes. When the initial MAC fraction is about 0.63%, the consumptions of LLMA and Pu will be nearly consistent in a fuel cycle length as the arrow A shown in the figure. The consumptions of LLMA and Pu are ∼24 UPWR/y in this case which has the better comprehensive effect on the system while satisfying the tritium breeding ratio (TBR) and power density limit. The volume fraction of the case in the blanket is 4.3, 0.63 and 95.07% for PuC, MAC and LiPb, respectively. TBR is ∼3.4 (≥1.1 viz. meets the tritium selfsustaining) and the power density is $\sim 100\ \mathrm{MW/m^3}$. And this case will be assumed as the referenced one while analyzing the influence of FP zones on the system below.

4.1.2. LLFP loading

FDS-I/DWT blanket arranges three divided FP zones for loading of LLFP fuels. The moderator-coated LLFP pebbles are loaded in the separated FP zone, respectively. According to the different capture cross sections of three isotopes ($\sigma_{^{99}\mathrm{Tc}} > \sigma_{^{129}\mathrm{I}} > \sigma_{^{135}\mathrm{Cs}}$), CsCl, NaI and Tc are loaded in FP-I, FP-I and FP-III distributed in radial direction, respectively considering the comprehensively consistent transmutation. Nuclear heat deposition of FP zones is relatively lower compared to the AC zones, in which helium gas is considered as the coolant.

The preliminary result shows that the reactivity level is less influenced by the FP zones. The transmutation capacity of three LLFP isotopes as a function of $UPWR_{LLFP}$ loading with different moderator fractions (40 and 60%, respectively) is shown in Fig. 3 while satisfying the solid fuel volume fraction limit (<80% in principle) and the upper limit of $UPWR_{LLFP}$. The neutron spectrum in FP zones can be great thermalized, but the relative lower neutron flux makes the low transmutation efficiency compared to the AC zones. From Fig. 3, the transmutation capacity of moderator fraction (60%) is much higher than that of 40% due to the good moderator effect. When the initial loading is about 30 $UPWR_{LLFP}$ for the case of 60% graphite, the transmutation of ^{135}Cs is near zero due to the transmutation capacity is not high enough to compensate the new generated ^{135}Cs mainly from the parasitic capture of amounts of ^{133}Cs. In addition, during the period of increasingly initial $UPWR_{LLFP}$ loading, the increase of transmutation capacity is slowed down mainly due to the capture reaction saturation of three LLFP isotopes. In the principle of comprehensive transmutation and balance of fuel loading consideration (∼237 $UPWR_{LLMA}$, ∼197 $UPWR_{Pu}$), the preliminar-

Table 1
Main parameters of typical homogeneous/heterogeneous cases

Case	K_{eff}	TBR	$\text{Pd}_{\text{average}}$ (MW/m^3)	Initial LLMA (kg/UPWR)	Initial Pu (kg/UPWR)	$\text{Consump}_{\text{LLMA}}$ (kg/UPWR)	$\text{Consump}_{\text{Pu}}$ (kg/UPWR)
Homogeneous	0.932	3.4	84	8274/238	56673/197	822/24	6860/24
Heterogeneous	0.927	2.0	MA: 5; Pu: 97	8274/238	60418/210	334/10	4666/16
Heterogeneous ($3000\text{UPWR}_{\text{LLMA}}$)	0.926	1.9	MA: 5; Pu:93	10410/300	86400/300	500/14	4396/15

ily optimized reference case is 200 $\text{UPWR}_{\text{LLFP}}$ initial loading with 60% moderator fraction. 13 $\text{UPWR}_{\text{Tc99}}$, 9 $\text{UPWR}_{\text{I129}}$ and 7 $\text{UPWR}_{\text{Cs135}}$ will be transmuted annually in this case which can at least incinerate the LLFP wastes generated by system itself.

4.2. Heterogeneous loading

In the homogeneous reference case, distributions of power density in AC zones are descending in the radial direction. Primary purpose of heterogeneous loading is to search the blanket with the minimized burnup swing which also means to flatten the radial power peaking factor. In the heterogeneous case, divided loading of MAC and PuC is considered to examine the performance of transmutation in comparison with homogeneous one. MAC fuels are plasma-oriented loaded to benefit the prompt fission of actinides, the outer are PuC fuels. The main parameters of two cases with same LLMA loading while resetting the Pu loading to satisfy the power density limit are listed in Table 1. The case of upper limit of loading (300 $\text{UPWR}_{\text{LLMA}}$) also listed in the table shows that the minor influence on the reactivity level with subtle decrease of K_{eff} from 0.927 to 0.926. In summary, this kind of heterogeneous case is not recommended in the FDS-I blanket.

5. Optimization of refueling period

The objective of optimization about FDS-I refueling is to seek an appropriate fuel cycle length of maximizing the transmutation capacity while minimizing the refueled batches based on high efficiency, safety and economics. Calculations above have given the information of initial loading and fuel consumptions annually. Main parameters of typical homogeneous case as a function of operation length (5 EFPY) are presented in Fig. 4. Apparently the reactivity swing $\Delta k\%$ is already 13 after 1-year operation due to the largely consumed Pu. As a result, it brings amounts of new LLMA products, which make the net LLMA transmutation capacity is near zero after 2-year operation. Although the Pu and LLFP isotopes are still decreasing after that, 2 EFPY is the effective operation of FDS-I blanket considering the principle of consistent transmutation. LLFP fuel cycle can be lengthened due to their relatively poor transmutation capacity and minor influence on reactivity level. Actually, LLFP transmutation can be sustainable enough during the in-pile cycle length supported by the fission products of AC zones themselves annually.

FDS-I blanket design with the excellent feature of flowing fuel will enable the fresh on-line refueling theoretically. Annual transmutation capacity with different refueling lengths is also presented in Fig. 4. It is found that the improvement of transmutation capacity by increasing the refueling batches is not as high as expected before. The reason is that the large accumulation of ^{238}Pu produced by the burned LLMA (mainly

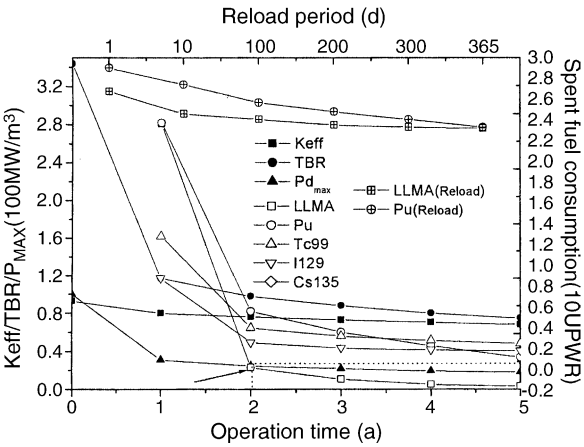

Fig. 4. Main parameters as a function of time variants.

Table 2
Equilibrium core characteristics

Thermal power (GW)$_{BOC/EOC}$				14.2/4.1
P_{max} (MW/m^3)$_{BOC}$				100
Top-up fuel composition	AC zone (vol.%)	FP zone (vol.%)		
	MAC (0.6)	CsCl (17.6)	NaI (1.7)	Tc (1.5)
	PuC (4.3)	Graphite (60)	Graphite (60)	Graphite (60)
	LiPb (95.1)	Helium for balance		
K_{eff}				
Initial		0.93		
Minimum		0.8		
Burnup reactivity swing (%Δk/365EFPD)		13		
AC Inventory, BOC (ton)		65		
Fuel burnup (GWd/tHM)		23		
Transmutation rate		LLMA ∼10%; Pu ∼12%; LLFP ∼6%		
Operation length (d)		365		

^{237}Np and ^{241}Am) will compensate the burnup reactivity swing by ^{238}Pu (n, γ)^{239}Pu reactions. The equilibrium core characteristics of 1-year operation length are listed in Table 2.

6. Conclusion

Fuel configuration and chemical form to be adopted in the FDS-I are clarified and analyzed based on the general survey. The analyses of optimization about fuel loadings and in-pile cycle length have been proposed based on the blanket design constraints and objectives so as to comprehensively consider the feasibility of engineering and technology, the transmutation capacity and the energy balance. The preliminary result shows that such a blanket can approximately transmute ∼24 UPWR$_{LLMA}$, ∼24 UPWR$_{Pu}$ and 7–13 UPWR$_{LLFP}$ by appropriate spatial and fractional arrangements. However, the multi-dimensional transport and burnup calculation is needed to examine the influence of simplified model. In addition, the study on relevant engineering and technology problems should be performed before this system can be seriously considered.

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