Preliminary Analysis of the Sensitivity of Neutronic Performance in a TRU-Loaded Molten Salt Fast Reactor Core for Marine Propulsion

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1. Introduction

Net zero emission by 2050 is also one of the most important goals for shipbuilding industry [1]. As an alternative to conventional diesel propulsion system, a nuclear propulsion system has got interest due to its high efficiency in the conversion, and long-time operation with a single-time fuel loading. Among the various nuclear propulsion systems, molten salt reactor (MSR) is considered for a good option since it operates with low pressure which simplifies the design of the system [2].

Meanwhile, spent fuels from conventional water cooled reactor have been one of the important pending issues in the nuclear industry due to their high radiotoxicity and long half-life from transuranic elements (TRU). In order to solve the aforementioned problem, a reactor with fast neutron spectrum has been widely recognized to manage the spent fuel.

In this work, a feasibility of solving the aforementioned two problems is studied via implementing spent fuels into a molten salt fast reactor (MSFR) core in terms of neutrons performance.

2. Design of Molten Salt Fast Reactor Core with TRU

2.1. Modeling on reference reactor core of MSFR

The reference core design employs a molten salt fuel composed of NaCl, KCl, and UCl_3, with respective fractions of 42.9%, 20.3%, and 36.8% [3]. The uranium chloride is enriched to 19.75 w/o, and the chlorine is enriched to 90 a/o in Cl-37. To enhance the neutron economy, a PbO reflector is incorporated and positioned at the periphery of the reactor core [4]. The radial and axial configurations of the reactor core are illustrated in Fig. 1, and the principal design parameters of the reference core are summarized in Table 1.

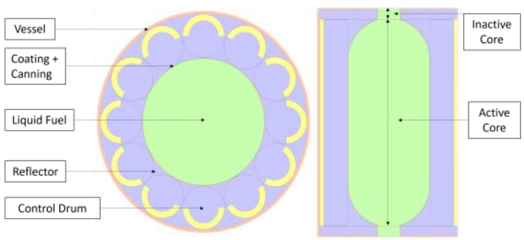


Fig. 1. Radial and axial view of reference MSR core.

Table 1. Reference core specification & materials

Region		Materials	Sizes	Values (cm)
Inner core	Active core	NaCl-KCl-UCl_3	Radius	100
			Height	581
	Coating	Alloy625	Thickness	0.08
	Canning	SS316H	Thickness	0.8
Outer core	Reflector	PbO	Thickness	69.12
	Vessel	SS316H	Thickness	5
Whole core			Radius	175
			Height	631

2.2. Isotopic composition of TRU via depletion calculation on a PWR assembly

The isotopic composition of TRU is obtained via depletion calculation on PLUS7 assembly loaded in APR1400. The PLUS7 assembly consists of 184 fuel rods with 4.5 w/o U-235 and 52 fuel rods with 4.0 w/o U-235 [5]. The depletion calculation is carried out using a continuous-energy Monte Carlo method implemented in Serpent 2.2. The fuel assembly model employed in the depletion calculation is illustrated in Fig. 2. The computational conditions are summarized in Table 3, and the results of depletion calculations are shown in Fig. 3.

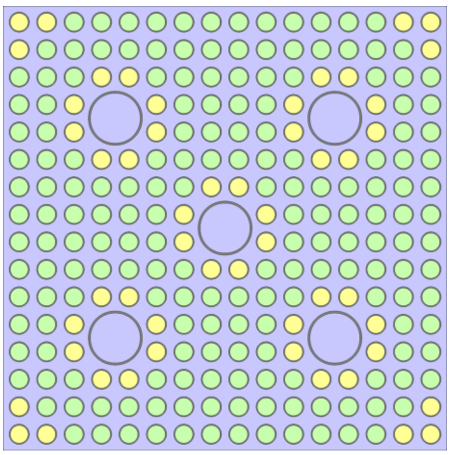


Fig. 2. A schematic of PLUS7 assembly.

Table 2. Computation conditions for depletion calculations

Parameters		Values
Computer code		Serpent 2.2
Cross section library		Continuous energy ENDF/B-VII.1 libraries
Depletion period		4.5 EFPY
Power density		3.18 MW/kgU
# of histories		100,000
# of cycles	Inactive	200
	Active	300

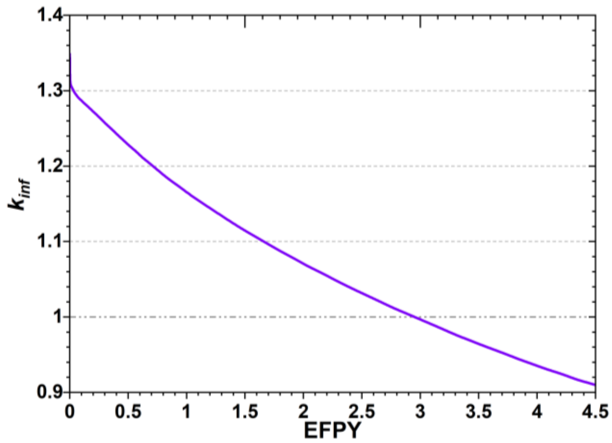


Fig. 3. Change of k_{inf} during depletion of the fuel assembly.

2.3. Modeling of MSFR cores with various TRU loading configurations

Two reactor core configurations are considered in the present analysis. In the first case, a homogeneous mixture of molten salt fuel with the isotopic composition obtained from Section 2.2 is employed. The second case involves loading integrated fuel rods into the assembly layer. The spent fuel layer is 35 cm away from radial center of the core which sharing the same axial midpoint. The reactor core configurations, including the reference core, are illustrated in Fig. 4.

Table 3. Specifications and materials of Case 2

Parameters	Values
Layer location (Distance from center)	35.705 cm
Number of fuel rods (4.5 w/o U-235)	472
Canning thickness (SS316H)	2.16 cm
Coating thickness (Alloy625)	0.08 cm

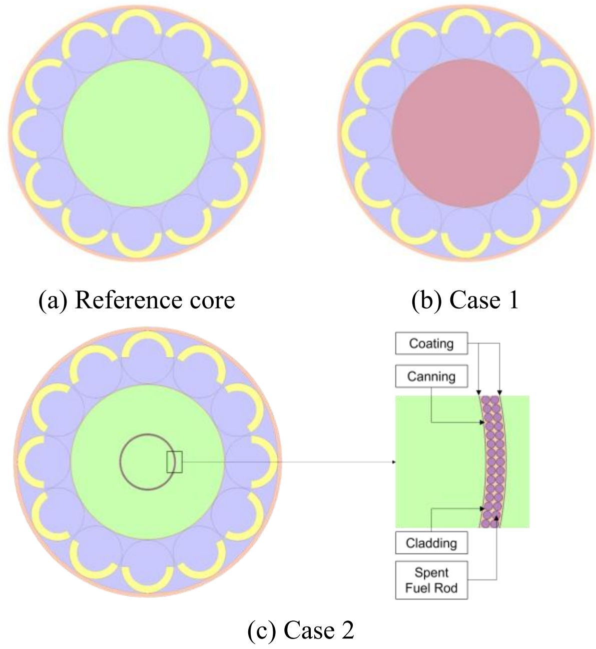


Fig. 4. Configurations of cores for sensitivity analysis.

A pinned arrangement of the spent fuel is adopted for Case 2 in order to enable their use with minimized modification. This arrangement increases the surface area in contact with the molten salt, which treated as a coolant of the layer. To enhance structural integrity against corrosion and mechanical stresses from the molten salt, coating and canning are applied to the layer of the spent fuel rods.

3. Analysis on Neutronic Performance of TRU-Loaded MSFR

3.1. Neutronic performance on the reference core

The neutron spectra and radial neutron flux distribution of the reference core are analyzed using Serpent calculations. The calculation conditions and k_{eff} and standard deviation obtained from the reference MSR core are shown in Table 4 and Table 5, respectively.

Table 4. Computation conditions of the reactor core

Parameters		Values
Computer code		Serpent 2.2
Cross section library		Continuous energy ENDF/B-VII.1 libraries
Depletion period		30 EFPY
Power		100 MWth
# of histories		500,000
# of cycles	Inactive	300
	Active	500

Table 5. k_{eff} of reference core

Parameters	BOC	EOC
k_{eff}	1.14114	1.07021
std	18 pcm	19 pcm

Neutron spectra in the reference core are illustrated in Fig. 5. In the core part, the shape of neutron spectrum is similar with those obtained from fast reactors. In the reflector part, the dominant neutrons are thermal neutrons.

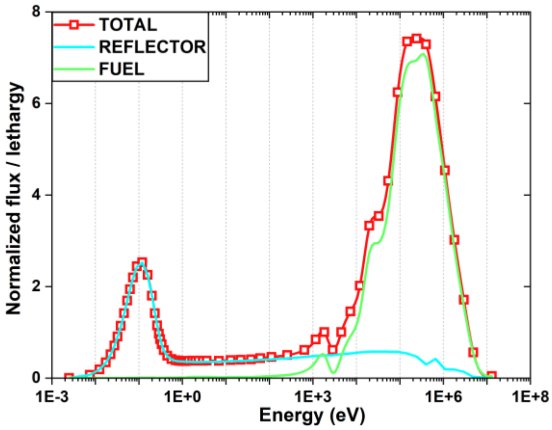


Fig. 5. Neutron spectra in the MSFR core.

Fig. 6. illustrates the neutron flux distribution in the radial direction. Fast neutrons are dominant in the central region of the reactor core, while their fraction decreases with increasing distance from the core center. In the reflector region, thermal neutrons are predominant, which is consistent with the results shown in Fig. 5.

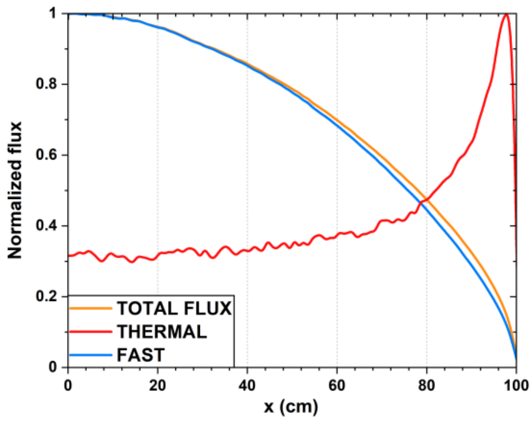


Fig. 6. Normalized radial neutron flux distribution.

3.2. Sensitivity on the configuration of TRU in MSFR

Sensitivity studies on the depletion of the reactor cores are performed for the cases discussed in Section 2.2. The results are compared with the reference core case. The change of multiplication factors for various cases shown in Fig. 7.

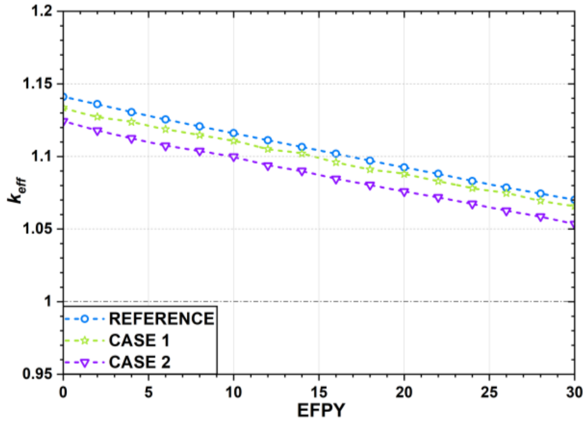
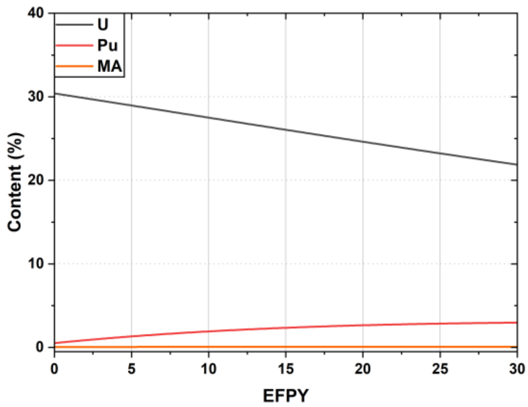
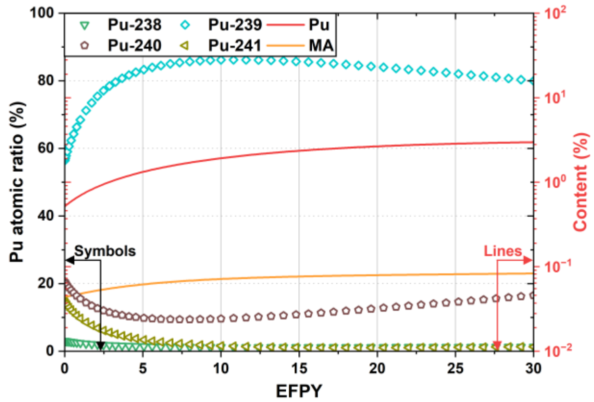


Fig. 7. Comparison of change of k_{eff} for various cases.

As shown in Fig. 7, the multiplication factor from case 1 is 570 pcm lower than that of the reference core. In Case 2, the multiplication factor is 1500 pcm lower, respectively, compared with the reference core. Nevertheless, all cases maintain multiplication factors greater than 1 over 30 years of operation.



(a) Actinide contents of the layer in case 2



(b) Atomic ratio of plutonium and minor actinides

Fig. 8. Change of actinides in the spent fuel rods under depletion.

Fig. 8 represents actinide ratio in the spent fuel rods during depletion for case 2. The result shows that minor actinides including Pu-239 are produced continuously due to fast neutron spectrum in the MSFR core but its gradient is decreased as the burnup increases, which is similar with ones shown in previous work [6].

4. Conclusions

In this study, the feasibility of TRU loading in a molten salt fast reactor (MSFR) core for marine propulsion was investigated. Two reactor core configurations were considered: (i) a homogeneous mixture of molten salt fuel with TRU, and (ii) positioning the rods 35 cm away from the core center. The neutronic performance of the both aforementioned cases were compared with that of the reference core in terms of the variation of multiplication factors over the operation period. Although differences in the multiplication factors are observed, all cases maintain values greater than 1 throughout 30 years of operation.

As future work, optimization of the reactor core will be pursued, including increasing the TRU fraction in the core, reducing excess reactivity, and other design improvements.

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