

# Feasibility Study on Mitigation of Reactivity Swing via Utilization of Spent Fuel Rods with Molten Salt Fast Reactor Cores for Maritime Propulsion System

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## 1. Introduction

According to the present interest of the maritime industry in reducing greenhouse gas emission, utilization of nuclear energy for maritime propulsion is considered to be one of the promising options for shipbuilders. Numerous types of reactors are suggested to replace conventional diesel engine, a Molten Salt Fast Reactor (MSFR) is regarded as a reliable reactor type of their kinds due to low operation pressure and long fuel cycle without refueling, which enables smaller reactor size and lesser maintenance frequency for the shipowner. Also, employment of liquid fuel allows continuous removal of fission gases to enhance neutron efficiency of the reactor [1]. For maritime applications, it is desirable to design a reactor core with a cycle length comparable to the service life of the ship's structural materials to enhance operational convenience for the ship owner. However, in such a case, a very large reactivity swing (i.e., 10,000 pcm) represents one of the most significant technical challenges associated with this design concept [2].

At the moment, continuously produced spent fuels from conventional water-cooled reactors are recognized to be one of the forthcoming problems in the nuclear industry because of the long-lived transuranic elements in the spent fuel. Due to the fast neutron spectra of MSFR core is expected to utilize effectively actinides in spent fuel, which enables the reactor to satisfy the demands of maritime and nuclear industries.

Our focus is on searching for spent fuel (SF) rods loaded MSFR core to mitigate the reactivity swing of the core which sustains thermal power of 100 MW<sub>th</sub> over 30 years with a single-fueled cycle, carrying power output and operation cycle for overseas vehicles nowadays [3]. To achieve the goal, several configurations incorporating loaded SF rods were systematically analyzed to mitigate reactivity swing during core depletion.

## 2. Implementation of TRU-Burner Concepts in MSFR Core

### 2.1 Design of Reference Core and Pin Lattice of MSFR

A reference MSFR core can be classified by two geometrical configurations; i) Inner core which contains 42.9 % NaCl, 20.3 % KCl, and 36.8 % UCl<sub>3</sub> liquid fuel,

enriched to 19.75 w/o in uranium and 90 a/o of Cl-37 in chlorine. Fuel salt density is assumed to be 3.232 g/cm<sup>3</sup> at operation temperature of 883 K. The region is canned of SS316H, coated with Alloy625 on the interface of fuel salt and canning. In detail, the cylindrical domain positioned at the center of the core is active fuel region while the rest of the fuel (e.g., dome and piping line) is inactive fuel region. External fuel volume that have not presented on Fig 1, such as heat exchanger, is not considered in the analyses. Fuel salt is considered to be a homogeneous liquid, and therefore noble gases such as Xe and Kr are continuously removed from the fuel salt to alleviate reactor poisoning. ii) Outer core, filled with PbO, functions as a reflector region for the inner core and is enclosed by a SS316H vessel. A total of 12 control drums are installed in the outer core region to provide reactivity control, performing an equivalent function to control rods in conventional water-cooled nuclear reactors. Drums can be rotated 360 degrees, making B<sub>4</sub>C padded half sides face the inner core, controlling reactivity. The liner is filled with PbO, identical to the reflector material, and is encapsulated in SS316H. Specific parameters are provided in Table I, and cross sectional views of lattice geometry with pins are shown in Figs. 1 and 2, respectively.

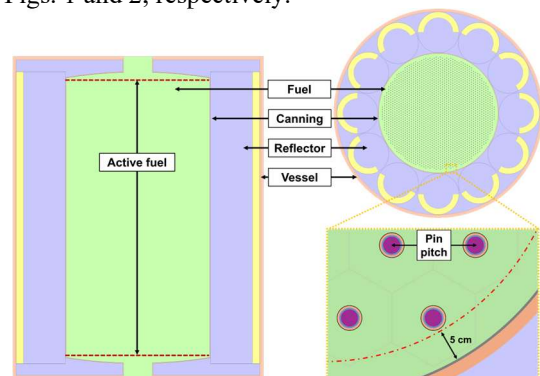


Fig. 1. Cross Sectional Views of a MSFR Core

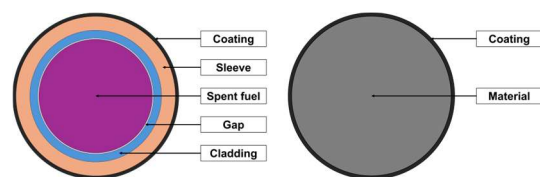


Fig. 2. Configuration of Pin Types in Hexagonal Lattice

Table I: Regional Parameters of a MSFR Core

Region	Material	Parameter	Value (cm)
Active fuel	NaCl-KCl-UCl <sub>3</sub>	Radius	100
		Height	390
Inactive fuel	NaCl-KCl-UCl <sub>3</sub>	Radius	20
		Height	60
Coating	Alloy625	Thickness	0.08
Canning	SS316H	Thickness	0.8
Reflector	PbO	Thickness	69.12
Vessel	SS316H	Thickness	5
Pin	ZrH <sub>1.6</sub> , SF rod	Radius	0.575
		Height	380.95
Pin coating	Alloy625	Thickness	0.025
Drum liner	PbO	Radius	34.34
		Height	407.07
Drum canning	SS316H	Thickness	0.1
Control pad	B <sub>4</sub> C	Thickness	10
Whole core		Radius	175
		Height	450

To reduce reactivity swing, pins are inserted into the active fuel region with a 5 cm margin from the inner core coating. These pins are centered in each cell of hexagonal lattice, which provides an indexing scheme without altering the actual volume of the inner core. Two groups of pins are categorized as follows: 1. Single-material pins (e.g., ZrH<sub>1.6</sub>) have been employed to implement the TRU-burner concept in previous work [4]; 2. Multi-layered SF rods with various sleeves incorporated into the MSFR core, which have been used for achieving breed-and-burn behavior over cycle in previous work [5]. Pins are composed of various materials and enveloped with Alloy625 to prevent corrosion from the fuel salt; detailed sizes are shown in Fig. 2 and Table I. The isotopic inventory of spent fuel is pre-calculated on a typical PWR assembly via Serpent 2 [6]. Spent fuel density is computed as 10.43 g/cm<sup>3</sup>, with averaged temperature of 964 K while in the MSFR core.

## 2.2 Sensitivity Study of Two-Dimensional MSFR Core

In order to determine an optimized configuration of the MSFR core, depletion calculations are performed via Serpent 2 with 200,000 histories per cycle, 200 active cycles, and 50 inactive cycles, resulting in a reasonably small standard deviation of approximately 19.1 pcm. Total depletion time is 30 effective full power years (EFPY), and the time step is increased gradually by 48 steps for the first 2 years, then 20 steps for another 2 years, 16, 13, 12 steps until year 10, and then 5 steps per year. The fuel cycle is divided into 3 step points; Beginning of cycle (BOC) at year 0, Middle of cycle (MOC) at year 15, End of cycle (EOC) at year 30. The

initial volume of the fuel salt is set to 16.18 m<sup>3</sup>, while each pin, including a coating, has a volume of 430.9 cm<sup>3</sup>. With the calculation settings, simulations are conducted on aforementioned single-material pins and SF rods with different sleeves, which are divided into several pin types in the same pin lattice of 2,503 pins with 3.6 cm for pin pitch. Fig. 3 describes  $k_{eff}$  over 30 EFPY with the pin types, which are listed in Table II, and multiplication factor with reactivity swing on different pin types are proposed in Table III.

Table II: Material Configuration of Pin Types

Pin type	Liner material	Sleeve material
Type 1	ZrH <sub>1.6</sub>	N/A
Type 2	SF rod	ZrH <sub>1.6</sub>
Type 3	SF rod	SS316H

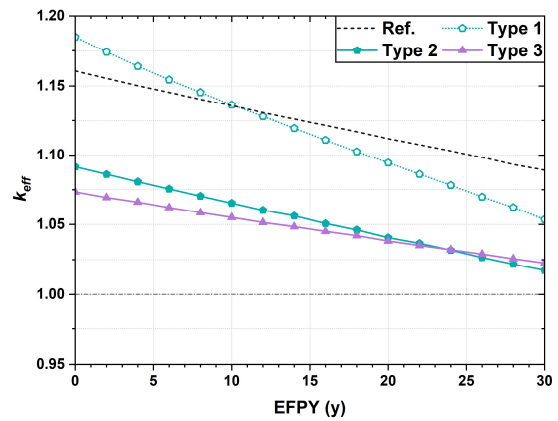


Fig. 3. Sensitivity on Pin Materials over 30 EFPY

Table III:  $k_{eff}$  with Reactivity Swing by Pin Types

Pin type	$k_{eff}$ [std (pcm)]		Swing ( $\rho_{BOC} - \rho_{EOC}$ )
	BOC	EOC	
Ref.	1.16062 [18]	1.08917 [19]	7,145
Type 1	1.18485 [17]	1.05357 [20]	13,128
Type 2	1.09157 [18]	1.01730 [20]	7,427
Type 3	1.07339 [19]	1.02254 [20]	5,085

Types 1 and 2, single-material pins, have shown rapid decrement of excess reactivity compared to the reference core, obtaining the highest difference of -5,983 pcm with Type 1. It is shown that these pin types are inappropriate to the objective of swing reduction. For the SF rods, ZrH<sub>1.6</sub> sleeved arrangements indicates that ZrH<sub>1.6</sub> is not a reasonable option for mitigating reactivity swing for the MSFR core with a long fuel cycle. Type 3 shows smaller swing than the reference core, as a difference of -2,060 pcm, respectively. Therefore, the Type 3, SS316H sleeved pin type, is chosen on whole-core study since the actual pin type exhibits the smallest reactivity swing amongst configurations.

### 3. Whole-Core Analysis on Spent Fuel Rod Loaded MSFR Core

#### 3.1 Neutronic Performance of MSFR Core

The whole-core computations are performed via Serpent 2 with 200,000 histories per cycle, 300 active cycles, with 100 inactive cycles, yielding an average standard deviation of 15.7 pcm. Initial fuel salt volume is reduced to 12.56 m<sup>3</sup> to match the whole-core model. In order to determine the optimized pin pitch for the whole-core configuration, sensitivity analyses are performed with the conditions listed on Table IV. Fig. 4 and Table V indicate the  $k_{eff}$  with different lattice configurations of SF rods over depletion period, and Fig. 5 illustrates neutron energy spectra of Case 2 in comparison to the reference core at the BOC and EOC.

Table IV: Configurations for Lattice Cases

Case	Number of pins	Pin pitch (cm)
Ref.	N/A	N/A
Case 1	2,029	4.0
Case 2	1,597	4.5
Case 3	1,069	5.5

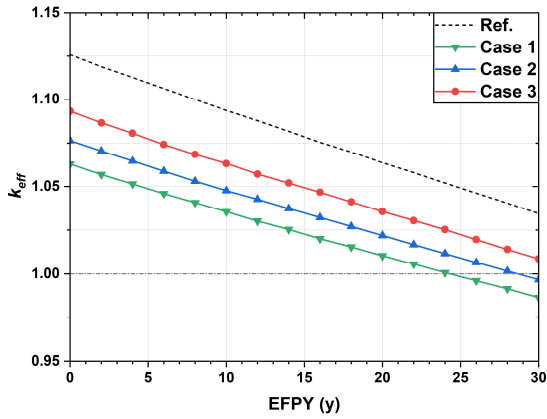


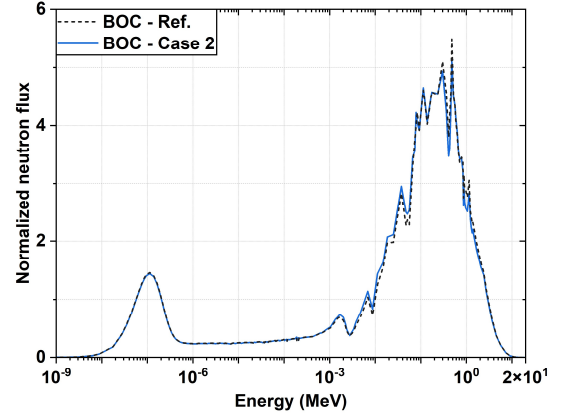
Fig. 4. Sensitivity on Lattice Cases over 30 EFPY

Table V:  $k_{eff}$  with Reactivity Swing by Different Cases

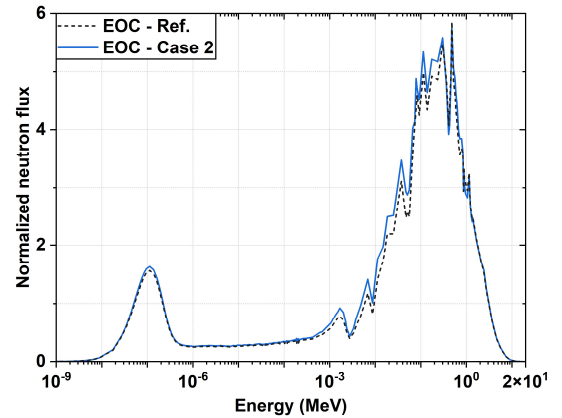
Case	$k_{eff}$ [std (pcm)]		Swing ( $\rho_{BOC} - \rho_{EOC}$ )
	BOC	EOC	
Ref.	1.12575 [15]	1.03435 [17]	9,140
Case 1	1.06298 [15]	0.98625 [17]	7,673
Case 2	1.07644 [16]	0.99655 [17]	7,989
Case 3	1.09318 [15]	1.00871 [17]	8,447

Fig. 4 and Table V denote that the number of SF rods are inversely proportional to  $k_{eff}$  over cycle, with an average decrement of 0.7 pcm per rod. This indicates that

the SF rods show an effect of reducing reactivity swing during the depletion, which can help maintain criticality over operation. Since the volume of fuel salt is occupied by the pins, loading SF rods also reduces the initial volume of fuel salt because of their portion to the active fuel region.



(a) Neutron energy spectra at BOC



(b) Neutron energy spectra at EOC

Fig. 5. Comparison of Neutron Spectrum at BOC and EOC

As shown in Fig. 5, insertion of SF rod pins results energy shift of the neutron in direction of broadening on fast energy region and minor rising on thermal energy region. For the further analysis, Case 2 is selected by maintaining its reactivity over 28.4 EFPY which has 0.947 in capacity factor based on 30 years of operation.

#### 3.2 Control Drum Worth of MSFR Core

A set of reactivity control devices, such as control drums of the MSFR, must provide enough amount of negative reactivity worth to attain subcritical state at any given time under operation period. Thus, computations with the same settings as above are executed at the BOL by differing drum conditions. Firstly, all control drums are mobilized to face inner core. Secondly, one of the drums is failed by stuck in position while others are successfully rotated. The utilization of drums is in Fig. 6, and drum worth by the conditions are listed in Table VI.

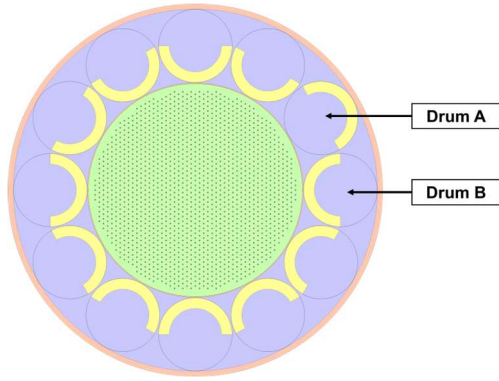


Fig. 6. Control Drums with Condition of Stuck in Position

Table VI: Drum Worth under Different Conditions

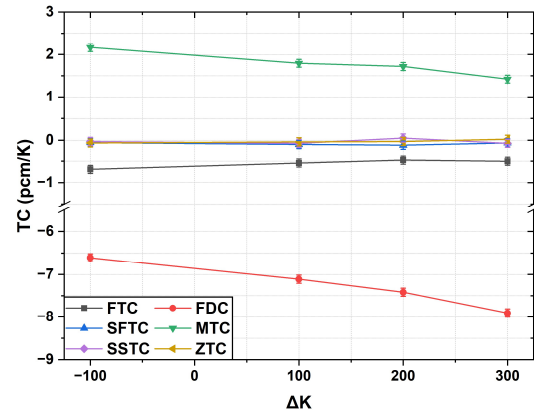
Drum condition		$k_{\text{eff}}$ [std (pcm)]	Drum worth (pcm)
All drums out		1.07644 [16]	N/A
All drums in		0.91662 [19]	15,982
Stuck in position	Drum A	0.92933 [17]	14,711
	Drum B	0.92922 [18]	14,722

Since the MSFR core is an axisymmetric cylinder with hexagonal lattice geometry inside, stuck of a control drum can be varied into two kinds; Drum A and Drum B, as proposed in Fig. 6. The drum worth is calculated via subtracting  $k_{\text{eff}}$  from All drums out condition in Table VI, and recorded the lowest reactivity worth of 14,722 on the Drum A stuck in position. Note that the results show that  $k_{\text{eff}}$  is less than 0.95, thereby satisfying the subcriticality criterion specified in regulatory guidelines, even when one of the drums is stuck.

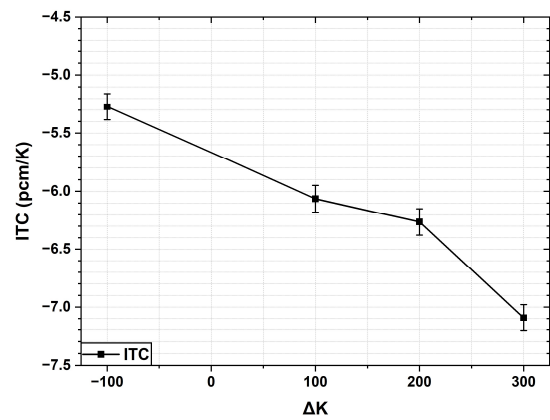
### 3.3 Temperature Coefficients of SF Rods Loaded MSFR

To ensure the safety of a reactor core, since temperature change leads to reactivity feedback, the following temperature coefficients (TCs) are computed; i) Fuel temperature coefficient (FTC), ii) Spent fuel temperature coefficient (SFTC), iii) Moderator temperature coefficient (MTC) for main core structures, and iv) Stainless-steel temperature coefficient (SSTC), v) Zircalloy temperature coefficient (ZTC) for pin lattice structures. vi) Fuel density coefficient (FDC) is also considered, since the fuel salt maintains liquidous form over cycle. The reactivity feedback owing to temperature change is then calculated by giving 100 K intervals to the  $\Delta K$ , then summarize i) ~ vi) to compute isothermal temperature coefficient (ITC).

These TCs are calculated via Serpent 2 with 2,000,000 histories per cycle, 500 active cycles, and 200 inactive cycles in order to yield a very small average standard deviation, represented as  $\sigma$ , of 0.047 pcm/ $\Delta K$ , derived from subtraction in reactivity divided by temperature interval. Fig. 6 represents TCs over temperature difference in range of  $-100$  to  $300$   $\Delta K$ .



(a) TC by different core materials ( $2\sigma$ )



(b) ITC, summarized ( $\sigma$ )

Fig. 7. Calculation of Thermal Coefficients at BOC

In Fig. 6a, the reactor core is highly impacted by main structure temperature coefficients such as MTC and FDC, and minor changes with FTC. For the structures in pin lattice, more pins in the lattice are expected to lower SFTC but the decrement is computed to be very small among the aforementioned fuel TCs. SSTC and ZTC can be ignored because of their contribution to the ITC is approximately zero with all pin arrangements. The ITC is shown in Fig. 6b, and searched to be negative in a range of  $-100$  K to  $+300$  K. This indicates, fuel salt in liquid phase, reactivity feedback due to the doppler broadening effect is anticipated to reduce reactivity of the MSFR core at the temperature range [7].

## 4. Conclusions

In this study, the feasibility of a spent fuel rod-loaded MSFR core was investigated to mitigate the reactivity swing for maritime applications. The computations of the two-dimensional MSFR core were performed on several material applications with hexagonal pin lattice in purpose of reducing excess reactivity. Among these arrangements, the SF rod with SS316H sleeve was considered to have the best performance in swing reduction among the pin types suggested, by reducing 2,060 pcm of excess reactivity. Based on the sensitivity

analysis on the pin types, whole-core analysis was performed to determine reactivity swing with neutron energy spectrum at each end of the cycle. The calculation was conducted to find optimal pin lattice with 1,597 pins which maintains 28.4 EFPY of operation, achieving swing reduction of 1,151 pcm and capacity factor of 0.947. For the selected reactor core configuration, the reactivity worth of the control drums was calculated to exceed 7,000 pcm of shutdown margin under the specified conditions. Furthermore, the temperature coefficients at the beginning of cycle (BOC) were found to be negative, thereby demonstrating compliance with regulatory requirements on reactivity. As future work, investigation of inventories in fuel salt and SF rods, search for a structure to fix pin lattice, and examination of thermohydraulic performances in the reactor core are to be performed.

### **ACKNOWLEDGEMENTS**

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### **REFERENCES**

- [1] V. Dos, K. Kim, E. E. Pettersen, J. G. Jensen, and D. Lee, "Dynamic burnup studies of Seaborg compact molten salt reactor by Serpent 2," *Transactions of the Korean Nuclear Society Virtual Autumn Meeting*, Dec. 16-18, 2020.
- [2] Y. Go, T. Park, S. Zee, J. Seo, and S. Yoon, "Conceptual core design study of a maritime molten salt fast reactor," *Annals of Nuclear Energy*, vol 222, Nov. 2025.
- [3] Jun-sung Lee, "Samsung heavy industries receives world's first approval for MSR-powered LNG carrier at U.S. Gastech," Korea IT Times, Sep. 9, 2025. [Online], Available: <https://www.koreaitimes.com/news/articleView.html?idxno=145532>. [Accessed Feb. 10, 2026].
- [4] F. Zhu, C. Yu, J. Chen, and X. Cai, "Assessment of TRU burning in a molten salt reactor moderated by zirconium hydride rods," *Nuclear Engineering and Design*, vol 387, Feb. 2022.
- [5] K. M. Sourov, Md. Hossain Sahadath, and H. Rainad Khan Rohan, "Enhancing fuel breed-burn performance in a sodium-cooled fast reactor using a novel reactivity control method," *Progress in Nuclear Energy*, vol 177, Dec. 2024.
- [6] H. Chung, J. Yoon, S. Kim, and Y. Lee, "Preliminary analysis of the sensitivity of neutronic performance in a TRU-loaded molten salt fast reactor core for marine propulsion," *Transactions of the Korean Nuclear Society Autumn Meeting*, Oct. 30-31, 2025.
- [7] M. Rose, and S. Thomas, "Production and chemical analysis of NaCl-KCl-UCl<sub>3</sub> salts," Argonne National Laboratory, Argonne, IL, USA, Rep. ANL/CFCT-21/04, Feb. 26, 2021.