Control Drum Design Optimization for a Passively-Cooled Molten Salt Fast Reactor

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1. Introduction

The Molten Salt Reactor (MSR) is one of the innovative reactor systems that needs further research and commercialization based on the Generation IV International Forum (GIF). The advantages of MSR are as follows[1]:

1. Safety: low-pressure operation; no danger of fuel melting; continuous online fuel refueling; easy removal of noble gases; the self-regulating core can follow demand loads with minimal or no control rods used.
2. Economics: compact structure; high-temperature operation; no need for fuel fabrication; no need to shut down for refueling.
3. Environmental: utilization of Thorium; recycling of Actinides could reduce the waste production from other Light Water Reactor (LWR); less waste heat.

Based on its spectrum, the MSR can be classified as the thermal and the fast MSR. The thermal MSR could have proliferation issue due to its actinides and fission product, while in fast MSR, that issue can be eliminated since the fast spectrum have highly burnt plutonium or uranium isotopes along with other minor actinides and fission product (uniform isotopic concentration of actinides)[2]. Accordingly, the **I**nnovative original technology of **S**evere **A**ccident-**F**re**E** **M**ulti-purpose & long-lifetime **S**mall modular molten salt reactor **R**esearch center (**i-SAFE-MSR**), was launched in South Korea to develop an innovative natural circulation molten salt fast reactor design called PMFR (the Passively-Cooled Molten Salt Fast Reactor).

The PMFR key concepts and requirements which consist of [3]:

- Operation of natural circulation on the primary system
- Separation of non-soluble fission products
- Severe-accident-free and passive safety system
- Long-lifetime core design
- Corrosion-resistant base material and coating in molten salts
- Original multi-physics numerical analysis platform

To guarantee an excellent safety system in PMFR, the installation innovation of a control drum is applied. This study aims to provide an optimization design of a control drum in a PMFR with a BeO moderator and a Burnable Absorber (BA) installed.

2. Methods and Results

The depletion calculation was performed using the Monte Carlo Serpent2 code version 2.1.31 with nuclear library ENDF/B-VII.1. The depletion step for this study was done every 1 year with a total of 33 years, while the total history used was 100,000 with 300 active cycles and 200 inactive cycles for a 300 MWth power. The case condition referred to as the 'without-control drum' should maintain its reactivity swing under 1,000 PCM, which incorporates a 40 cm BeO moderator with a BA installed[4]. Similarly, the 'with-control drum' case should also be maintained in the same manner under the 'drum-out' condition, so that the BA configuration will alter correspondingly.

2.1 Control Drum and BA Configuration

The control drum was installed inside the moderator region which consists of a pad with a buffer region in between the layer part. To optimize the design of the control drum, all possible parameters were studied to achieve the greatest control drum worth, while maintaining an initial reactivity coefficient below 0.99 (subcritical). The parameter considered here includes total control drum, pad angle, radius, pad thickness, layer thickness, buffer thickness, and buffer material. A sensitivity test is also conducted while maintaining the reactivity profile by adjusting the BA design.

The optimized control drum design is obtained with a total of 20 drums with a 90° angle of pads encircling the PMFR active core with a 16.5 cm radius of the drums. The control drum specification is defined in Table I, while its configuration details are shown in Figs. 1 and 2.

Table I: Control Drum Specification

Control Drum Parts	Material	Thickness [cm]
Pad	B_4C (95% B-10 enrichment)	10.6
Layer	SS-304	0.1
Buffer	Helium Gas at 823 K	0.2

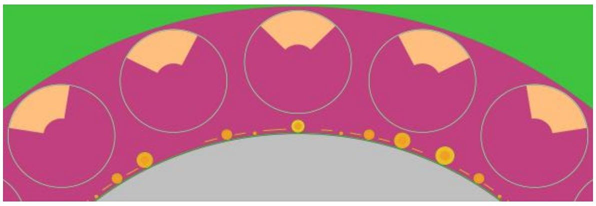

Fig. 1. Configuration of control drum, all drum-out conditions in X-Y plane

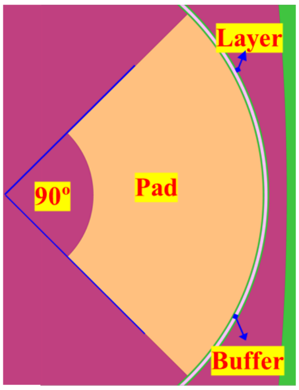

Fig. 2. Detailed control drum parts

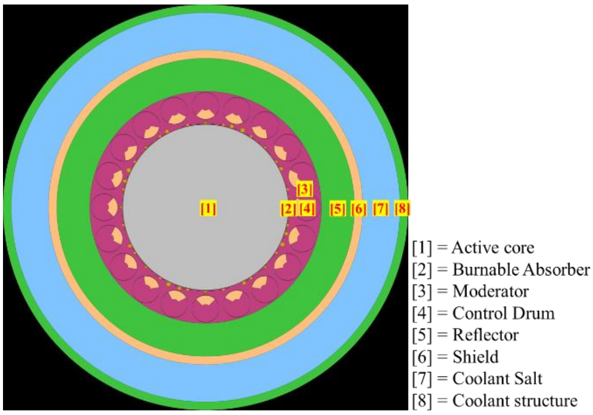

Fig. 3. Control drum-in conditions

The control drum worth is calculated in Beginning of Life (BOL) and End of Life (EOL) conditions. In this study, the BOL condition is at 0 years while the EOL condition is at 30 years for the with-control drum case and 40 years for the without-control drum case. The worth was calculated based on the difference between all drum-out and drums-in conditions. All drums-in conditions are shown in Fig. 3.

BA design configuration adjustment was done to maintain the reactivity swing to be under 1,000 PCM throughout the operation. The BA was equipped with B_4C material with 0.5 mm thickness of SS-304 layer, and located inside the moderator region, right after the active core periphery. In this study, 2 different BA type was used, the rod type and the pad type, both were divided into several layers (area division) for depletion calculation purpose.

The summary of BA configuration in both cases is shown in Table II.

Table II: BA Configuration Summary

Case	BA Type	Radius Size/ Length [mm]	Total Qty	No. of Layer
w/o control drum	Rods	34.00	8	6
		29.00	4	5
		25.00	8	4
		16.25	16	2
		5.50	16	1
	Pads	20.00	44	2/ 3 mm thickness - 10 mm distance
		23.00	8	
w/ control drum	Rods	29.0	4	5
		25.0	8	4
		20.0	8	6
		16.5	16	2
		6.0	16	1
	Pads	20.0	36	2/ 3 mm thickness - 10 mm distance
		23.0	8	
		40.0	8	

In both cases, the rod variety used is 5 different sizes in which the largest radius in the without-control drum case was 5 mm larger. On the contrary, the pad type of BA used in the with-control drum case is 3 different sizes with the total volume of BA is 0.1138 m^3, while for the without-control drum case is 0.1477 m^3.

The Boron Carbide (B_4C) material used in the control drum was enriched to 95% for the boron isotope (B-10) to reach the optimum absorption cross-section[5]. The existence of a control drum minimizes the neutron leakage outside the PMFR core since it was absorbed by the B_4C material inside the control drum, thus the total volume of BA needed is smaller.

2.2 Neutronic Results

Shown in Fig. 4 is the neutronic performance of PMFR and Table III is the excess reactivity summary in both cases.

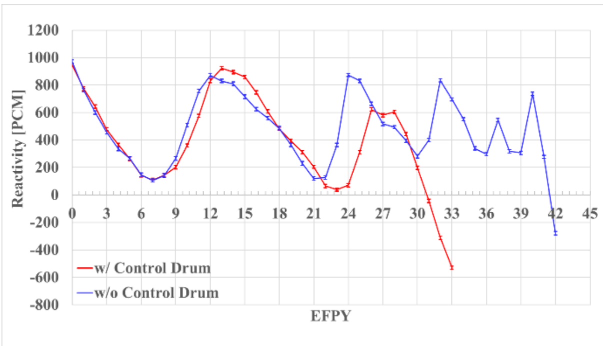

Fig. 4. Reactivity profile comparison

The reactivity profile in both cases can be maintained between 0- 1,000 PCM throughout the operation by modifying the BA design. The average reactivity in the with-control drum case is only 42 PCM smaller than the without-control drum case. As shown in Table IV, the installation of a control drum makes the lifetime of PMFR shorter by 10.41 years.

Table III: Excess Reactivity Summary

Case		EFPY	ρ [PCM]	
			Value	Unc.
w/o control drum	Max.	0	973	13
	Min.	7	107	13
	Avg.	-	500	12
w/ control drum	Max.	0	947	13
	Min.	23	39	12
	Avg.	-	458	12

Table IV: Lifetime Result

Case	Lifetime [years]
w/o control drum	41.45
w/ control drum	31.04

Figure 5 shows the burnup and conversion ratio profile in each case, while Table V gives detailed info at EOL. Since the without-control drum case had a higher lifetime, the available heavy material will last longer and make the burnup higher than the with-control drum case. The same behavior also happens in conversion ratio value.

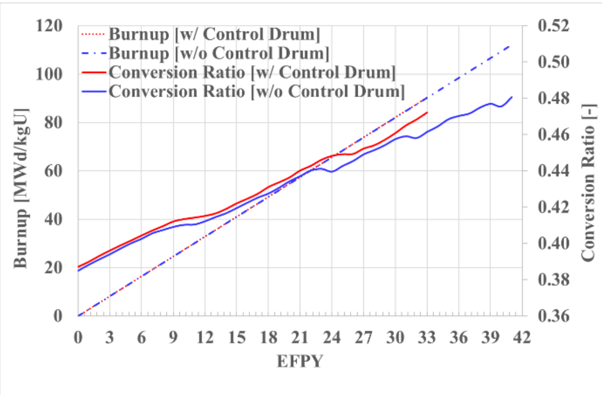

Fig. 5. Burnup and conversion ratio comparison

Table V: Burnup and Conversion Ratio at EOL

Case	Burnup at EOL [MWd/kgU]	Conversion Ratio
w/o control drum	112.21	0.481
w/ control drum	82.09	0.461

Shown in Table VI, is the summary of control drum worth in 3 different operation times. At initial, when all drums-in conditions are applied, the PMFR can undergo a sub-criticality with a Keff value of ~0.98939. Further investigation is needed to increase the control drum's worth at the initial. Secondary poison (liquid or solid), changing the moderation, and changing the amount of fissile material in the core are other options to control the reactivity in a reactor [6]. Additional installation of Shutdown Safety Devices (SSD) may also be utilized [5].

Table VI: Control Drum Worth Summary

Case		Keff		ρ [PCM]		Control Drum Worth [PCM]	
		Value	Unc.[PCM]	Value	Unc.	Value	Unc.
BOL	Drum Out	1.00956	13	947	13	2020	19
	Drum In	0.98939	14	-1073	14		
MOL	Drum Out	1.00866	12	859	12	4516	18
	Drum In	0.96472	14	-3657	14		
EOL	Drum Out	1.00198	12	198	12	8115	19
	Drum In	0.92664	15	-7917	15		

2.3 Flux Distribution

Figures 6 and 7 are the radial flux distribution of fast neutrons at BOL and EOL conditions respectively in each case. Since the volume of BA is lower in the without-control drum case, the radial flux appears lower at EOL along with the burnup.

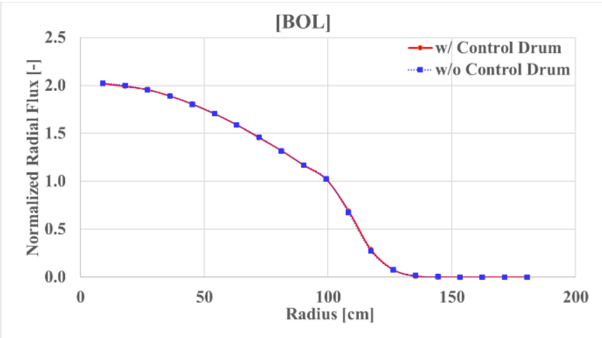

Fig. 6. Radial flux distribution of fast neutron at BOL

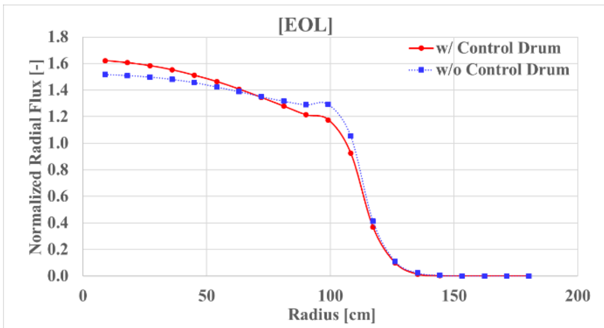

Fig. 7. Radial flux distribution of fast neutron at EOL

Shown in Figs. 8 and 9, are the radial flux distribution of thermal neutrons at BOL and EOL conditions. The thermal flux only appears in the moderator and reflector regions. The radial flux was distorted at a radius of 140~150 cm in the with-control drum case due to neutron absorption by the pad material of control drums. The maximum flux in this case decreased to 1.70 from 2.04 compared with the without-control drum case which increased to 3.30 from 3.11.

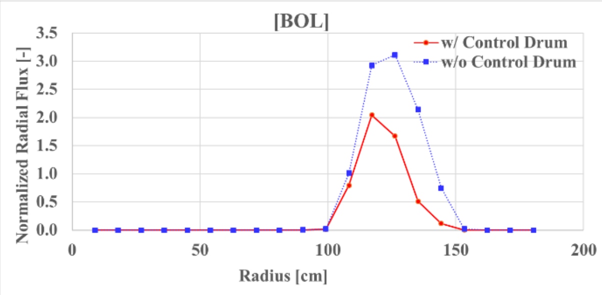

Fig. 8. Radial flux distribution of thermal neutron at BOL

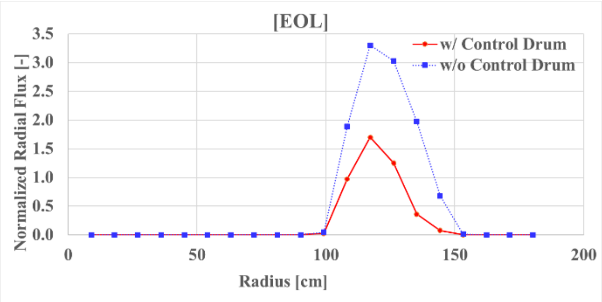

Fig. 9. Radial flux distribution of thermal neutron at EOL

2.4 Energy Spectrum

Figure 10 shows the energy spectrum of PMFR for both cases at BOL and EOL conditions. The spectrum became softened at EOL due to the moderator installation. The without-control drum case has the hardest thermal spectrum in the EOL condition due to less absorption reaction in the moderator and reflector regions (no control drum present). The softer spectrum of the with-control drum case also contributes to the 10.41 shorter lifetime operation than the without-control drum case.

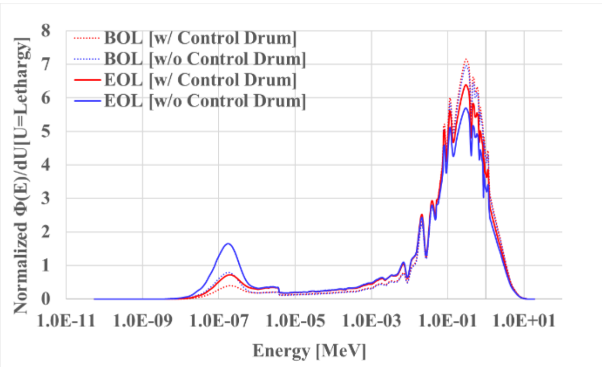

Fig. 10. The energy spectrum of PMFR

2.5 Power Profile

As shown in Figs. 11 and 12, the radial power distribution of PMFR at BOL and EOL for both cases is gradually increased in the reactor core-periphery, while it gradually decreased in the core center. The hump occurred at EOL in the with-control drum case is 1.5 lower due to the presence of control drums. The low-energy neutrons are mostly absorbed by the control drums and make the power density at the core boundary significantly lower than the without-control drum case. Meanwhile, the axial power distribution in both cases is not significantly different as shown in Fig. 13.

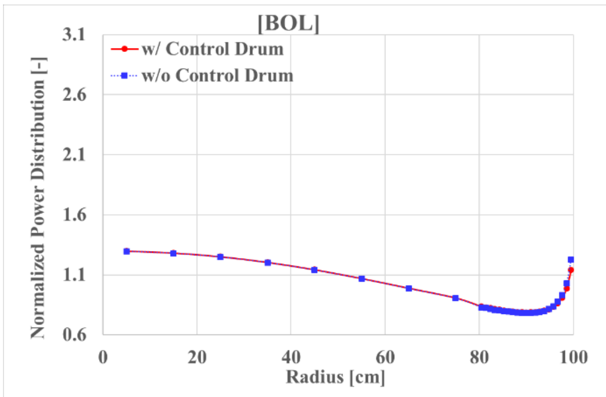

Fig. 11. Radial power distribution of PMFR at BOL

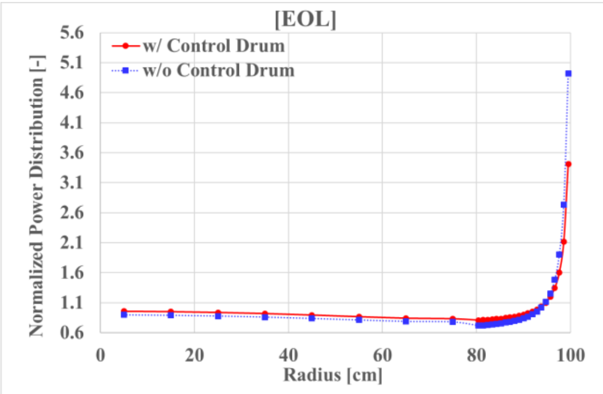

Fig. 12. Radial power distribution of PMFR at EOL

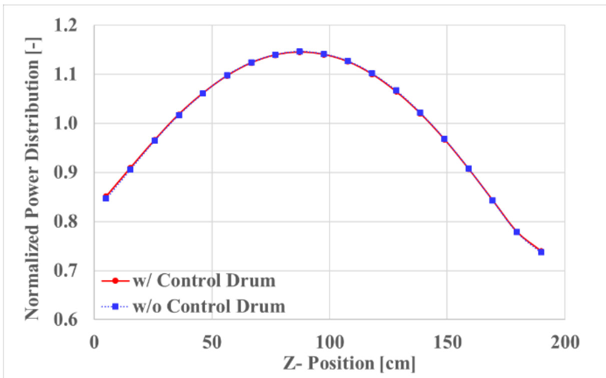

Fig. 13. Axial power distribution of PMFR at BOL

Figures 14 and 15 are the 2D power profiles obtained in the BOL condition for the with-control drum case and the without-control drum case respectively. Consistent behavior is also observed in this power profile data display, the power density at the core center was higher and significantly lower in the core-periphery for the with-control drum case.

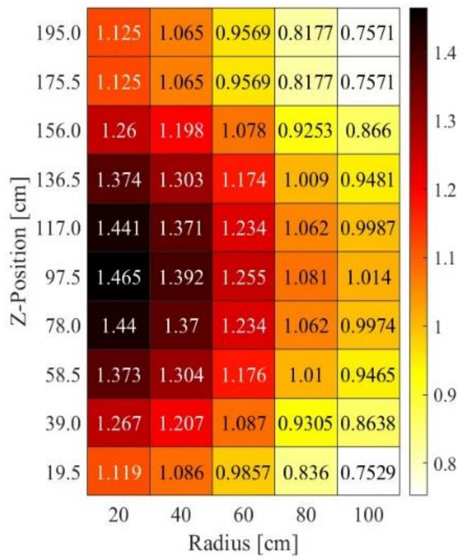

Fig. 14. Normalized 2D Power Profile at BOL in with-control drum case

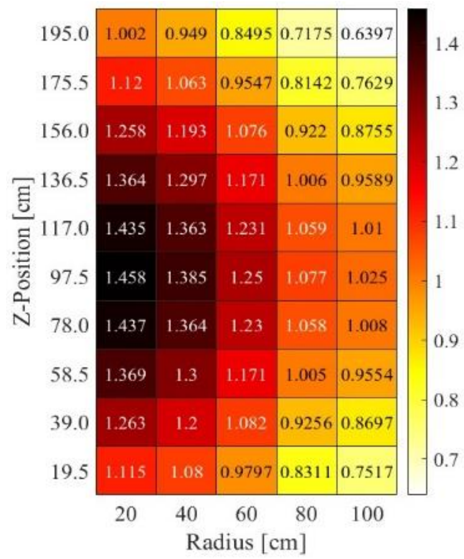

Fig. 15. Normalized 2D Power Profile at BOL in without-control drum case

3. Conclusions

A control drum design optimization for the Passively-Cooled Molten Salt Fast Reactor has been successfully studied. The usage of pad types control drum with SS-304 layer and Helium gas buffer resulted in a total of 31.14 years of lifetime operation, shorter by 10.4 years compared to the without control drum cases. The maximum and minimum excess reactivity throughout the whole operation is 947 ± 13 PCM and 39 ± 12 PCM respectively with a maximum burnup value of 82.09 MWd/kgU. The installation of a control drum can increase the PMFR safety system with its drum worth up to 2020 PCM to 8115 PCM throughout the operation. A study of drain tank installation is needed to further increase the safety feature in a PMFR design.

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