Shutdown Margin Study for a Passively-cooled Molten Salt Fast Reactor

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1. Introduction

The Molten Salt Reactor is an advanced type of nuclear reactor design that utilizes a liquid fuel mixture, typically a molten fluoride or chloride salt, as fuel and the coolant. MSR is one of the nuclear reactor designs categorized as Generation IV by the Generation IV International Forum. Molten Salt Reactors (MSRs) offer safety advantages, including low-pressure operation and continuous online refuelling, economic benefits such as compact structure and high-temperature operation without the need for shutdowns, and environmental advantages such as Thorium utilization, Actinide recycling to reduce waste production, and decreased waste heat generation compared to Light Water Reactors (LWRs)[1].

The establishment of the i-SAFE-MSR research centre in the Republic of Korea aims to advance the development of the Passively-cooled Molten Salt Fast Reactor (PMFR), which encompasses the fundamental concepts and necessary specifications as outlined below [2]:

- 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

In previous research, several analyses have been carried out, such as burnup, conversion ratio, control drum worth, and power distribution. More complete details regarding materials and design can be found in these two papers [3] and [4]. However, the research has not explored one safety aspect: shutdown margin. Studying shutdown margin is crucial for safety in nuclear engineering. It ensures enough control to shut down reactors safely during emergencies or maintenance, meets regulatory standards and prevents accidents by effectively managing power levels. This investigation seeks to achieve an adequate shutdown margin at the beginning of life (BOL) while maintaining the other reactor's performance by optimizing the burnable absorber and control drum.

2. Methods and Result

The calculation was calculated using the Monte Carlo Serpent 2 code version 2.1.31 with nuclear library ENDF/B-VII.1. For the burnup scheme, 30,000,000 histories are used in which the simulation involves 100,000 particles and 500 cycles by eliminating the calculations of the initial 200 cycles. At the same time, the depletion step for this study was done every year with a total of 40 years for a 300 MWth power. The reactor simulation is operated at 923 K, and no fuel salt moving effect was considered in this neutronic study. The optimized design should maintain its reactivity swing under 1,000 pcm, incorporating a 40 cm BeO moderator with a BA and control drum installed [3]. In this study, changes were made to the size of the control drum and BA to obtain a shutdown margin value over 1000 pcm when cold zero power (CZP) and hot zero power (HZP), and for more complete change details are discussed in the next section.

2.1. BA Design and Control Drum Configuration

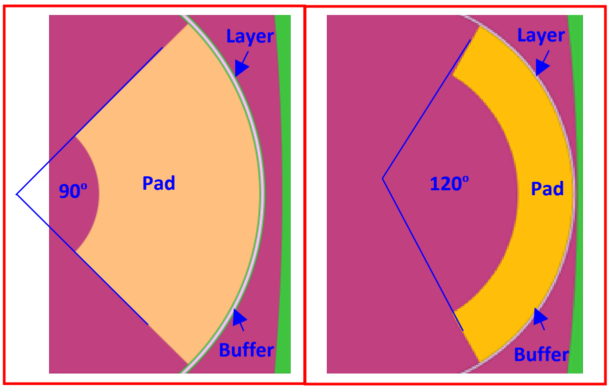

Fig. 1. Detailed previous (left) [4] and optimized (right) control drum parts

The previous model design adopts control drums positioned within the moderator region, comprising a pad with a buffer region between the layered components. The design entails 20 drums with pads angled at 90°, encircling the PMFR active core with a 16.5 cm radius. Inside each drum is a B_4C pad 10.6 cm thick, where the B-10 enrichment was 95% [4]. 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 previous and optimized model of the control drum is shown in Figure 1.

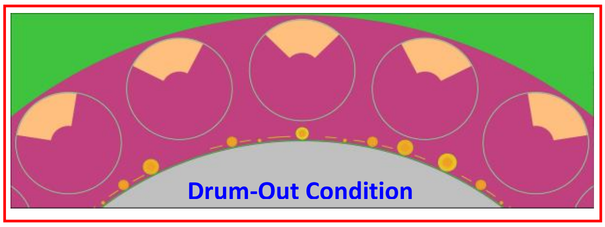

Fig. 2. Configuration of previous control drum, all drum-out conditions in X-Y plane

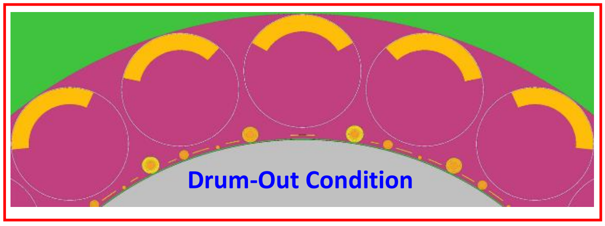

Fig. 3. Configuration of optimized control drum, all drum-out conditions in X-Y plane

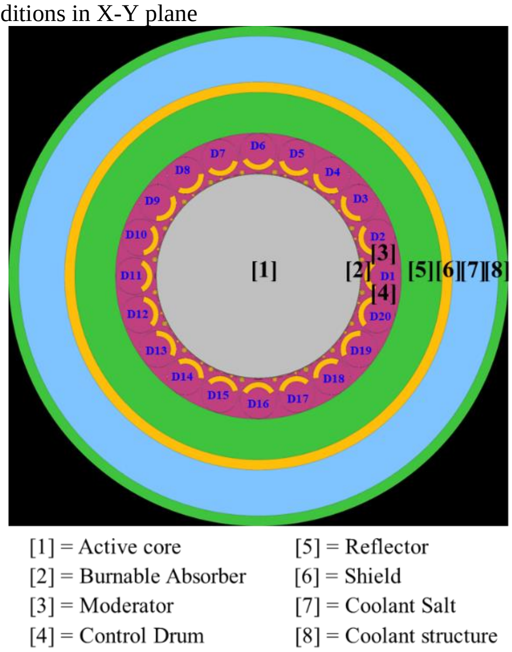

Fig. 4. Control drum-in conditions (Optimized Model)

The control drum radius is increased from 16.5 cm to 17.95 cm to increase the shutdown margin. Increasing the Control Drum Radius is carried out so that the neutron-absorbing material (B_4C) will be much closer to the reactor core when the control drum is in the drum in position so that more neutrons will be captured, and the shutdown margin will increase. Apart from that, to increase the reactor lifetime, the pad thickness was reduced from 10.6 cm to 5.3 cm, the pad angle increased from 90° to 120°, and the thickness of the Layer and Guide tube changed from 0.1 cm to 0.03 cm. All of the changes also caused the burnable absorber configuration to change. Detailed updated and previous specifications are provided in Table I, and configuration details are illustrated in Figures 2 and 3.

Due to changes in the control drum dimensions, it is necessary to adjust the BA configuration to maintain swing reactivity below 1000 pcm. The specifications used are similar to the BA used in the previous model, only differing in size and quantity used. There are two types used in reactors, namely rod type and pad type, both of which are coated with a 0.5 mm thickness of SS-304 layer. Table II shows the summary of BA configuration in the previous and optimized model. The optimized model is shown in Figure 4.

Table I: control drum specification

Control Drum Parts	Material	Thickness [cm]	
		Previous	Updated
Pad	B_4C (95% B-10 enrichment)	10.6	5.3
Layer	SS-304	0.1	0.03
Buffer	Helium Gas at 823 K	0.2	0.2
Guide Tube	SS-304	0.1	0.03

Table II: BA configuration summary of the previous and optimized model [4]

Case	Previous Model			Optimized model		
BA Type	Radius Size [mm]/ angle [°]	Total Qty	No. of Layer	Radius Size [mm]/ angle [°]	Total Qty	No. of Layer
Rods	29.0	4	5	27.0	8	6
	25.0	8	4	26.0	4	5
	20.0	8	6	25.0	8	4
	16.5	16	2	15.0	16	2
	6.0	16	1	6.0	16	1
Pads	2.0	36	2 / 3 mm thickness - 10 mm distance	4.45	4	3 mm thickness - 14 mm distance
	2.3	8		1.55	8	
	4.0	8		3	16	
				2.5	12	
				1	4	

2.2. Depletion Result

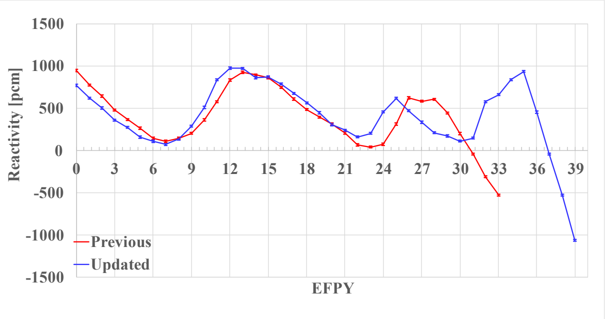

Fig. 5. Reactivity profile comparison

Based on Table III, by optimizing BA and Control Drum configuration, the lifetime of PMFR is 5.87 years longer than the previous model see Figure 5. The reactivity profile in the optimized model can also be maintained between 0 and 1000 pcm throughout the reactor lifetime.

Table III: Burnup and conversion ratio at EOL

Case	Burnup at EOL [MWd/kgU]	Conversion Ratio	Lifetime
Previous	82.09	0.461	31.04
Optimized	98.51	0.472	36.91

2.3. Energy Spectrum

Figure 6 compares the energy spectrum of PMFR between the previous and optimized models. The energy spectrum does not show a significant change at BOL, but the Optimized model has a softer spectrum at EOL. This softening causes the optimized model to have a longer lifetime of 5.87 years.

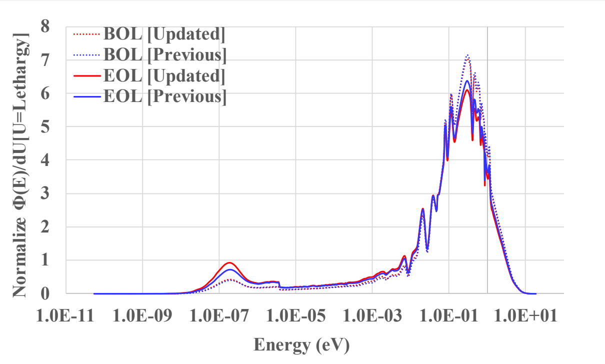

Fig. 6. The energy spectrum of PMFR

2.4. Temperature Coefficient

The temperature coefficient calculation is carried out by varying the material temperature from 823 K to 1023 K, which is based on the inlet temperature of molten salt at 600 °C and the outlet temperature of molten salt at 700 °C. Temperature coefficient consists of Fuel Temperature Coefficient (FTC), Reflector Temperature Coefficient (RTC), and Isothermal Coefficient (ITC). These parameters are observed across the Beginning of Life (BOL), Middle of Life (MOL), and End of Life (EOL) conditions. Unc. is an abbreviation for uncertainty.

Table IV: Temperature coefficient evaluation

Case	Condition	Temperature Coefficient [pcm/K]	
		Value	Unc.
FTC	BOL	-13.45	0.03
	MOL	-11.01	0.03
	EOL	-8.12	0.02
RTC	BOL	0.04	0.03
	MOL	0.49	0.03
	EOL	1.40	0.03
ITC	BOL	-13.41	0.06
	MOL	-10.52	0.06
	EOL	-6.71	0.05

Table IV shows that the FTC at BOL for the optimized model has a high value, namely -13.45 pcm/K. However, during the entire operation, the FTC value decreases due to the softened neutron spectrum originating from BA burnup. Meanwhile, RTC has a positive value, namely 0.04 pcm/K, because the nuclei in the moderator are in the hard spectrum due to temperature increase. In other words, the probability of parasitic capture is reduced. If the moderator has sufficient thickness, it can increase neutron absorption in the fuel so that the RTC has a slightly positive value. ITC is the change in reactivity per degree of temperature change in both fuel and moderator/reflector. The ITC calculation is simple by adding up the RTC and FTC. It can be seen that ITC has a value of -13.41 pcm/K at BOL. The PMFR has a negative temperature reactivity coefficient, which indicates that it has inherent passive safety. However, when the reactor is at low temperatures, it will be challenging to control because the excess reactivity is high. Therefore, drum control optimization should be done to have a sufficient shutdown margin or rod worth at low temperatures.

2.5. Control Drum Worth

The control drum worth was determined by calculating the difference between the reactivity values at the drum-out condition and the drum-in condition at the Beginning of Life (BOL). All drums-in conditions for the optimized model are shown in Fig. 4. Tables V and VI show the summary of control drum worth in BOL at operational temperatures (923 K) in both cases.

Table V: Control drum worth summary at BOL at operational temperatures 923 K (previous model)

Case		k_{eff}	Reactivity [pcm]		Control Drum Worth [pcm]	
		Value	Value	Unc.	Value	Unc.
BOL	Drum Out	1.00956	947	13	2020	19
	Drum in	0.98939	-1073	14		
MOL	Drum Out	1.00866	859	12	4516	18
	Drum in	0.96474	-3657	14		
EOL	Drum Out	1.00198	198	12	8115	19
	Drum in	0.92664	-7917	15		

Table VI: Control drum worth summary at BOL at operational temperatures 923 K (optimized model)

Case		k_{eff}	Reactivity [pcm]		Control Drum Worth [pcm]	
		Value	Value	Unc.	Value	Unc.
BOL	Drum Out	1.00773	767	13	3602	19
	Drum In	0.97243	-2834	14		
MOL	Drum Out	1.00566	563	12	8231	18
	Drum In	0.92878	-7667	14		
EOL	Drum Out	1.00455	453	11	15361	18
	Drum In	0.87026	-14908	14		

In the BOL for the previous model, when the control drum conditions are at the drum in position, PMFR can reach the subcritical phase with k_{eff} 0.98939. However, the control drum's worth is still small due to the temperature operating conditions. Suppose the reactor is in a Hot Zero Power (HZP) condition; in that case, the k_{eff} value will increase, considering that the density of the fuel molten salt increases, so the number of fission reactions increases. The solution for this issue is to increase the radius of the control drum. Table VI shows that the control drum's worth is more significant and meets the shutdown margin at the BOL at the Hot Full Power (HFP) temperature of 923 K.

2.6. Shutdown Margin

The shutdown margin (SDM) is the negative reactivity required for the reactor to reach the subcritical phase if all reactivity control mechanisms, in this case, the control drum, are fully inserted into the core except one with the most reactive mechanism. This calculation uses a historical number of 1,000,000 particles with 200 inactive and 300 active cycles to achieve an uncertainty value below 10 pcm. Table VII evaluates the control drum worth and shutdown margin when the BOL condition is at HZP temperature.

The theoretical density of the fuel salt density at a temperature of 298 K is 4.56035 g/cm^3. However, it should be noted that this density is almost impossible to achieve physically. Therefore, the density of the fuel salt needs to be adjusted so that in CZP calculations, a density of 3.85093 g/cm^3 fuel density at 873 K, which is at melting temperature, is used. Table VIII shows the shutdown margin evaluation during BOL at CZP temperature with adjusted fuel salt and molten salt densities. Also, helium flows through the off-gas system in actual cases, meaning the fuel density will be lower than the theoretical density. However, this study neglects this assumption, and further study needs to be conducted.

Table VII: SDM evaluation (optimized configuration) at HZP with a temperature of 873 K

Case	**k$_{eff}$**	**Drum Worth [pcm]**	**Single Drum Worth [pcm]**	**SDM [pcm]**
All DO	1.014904	3514	-	-
All DI	0.979953			
D1 Out	0.982267	3274	240	1773
D2 Out	0.981281	3376	138	1872
D3 Out	0.981435	3360	154	1856
D4 Out	0.981264	3378	136	1874
D5 Out	0.981257	3379	136	1874
D6 Out	0.982226	3278	236	1777
D7 Out	0.981260	3378	136	1874
D8 Out	0.981376	3366	148	1862
D9 Out	0.981254	3379	135	1875
D10 Out	0.981223	3382	132	1878
D11 Out	0.982273	3273	241	1773
D12 Out	0.981289	3375	139	1871
D13 Out	0.981417	3362	152	1858
D14 Out	0.981324	3372	143	1868
D15 Out	0.981273	3377	137	1873
D16 Out	**0.982352**	**3265**	**249**	**1765**
D17 Out	**0.981162**	**3389**	**126**	**1884**
D18 Out	0.981377	3366	148	1862
D19 Out	0.981242	3380	134	1876
D20 Out	0.981325	3372	143	1868

When HZP, in all drum-in conditions, the PMFR shows in the subcritical phase with a k$_{eff}$ of around 0.979 with a drum worth of 3514 pcm. D17 has the highest single drum worth at 1884 pcm, while D16 has the lowest at 1765 pcm. All control drums can compensate for excess reactivity when transitioning from HFP to HZP.

Table VIII: SDM evaluation (optimized configuration) at CZP with the temperature at 298 K and with fuel density adjustment:

Case	**k$_{eff}$**	**Drum Worth [pcm]**	**Single Drum Worth [pcm]**	**SDM [pcm]**
All DO	1.023105	3425	-	-
All DI	0.988464			
D1 Out	0.990797	3187	238	920
D2 Out	0.989894	3279	146	1011
D3 Out	0.990080	3260	165	992
D4 Out	0.989923	3276	149	1008
D5 Out	0.989910	3278	148	1009
D6 Out	**0.990931**	**3174**	**252**	**907**
D7 Out	0.989871	3282	144	1013
D8 Out	0.990014	3267	158	999
D9 Out	0.989932	3275	150	1007
D10 Out	**0.989842**	**3285**	**141**	**1016**
D11 Out	0.990911	3176	250	909
D12 Out	0.989890	3280	146	1011
D13 Out	0.990142	3254	171	986
D14 Out	0.989888	3280	146	1011
D15 Out	0.989860	3283	143	1014
D16 Out	0.990817	3185	240	918
D17 Out	0.989866	3282	143	1013
D18 Out	0.990129	3255	170	987
D19 Out	0.989907	3278	147	1009
D20 Out	0.989866	3282	143	1013

Meanwhile, in CZP conditions, the shutdown margin evaluation shows a k$_{eff}$ of around 0.988 with a drum worth 3425 pcm at all drum-in conditions. In contrast to the HZP condition, D10 has the highest drum worth, with a drum worth of 1016 pcm, and the smallest is D6, with a drum value of 907 pcm. Only 12 single control drums have a shutdown margin above 1000 pcm in this condition.

3. Conclusion

Neutronic calculations for the PMFR have been conducted. Changing the control drum design was followed by adjustments to the new BA configuration, increasing the lifetime by 5.87 years compared to the previous model. Assuming the fuel salt use density is at Temperature 831 K (Melting Temperature), the new control drum worth can compensate for the excess reactivity at BOL at CZP, which is 3425 pcm. All new control drums can achieve a shutdown margin of over 1000 pcm at HZP, while at CZP, only 12 control drums reach over 1000 pcm. A further study of helium flow by an off-gas system should be assessed to provide a complete picture of PMFR during operation.

REFERENCES

[1] T. J. Dolan, “1 - Introduction,” in *Molten Salt Reactors and Thorium Energy*, T. J. Dolan, Ed., Woodhead Publishing, 2017, pp. 1–12. doi: https://doi.org/10.1016/B978-0-08-101126-3.00001-4.

[2] J. PARK et al., “Design Concepts and Requirements of Passive Molten Salt Fast Reactor (PMFR),” in *Transactions of the Korean Nuclear Society Spring Meeting,* South Korea, 2022.

[3] N. N. Aufanni, E. Lee, T. Oh, and Y. Kim, “[ICAPP 2023] Burnable Absorber Design Study for a Passively-Cooled Molten Salt Fast Reactor,” *Nuclear Engineering and Technology*, 2023, doi: 10.1016/j.net.2023.11.001.

[4] N. N. Aufanni, E. Lee, and Y. Kim, “Control Drum Design Optimization for a Passively-Cooled Molten Salt Fast Reactor.” in Reactor Physics Asia 2023 (RPHA2023) Conference, South Korea, 2023.

[5] O. Ashraf, A. Rykhlevskii, G. V. Tikhomirov, and K. D. Huff, “Preliminary design of control rods in the single-fluid double-zone thorium molten salt reactor (SD-TMSR),” *Ann Nucl Energy*, vol. 152, Mar. 2021, doi: 10.1016/j.anucene.2020.108035.