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Feasibility Study on Long-Term Reactivity Management of a Molten Salt Reactor for Marine Propulsion Using Rotatable Hybrid Reflector Drums

Hyunjun Chung [a], Jinho Song [a], Joon Eon Yang [a], Sung Joong Kim [a, b*]
[a]*Department of Nuclear Engineering, Hanyang University,*
222 Wangsimni-ro, Seongdong-gu, Seoul 04763, Republic of Korea
[b]*Institute of Nano Science & Technology, Hanyang University,*
222 Wangsimni-ro, Seongdong-gu, Seoul 04763, Republic of Korea

[*]*Corresponding author: sungjkim@hanyang.ac.kr*

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1. Introduction

Net-zero emission targets have increased interest in nuclear marine propulsion because nuclear systems offer high energy density and long operating periods. Among them, Molten Salt Reactors (MSRs) have attracted significant attention for marine applications owing to their high energy density, low operating pressure, and potential for long-term operation without frequent refueling [1, 2]. In particular, chloride fueled MSRs have been investigated as a promising reactor concept for long life marine propulsion.

In long life MSRs, continuous fuel depletion reduces the fissile inventory and consequently the reactor reactivity over the fuel cycle. Maintaining sufficient end of cycle (EOC) reactivity margin therefore requires sufficient excess reactivity at the beginning of cycle (BOC), which increases the required reactivity control range and shutdown worth. Various reactivity control methods, including control drums and burnable absorbers, have been proposed to compensate for the reactivity loss caused by fuel depletion [2, 3]. However, excessive BOC reactivity can increase the control burden and complicate reactivity management over the fuel cycle.

Therefore, a means of releasing reserve reactivity in stages over the fuel cycle is desirable for long life marine MSRs. A rotatable hybrid reflector drum can provide reactivity control by changing the neutron reflection and absorption characteristics through the relative positioning of reflector and absorber regions.

In this study, sixteen rotatable hybrid reflector drums incorporating MgO, BeO, and B_4C regions were investigated for long-term reactivity management. Single material reflector and drum cases were compared to evaluate the effects of reflector material and sector separation angle. Full core depletion calculations were then performed over 30 effective full power years (EFPY) to assess whether the reserve worth released by the hybrid drums is sufficient to sustain criticality over the cycle.

2. Design of MSR Core and Hybrid Reflector Drums

2.1 Reference core configuration and specifications

A full height MSR model was established to evaluate long-term reactivity management using reflector drums. The model consists of a homogeneous fuel salt region, structural layers, an MgO reflector, and the reactor vessel. The fuel salt is NaCl-KCl-UCl3 (42.9-20.3-36.8 mol%) [2], with uranium enriched to 19.75 wt% U-235 and chlorine enriched to 99 at% Cl-37. Figure 1 shows the core geometry, and Table 1 summarizes the principal dimensions and materials.

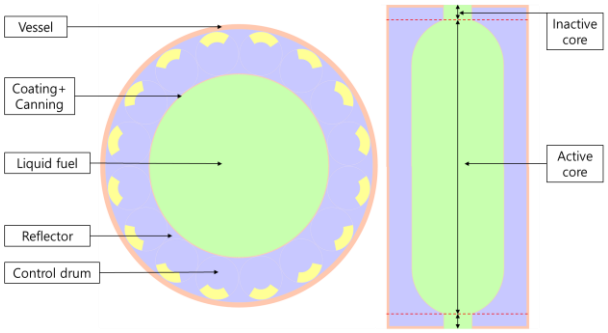


Fig. 1. Radial and axial views of the MSR core.

Table 1: Core specifications and materials

Region		Materials	Sizes	Values [cm]
Inner core	Active core	NaCl-KCl-UCl_3	Radius	83.25
			Height	567.5
	Coating	Alloy 625	Thickness	0.08
	Canning	SS 316H	Thickness	0.8
Outer core	Reflector	MgO	Thickness	40.45
	Vessel	SS 316H	Thickness	4.63
Whole core			Radius	129.14
			Height	631

2.2 Computational conditions

Calculations are performed with Serpent 2.2.1 using the ENDF/B-VIII.0 continuous energy library. The full height cores are modeled at 100 MWth with a vacuum outer boundary, and xenon removal is represented by a constant of 0.02039 s^{-1} [4]. Table 2 summarizes the computational conditions.

Table 2: Computational conditions

Parameter		Values
Computer code		Serpent 2.2.1
Cross section library		Continuous energy ENDF/B-VIII.0 libraries
Depletion period		30 EFPY
Power		100 MW_{th}
# of histories		100,000
# of cycles	Inactive	200
	Active	300

Salt outside the core is excluded; therefore, no reactivity credit is assigned to the out of core fissile inventory.

2.3 Reflector material comparison and hybrid drum configuration

The fixed MgO and BeO cores were first evaluated separately to isolate the reflector material effect before constructing the hybrid drum.

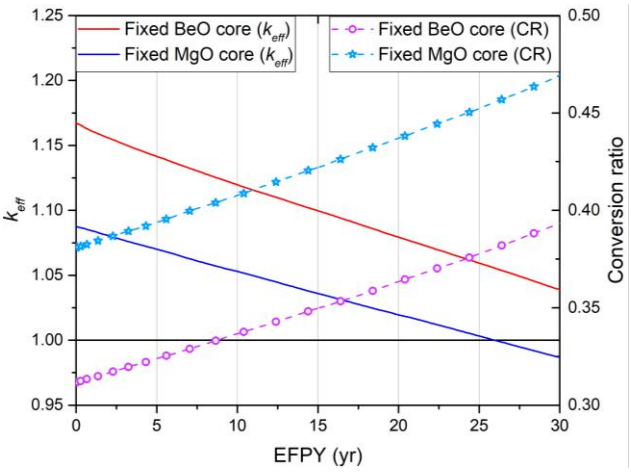


Fig. 2. k_{eff} and CR changes of fixed MgO and BeO cores.

Figure 2 shows that the fixed BeO core maintains a higher k_{eff}, whereas the fixed MgO core retains a higher conversion ratio (CR). This contrast is associated with the spectral differences examined in Figure 3.

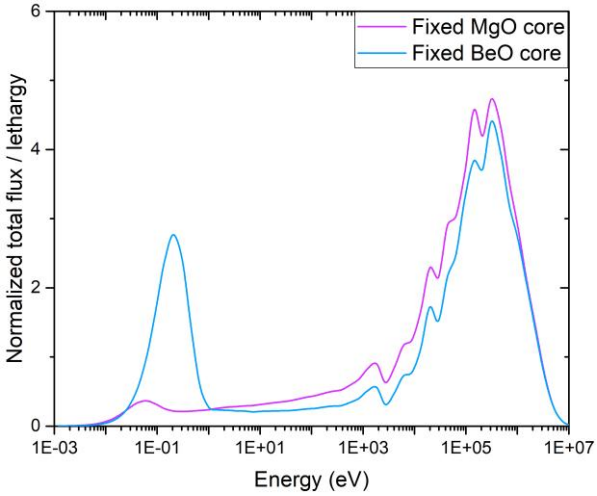


Fig. 3. Neutron spectra of the fixed MgO and BeO cores.

Figure 3 shows that the BeO case has a larger low energy neutron component than the MgO case. Table 3 lists their BOC and EOC multiplication factors.

Table 3: k_{eff} of the fixed MgO and BeO cores

Parameter	MgO	BeO
k_{eff} (BOC)	1.08735	1.16822
k_{eff} (EOC)	0.98698	1.03928

At BOC, the fixed BeO core provides 6,367 pcm more reactivity, whereas MgO maintains the higher cycle average CR. This contrast motivates an operating strategy that preserves the higher conversion MgO facing state early in life and introduces the higher reactivity BeO facing state as depletion reduces the operating margin.

Figure 4 shows the proposed core arrangement and the material regions of an individual hybrid reflector drum. Each of the sixteen drums incorporates a BeO sector and a B_4C absorber pad within an MgO body.

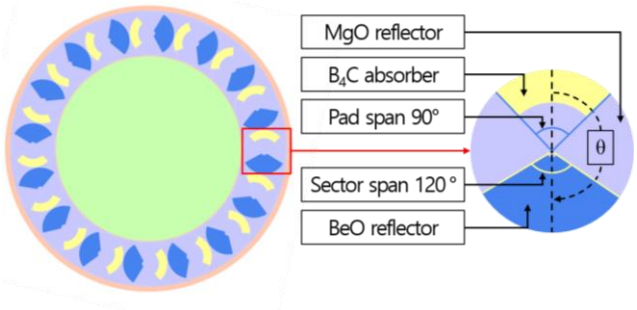
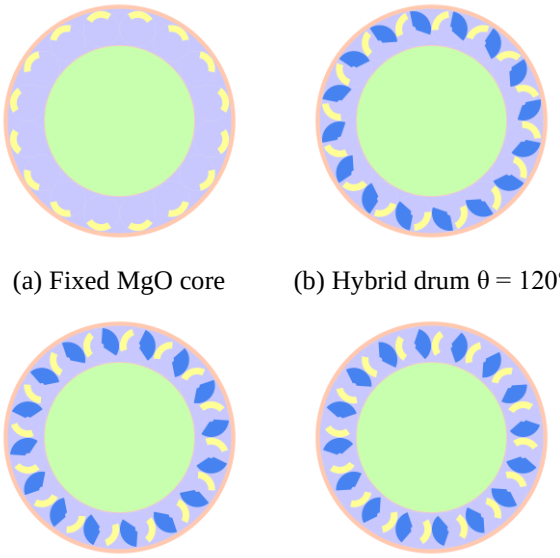


Fig. 4. Configuration of hybrid reflector drum and core.

By rotating a drum, the MgO, BeO, or B_4C region can face the core. The MgO facing state favors conversion, the BeO facing state adds the reactivity needed later in the cycle, and the B_4C facing state provides shutdown.

Figure 5 shows the fixed MgO core and hybrid drum configurations evaluated at θ = 120°, 150°, 180°. Each drum has a 120° reflector-material sector span and a 90° B_4C pad span. A rotation step of 90° changes the material facing the core. The sector separation angle θ is the angle between the centerlines of the reflector-material sector and the B_4C pad; at θ = 180°, successive rotation steps select the MgO-, BeO-, or B_4C-facing states.



(a) Fixed MgO core (b) Hybrid drum θ = 120°

(c) Hybrid drum θ = 150° (d) Hybrid drum θ = 180°

Fig. 5. Reflector drum configurations with different sector separation angles.

For staged operation, the sixteen drums are divided into four batches of four evenly spaced drums. This arrangement preserves rotational symmetry while the reserved worth is released in four steps; the rotation schedule is specified in Section 3.1.

2.4 Core configurations for comparative analysis

Table 4: Definition of the evaluated cases

Cases	Body / sector	Drums over 30 EFPY
Fixed BeO core	BeO / BeO	Held, B_4C outward
Fixed MgO core	MgO / MgO	Held, B_4C outward
MgO drum core	MgO / MgO	Staged release, 4 steps
Hybrid drum core	MgO / BeO	Staged release, 4 steps

Table 4 defines the configurations used to separate the effects of reflector material, absorber withdrawal, and sector separation angle. All cases share the same sixteen drum mechanical configuration; in the fixed MgO and BeO cores the drum sectors are uniform in material and the B_4C pads are held facing away from the core throughout depletion, so these cases act as fixed single material reflectors with no releasable worth. The depletion cases are defined in Section 3.1, and the BOC released worth in Fig. 6 is evaluated at θ = 120°, 150°, and 180° for both drum cores. The fixed MgO core plotted in Figures 2 and 8 is this same configuration; it is the MgO drum core with all drums held in the B_4C-outward orientation.

2.5 Effect of sector separation angle

Figure 6 compares the released drum worth of the MgO drum and hybrid drum core as the sector separation angle changes, together with their difference, which corresponds to the BeO contribution.

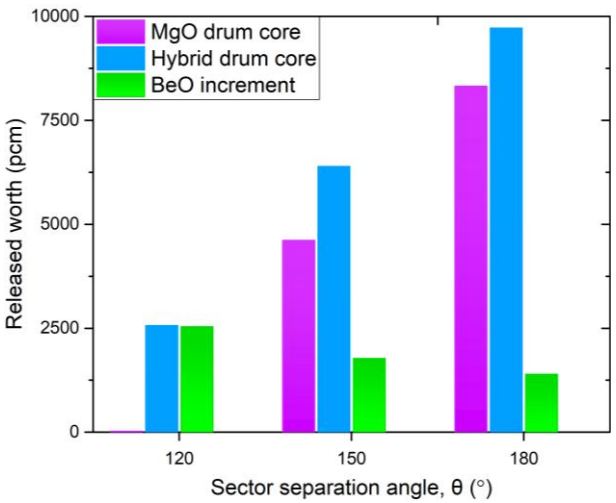


Fig. 6. Released worth of MgO drum core, hybrid drum core and the corresponding BeO increment.

At BOC, although the BeO increment decreases from 2,540 to 1,398 pcm as θ increases, the total released worth increases monotonically, reaching 8,323 pcm for the MgO drum core and 9,721 pcm for the hybrid drum core at θ = 180°. The difference between the two drum cases at this angle represents the positive BeO contribution beyond the common B_4C withdrawal effect. Therefore, among the evaluated angles, θ = 180° was selected as the reference configuration for the subsequent depletion analysis.

3. Analysis of Long-Term Reactivity Management

3.1 Depletion analysis and drum rotation schedule

Unlike a conventional control drum, which is rotated continuously to hold the core critical, the drums here change the material facing the core in discrete steps and

are not used as the fine-control device. Their rotations are a coarse, staged release of the reserve worth stored in the drums; the four rotation steps are a modeling schedule chosen to test whether that reserve is sufficient over 30 EFPY, not an operating prescription. Between steps, the margin above criticality shown in Fig. 8 is the reactivity that an independent fine-control means must hold down. This distinction bounds the scope of the present feasibility study.

The depletion cases use the dimensions in Table 1, a 120° material sector span, a B_4C pad, a sector separation angle of $\theta = 180°$, and drum rotations at 1, 9, 17, and 25 EFPY. The MgO drum and hybrid cases differ only in whether the 120° sector is MgO or BeO. From BOC to EOC, the leakage fraction decreases from 1.55% to 1.26% in the MgO drum core and from 1.05% to 0.86% in the hybrid drum core.

3.2 Conversion ratio behavior

Figure 7 compares the CR histories of fixed MgO core, MgO drum core, and hybrid drum core over 30 EFPY.

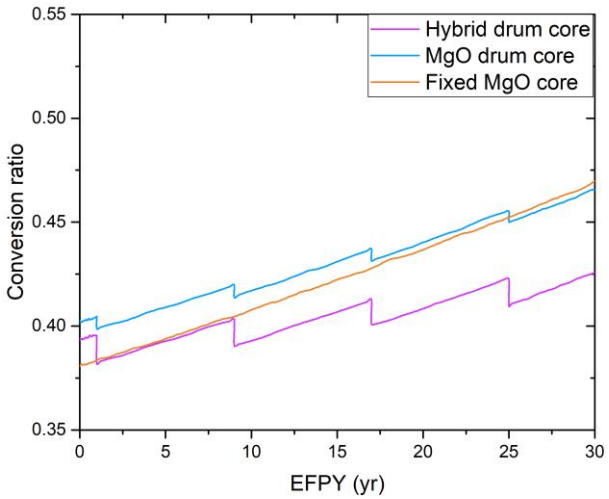


Fig. 7. CR histories of the fixed MgO core, MgO drum core, and hybrid drum core.

Before the first rotation, the MgO drum core has the highest CR, followed by the hybrid drum core and the fixed MgO core. The drum cores have the higher CR because their partly exposed B_4C pads harden the spectrum. Each rotation lowers the CR, with a larger decrease when BeO faces the fuel. The unrotated batches therefore preserve conversion early in life, whereas later rotations trade part of this conversion advantage for the reactivity needed to sustain criticality as the fissile inventory is depleted.

3.3 Long-term reactivity performance

Figure 8 compares the 30 EFPY k_{eff} histories of the evaluated cases, and Table 5 summarizes their principal reactivity margins.

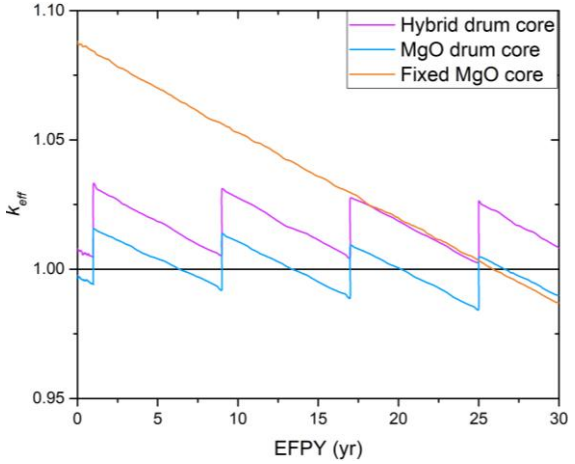


Fig. 8. k_{eff} histories of the fixed MgO core, MgO drum core, and hybrid drum core.

The fixed MgO core loses reactivity monotonically, whereas the drum cases show stepwise recovery after each rotation. Only the hybrid drum core remains above criticality throughout the evaluated cycle. The curves show the reactivity available with the drums in their scheduled orientation; in operation, the margin above $k_{eff} = 1$ at each point is the amount that fine control must compensate.

Table 5: Excess reactivity and BOC/EOC reactivity margin

Cases	ρ [pcm]		
	Excess reactivity	BOC	EOC
Fixed MgO core	+8,033	+8,033	-1,319
MgO drum core	+8,050	-251	-1,024
Hybrid drum core	+10,491	+694	+815

In Table 5, the excess reactivity is the BOC reactivity with every drum in its maximum-reactivity orientation, i.e., the reactivity that the drums can make available through rotation. The MgO drum core (+8,050 pcm) and the fixed MgO core (+8,033 pcm) are equivalent within statistics, confirming that the MgO drums only withhold reactivity that the core already carries. The hybrid drum core carries 2,441 pcm more, supplied by the BeO sectors; the hybrid drums therefore do not reduce the excess reactivity of the core but enlarge the reserve that can be released in stages. The BOC and EOC columns give the reactivity with the drums in their scheduled orientation.

The fixed MgO core starts at +8,033 pcm, becomes subcritical at 25.9 EFPY, and ends at -1,319 pcm. The MgO drum core starts at -251 pcm and is subcritical before its first rotation; it is therefore a common schedule material comparison rather than a feasible startup sequence. Rotations temporarily restore criticality, but its

minimum and EOC margins are -1,582 and -1,024 pcm, respectively.

The hybrid drum core remains critical at every calculated depletion point, with a minimum margin of +273 pcm and an EOC margin of +815 pcm. The stepwise reactivity recovery in both drum cases is governed primarily by B_4C withdrawal. The BeO sector provides additional reflector worth, changing the EOC margin from -1,024 pcm in the MgO drum core to +815 pcm in the hybrid drum core under the same geometry and rotation schedule at this design point.

Unlike a burnable absorber, each unrotated batch preserves its unused worth outside the high reactivity orientation until required [3].

3.4 Shutdown performance assessment

The shutdown state is evaluated by rotating all sixteen B_4C absorber pads toward the core, with a criterion of $k_{eff} \leq 0.95$. The maximum operating reactivity occurs immediately after the first batch rotation at 1 EFPY; therefore, the shutdown calculation uses the fuel composition at this point.

Table 6: Shutdown results at maximum reactivity

Cases	**Shutdown k_{eff}**	**Shutdown worth**
Hybrid drum core	0.83217	23,361 pcm
MgO drum core	0.83175	21,752 pcm

Both cases in Table 6 satisfy the shutdown criterion. From the maximum reactivity state, full drum rotation removes more than 21,000 pcm and reduces k_{eff} to approximately 0.832.

4. Conclusions

The material comparison identifies MgO as the higher conversion state and BeO as the higher reactivity state. In staged operation, B_4C withdrawal provides the stepwise recovery, while BeO exposure supplies the additional worth needed as depletion reduces the operating margin.

The fixed MgO core becomes subcritical at 25.9 EFPY, and the common schedule MgO drum case reaches a minimum of -1,582 pcm and ends at -1,024 pcm. Under the same geometry and schedule, the hybrid drum core remains critical with a minimum margin of +273 pcm and an EOC margin of +815 pcm. The selectable BeO state therefore changes the operating outcome without applying the full BeO worth at BOC. The hybrid drums do not reduce the excess reactivity of the core; they make 2,441 pcm more worth available than the MgO drums and release it in stages, with fine criticality control assumed to be provided independently.

From the maximum reactivity state at 1 EFPY, rotating all drums to the B_4C facing state provides more than 21,000 pcm of shutdown worth and reduces k_{eff} to approximately 0.832. Future work will evaluate drum rotation transients, optimize the BeO sector thickness and core dimensions, and include the out-of-core salt inventory in the depletion model, since it reduces the core size required for a 30-EFPY cycle and in turn changes the reactivity worth of the drums.

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