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Preliminary Core Design with Internal Structure for Small-Sized Molten Salt Fast Reactor

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1. Introduction

In the case of the Molten Salt Fast Reactor(MSFR), the nuclear reactor core design should take into account neutronics and thermal hydraulic behavior caused by liquid fuel flow movement inside the reactor. While traditional MSFRs do not require an internal moderator, the flow patterns inside the core are complex, making it difficult to construct adequate fields. Depending on the flow rate or core geometry, unstabilized flow distribution might lead to recirculation or stagnation issues. To ensure a stable flow field within the core, special treatments as well as coupled neutron and thermohydraulic simulations should be considered.

In our previous studies, we analyzed several reflector candidates and options for utilizing fast spectrum while preserving sufficiently compact core. Beryllium oxide (BeO) was selected as the most promising reflector choice for increasing reflector efficiency due to its superior moderation and scattering capabilities. However, the interface between fuel salt and reflector around the active core becomes the main heat surface with thermal fission increasing as reflector thickness grows. Heat accumulation near the reflector raises the active core wall temperature, increasing the likelihood of recirculation and hotspots.

In this study, to further improve the conceptual geometric design of our MSFR, the interior structure of the internal active core was proposed as a reflector and flow-guided structure, and the efficiency and practicality of neutronics design were first assessed.

2. Methods and Results

As mentioned in the preceding paragraph, using a BeO reflector requires a high flow rate to the near reflector region. Additionally, in the current design, the inlet and outlet nozzles are located in the lower and upper areas in the axial directions, respectively, whereas, the actual flow rate is focused in the core's center. Moreover, the relatively high flow velocity compared to the small core size makes it difficult to obtain the desired flow distribution.

Therefore, an internal structure is developed to ensure sufficient flow to the outer core's surface for heat removal and a stable temperature field. Considering the safety uncertainty of the internal structure's integrity with molten salts, nickel-coated SS316H is utilized as clad to ensure safety in the risk of corrosion acceleration within the high local temperature at the reflector contact. The internal structure can potentially be used as additional reflector positioned within the core. This brings additional excess reactivity and may allow for further reduction in core size.

To lower the uncertainties associated with geometrical modeling, OpenMC, a program developed at the Massachusetts Institute of Technology, has been used for all calculations. Stationary fuel and steady state conditions were first considered at this stage, and cross-section library of ENDF/B-VII.1 has been used for iterative K-eigenvalue calculations.

2.1 Cylindrical internal reflector model

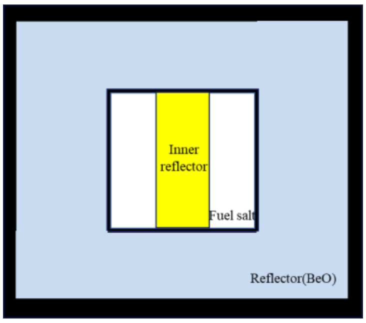

Fig. 1. Conceptual core design with a single cylindrical internal structure.

Our goal is to design the simplest structure to mitigate power peaking and allow molten salt to circulate through the whole core without stagnant flow. Simple cylindrical columns are designed at the active core's center as shown in figure 1. In order to enhance internal structure design, we examine multiple material candidates to identify neutronics phenomena.

By inserting a simple cylindrical structure, the region of nuclear fission at the same power expanded, which will have the effect of flattening the power and lowering the peak power. The burden of lowering boundary reflector surface temperature can be alleviated by the decreasing volume of the flow space. The swirl flow formed by the internal structure pulls the inlet flow upward, and the outer flow rate is relatively greater than the core center where the structure is located, which can be beneficial in terms of minimizing the amount of delayed neutron precursors.

Criticality sensitivity study was carried out under various conditions based on material candidates and thicknesses. Except for graphite, which has been proven chemically safe with molten salt, canning is assumed in the same way. The Fuel salt, KCl-UCl_3 with HALEU (high assay low enriched uranium) which contains approximately 19.75% enriched U-235, was evaluated.

Since the molten salt reduced by the volume of the internal structure is assumed to exist within the primary loop, the total amount of molten salt in all cases in the table below is constant, and the change in reactivity for the same power and operating period is similarly calculated.

Table I: Criticality sensitivity evaluation based on the thickness of pillar shaped internal structure candidate materials

Case	Internal structure (Radius)	K-eff (SD, [pcm])	Difference [pcm]
Ref	None	1.03413(17)	-
1.1	BeO(10 cm)	1.04324(19)	+911
1.2	BeO(15 cm)	1.04852(18)	+1439
1.3	BeO(20 cm)	1.04177(18)	+764
2.1	Graphite(10 cm)	1.03109(17)	-304
2.2	Graphite(15 cm)	1.03547(17)	+134
2.3	Graphite(20 cm)	1.03623(17)	+210
3.1	$YH_{1.5}$(5 cm)	1.04272(15)	+859
3.2	$YH_{1.5}$(10 cm)	1.00185(16)	-3228
4.1	Be_2C(10 cm)	1.04269(17)	+856
4.2	Be_2C (15 cm)	1.04967(18)	+1554
4.3	Be_2C (20 cm)	1.04620(18)	+1207

As shown in the table above, BeO, Graphite, $YH_{1.5}$, and Be_2C were considered as structural material candidates. Be materials were able to achieve the highest excess reactivity. Due to the high scattering XS and moderation power, more fission is induced at the interface of its internal structure. As the thickness increases from 5 cm to 25 cm, the criticality rises even though the amount of fuel in the active core drops. Assuming that the total fuel salt content in the primary circuit remains constant, the relative volume of fuel salts in the outer loop increases, lowering depletion reactivity and making it easier to control excess reactivity during operation. Graphite's performance is poorer than BeO due to its low moderating power and low multiplicative fission effect such as (n,2n) reactions. Using $YH_{1.5}$ at a thickness of 5 cm or less can act as a moderator and increase reactivity, but using it at a thickness above that can only act as a shield due to its excessive neutron absorption. Be_2C showed comparable performance to BeO, but was ultimately rejected due to manufacturability issues.

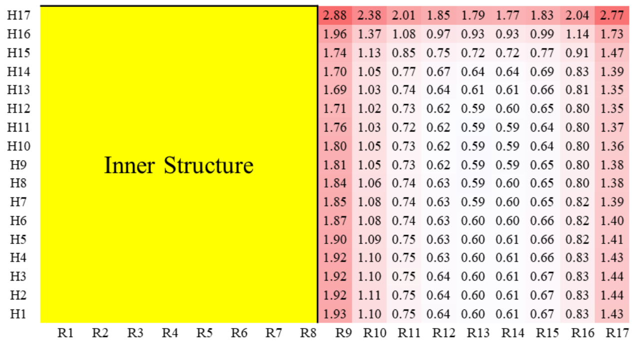

Fig. 2. Normalized power distribution inside quarter core with a single pillar shaped internal structure.

The figure above shows the 1/4 core results divided into a mesh of constant thickness in the radial and axial axes, with the generated power normalized in each area. Without internal structure, the maximum power peaking factor exceeds 4.0, but by locating BeO internal structure, the maximum power peak is reduced to 2.88. The power load is partially shifted from the reflector interface to the structure surface due to the increased contribution of thermal neutrons. However, since the volume of the mesh in the outer core is larger than that of the internal mesh, the actual power remains high around reflector. Current design substantially favors the formation of an axial flow, and because the molten salt actually goes through a much narrower channel, the likelihood of a recirculation area happening can also be greatly reduced. Later on, thermal hydraulic evaluation and coupled neutronics will be evaluated and the use swirl flow to improve fluid design is considered.

Table II: Evaluation of temperature coefficient of a single pillar shaped internal structure model

Case 1.2		Reactivity coefficient [pcm/°C]	Fuel salt T [°C]	internal structure T [°C]	Reflector [°C]	Fuel salt density [g/cm3]
Ref.		-	635	635	635	3.703
1	△ Salt T	-0.92	735	635	635	3.703
2	△internal structure T	+0.48	635	735	635	3.703
3	△Salt density	-4.59	635	635	635	3.581
4	△Outer reflector T	+1.52	635	635	735	3.703
1+2+3+4		-3.54	735	735	735	3.581

The internal structure presents a potential benefit of size reduction and appropriate flow formation based on the preceding results. It is vital to confirm that the current design may have a negative temperature coefficient, though, because higher temperatures cause an increase in the scattering XS of BeO, which softens the neutron spectrum. Temperature coefficient analysis is divided into four effects depending on the temperature variation of the fuel, structure, and reflector and the density of the fuel salt.

It is negatively reactivity coefficient was validated, as indicated by the figures above, and its overall temperature coefficient managed to secure -3.54pcm/K. Although the fuel salt temperature coefficient was determined to be a very small absolute value, intrinsic safety and autonomous operation can be guaranteed.

2.2 Double layer design

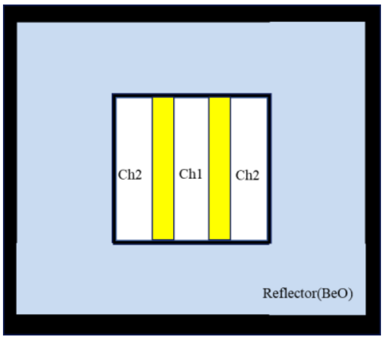

Fig. 3. Conceptual core design with a hollow cylinder shaped internal structure.

Another internal structure option is shown in the figure 2 above. It was devised to secure stable flow distribution by designing a hollow cylindrical structure and intentionally separating the channels through which the molten salt passes. In this case, thermalized neutrons can be further induced for fission at the double channel surface. Critical sensitivity analysis based on thickness difference was applied to the structural candidate that was the same as the one in the prior analysis.

Table III: Criticality sensitivity evaluation based on the thickness of hollow cylinder shaped internal structure candidate materials

Case	Ch1 (Radius)	Internal structure (Radius)	Ch2 (Radius)	K-eff (SD, [pcm])	Difference [pcm]
1	35 (w/o internal structure)			0.97653(20)	-
2	5	15	15	1.02610(18)	4957
3	6	15	14	1.03215(18)	5562
4	8	15	12	1.04289(15)	6636
5	10	15	10	1.05222(17)	7569
6	12	15	8	1.05935(13)	8282
7	14	15	6	1.06309(14)	8656
8	15	15	5	1.06137(16)	8484

Based on the structure's thickness and the volume ratio of channels 1 and 2, the calculation case for the critical sensitivity evaluation was chosen. The highest 8656 pcm reactivity was found at 15 cm thickness of the structure, and a 1:1 volume ration between ch1 and ch2 was calculated. On the other hand, as the thickness increases, the volume reduction effect of the molten salt itself takes precedence over BeO and is observed to be comparatively less effective than a single pillar shape.

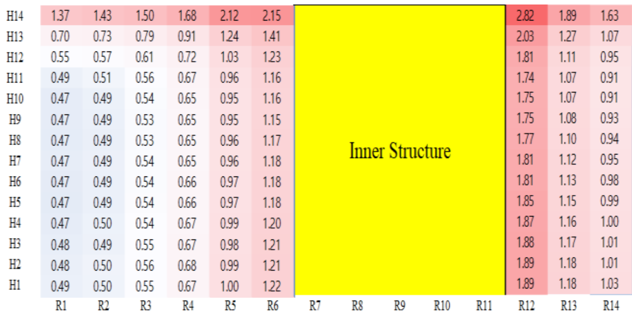

Fig. 4. Normalized average power distribution inside quarter core with a hollow cylinder shaped internal structure.

In comparison to the previous single column shape, the highest peak power factor has dropped to 2.0, and the power distribution has also been moved to the core's center, as can be seen from the normalized average power distribution shown in figure 4 above. This is because if it is designed as a multi-channel as opposed to a double channel, higher reactivity can be predicted due to both the better reflection effect and moderation.

Table IV: Evaluation of temperature coefficient of a hollow cylinder shaped internal structure model

Case 7		Reactivity coefficient [pcm/℃]	Fuel salt T [℃]	internal structure T [℃]	Reflector [℃]	Fuel salt density [g/cm3]
Ref.		-	635	635	635	3.703
1	△ Salt T	-0.94	735	635	635	3.703
2	△internal structure T	+1.20	635	735	635	3.703
3	△Salt density	-3.92	635	635	635	3.581
4	△Outer reflector T	+1.67	635	635	735	3.703
1+2+3+4		-2.03	735	735	735	3.581

The temperature coefficient evaluation results are shown in the above table. Because the scattering XS grows with temperature and the situation appears to deteriorate with increasing structure volume, the BeO reflector causes a positive reactivity insertion. Nevertheless, the density coefficient still has a negative reactivity coefficient value with a large enough absolute value, and consequently the summation of temperature coefficient is a negative value. However, because the stability of the core in the early stage of an accident is affected by the Doppler effect which has a relatively fast feedback response, a more thorough examination is required to confirm the positive internal structural coefficient effect before adopting the dual channel concept.

3. Conclusions

Criticality sensitivity evaluation of internal structure materials and thickness was carried out in order to analysis safety and advantages of nuclear design for the purpose of developing a small-sized molten salt fast reactor. A BeO reflector was employed to effectively reduce the core, however this led to a concentration of power in the vicinity of reflector and the core, necessitating the formation of a significant volume of flow. In order to address this, an additional structure was introduced inside the core to serve as a reflector and to prevent the development of stagnant circulation as a result of local temperature rise.

Internal structures designed to resemble cylinders and hollow cylinders were assessed. It was confirmed that the size of the core could be decreased by securing extra margin. The contribution of thermal neutrons to nuclear fission on the structure's surface increased as predicted, and the maximum peak power value could be lowered by around two times.

However, scattering XS at a higher temperature can cause neutron spectrum hardening and a positive reactivity coefficient, depending on the interior structure's design. Additional research is required to confirm the viability of this idea.

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