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Burnable Absorber Design Study for Fast-spectrum Molten Salt Reactors

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1. Introduction

The development of MSR (Molten Salt Reactor) is rekindled these days as one of the candidates for Generation IV reactors [1] due to its inherent safety features which exclude the occurrence of severe accidents. However, conventional thermal-spectrum MSR design has unsurmountable adversities including proliferation concerns from online reprocessing and radioactive waste generation from the usage of graphite moderator. Therefore, attention was drawn to the concept of MSFR (Molten Salt Fast Reactor) which could overcome such aforementioned problems through the utilization of a fast spectrum [2].

To procure both economy and proliferation resistance, it is desirable to design a long-life reactor that does not demand any fuel re-processing or refueling procedures. Hence, it is compulsory to start the operation with high enough excess reactivity as possible. However, for normal operation, excess reactivity must be confined within the manageable extent of the reactivity control device. Therefore, any means for holding down the excess reactivity is required for the realization of long-life proliferation-resistant MSFR. For such a purpose, a similar concept to that of the burnable absorbers in PWR [3] for the MSFR environment is proposed and its feasibility is investigated in this work.

2. Applications on Four Reactors and Results

In conventional MSFR, the application of burnable absorbers is expected to be ineffective due to fast-spectrum neutrons. To overcome such a problem and render the usage of burnable absorbers to be pragmatic, a localized moderator concept at the outer periphery of the active core is proposed. Note that burnable absorbers can be placed in the vicinity of the moderator region for exploitation of the softened neutron spectrum for effective reactivity control.

Four different MSFR designs based on TRU (transuranic) or LEU (Low-enriched uranium) with either beryllium or beryllium oxide moderators have been considered. Note that all the reactors have an equal size of diameters and heights, i.e., square cylinder, and the volumes of the active and inactive cores are presumed to be identical. More detailed design specifications can be found in Table 1.

- Case A: TRU-loaded reactor
- Case B: LEU-loaded large reactor
- Case C: LEU-loaded miniaturized reactor
- Case D: LEU-loaded long-life reactor

Table I: Designing factors of 4 reactors

	Case A	Case B	Case C	Case D
Fuel	62NaCl-18MgCl$_2$-20TRUCl$_3$	46KCl-54UCl$_3$	46KCl-54UCl$_3$	46KCl-54UCl$_3$
Uranium enrichment	-	19.75 wt.%	19.75 wt.%	19.75 wt.%
Active core diameter	106 cm	206 cm	~ 100 cm	206 cm
Heavy metal loading	1,681 kg	29,750 kg	~ 3,000 kg	29,750 kg
Moderator	Be	Be	Be or BeO	BeO
Moderator thickness	37.5 cm	10 cm	~ 35 cm	40 cm
Power	6 MW	300 MW	6 MW	300 MW

For numerical analysis, Monte Carlo-based program Serpent 2 with ENDF-B/VII.1 library has been used. All the presented calculation results are based on 50,000 histories, 200 inactive and 300 active cycles.

2.1 TRU-loaded reactor (Case A)

For the TRU-loaded MSFR (Case A), ternary fuel salt of NaCl-MgCl$_2$-TRUCl$_3$ under eutectic condition (molar composition of 62-18-20) has been used [4], and a thickness of about 37.5 cm beryllium moderator has been added radially. The reactor vessel between moderator and active core consists of 2.4 cm SS316 coated with 0.1 cm Hastelloy-N. The thickness of Hastelloy-N had to be minimized to reduce the reactivity loss from the neutron absorption by nickel. The reflector is composed of SS316, and the thickness of the reflector-moderator-vessel region is about 45 cm. The outermost inactive core region is surrounded by a reflector which contains Hastelloy-N to accommodate the presence of a heat exchanger. All the details can be found in Table I and Fig. 1. Note that all the other cases share similar structures to that of Case A.

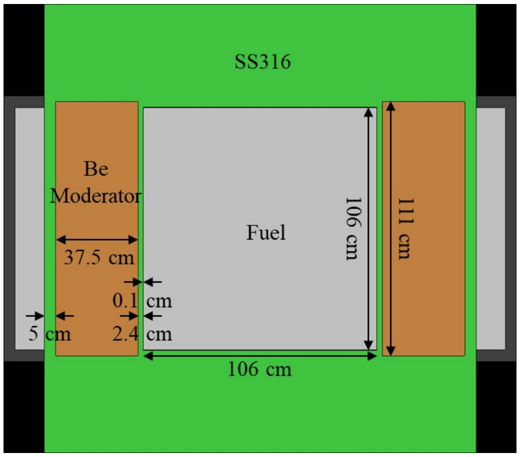

Fig. 1. Structures and dimensions of TRU-loaded reactor with moderator (Case A)

Figure 2 depicts the neutron spectrums evaluated at the active and whole core regions to illustrate the effect of the presence of Be reflector. Note that to represent the reactor without moderation, the compartment filled with Be was simply replaced with SS316. It could be seen that the spectrum appraised at the active core region remains hard regardless of the inclusion of a moderator, and only the spectrum at the whole core region with a moderator exhibits a thermal peak. Such observations attest to the fact that the effect of the moderator is localized to the outer region of the active core, and hence remains as a fast reactor.

To hold down the excess reactivity, the burnable absorber (BA) layer composed of natural boron is added to the inner surface of the moderator as an annulus shape whose thickness is 90 μm.

To examine the effect of the burnable absorber, depletion calculations with 6 MWth power have been performed for the following three cases; the reactor without the moderator, the reactor with the moderator, and the reactor with moderator and 90 μm BA layer. The results are visualized in Fig. 3.

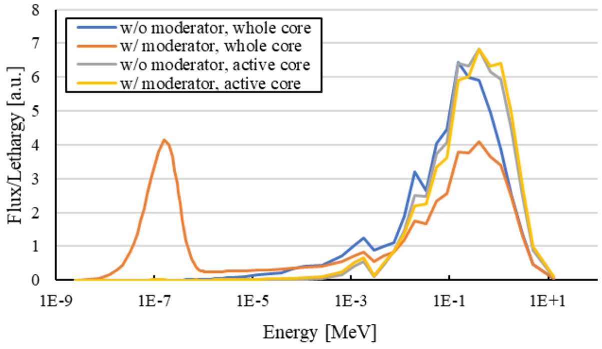

Fig. 2. Neutron spectrums about Case A in the whole region and the active core region

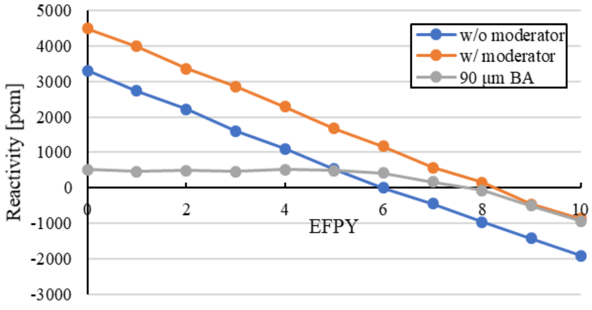

Fig. 3. Time dependent reactivities of Case A

Through the inclusion of a moderator, the excess reactivity is increased by about 1,000 pcm and the reactor lifetime could be extended up to 8 years. With the application of the BA layer, the reactivity swing could be decreased to about 520 pcm and the reactivity is maintained almost constant throughout the lifetime, providing the stability for the operation of the reactor.

2.2 LEU-loaded large reactor (Case B)

For Case B, eutectic KCl-UCl_3 with a uranium enrichment of 19.75 wt.% is used for the fuel, whose molar composition is 46-54 as referred to in [5]. The structure and material of the reactor vessel and reflector are the same as those of Case A. Note that a beryllium moderator with a thickness of 10 cm has been added radially. The details can be found in Table I and Fig. 4.

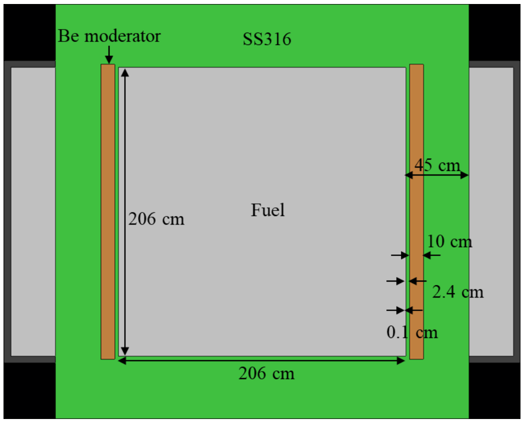

Fig. 4. Structures and dimensions of LEU-loaded large reactor with moderator (Case B)

Table II: Burnable absorber Types used in Case B

	Type I	Type II	Type III
Material	B_4C (Natural boron)		
Shape	Annulus	Rods	Pads and rods
Thickness	0.17 cm	-	0.17 cm
Rod number	-	360	180
Rod diameter	-	0.8 cm	0.7 cm

To manage the excess reactivity of Case B, three different Types of burnable absorbers are used: annulus, rods, and a combination of pads and rods. They are named Type I, II, and III, respectively, and the details can be found in Table II.

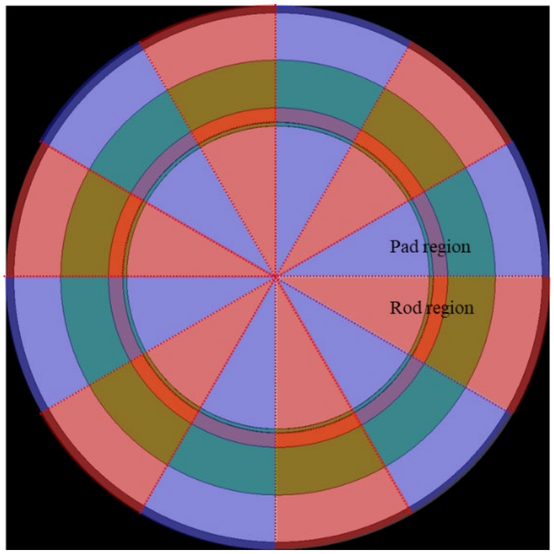

Fig. 5. Top view of Case B equipped with BA Type III

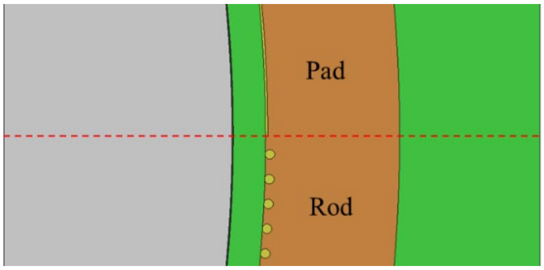

Fig. 6. Zoom-in of Fig. 5 at the BA region

In Type III, the reactor has been separated into 12 regions in the circumferential direction, and pad-shaped absorbers and rod-shaped absorbers have been allocated to these zones alternately as illustrated in Figs. 5 and 6.

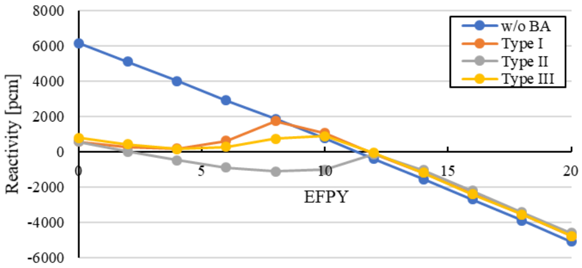

Fig. 7. Time dependent reactivities of Case B

Observing the results of depletion calculations with 300 MWth, for Case B and its burnable-absorber-added cases, the annulus-shaped absorber of Type I burns too fast, and the burnable absorber which is composed of many rods (Type II) burns too slow to maintain the appropriate reactivity. Therefore, Type III, as the appropriate combination of Type I and Type II, could give a moderate result of about 860 pcm of reactivity swing. This study indicates the configuration of the burnable absorber can affect the reactivity behavior through adjustment of self-shielding and could be optimized for stable operation of the reactor.

2.3 LEU-loaded miniaturized reactor (Case C)

For Case C, the same molten salt as Case B has been used for the fuel and overall structures are similar to previous cases except for the configuration pertaining to the moderator. The moderator is placed close to the active core region to enhance the extent of reactivity increment through moderation as shown in Fig. 8. Note that reactivity loss from the absorption by nickel in the reactor vessel can be minimized which results in reduced reactor size for criticality. To maintain the material's integrity, a protective layer composed of 0.1 cm Hastelloy-N and 0.3 cm SS316 is placed between the active core and the moderator, where the active core size can be reduced to about 100 cm in diameter.

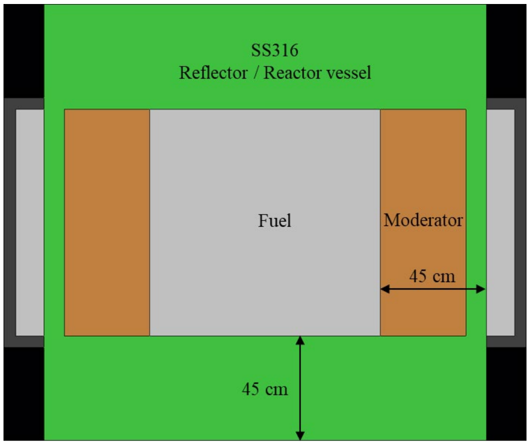

Fig. 8. Structures and dimensions of LEU-loaded miniaturized reactor with moderator (Case C)

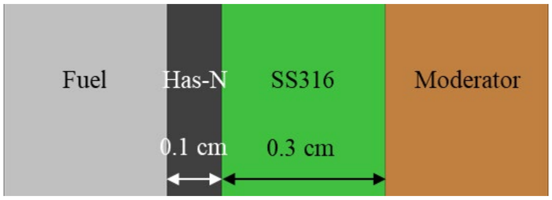

Fig. 9. Zoom-in of Fig. 8 between fuel and moderator

Two different moderator materials have been considered for Case C: Be and BeO, and different reactor dimensions have been postulated respectively as enumerated in Table III. As it can be found in Fig. 10, Be shows better performance as the moderator than BeO because the average atomic mass of the former is smaller than that of the latter. However, they hardly affect the neutron spectrums in the active core as aforementioned.

Table III: The reactor and moderator information used in LEU-loaded miniaturized reactor (Case C)

Moderator material	Be	BeO
Moderator thickness	37 cm	35 cm
Active core diameter	97 cm	98 cm
Heavy metal loading	3,123 kg	3,219 kg

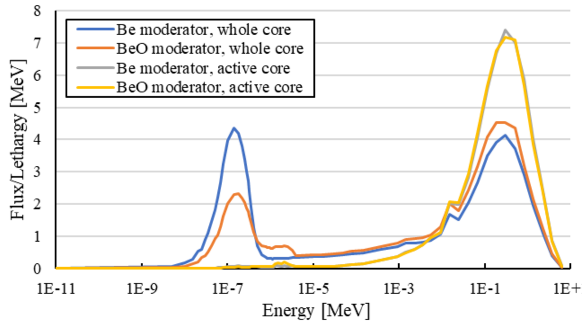

Fig. 10. Neutron spectrums about Case C in the whole region and the active core region

On the inner surface of each moderator, a burnable absorber layer composed of B_4C (natural boron) has been coated as an annulus shape similar way to Case A. The thickness of the absorber is 4 μm for Be moderator, and 5 μm for BeO moderator.

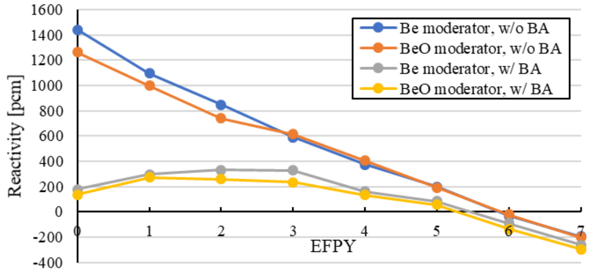

Fig. 11. Time dependent reactivities of Case C

Depletion calculations have been performed with 6 MWth power. For all the cases, reactor lifetimes are estimated to be between 5 and 6 years, where the inclusion of burnable absorbers effectively stifles the reactivity swing. For the case of having Be moderator, the reactivity swing has been reduced from 1,440 pcm to 330 pcm, and for the BeO moderator, the reactivity swing has dwindled from 1,260 pcm to 270 pcm. Such observation plainly indicates that the proposed burnable absorber concept effectively stabilizes the MSFR operation in terms of reactivity control.

2.4 LEU-loaded long-life reactor (Case D)

To maximize the life of the reactor, the same approach discussed for Case C has been applied to Case B without changing the reactor core size. The BeO moderator is contained in the reactor vessel and a protective layer is added between the moderator and active core, where detailed descriptions can be found in Figs. 12 and 13. It is expected that the reactor will have an extended lifetime with a large excess reactivity at the beginning of lifetime.

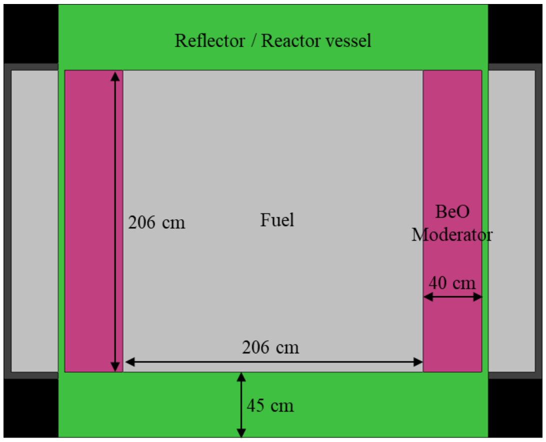

Fig. 12. Structures and dimensions of LEU-loaded large reactor with moderator (Case D)

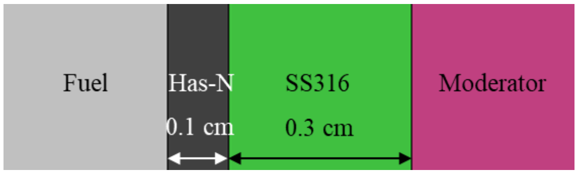

Fig. 13. Zoom-in of Fig. 12 between fuel and moderator

For the management of the large excess reactivity, four-different types of BA have been envisioned as shown in Figs. 14 and 15. Types I, II, and III are rod-shaped BA with different diameters, and Type IV is a pad-shaped BA with 0.1 cm thickness. All the considered BAs are composed of B_4C (natural boron), and further details can be found in Table IV.

Table IV: Types of rod-shaped BA for Case D

Type	I	II	III
Number	20	20	80
Diameter	4.2-4.3 cm	2.9-3.0 cm	1.0 cm

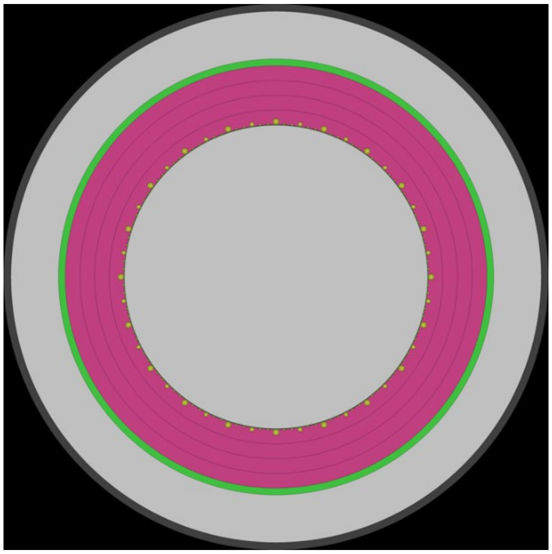

Fig. 14. Top view of Case D equipped with BA Type I, II, III, and IV

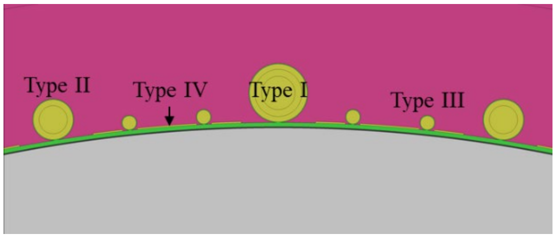

Fig. 15. Zoom-in of Fig. 14 at the BA region

Figure 16 summarizes depletion calculation results with 300 MWth of power. Without the presence of BAs, a huge excess reactivity of about 19,000 is estimated, which can be effectively controlled through the usage of BAs. The extent of depletion of each BA varies with respect to its geometrical configuration, i.e., spatial self-shielding. For instance, Type IV has the fastest depletion rate, which is followed by Types III, II, and I BAs. It is noteworthy to articulate that Type I BA mainly contributes to the control of excess reactivity near the end of lifetime. By the combination of these four Types of BAs, the excess reactivity of the reactor can be managed under 1,000 pcm, and the feasibility of a long-life operation of about 30 years can be attained.

3. Summary and Conclusions

In this study, the applicability of burnable absorber concepts for MSFR has been thoroughly investigated and four different cases of MSFR designs are envisioned. To achieve meaningful mitigation of excess reactivity during depletion via the usage of burnable absorber concepts, a localized moderator comprised of either Be (beryllium) or BeO (beryllium oxide) has been radially considered.

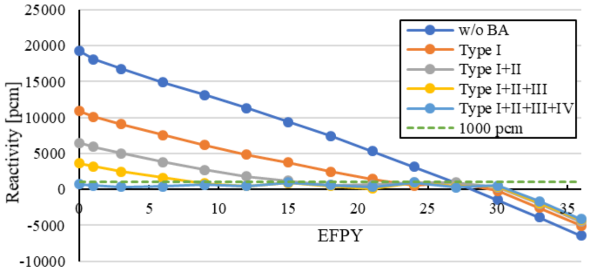

Fig. 16. Time dependent reactivities of Case D

It was found that reactivity swing could be managed below 1,000 pcm for all the considered MSFR designs, which clearly attests to the applicability of the proposed burnable absorber concepts. The proposed scheme can be applied for various molten salt fast reactor concepts, including the development of TRU-based MSFR, reduction of uranium enrichment for enhancing economics, and miniaturization of MSFR for utilization as a mobile reactor. Comprehensively, the suggested unique burnable absorber concepts could contribute to designing economically feasible and long-life operation MSFRs.

ACKNOWLEDGEMENTS

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