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Nuclear Design Study for Chlorine-based Micro Molten Salt Reactor Utilizing HALEU

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1. Introduction

With the concerns about climate change and fossil fuel depletion, nuclear technology is expected to be essential for generation of electricity. As one of the techniques of new generation, Molten Salt Reactor (MSR) is widely developed with full of attention due to its major safety properties such as possible elimination of severe accident and strong negative feedback from thermal expansion of liquid fuel. [1] To reduce the dependence of diesel on special applications that require frequent movement, Micro reactor can be developed as portable reactor.

For global commercialization, nuclear non-proliferation should be guaranteed, therefore, the uranium considered is limited to HALEU. (High-Assay Low Enriched Uranium). For more efficient utilization of nuclear fuel with enhanced conversion ratio, chlorine-based salt has been considered. [2] In this work, and feasibility of chlorinated HALEU-based micro MSR based on the result of basic properties will be examined.

2. Reactor Model

The application of HALEU-based molten salt on the micro reactor is actually not easy due to the dilemma between size and uranium enrichment. To achieve enough reactivity, large size of reactor or high enrichment are required, but both are limited for identity as micro reactor and non-proliferation, respectively. In this section, the reactor model is detailed to meet those issue.

To achieve criticality at small size of reactor, molten salt of eutectic composition for maximization of heavy metal density and minimization of melting temperature has been used. As depicted in Fig. 1, the fuel is $KCl\text{-}UCl_3$ and the composition is 46-54.

Figure 2 illustrates the model of micro MSR. Overall shape of the active core is cylinder and the reflector encompassing the active core is composed of various materials, such as BeO, graphite, and CaH_2. This device is the main strategy to achieve enough reactivity without upsizing reactor or high enriching uranium. Inner surface of the reflector is coated with nickel and stainless steel to protect it from corrosive circumstance. On the outermost surface, stainless-steel reactor vessel is surrounding the reflector. B_4C neutron shielding is installed between reflector and reactor vessel to absorb neutrons softened by the reflector. Inactive core is placed outside the reflector. Through such a modelling, the active core size could be reduced to less than 1 meter and the total reactor weight could be reduced to less than 15 tons.

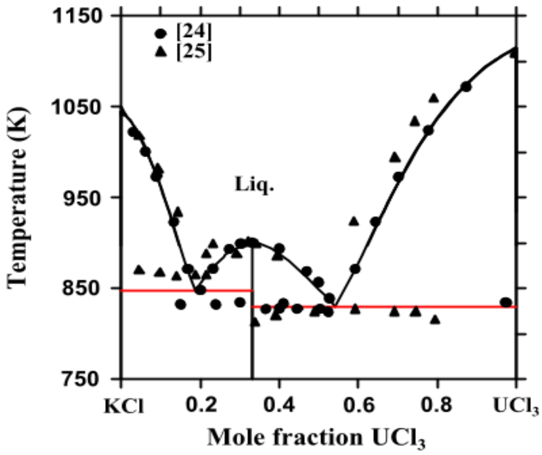

Fig. 1. Phase diagram of $KCl\text{-}UCl_3$ [3]

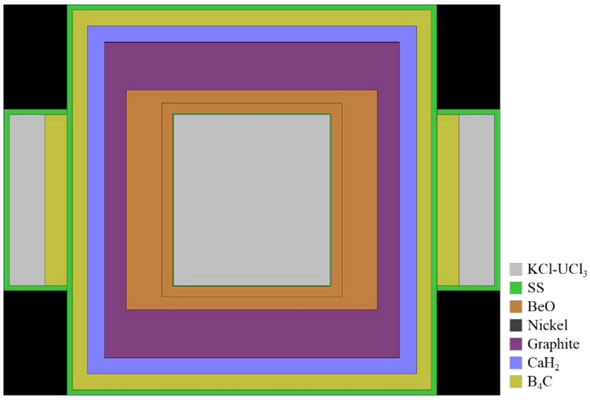

Fig. 2. Side view of micro MSR

Inside the reflector, looking through Fig 3, drum-shaped reactivity control devices can be found. They are composed to 6 drums, reactivity can be controlled with location of each drum and neutron absorption by B_4C pad. At the inner surface of the reflector, burnable absorbers (BAs) are equipped for alleviation of excess reactivity. [4] They are composed thin B_4C pads with two different thicknesses. Their structure can be referenced in Fig. 4, however, note that the thicknesses of the burnable absorber are exaggerated in this picture.

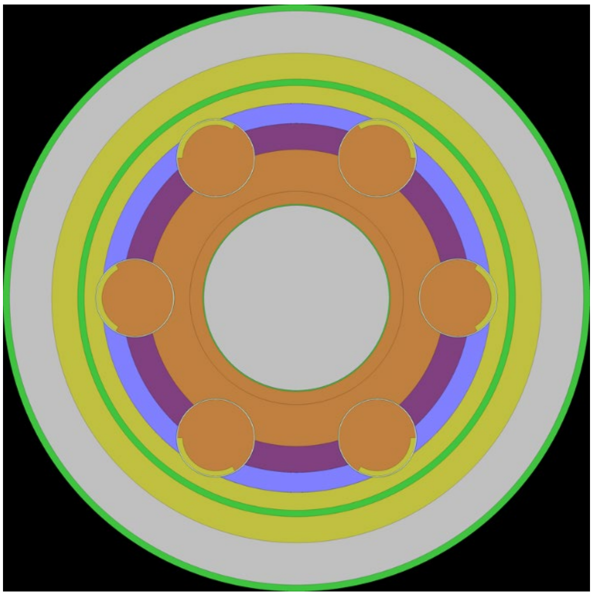

Fig. 3. Top view of micro MSR

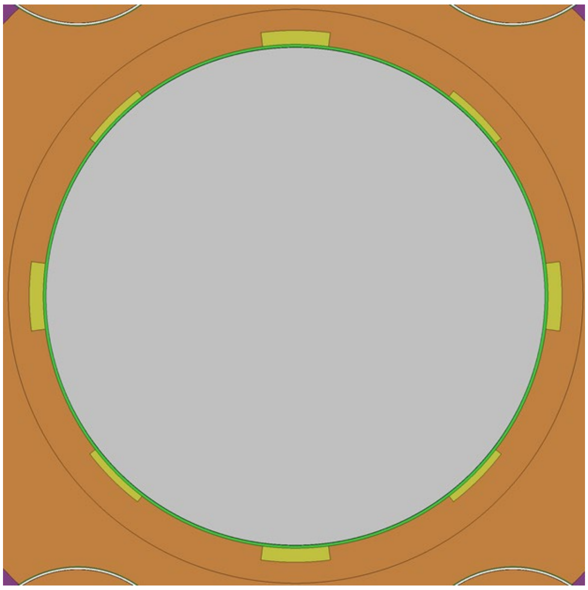

Fig. 4. Location and shape of burnable absorber (not in scale)

3. Numerical Results

To examine the feasibility of the micro reactor, analyses and calculations are conducted with Monte Carlo-based tool. The program is Serpent 2.2.1, referenced library is ENDF/B-VIII.0. The number of histories per cycle is 100,000, and the numbers of inactive and active cycles are 100 and 300, respectively. Exceptionally, larger number of samples have been used in the case of assessing temperature coefficient. The operating power is assumed to 7 MWth.

2.1 Reactivity, Conversion Ratio, and Kinetic Parameters

Figure 5 gives the results of reactivity vs full-power operation time in effective full-power year (EFPY). The results indicate that the design can guarantee a reactor lifetime of at least 4 years. If there is no BA, the initial excess reactivity reaches 3,000 pcm. Through the usage of BA, maximum excess reactivity can be about 500 pcm.

Fig. 6 shows the burnup and conversion ratio throughout the lifetime. Because of the usage of the micro reactor, high discharge burnup and sufficient conversion ratio could not be achieved, but considering the size of the reactor, fuel utilization could be raised by using chloride salt. Initial conversion ratio of reactor with BA is higher than the case without BA because thermal neutrons are absorbed by BA and the neutron spectrum is slightly harder.

Fig. 7 shows the kinetic parameters including effective delayed neutron fraction (Beta) and adjoint-weighted prompt neutron generation time. Effective delayed neutron fractions of the both cases behave similarly, slowing decreasing throughout the lifetime. Meanwhile, there are big difference between prompt neutron generation times of the cases with and without BA at initial state. That is because considerable number of neutrons of BA-quipped reactor are absorbed by BA.

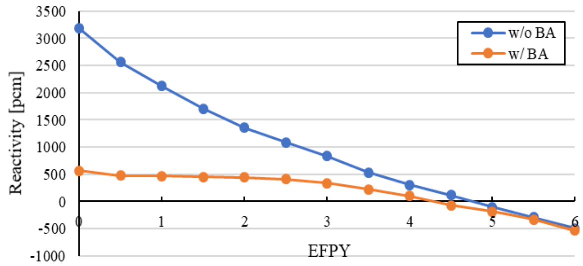

Fig. 5. Reactivity vs full-power operation time with and without BA.

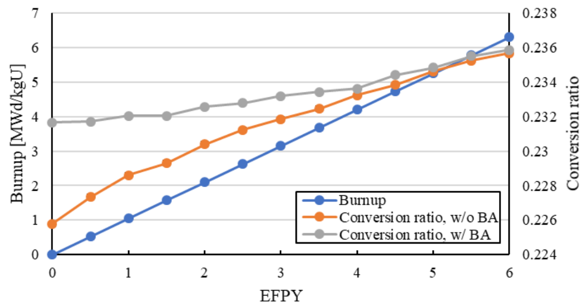

Fig. 6. Burnup and conversion ratio vs full-power operation time with and without BA.

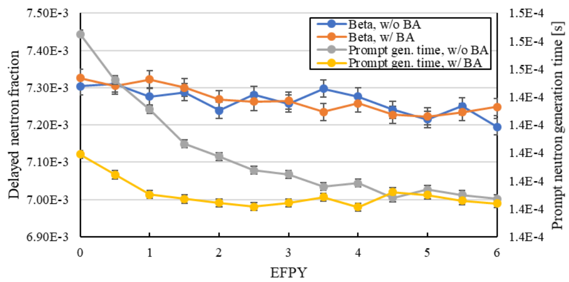

Fig. 7. Effective delayed neutron fraction and adjoint-weighted prompt neutron generation time vs full-power operation time with and without BA.

2.2 Neutron Current, Spectrum and Power Distribution

The modeled reflector serves not only as a reflector, but also as a moderator. Fig. 8 shows the role of reflector as the moderator. Neutron spectrum in the active core shows dominance of fast neutrons, and neutron spectrum in the inactive core shows dominance of thermal neutrons. There is almost no difference in the neutron spectrum depending on burnup, because the burnup level is not significant.

The moderator also serves as assistance of neutron shielding by softening neutron spectrum for more neutrons to be absorbed by B_4C zone between moderator and reactor vessel. Table I shows neutron net current of inner surface of the reactor vessel, whose direction is outgoing direction. The arrangement of the materials composing reflector could reduce the neutron net currents of axial and radial directions in the order of 1e+9 #/cm^{2}s.

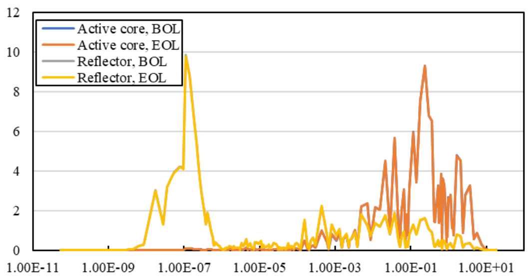

Fig. 8. Neutron spectrum in the active core and reflector in BOL and EOL.

Table I: Neutron net current of inner surface of reactor vessel (unit: #/cm^{2}s)

EFPY	Axial	Radial
0	1.099E+09	9.86E+08
1	1.108E+09	9.82E+08
2	1.111E+09	9.99E+08
3	1.106E+09	9.85E+08
4	1.123E+09	9.98E+08

Power distribution of the reactor with BA has been estimated. Figures 9 and 10 depict axial and radial power distributions. High power is measured in the marginal region because softer spectrum can be found in there. Although there is no significant difference, marginal power of radial direction is decreased as burnup increases because BA is being burned.

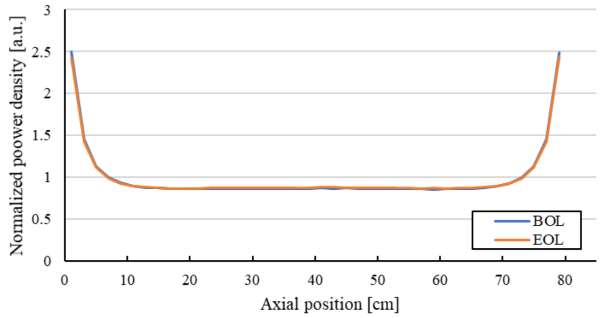

Fig. 9. Axial power distribution.

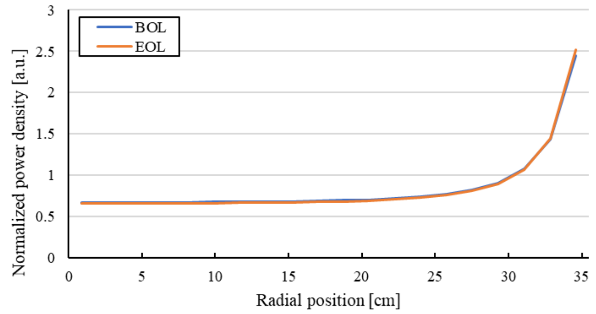

Fig. 10. Radial power distribution.

2.3 Temperature Coefficient and Reactivity Worth

One of the major properties of MSR is intensive inherent safety from the heat expansion. For the analysis of temperature coefficients, 250,000 histories have been used for more accurate results, whereas the numbers of active and inactive cycles are the same. Table II contains enumerated fuel, reflector, and isothermal temperature coefficients (FTC, RTC, and ITC) of the micro MSR. Obviously, negative FTC can be found due to fuel expansion, however, it can be found that RTC is positive value, therefore, positiveness of ITC be diluted. It is because if the temperature of reflector goes high, neutron spectrum at the region becomes slightly harder, and the larger number of neutrons are reflected and contribute on fission reaction.

Table II: Temperature coefficients (unit: pcm/K)

	Temperature	BOL	EOL
FTC	535-735°C	-6.13 ± 0.07	-6.00 ± 0.07
RTC	535-735°C	3.85 ± 0.07	4.34 ± 0.07
ITC	535-735°C	-2.28 ± 0.10	-1.66 ± 0.10

Lastly, analysis for the reactivity control drum has been conducted. Table III contains reactivities and reactivity worths of various conditions. The results show that reactivity worths of drum device are enough in all situations.

Table III: Reactivities and worths of various conditions

	Condition	Reactivity [pcm]
BOL	Drum-out	568 ± 16

	Drum-in	-9680 ± 18
	Worth	10,248 ± 24
EOL	Drum-out	100 ± 15
	Drum-in	-10,415 ± 18
	Worth	10,515 ± 23

4. Conclusions

Nuclear design study has been conducted for application of chlorinated HALEU-based MSR on micro reactor, and the feasibility has been shown in aspects of neutronics. Total mass of the reactor has been estimated to lower than 15 metric tons and neutron current has been estimated to about 1e+9 $\#/cm^2s$. Other properties assess in this work have indicated there are possibly little problems for normal operation in the aspect of neutronics. For the utilization on the widespread industry field, further researches should be conducted to prove its possibility in more diverse aspects.

ACKNOWLEDGEMENT

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