Core Design of Molten Salt Fast Reactor using PbO Reflector and Cycle Study

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1. Introduction

A long-life maritime Molten Salt Reactor (MSR) capable of operating for 30 years with a thermal power of 100 MW is currently under development. One of the main advantages of MSRs is their inherent safety due to the use of liquid fuel, which significantly reduces the risk of severe accidents. Additionally, MSRs allow for online refueling and selective removal of specific isotopes during operation.

In this study, we evaluate the feasibility of extending the reactor's operational cycle beyond the initial 30-year period by reprocessing the spent fuel with minimal fresh fuel supply. The proposed reactor design utilizes chloride-based fuel salt and a PbO reflector, enabling a fast neutron spectrum. As a result, plutonium (Pu) production is significantly higher than in thermal spectrum reactors. The initial fuel cycle operates with NaCl-KCl-UCl_3 fuel containing HALEU, and after the first cycle, partial reprocessing is conducted. By recycling the transuranic (TRU) elements with a few supplement of HALEU, the reactor can operate for an extended period from the first cycle.

2. Methods and Results

The MSR core design, initial fuel cycle depletion, and subsequent fuel cycle depletion after reprocessing were analyzed. These calculations were carried out with OpenMC, a Monte Carlo neutron transport code capable of criticality calculations, burnup analysis, and complex geometry modeling. Version 0.14.1 of OpenMC was used, and nuclear reaction cross-sections were evaluated based on ENDF-B/VII.1.

2.1 MSR Core Design and Features

The MSR consists of an active core, fuel salt, coating, cladding, reflector, control drums, and a vessel. Figure 1 shows a schematic of the MSR core. The reactor operates on fuel enriched to 19.75 w/o HALEU, and its core specifications are listed in Table 1. The fuel salt composition is NaCl (42.9%), KCl (20.3%), and UCl_3 (36.8%), with Cl-37 enrichment of 99a/o. The reactor is designed to operate at 100 MWth for 30 years.

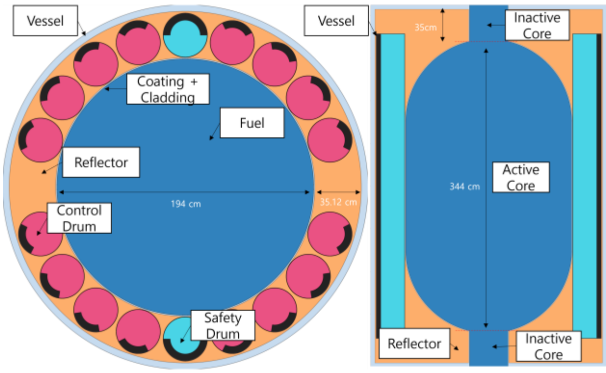

Fig. 1. The MSR core consists of fuel salt, coating, cladding, reflector, control drums, and the vessel. The left figure shows the x-y cross-sectional view of the core. The right figure shows x-z cross-sectional view of the MSR core, with an active core height of 344 cm, a diameter of 194 cm, and a reflector thickness of 35 cm.

Table I: Core Specifications & Materials

Parameter	Value	Material
Active Core Radius	97cm	NaCl-KCl-UCl_3
Active Core Height	344cm	NaCl-KCl-UCl_3
Coating Thickness	0.08cm	Alloy625
Cladding Thickness	0.8cm	SS316H
# of Drums	16/2	B_4C
Reflector Thickness	35cm	PbO
Vessel Thickness	5cm	SS316H

The neutron spectra in the reflector and fuel regions are shown in Fig. 2. Fast neutrons cause the majority of fissions. Consequently, Pu production will be higher than in to a thermal reactor. If the Pu generated during the first cycle is utilized for subsequent cycles, the reactor is expected to achieve a longer operational period beyond the initial 30-year cycle operation.

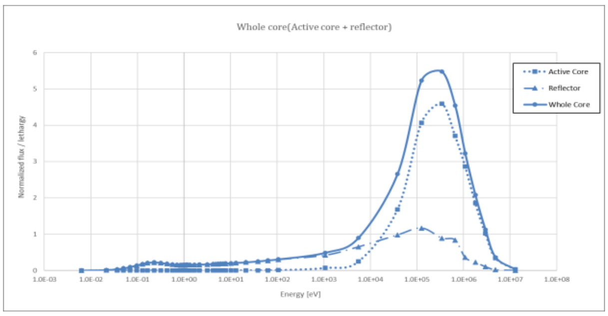

Fig. 2. Neutron spectrum of the MSR core and reflector. Most neutrons are observed in the fast neutron region above 0.1 MeV.

2.2 Depletion Calculations

When operating a fast reactor, a more nuclear fuel is required than in a thermal reactor. However, high-energy neutrons allow for a higher conversion ratio, resulting in enhanced Pu-239 production. This improves fuel utilization efficiency in subsequent cycles. The depletion calculations are shown in Fig. 3.

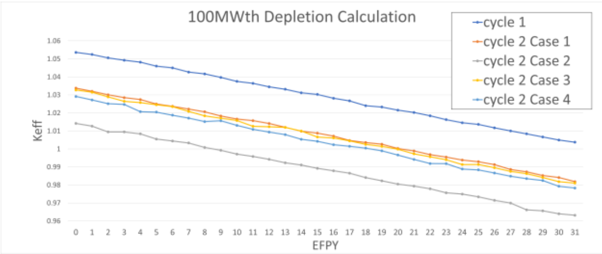

Fig. 3. Depletion calculations of first cycle, second cycle case 1 to 4. First cycle has 30 EFPY life length, after refueling, case 1 ~ 4 extended 20 years, 8 years, 19 years, 18 years.

In the first cycle, molten salt fuel composed of NaCl-KCl-UCl_3 with 19.75 w/o HALEU was used. The reactor operated at 100 MWth for 30 years with all control drums fully rotated outward. After the first-cycle burnup calculation, the spent fuel composition was analyzed, and four separate depletion calculations were performed after removing fission products and TRU. In all cases, HALEU were replenished:

- Case 1: Only fission products were removed.
- Case 2: Noble Gas (He, Ne, Ar, Xe) & Noble Metal (Rn, Ru, Rh, Pd) were removed.
- Case 3: 95 % All Fission Products were removed.
- Case 4: Noble Gas & Noble Metal + Zr, Mo, I, Cs, La, Pr, Nd were removed.

The conversion ratio for the first cycle was calculated, revealing that 544 kg of Pu-239 were generated while 1330 kg of U-235 were consumed over a 30-year period, yielding a conversion ratio of approximately 0.4. While this is higher than that of a thermal MSR, it does not surpass 1.0, indicating that the reactor does not function as a breeder. To improve fuel utilization, a strategy was implemented that involved removing noble gases, noble metals, and some TRU before recycling the fuel for subsequent cycles. The fuel composition ratio of fissile, fertile and fissionable isotopes is shown in Table II and Table III.

Table II: Fuel Composition of First Cycle's fissile, fertile and fissionable Materials

Isotopes	Cycle 1 BOC [wo]	Cycle 1 EOC [wo]
Na	0.0583	0.0578
K	0.0469	0.0464
Cl	0.3790	0.3759
U235	0.1019	0.0811
U238	0.4139	0.3995
Pu239	0.0000	0.0082
FP	0.0000	0.0185
TRU	0.0000	0.0126

Table III: Fuel Composition of Second Cycle Cases' fissile, fertile and fissionable Materials

Isotopes	Case 1 BOC [wo]	Case 2 BOC [wo]	Case 3 BOC [wo]	Case 4 BOC [wo]
Na	0.0578	0.0578	0.0578	0.0578
K	0.0464	0.0464	0.0464	0.0464
Cl	0.3759	0.3759	0.3759	0.3759
U235	0.0848	0.0822	0.0846	0.0847
U238	0.4143	0.4041	0.4136	0.4142
Pu239	0.0082	0.0082	0.0082	0.0082
FP	0.0000	0.0128	0.0009	0.0001
TRU	0.0126	0.0126	0.0126	0.0126

In Case 1, where all fission products were removed and then HALEU was properly replenished, the reactor achieved an extended cycle length of 20 years. Case 1 exhibited the longest extension among all cases due to the complete removal of fission products and the largest amount of HALEU replenishment. In Case 2, only noble gases and noble metals were removed, and HALEU was added, extending the cycle by only 8 years. In contrast, Case 3, which involved removing 95% of fission products, resulted in an extended operation of 18 years. Case 4, which selectively removed noble gases, noble metals, and specific isotopes such as Zr, Mo, I, Cs, La, Pr, and Nd, resulted in a 19-year extension after HALEU replenishment.

The results from Case 1, 3, and 4 indicate that targeted removal of specific fission products can result in a nearly 20-year cycle extension.

3. Conclusions

A maritime MSR capable of 30 years of operation with a thermal output of 100 MW has been designed. Various core concepts have been examined, and one advantage of using a PbO reflector is that the fast spectrum leads to a higher Pu production than reactors that use the thermal spectrum. This enhanced Pu production was leveraged to test if extended operation cycles beyond the initial 30 years could be achieved after the first cycle. By removing sorely fission products, operating cycles were extended for more than 8 years. However, when the majority of the FPs were removed, cycle length improved by up to 20 years.
This shows that softening the neutron spectrum may reduce the cycle length by increasing the production of actinides. Therefore, the reduced actinide production characteristic of fast-spectrum reactors implies that adopting a fast-spectrum design is more advantageous in terms of extending the operation cycle, although it

may not be possible to maintain the same core size and cycle duration when changing the reflector.

In conclusion, while a fast reactor may require a larger initial amount of nuclear fuel, given subsequent operational cycles, such a design allows for substantially longer operation with only minimum additional fuel supply.

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