*Transactions of the Korean Nuclear Society Autumn Meeting*
*Yeosu, Korea, October 25-26, 2018*

# Neutronics Analysis on Online-Feeding Options in a Molten Salt Fusion-Fission Hybrid System

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## 1. Introduction

Fusion-Fission Hybrid System (FFHS) is one of the promising options to transmute long-lived radioisotopes in the spent nuclear fuel (SNF) [1-5]. Compared to the critical fast reactor, FFHS has the same fast neutron spectrum but fewer constraints on reactivity control during a cycle length. The decrease of k-eff caused by fissile burning can be compensated by controlling the external neutron source rate to a subcritical system. While, this advantage leads to a shortcoming of practical application, because it is not easy to change the required external source rate depending on a large reactivity swing. In FFHS, the fusion power should be increased a lot during a cycle causing the significant change in neutron irradiation wall loading as well as big change in tritium supply rate, those are difficulties in plasma tokamak operation.

However, FFHS can be driven with constant fusion power by using a molten salt fuel system. In this system, feeding and extracting of fuel and waste is available anytime with desired rate through online treatment. In this paper, FFHS with constant fusion power was designed on the online-feeding scenarios, then evaluation of neutonics performance was conducted for comparison. All neutronics calculations were performed by SERPENT 2.1.29 with ENDF/B-VII.0 neutron cross section library to simulate online-feeding using mass flow option [6].

## 2. Calculation Model

### *2.1 Design of Dual Fluid Fusion-Fission Hybrid System*

In this paper, dual fluid FFHS was designed as shown in Fig. 1. Dual fluid system uses two fluid loops for coolant and fuel separately [7]. It is distinguished from conventional molten salt system in which molten salt acts fuel as well as coolant. The fuel zone is filled with a lot of pipes. The molten salt as the fuel flows through pipes and coolant flows out of pipes. The allowable power density is increased by separating the coolant and fuel in the dual fluid system. In addition, it becomes more suitable system to transmute transuranics (TRU) by using PbBi coolant compared to the conventional molten salt system. Dual fluid FFHS was designed based on Hyb-WT designed by Kyung Hee University design team as listed in Table I [3]. The maximum design fusion power is 150 MW, thermal power of the fission blanket is 2,000 MW. Cycle length is 2,400 days. The fuel salt is (U-Pu-minor actinide (MA))$Cl_3$, which can be adapted to various feeding scenarios [8]. At this time, the uranium (U) and TRU have the same compositions as that reprocessed from a 3,000 $MW_{th}$ pressurized light water reactor with depleted burnup rate of 55,000 MWD/ton after 10 years of cooling. The tritium breeding zone (TBZ) was designed FLiNaBe breeder with natural lithium that is beneficial to tritium breeding and TRU transmutation through parametric study.

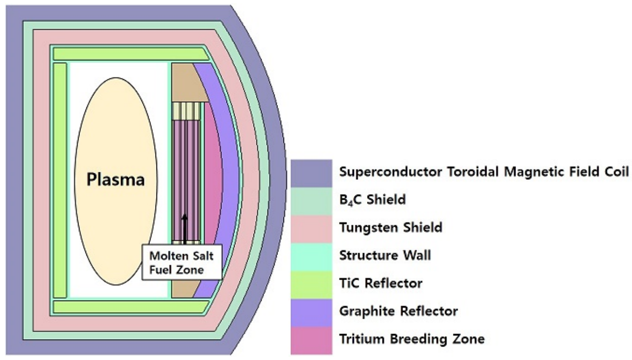


Fig. 1. Configuration of dual fluid fusion-fission hybrid system.

Table I: Design Parameters of dual fluid fusion-fission hybrid system.

| | |
|---|---|
| Total Operation Period | 2,400 day |
| Max. Fusion Power | 150 MW |
| Thermal Fission Power | 2,000 MW |
| k-eff | < 0.97 |
| Molten Salt Fuel | (U-Pu-MA)$Cl_3$ |
| Fuel Tube Inner Radius | 0.725 cm |
| Fuel Tube Outer Radius | 0.825 cm |
| SiC Coating Thickness | 0.1 cm |
| Fuel Pin Pitch | 1.978 cm |
| Coolant | PbBi (44.5/ 55.5 wt.%) |
| Tritium Breeder | LiF-NaF-$BeF_2$ |

### *2.2 Process of Online-Feeding*

The online-feeding process considered in this paper is shown in Fig. 2. The burned fuel salt flows from the fuel zone to the fuel processing unit. Fission products (FP) with 10 % uncertainty are removed from the burned fuel salt in the fuel processing unit. This is because parasitic absorption by FPs degrades the neutron economy in the system. Then the fresh salt is added. This mixture of burned salt and fresh salt is injected into the fuel zone. These processes are repeated continuously.

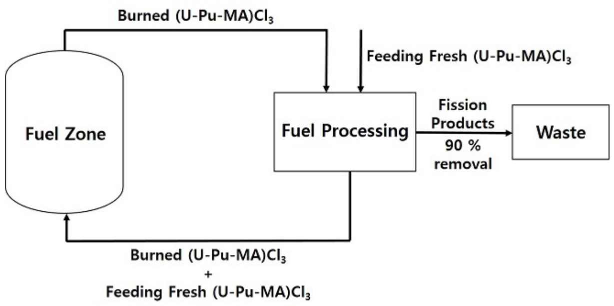


Fig. 2. Online-feeding process of dual fluid fusion-fission hybrid system.

## 3. System Performance for Online-Feeding Rate in a Pyro-processing Scenario

Currently, a pyro-processing is the only acceptable option for recycling the SNF in Republic of Korea. Therefore, in this chapter, FFHS on the feeding rates of $(TRU)Cl_3$ fuel was designed then evaluation of system performance was conducted as listed in Table II. The once-through cycle without removal of FP and feeding like a solid fuel system was considered for comparison. The feeding rates are about 0.5 % (1.05 kg/day), 1.0 % (2.1 kg/day) and 1.5 % (3.23 kg/day) of actinide mass in the initial core.

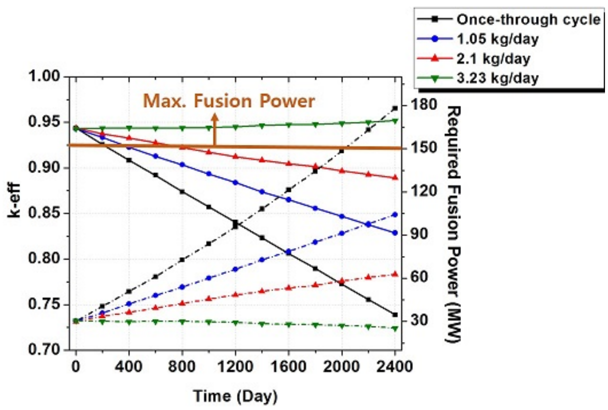


Fig. 3. K-eff and the required fusion power on the online-feeding rates.

The required fusion power with the once-through cycle option exceeds the design maximum power due to large reactivity swing during the cycle as shown in Fig. 3. Reactivity swing is reduced by online-feeding. The k-eff with the 3.23 kg/day option is constant. TBR, the ratio of number of produced T to number of consumed T, is increased with increasing the feeding rate. Because amount of the consumed tritium is reduced by reduction of the required fusion power. As shown in Fig. 4, there are significant differences on the reaction rate by online-feeding. Since the reaction rate of fission and capture is reduced during the cycle, neutron economy of the once-through cycle option is also reduced. The decrease of reaction rate caused by burning of $^{239}$Pu and $^{241}$Pu. In other words, plutonium (Pu) reacts with neutrons as a result, Pu burns at the beginning of the cycle (BOC). Then the reaction rate with MA is increased due to decreased amount of the Pu. Therefore, MA burns at the end of the cycle (EOC). While, the reaction rate with the 3.23 kg/day option is not decreased by online-feeding during the cycle. However, the high reaction rate with Pu is maintained until the EOC, since most of neutrons react with Pu in the TRU. Therefore, transmutation performance with Pu is improved compared to the once-through cycle. On the other hand, transmutation with MA is degraded. This is because the reaction rate with MA is reduced and amount of MA in the core is increased by online-feeding.

Table II: Mass variation and tritium breeding performance on the online-feeding rate.

| Feeding rate | Once-through cycle | 1.05 kg/day | 2.1 kg/day | 3.23 kg/day |
|---|---|---|---|---|
| Initial TRU loading (kg) | 20400 | | | |
| Total feeding mass (kg) | 0 | 2550 | 5010 | 7760 |
| Total fuel mass (kg) | 20400 | 23000 | 25400 | 28200 |
| Np (kg) | -448 | -444 | -440 | -435 |
| Pu (kg) | -4120 | -4210 | -4310 | -4410 |
| Am(kg) | -161 | 51.8 | 102 | 160 |
| Cm (kg) | 117 | 126 | 115 | 103 |
| Number of consumed T | 5.81E27 | 3.92E27 | 2.8E27 | 1.69E27 |
| Number of produced T | 5.48E27 | 5.28E27 | 5.07E27 | 4.86E27 |
| TBR | 0.95 | 1.35 | 1.81 | 2.87 |

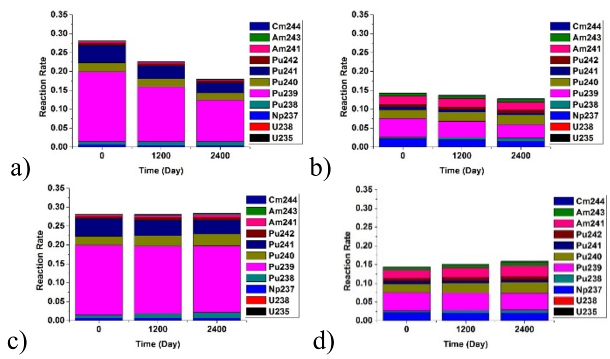

Fig. 4. Reaction rate of fission and capture for the online-feeding rate;
a) fission - the once-through cycle option,
b) capture - the once-through cycle option,
c) fission - the 3.23 kg/day option,
d) capture - the 3.23 kg/day option.

## 4. System Performance for Online-Feeding Scenarios to Improve Transmutation of Minor Actinide

In this chapter, evaluation of system performance on the feeding scenarios to improve MA transmutation performance with constant k-eff was conducted. There are two main scenarios. First is adding U in the initial core in order to reduce amount of the required feeding through $^{239}$Pu breeding. If amount of the feeding is reduced, amount of injected MA in the core is also reduced. Second is reducing the Pu ratio by separating Pu and MA instead of TRU.

### *4.1 System Performance for (U-TRU)$Cl_3$ Feeding Scenario*

This option is that the (U-TRU)$Cl_3$ fuel is loaded only in the initial core and feeding is the (TRU)$Cl_3$ fuel. As listed in Table III, FFHS with constant k-eff was designed then performances were compared on the ratio of U. Feeding options represent the ratio of U. Amount of the feeding is reduced by adding U fuel through fissile breeding of $^{238}$U. This effect is proportional to the ratio of U. As a result, amount of the produced MA is reduced, however the reduced amount is very slight. Adding U leads to decreased TBR. Flux in the TBZ is reduced because amount of the absorbed neutron in the fuel zone is increased by absorption of U.

Table III: Mass variation, k-eff and tritium breeding performance on (U-TRU) feeding options.

| Feeding option | 3.23 kg/day | U40 | U50 | U60 |
|---|---|---|---|---|
| U / TRU fraction in the fuel salt | w/o U/ 0.1 | 0.11/ 0.16 | 0.19/ 0.19 | 0.33/ 0.22 |
| Initial loading [TRU/U] (kg) | 20400 | 20400/ 13500 | 20300/ 20200 | 20400/ 30400 |
| Total feeding mass (kg) | 7760 | 6090 | 5610 | 4810 |
| Total fuel mass (kg) | 28200 | 40000 | 46110 | 55610 |
| K-eff [BOC/EOC] | 0.94311/ 0.95202 | 0.95253/ 0.95360 | 0.95506/ 0.95346 | 0.95345/ 0.95414 |
| U (kg) | | -521 | -745 | -1060 |
| Np (kg) | -435 | -388 | -368 | -342 |
| Pu (kg) | -4410 | -3660 | -3350 | -2890 |
| Pu w/o $^{239}$Pu (kg) | -784 | -761 | -745 | -717 |
| Am(kg) | 160 | 154 | 153 | 154 |
| Cm (kg) | 103 | 90.6 | 86.9 | 81.8 |
| Number of consumed T | 1.69E27 | 1.5E27 | 1.5E27 | 1.49E27 |
| Number of produced T | 4.86E27 | 4.82E27 | 4.75E27 | 4.64E27 |
| TBR | 2.87 | 3.22 | 3.18 | 3.13 |

### *4.2 System Performance for (Pu-MA)$Cl_3$ Feeding Scenario*

As listed in Table V, performance evaluation on the ratio of MA was performed. The feeding options represent the ratio of MA. Fig. 5. shows the reaction rates of the MA20 option with the lowest MA ratio and the MA80 option with the highest MA ratio within (Pu-MA)$Cl_3$ feeding scenario. There are no significant differences between the 3.23 kg/day option and the MA20 option. The reaction rate with Pu is still high. Transmutation with MA is slightly improved because of the high ratio of MA compared to the 3.23 kg/day option. On the other hand, the reaction rate with the MA80 option is completely different. The capture reaction is dominant compared to fission reaction due to the increased ratio of MA. As a result, constant k-eff is maintained by not fuel feeding but produced $^{238}$Pu through the capture reaction of neptunium. Therefore, amount of the required feeding to maintain constant k-eff is very small. The reaction rate of capture is reduced during the cycle since MA burns. However, the high reaction rate of capture leads to decreased the neutron economy. In consequence, initial TRU loading is increased rapidly and amount of the produced tritium is reduced due to reduced flux in the TBZ. Additionally, Pu is produced by softening flux.

Table V: Mass variation, k-eff and tritium breeding performance on (Pu-MA) feeding options.

| Feeding option | 3.23 kg/day | MA20 | MA40 | MA60 | MA80 |
|---|---|---|---|---|---|
| Initial TRU loading (kg) | 20400 | 22200 | 28700 | 38800 | 49600 |
| Total feeding mass (kg) | 7760 | 7560 | 7560 | 4710 | 982 |
| Total Fuel mass (kg) | 28200 | 29800 | 35200 | 43510 | 50600 |
| k-eff [BOC/EOC] | 0.94311 / 0.95202 | 0.95475 / 0.96042 | 0.95812 / 0.96609 | 0.95376 / 0.96003 | 0.95330 / 0.96044 |
| Np (kg) | -435 | -589 | -1280 | -2080 | -3150 |
| Pu (kg) | -4410 | -4050 | -2440 | -489 | 2220 |
| Pu w/o $^{239}$Pu (kg) | -784 | -611 | 409 | 1630 | 3310 |
| Am(kg) | 160 | -17.7 | -852 | -1880 | -3330 |
| Cm (kg) | 103 | 115 | 185 | 203 | 217 |
| Number of consumed T | 1.69E27 | 1.4E27 | 1.41E27 | 1.21E27 | 1.35E27 |
| Number of produced T | 4.86E27 | 4.8E27 | 4.35E27 | 3.78E27 | 3.54E27 |
| TBR | 2.87 | 3.43 | 3.07 | 3.13 | 2.61 |

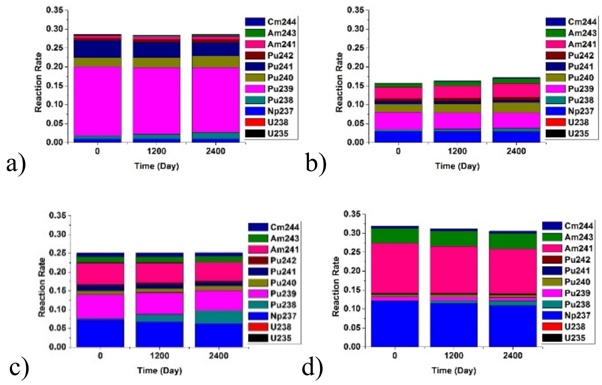


Fig. 5. Reaction rate of fission and capture on (Pu-MA) feeding scenarios;
a) fission - the MA20 option,
b) capture - the MA20 option,
c) fission - the MA80 option,
d) capture - the MA80 option.

## 5. Conclusions

In this paper, FFHS with constant k-eff by online-feeding of the molten salt fuel was designed. It is because change of the required external source rate can be reduced by control the k-eff. At first, comparison evaluation for performance on the feeding rate of TRU fuel with pyro-processing was conducted. The reactivity swing and amount of the consumed tritium are reduced as the feeding rate increases. However, only transmutation with Pu is dominant because most of neutrons react with Pu in the TRU. As a result, transmutation with MA is degraded. Since the reaction rate with MA is reduced and amount of MA in the core is increased by the feeding.

Therefore, comparison evaluation for performance on the feeding scenarios in order to improve the transmutation of MA was conducted. U fuel was added in the initial core to reduce amount of the required feeding for constant k-eff. As a result, there is a no significant difference on the transmutation performance, although amount of the required feeding is reduced. TBR is reduced because number of absorbed neutron in the fuel zone is increased by U fuel. Feeding option of separating Pu and MA leads to completely different result. As the ratio of MA increases, constant k-eff is maintained by not fuel feeding but the increased fission reaction of $^{238}$Pu. As a result, amount of the required feeding is significantly reduced. While, the capture reaction is dominant in the system due to the high ratio of MA. Therefore, Pu is produced and number of produced tritium is reduced because of decreased flux in the TBZ.

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