Spent Nuclear Fuel Option Study on Hybrid Reactor for Waste Transmutation

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1. Introduction

SNF (Spent Nuclear Fuel) disposal is one of the problems in the nuclear industry. Using interim storage facility is not permanent solution, because most of nuclides in SNF have high radioactivity and long half-life. Therefore, reusing of SNF through reprocessing as a nuclear fuel has been actively researched.

FFHR (Fusion-Fission Hybrid Reactor) is one of the most attractive option on reuse of SNF as a waste transmutation system. Because subcritical system like FFHR has some advantages compared to critical system. Subcritical systems have higher safety potential than critical system. Also, there is suppressed excess reactivity at BOC (Beginning of Cycle) in critical system, on the other hand there is no suppressed reactivity in subcritical system.

Our research team could have designed FFHR for waste transmutation; Hyb-WT [1]. Various researches have been conducted on fuel and coolant option for optimization of transmutation performance [2], [3].

However, Hyb-WT has technical disadvantage. It is required fusion power (P_{fus}) which is the key design parameter in FFHR is increased for compensation of decreasing subcritical level. As a result, structure material integrity is damaged under high irradiation condition by increasing $P_{fus.}$ Also, deep burn of reprocessed SNF is limited by weakened integrity of structure material.

Therefore, in this research, SNF option study will be conducted on DUPIC (Direct Use of Spent PWR Fuel in CANDU Reactor) fuel, TRU fuel and DUPIC + TRU mixed fuel for optimization of Hyb-WT performance. Goal of this research is design check for low required fusion power and high waste transmutation.

In this paper, neutronic analysis is conducted on Hyb-WT with DUPIC nuclear fuel. When DUPIC nuclear fuel is loaded in fast neutron system, supplement fissile materials need to be loaded together for compensation of low criticality level. In this paper, (U-10Zr) fuel is loaded as supplement fissile material.

MCNPX 2.6.0 with ENDF/B-VII.0 neutron cross section library is used for computational analysis.

2. Design of the Hyb-WT with DUPIC

Hyb-WT with DUPIC is designed based on Hyb-WT [1]. Some parts of subcritical blanket design are changed suitable for DUPCI fuel.

MCNPX modeling of Hyb-WT with DUPIC is shown in Fig. 1. Design parameters of Hyb-WT with DUPIC subcritical fission blanket are listed in Table Ⅰ and detail design parameters on plasma and blanket are listed in reference [1]. TBZ (Tritium Breeding Zone) is designed in inner blanket and outer blanket because Pb-Bi is used as a coolant in Hyb-WT with DUPIC. Be zone is designed for neutron multiplication in front of TBZ. If LiPb is used as a coolant, many neutrons are absorbed in Li for tritium breeding. As a result, Hyb-WT with DUPIC has low subcritical level. (U-10Zr) fuel which U-235 is enriched 18 w% is loaded for compensation low subcritical level. DUPIC nuclear fuel composition comes from reference [4].

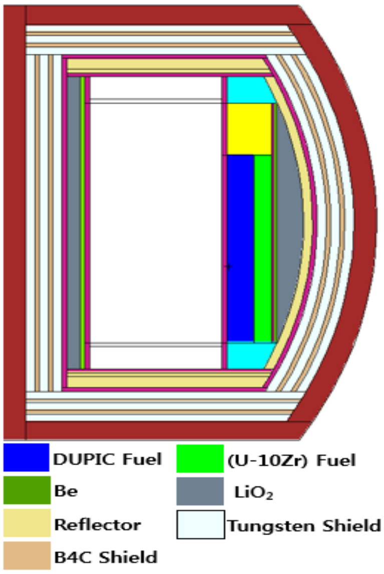

Figure 1. MCNPX Modeling of Hyb-WT with DUPIC.

Table Ⅰ. Material Specification of Hyb-WT with DUPIC.

Region	Thickness (cm)	Composition (%)
DUPIC Fuel Zone	29.1	DUPIC:36; Coolant:32; SiC: 6.03; Clad: 13.86; Pb-Bond: 12.1
(U-10Zr) Fuel Zone	38.8	U-10Zr:36; Coolant:32; SiC: 6.03; Clad: 13.86; Pb-Bond: 12.1
Structure Wall	3	ODS Steel(MA957):70; He-gas:30
LiO_2 Zone	15, 29	Li: 20 (Li6:18, Li7:2); O:40; He-gas: 40
Be Zone	5	Be: 70; He-gas:30
Tungsten Shield	10	W (W182:26.5; W183:14.3 W184:30.7; W186:28.5)
B_4C Shield	5	B (B10:16; B11:64; C:20)

Superconductor Toroidal MF Coil	20	Nb93:70; Sn116:5; Sn117:2.6; Sn118:8.3; Sn119:2.9; Sn120:1.1; He:10.1
Reflector	20	C:90; He-gas:10

3. Neutronic Analyses

Neutron analyses are conducted on subcritical level, neutron flux, EM (energy multiplication) factor and mass variation.

3.1 Subcritical Level

K_{eff} level with increasing time is shown in Fig.2. It is increased by fertile conversion to fissile material as a result, required P_{fus} is decreased from 47MW to 26MW. Required P_{fus} is calculated from equation (1) [5]. ν is neutrons produced per fission. E_{fis} is released energy per fission reaction and E_{fus} is released energy per fusion reaction. K_m is multiplication factor.

K_{eff} does not exceed maximum subcritical level (0.98), therefore Hyb-WT with DUPIC can be operated during more long cycle.

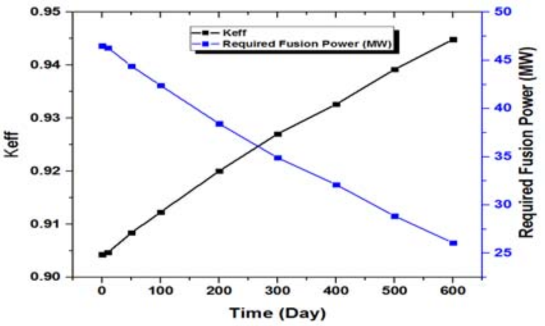

Figure 2. K_{eff} value with increasing time.

$$P_{fus} = \frac{E_{fus}}{E_{fis}} \nu \frac{(1-k_m)}{k_m} P_{fis} \qquad (1)$$

3. 2 Neutron Flux

Neutron flux depending on radial direction from plasma at BOC is shown in Fig. 3. Thermal neutron flux with (U-10Zr) fuel zone is lower compared to DUPIC fuel zone by fission reaction of fissile materials.

Flux with Be zone is moderated compared to (U-10Zr) fuel zone, it can be good for tritium breeding.

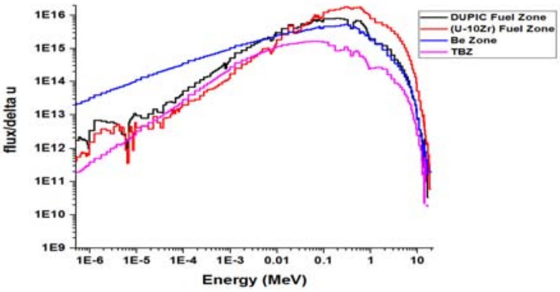

Figure 3. Neutron Flux at BOC.

3. 3 Energy Multiplication Factor

The EM is the key parameter in Hybrid for energy production system. High EM is advantage in fission blanket because it makes the plasma parameter easy to achieve [4]. EM with Hyb-WT with DUPIC is more than 50. It is grateful performance because when the power is 3000MW$_{th}$, minimum EM is 6. However, large swing of EM may cause difficulty of plasma operation.

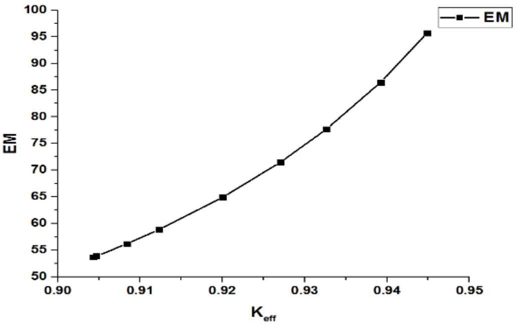

Figure 4. EM with increasing keff.

3. 4 Mass Variation

Total mass variation of actinides is 0.15ton (0.24%) in DUPIC fuel and 1.52ton (1.62%) in (U-10Zr) fuel. Long lived actinides (half life > 100 years) are burned 1.69ton (2.71%) and middle lived actinides (10 years < half life ≤100 years) are produced 18.9kg (55.4%) in DUPIC fuel.

Mass variation of actinides are shown in Fig 5, 6 and 7. The most remarkable variation is U-235, U-238 and Pu-239 in Fig. 5. U-238 is converted to Pu-239 by neutron capture, it is fissile breeding effect. Therefore, k_{eff} level of Hyb-WT with DUPIC is increased with increasing time. And fissile breeding effect can make long cycle length of the reactor. U-238 in DUPIC and (U-10Zr) fuel is burned about 2.5% of the initial mass.

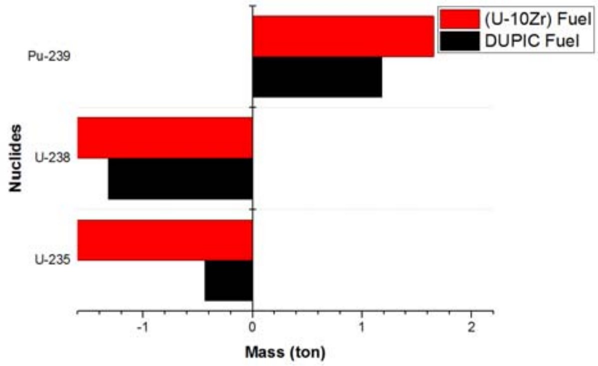

Figure 5. Mass Variation of Actinide.

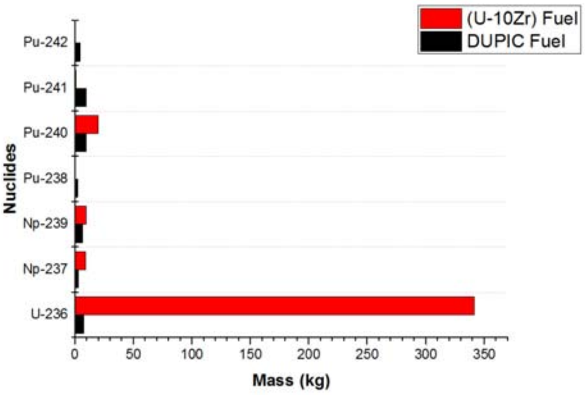

Figure 6. Mass Variation of Actinides.

Nuclides in Fig. 6 are produced. U-236 in (U-10Zr) fuel is produced from U-235 by neutron capture.

Breeding effect from Th-232 to U-233 in DUPIC fuel can be shown in Fig. 7. Am-242 in DUPIC fuel is converts to Cm-243.

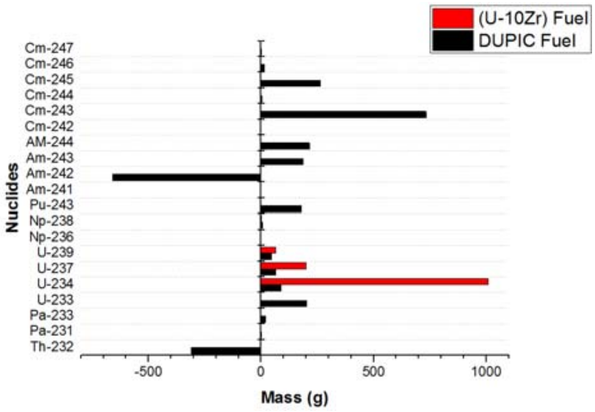

Figure 7. Mass Variation of Actinides.

4. Conclusion

DUPIC nuclear fuel can be used in hybrid reactor by compensation of subcritical level through (U-10Zr) fuel.

Energy production performance of Hyb-WT with DUPIC is grateful because it has high EM factor and performs waste transmutation at the same time.

However, waste transmutation performance should be improved by different fissile fuel instead of (U-10Zr) fuel. Because (U-10Zr) fuel also makes high level waste.

Subcritical level is increased with increasing time by fissile breeding, as a result, long time operation is feasible.

However, more detail analyses are required on heat removal capability, activation analysis, structure material analysis during more long cycle.

REFERENCES

[1] M. Tariq, et al., Conceptual design study of Hyb-WT as fusion–fission hybrid reactor for waste transmutation, Annals of Nuclear Energy 65 (2014) 299–306.

[2] M. Tariq, et al., Physical investigation for neutron consumption and multiplication infusion–fission hybrid test blanket module, Fusion Engineering and Design 89 (2014) 2679–2684.

[3] S. HONG, et al., Transmutation performance analysis on coolant options in a hybrid reactor system design for high level waste incineration, Fusion Engineering and Design 100 (2015) 550–559.

[4] G. SONG, et al, Irradiation Test and Performance Evaluation of DUPIC Fuel, KAERI/RR-2236/2001, Final report.

[5] W. M. Stacey, Tutorial Principles and Rationale of the Fusion-Fission Hybrid Burner Reactor, in FUNFI-2011 (Fusion for Neutrons and Sub-Critical Fission Systems), Varenna, Italy, Sep. 13, 2011.